Section II – Iron Technology

Vibha Tripathi and R Balasubramaniam with Delhi Iron Pillar

Vibha Tripathi
Iron lumps formed from the ancient copper smelting: An example from Naganobori, Japan

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ABSTRACT The iron lump formed from copper smelting at the ancient Naganobori mine, Japan, was compared with the iron-copper alloy produced by the replication experiment and also with the iron lumps unearthed from an ancient bronze casting workshop. The compositions of the metals and matte in the iron lumps from three cases are similar in each other. The iron contains 1.4-10 % Cu. The copper contains 0.4-4 % Fe. The bornite solid solution consists of two phases, dark phase (ca. 58 % Cu) and light phase (ca. 66 % Cu). The carbon content of the iron varies from less than 0.01 to over 0.77 %. The important factor for the formation of iron lumps is the presence of a small amount of sulfur in higher-temperature reducing conditions.

Introduction

The use of man-made iron gradually increased in the second millennium BC and it became on a large scale in 1200-1000 BC in regions of the eastern Mediterranean (Waldbaum, 1999, p. 32; Tylecote, 1992, p.47). It is, however, still not known when and where iron was intentionally smelted from iron ores in the Bronze Age. Iron was formed frequently as a byproduct of copper smelting (Gale et al., 1990; Hauptmann, 2007, p. 207), and copper-smelting sites might be mistakenly interpreted as iron smelting remains. It is therefore important to know the characteristics of the byproduct iron.

Naganobori

The Naganobori mine site lies in Mito-cho, Yamaguchi-ken, southwest Japan. In the 8th century copper from the mine was used for casting a huge bronze statue of Buddha (AD 749) at the Todaiji temple in Heijokyo (present Nara city). The Naganobori mine site lies in the eastern foot of a limestone plateau, Akiyoshidai. There are several small copper skarn deposits at the eastern edge of the Akiyoshi limestone plateau. The deposits were formed around a granite porphyry stock of the Cretaceous age. The primary ore minerals are mainly chalcopyrite with bornite, tetrahedrite, magnetite, pyrite, pyrrhotite and arsenopyrite. In the weathered profile, oxidized ore is capped by reddish-brown limonite (gossan).
Unearthed materials from the Ōgiri smelting site include ores, slags and fragments of furnace. The result of the observation of more than one hundred unearthed ores revealed that ores were classified into two types; malachite-bearing garnet skarn ore and copper-bearing limonitic ore (Yoshikawa et al., 2005, p.33; Izawa, 2009). Garnet skarn ores are disseminated by malachite and chrysocolla and contain 3 to 10 % Cu and less than 10 ppm to 53 ppm As. Limonitic ores consisting of goethite and hematite contain 1 to 18 % Cu and are often rich in arsenic (0.4 to 11 % As).

Arsenic minerals were identified as olivenite \( (\text{Cu}_2\text{AsO}_4\text{OH}) \) and cornwallite \( \text{Cu}_5(\text{AsO}_4)_2(\text{OH})_4 \). There is no sulfide ore, though a small amount of partially oxidized chalcopyrite occurs in some samples. Table 1 shows the chemical composition of representative ores, which were unearthed from the Ōgiri site.

### Table 1. Composition of ores and slags (XRF analyses).

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Naganodori (8th century)</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>030820-6</td>
<td>030823-7</td>
</tr>
<tr>
<td>Malachite</td>
<td>SiO(_2) (%)</td>
<td>TiO(_2)</td>
</tr>
<tr>
<td>are</td>
<td>42.11</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Limonitic</td>
<td></td>
<td>0.01</td>
</tr>
<tr>
<td>are</td>
<td>42.25</td>
<td>0.01</td>
</tr>
<tr>
<td>Slag*</td>
<td>55.20</td>
<td>0.10</td>
</tr>
<tr>
<td>Slag**</td>
<td>0.10</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Total Fe is expressed as Fe\(_2\)O\(_3\) or FeO; = not determined. *Outside of the iron, **Furnace bottom slag.

The iron lump was microscopically examined and analyzed using EPMA. Coexistence of iron and copper with a small amount of matte is a characteristic of the iron lump (Fig. 3). Osawa (2008, p. 87) examined etched structures of iron and concluded that the central part of the iron was ferrite (\(\alpha\)-iron: <0.01 % C) but rimmed by pearlite (0.77 % C). Iron contains 4.0 to 9.9 % Cu and copper contains 1.8 to 4.2 % Fe in solid solution, plus invisible minute inclusions.

The matte phase is bornite solid solution consisting of two phases. The curved irregular shaped dark phase exsolved from the originally

### Table 2. EPMA analyses of iron, copper and bornite solid solution in the iron lump from the Naganobori (8th century) slag. Sample 030820-17a.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Iron</th>
<th>Copper</th>
<th>bornite-ss</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dark</td>
<td>Light</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P1</td>
<td>P2</td>
<td>P3</td>
</tr>
<tr>
<td>Cu (%)</td>
<td>4.03</td>
<td>5.98</td>
<td>9.94</td>
</tr>
<tr>
<td>Fe</td>
<td>92.80</td>
<td>90.53</td>
<td>90.21</td>
</tr>
<tr>
<td>S</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>96.83</td>
<td>96.51</td>
<td>100.15</td>
</tr>
</tbody>
</table>
homogeneous bornite solid solution. The dark phase is relatively copper poor and contains 57.6 to 59.2 % Cu. The light matrix phase contains 64.6 to 65.9 % Cu (Table 2).

In other slag samples there are several small prills of metal and matte. Some metals are As-rich copper (17 % As) and others are Sn-rich copper (11 % Sn).

**Replication experiment**

A replication experiment of ancient copper smelting was performed at Naganobori in November 2006, using Chilean malachite ore and copper-bearing limonite from Naganobori itself (Izawa et al., 2009). They were pelletized with calcium carbonate and the ore pellets were prepared for smelting. A shaft furnace, 97 cm in height and with an inner diameter of 37 cm, was constructed (Fig. 4). About 60 kg of ore pellets and an equal weight of charcoal were used for smelting and slag was tapped three times during a 4 hours and 30 minutes operation.

After the furnace cooled, its upper part was broken and layers of un-melted ore pellets were removed (Fig. 5). Osawa (2008, p. 75) examined the reaction process at the beginning of smelting using one of the pellets. The pellet consists of quartz, kirshsteinite (CaFeSiO₄), magnetite, copper and iron, with small amounts of cristobalite, and glass. Copper - with a small amount of iron and magnetite - was formed in a fragment of original malachite (Fig 6) and many minute grains of iron with a small amount of copper were formed in a fragment of original limonite.
A mass of a mixture consisting of copper, iron, slag and charcoal was recovered from the furnace bottom (Fig 7). The whole mass is 30 kg in weight, 35 cm wide and 12 cm thick. Iron-rich Cu-Fe alloy occurs in the upper portion and copper-rich alloy occurs near the bottom.

The iron content of slag decreased from early tapped slag (19 % FeO) to the slag that stayed on the furnace bottom (12 % FeO: Table 1) indicating that the iron-copper alloy reacted with the surrounding slag and extracted iron from the slag on the furnace bottom. Fayalite is the major constituent phase in early tapped slag and ferrowollastonite is the major constituent phase in slag that stayed with metals on the furnace bottom.

The constituent phases of the Cu-Fe alloy are copper, iron and matte (bornite solid solution) and the same as those of the ancient alloys (Figs, 8 and 9). The compositions of the metals and matte are also similar to those determined in ancient materials (some representative compositions are shown in Table 3). Iron contains 1.4 to 2.8 % Cu and 3.9 to 8.8 % As. Copper contains 0.4 to 2.8 % Fe and 0.3 to 3.2 % As. The bornite solid solution consists of two phases, dark phase (57.0 to 59.2 % Cu) and light phase (64.2 to 67.2 % Cu).
Iron shows a carbon content similar to that of the ancient iron lump (Osawa, 2008, p.64-67) which varied from less than 0.01% C (ferrite = α-iron) to over 0.77% C. High carbon steel was formed at the contact place with charcoal and was often associated with Fe$_3$P.

Replication experiments at Naganobori were repeated several times before November of 2006. During the experiment in August of 2006, a miniature (1/30) of the Nara great Buddha was cast at Naganobori using modern copper and tin. At that time a piece of iron-rich copper (180 g in weight), formed in one of the replication experiments, was thrown into molten copper in a crucible as an additional casting metal. The copper dissolved immediately, and three pieces of iron lumps floated on the surface of the molten copper (Fig.10). The iron was removed from the molten copper. The weight of the iron was 120 g, indicating that 60 g of copper were separated from original alloy. The iron was a waste material for the purpose of casting the statue. It is conceivable that iron lumps were similarly thrown away as useless materials in ancient copper casting sites or refining sites.

### Iron lumps from Kajiyashiki

The Kajiyashiki site is an ancient (8th century) workshop for copper casting. The site is located in Kōka-shi, Shiga-ken, near the old capital Heijokyo (Nara). A large number of iron lumps were unearthed from the site, together with copper objects and slag in 2004.

![Figure 11. Photograph of iron lumps unearthed from Kajiyashiki](Shiga-ken Board of Education, 2006, Plates 121 and 122)

Osawa and Suzuki (2006) reported the results of the metallurgical investigation on seven samples of iron lumps, with sizes ranging from 6 to 18 cm in length and from 75 to 1370 g in weight (Fig. 11). The appearance, size, chemistry and mineralogy of the iron lumps from Kajiyashiki resemble the iron lumps of the replication experiment and from ancient Nagano. Iron, copper and bornite solid solution were analyzed by electron microprobe (Osawa and Suzuki, 2006, Plates 180 and...
Discussion

The formation process of the iron lump can be interpreted on the basis of phase relations in the copper-iron-sulfur system by Schlegel und Schüller (1952). In the ancient copper smelting at Naganobori and also in the replication experiment, the ore contained ca. 10 % Cu, 0.1-0.8 % S, and over 20 % of the total Fe with a few % of As. At least three liquid phases coexisted in the furnace at 1200°C, that is, copper-rich liquid, matte liquid and slag liquid. A small amount of sulfur in the copper-rich liquid helped the formation of a Cu-Fe alloy reacting with the iron present in the slag. At around 1300°C, the Cu:Fe ratio in the alloy reached almost 50:50.

During the cooling period the iron (γ-Fe) solidified and separated from the Cu-Fe alloy, leaving copper-rich liquid and a small amount of matte liquid. At around 1077°C the matte solidified as bornite solid solution (Cu₄FeS₃.0₈; 62.2 % Cu) (Fig. 12). Below 1000°C this phase was separated into two phases: a Cu-poor phase and a Cu-rich phase.

The coexistence of iron, copper and bornite solid solution is a common feature seen in iron lumps from the ancient Naganobori and the replication experiment (Fig. 12). The iron contains a few % of Cu and the copper contains a few % Fe. The matte phase (bornite solid solution) shows complicated exsolution textures. Although the electron microprobe data of Kajiyashiki do not fit the proper single-phase area on the Cu-Fe-S diagram, the data suggest the existence of two-phase bornite solid solutions (Fig. 12).

The most important factor for the formation of iron lumps is the use of iron rich copper ores and the existence of a small amount of sulfur. Craddock and Meeks (1987, p. 198) emphasized the role of sulfur in significant quantity (>2 %). However, even less than 1 % of S is sufficient for the production of an iron-rich Cu-Fe alloy. In the case of the replication experiment, an iron-rich alloy was produced from the sulfur poor ore (22 % Cu, 77 % Fe and 0.8 % S as calculated ratio). The Cu-Fe-S diagram (Schlegel und Schüller, 1952, p. 424) indicates large compositional range of Cu-Fe alloy (liquid) above 1300°C.

Many skarn deposits have an oxidized outcrop (gossan) which sometimes is rich in copper as at Naganobori. In the higher temperature operation with high fuel ratio, the iron-rich copper ore will be reduced to form a Cu-Fe alloy containing a few % of S. On the furnace bottom the Cu-Fe alloy grows by extracting iron from the surrounding slag (liquid). Products will be iron-containing copper, copper containing iron and a small amount of matte (bornite solid solution). Finally liquid copper and liquid matte with a low melting temperature flow downward leaving a solidified iron lump. This liquation of copper from a Cu-Fe alloy can produce a very iron-rich lump in the upper portion of the mass on the furnace bottom.

Figure 12. Plot of the compositions of iron, copper and bornite solid solution on the Cu-Fe-S diagram of Schlegel und Schüller (1952). Representative compositions of phases were selected for the iron lump in the ancient Naganobori slag (sample 030820-17a) (Table 2), the Fe-Cu alloy formed from the replication experiment (sample 061105-1a3) (Table 3), and iron lumps from Kajiyashiki remains (Osawa and Suzuki, 2006, Plates 180 and 181). The stable phase at 1077°C, Cu₄FeS₃.0₈, is shown by small dot. The lower temperature phases are bornite solid solution (bn-ss), intermediate solid solution (iss), pyrrhotite (po; Fe₈₋₁₋₋₋₋S), chalcocite (cc; Cu₂S), bornite (bn; Cu₅FeS₄) and chalcopyrite (cp; CuFeS₂).
Crude copper produced from iron-rich copper ore contains several % of iron which will be lowered to about 0.5 % by simple remelting (Craddock and Meeks, 1987, p. 192). Refining by simple remelting was probably a necessary process in copper-casting workshops such as Kajiyashiki. If crude copper contained an iron rich Cu-Fe alloy, the iron lumps would float on the molten copper during remelting. The separated lump of iron was a waste material and was rejected around the casting site.

Conclusions

1. Iron lumps are frequent by-products from smelting iron-rich oxidized copper ores.
2. The important factor for the formation of iron lumps is the presence of a small amount of sulfur in higher-temperature reducing conditions.
3. Sulfur remains as matte (bornite solid solution) coexisting with copper and iron.
4. The bornite solid solution has the average composition of about 62 % of Cu and shows a lamellar texture formed during cooling.
5. The carbon content of the iron lumps varies from less than 0.01 % C (ferrite = $\alpha$-iron) to over 0.77 % C.

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References

Mass and Heat Balance of Pig Iron Making by Tatara

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ABSTRACT Tatara had been the Japanese traditional technology for making pig iron and high carbon steel bloom in a row. The furnace is made of clay in box type with 1.2m height, about 3m length and about 1m width. In one campaign during about 70 hours, 1.5 tons of pig iron called “Zuku” and 1.5 tons of high carbon steel bloom called “Kera” had been produced from 12 tons of iron sand and 12 tons of charcoal. “Noro” was fayalite slag composed of about 35 mass% silica and about 55 mass% FeO including about 10 mass% TiO₂. The silica came about 40% from iron sand and about 60% from clay of furnace. The clay in the lower part of furnace was eroded by “Noro” and the thickness of lower part of wall gradually became thin. After about 70 hr, the furnace was broken. About 50% of iron in iron sand became pig iron and bloom and the other became “Noro”. Almost 50% of oxygen in blown air passed through the furnace without burning charcoal. About 50% of heat produced from charcoal burning was wasted in out gas, about 20% was radiated from furnace wall and about 10% was the latent heat of slag and about 10% was that of pig iron and bloom. The fuel ratio was about 4 and the heat efficiency of Tatara was almost same as a charcoal blast furnace in Europe in 18 century.

The History of Tatara

Tatara is the Japanese traditional technology for making pig iron and high carbon steel bloom in a row. The technology of Tatara was transferred from China to Japan through Korea in the late 6th century AD and was perfected in the Middle Edo Period. The commercial production of Tatara ended in 1923, but the old Japanese army continued to produce it until 1945, at the end of World War II, in order to obtain good quality steel, the so called “Tama Hagane”, for making Japanese swords. In 1969, 24 years after the end of the Tatara production in 1945, the Iron and Steel Institute of Japan reconstructed the “ISIJ Tatara” furnace in the Sugaya village, Shimane prefecture, and studied the operation technique. In 1977, the Society for Preservation of Japanese Art Swords reconstructed the “Nitoho Tatara” in Yokota, Shimane prefecture. Since then, Tatara furnaces have been in action for 3 campaigns in every winter season.

The Construction of Tatara furnaces

The Tatara furnace is made of clay, and is of box type, with 1.2m height, about 3m length and about 1m width (fig.1). They have 40 tuyeres installed in the lower part of the two longer walls. Cold air is blown through bamboo pipes, called “Kiro Kan”, from a distributor, called “Tsuburi”(fig.2). Two bellows, called “Tenbin Fuigo”, actioned by human power are installed on both sides of the Tatara furnace (fig.3). Very fine powder of iron sand and charcoal lumps are loaded every 30 minutes. Until 1945, in one campaign of around 70 hours, 1.5 tons of pig iron called “Zuku” and 1.5 tons of high carbon steel bloom called “Kera” were produced by employing 12 tons of iron sand and 12 tons of charcoal. Since 1977, the “Nitoho Tatara” has produced 2.5 tons of “Kera” and some “Zuku” from 10 tons of iron sand and 10 tons of charcoal.
Underground construction

In order to obtain a high temperature zone in the furnace and because of the endothermic reaction, humidity should be prevented from vaporizing inside the furnace. The underground construction of the Tatara furnace is called “Tokotsuri” (fig.4) and is divided in upper and lower part by a “Kawara”, a dense clay layer in which water does not penetrate. In the upper part, there is a “Hondoko”, consisting of a charcoal bed under the Tatara furnace, and two “Kobune” (tunnels) on both
sides of the furnace. The upper system has the function of drying the furnace during the operation. The charcoal of the “Hondoko” absorbs water from the clay of the furnace and acts as an insulator. As the “Kobune” is always kept at about 40 during the operation, heat and humidity flow from the furnace to the “Kobune” and disperse outside. In the lower part, under the “Kawara”, there are layers of charcoal, a mixture of stones and sand, and a drain in the center of the bottom. The lower system had the function of stopping and draining water from the underground.

Power of the bellows

In ancient times in Japan, the box type bellow with a piston, called “Fukisasi Fuigo”, was used. In the middle ages, a seesaw type bellow called “Fumi Fuigo” (fig.5) was used. In 1719, the “Tenbin Fuigo” bellow (fig.3) was invented and the air blowing improved. One or two workers, called “Banko”, stood in the center of the bellow and pushed two wooden pedals that activated it. The workers on both “Tenbin Fuigo” bellows pedaled according to the frequency of the human breath, and coordinated by the rhythm of the Tatara song. Professor Kuniichi Tawara investigated the Tatara works and their operations in the late of Meiji period. The size of one wood plate in “Kotoribara Fumi Fuigo” was 1590 mm x 848 mm and the maximum depth of step was 315 mm. Therefore, the volume of air from one step was 0.212 m$^3$. In the case of the “Tonami” Tatara furnace, with 38 tuyeres on both sidewall, the step rate was 28 times per minute in the early stage of operation and 40 times per minute in the final stage. The maximum rate of blowing was 7.44 l/s per each tuyere. The pressure of air was around 3cm water column, i.e. 294 Pa. The force on one plate was 40.4kg-force and corresponded to a human weight. In the case of the “Ataidani Tatara” in Iwami, the maximum rate of blowing was 9.44 l/s per tuyere and the force on one wooden plate was 39.6 kg-force.

Soft blowing of air preventing iron sand from flying out

In order to prevent the iron sand from flying out, the air had to be blown softly into the furnace. Iron sand and charcoal were also loaded next to the furnace walls so that the high temperature gas passed through the center of the furnace (fig.6). The internal lower part of the furnace had a V shape, and a set of 2 narrow tuyeres faced each other. A strong air blast came into the narrow tuyeres in order to produce a high temperature zone in the burning charcoal. When around 20 parallel sets of tuyeres were installed, the Tatara furnace acquired a box type shape.

High oxygen potential for the reduction of iron sand

High temperature gasses, such as CO, CO$_2$ and N$_2$, were produced by burning charcoal in air. The oxygen
partial pressure in front of a tuyere is about $1 \times 10^{-12}$ atm at around $1350^\circ$C. Under this atmosphere, only iron oxide is reduced to iron and the impurities dissolve as oxides into the molten slag, called “Noro”. Thus, “Zuku” and “Kera” have less impurities (see table 1). In spite of the high oxygen potential, reduced iron powder in contact with burning charcoal absorbs carbon very fast. Thus, molten pig iron - the “Zuku” and then a bloom - the “Kera”- are rapidly produced in around 40 minutes (fig. 7).

![Figure 7 Production of pig iron on burning charcoal: bright dots were pig iron particles](image)

**Table 1** Compositions of pig iron “Zuku” and bloom “Tamahagane” (mass%)

<table>
<thead>
<tr>
<th>Composition</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zuku</td>
<td>3.63</td>
<td>Trace</td>
<td>Trace</td>
<td>0.10</td>
<td>0.003</td>
<td>Trace</td>
</tr>
<tr>
<td>Tamahagane</td>
<td>1.32</td>
<td>0.04</td>
<td>Trace</td>
<td>0.014</td>
<td>0.006</td>
<td>Trace</td>
</tr>
</tbody>
</table>

Note: “Tamahagane” is a good quality steel in the “Kera”.

**Tatara flame**

Air is cyclically blown into the furnace with the rhythm of human breath, and the flame also cyclically rises at the top of the furnace (fig.8). The condition of the Tatara operation can be judged by the color of the flame, the flowing pattern of “Noro”, the round shape of the inside of the tuyeres, and the sound coming from the furnace. Fig. 9 shows the flowing pattern of “Noro” poured from the holes on both sides of the furnace.

![Figure 8 Flame on Tatara furnace](image)

The color of the flame most sensitively changes depending on the furnace condition. There are 4 types of flame color. The best condition produces a golden colored flame, the so-called “Yamabuki Bose” or “Kiwada Bose”. “Bose” means flame. An overload of iron sand is the cause of a blackish flame, called “Kuro Bose”. On the other hand, an insufficient load of iron sand renders the flame reddish, and it is called “Aka Bose”. By these means, the amount of loaded iron sand could be controlled. When a tuyere is clogged and the air cannot pass through, the color of the flame becomes bluish or purplish, and it is then called “Yakan Bose”. In this case, the tuyeres are opened with an iron stick, called “Hodo Tuki”, and repaired so as to achieve a round shape that looks like the moon.

The yellow color of the flame results from the D line of the spectrum of sodium, when sodium oxide is vaporized in the flame. The sodium oxide (Na$_2$O) is included in charcoal ash as stable sodium silicate slag. In this case, the flame is bluish or purplish. When iron sand is loaded, the iron oxide (FeO) dissolves in the silicate slag that turns to fayalite slag; then the activity of sodium oxide in the slag and the vapor pressure increase. During a campaign, the flame color gradually changes from the color of sunrise in the early operation stages to the sunset color in the last stage. The master of the Tatara operation, the so called “Murage”, carefully controls the condition of the Tatara furnace.

**ISIJ Tatara**

The Iron and Steel Institute of Japan reconstructed the “ISIJ Tatara” furnace and worked 3 campaigns to produce “Zuku” and “Kera” from October 25 to November 8 in 1969. The committee for the planning of the Tatara reconstruction in ISIJ (1st chairman Prof. Takao Sasabe and 2nd Prof. Yukio Matsushita) was
nominated in 1967. The masters of Tatara - or “Murage” - were Mr. Yoshiro Horie (83 years old), Mr. Kenjiro Honma (70) and Mr. Daizo Fukuba (83).

Table 2 illustrates the sizes of the furnace and the underground construction of 5 Tatara works. The furnace size of the ISIJ Tatara was 1.1m height, 2.65m length and 0.93m width, and that of the underground construction was 3.18m depth, 6.36m x 6.36m square. These sizes are not so different from those of other Tatara furnaces. The tuyeres were 32 less than in the “Nittoho Tatara”. Air was continuously blown through the tuyeres by an electric bellow. This version was very different from other Tatara.

Mass balance

The weights of iron sand, charcoal and produced “Zuku”, “Kera” and “Noro” for some Tatara works are shown in Table 3. The mass balance for the ISIJ Tatara in the 2nd run was calculated. The amount of dissolved wall was estimated. 4,804kg of Noro was composed of 686.5kg in the first half run, called “Komori” in 22 hrs, 46 min; and 4,117.5kg in the late half run, called “Kudari”, in 48 hrs 35 min. The compositions of “Noro” of the first and late run were 29.57 mass% and 21.11 mass%, respectively. The amount of SiO$_2$ in the “Noro” was 1,072 kg. 1,900 kg of iron sand, named “Akome kogane”, was loaded during the “Komori” period and 5,328 kg of iron sand named “Masa kogane” was loaded during the “Kudari” period. The SiO$_2$ in iron sand was 9.24 mass% in the “Akome kogane”, and 4.24 mass% in the “Masa kogane”, respectively. The amount of SiO$_2$ in iron sand was 401 kg. The difference of SiO$_2$ in the 671 kg came from the dissolved wall. The composition of SiO$_2$ in the wall clay was 66.03 mass%. Therefore, the amount of dissolved wall was 1,016 kg.

The total iron in the “Akome kogane” and the “Masa kogane” were 54.06 mass% and 61.21 mass%, respectively. The amount of iron in “Zuku” was 96.0 mass% and the amount of iron in 310 kg of “Zuku” was 299 kg. The iron in “Kera” was 99.142 mass% and the amount of iron in 1,380 kg of “Kera” was 1,368 kg. The total iron in “Noro” during the “Komori” and “Kudari” periods was 35.29 mass% and 46.50 mass%, respectively. The amount of iron in “Noro” was 2,157 kg. Thus, the total amount of iron in output was 3,824 kg. The difference of iron between input and output was 489 kg. This difference could be the amount of iron sand flying out and corresponds to 11.5 mass% of loaded iron sand. The loss of iron sand is caused from continuous blowing of air because of 1.69 mass% for cyclic blowing by “Tenbin Fuigo”.

The amount of emitted gas was also calculated. The consumed charcoal was 7,689 kg. The composition of carbon in charcoal was 92.19 mass% and the amount of consumed carbon was 7,088 kg. The carbon in “Zuku” and “Kera” was 3.50 mass% and 0.80 mass%, respectively, and the amount of carbon dissolved in “Zuku” and “Kera” was 22 kg. Thus, the amount of burned carbon in air was 7,066 kg. The emitted gas was sampled inside at about 20 cm from the furnace wall and at 20 cm from the top of the furnace. The average of CO, CO$_2$, H$_2$O and N$_2$ in the “Komori” period was 30.7%, 4.4%, 0.9% and 64.0%, respectively, and that in the “Kudari” period was 27.2%, 3.6%, 0.9% and 68.35%, respectively. The emitted gas shows that iron is thermodynamically stable and iron sand is reduced to iron at the temperature between 800°C and 1,500°C.
Burned carbon of 588.8 kmol (7,066 kg) consumed air of 42,340 m$^3$ at 21.5$^\circ$C. On the other hand, as the rates of blown air in the “Komori” and “Kudari” periods were 720 m$^3$/hr and 1,548 m$^3$/hr, the total amount of blown air was 91,600 m$^3$. Thus, about 50% of air passed through the furnace without burning charcoal. In the case of cyclic blowing, only 10% of air passed without reaction.

**Heat balance**

The heat balance for the second run of the ISIJ Tatara operation was reported as shown in Table 4. 95% of the generated heat was the burning heat of charcoal and about 50% of the dispersed heat was the latent heat of emitted gas. Radiation heat from the furnace wall was about 20%, latent heat of the Noro was about 10% and the heat in the furnace at high temperature was 10%.

**Table 4** Heat balance of 2nd run of ISIJ Tatara

<table>
<thead>
<tr>
<th>Kind of heat</th>
<th>Heat (kJ)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input heat</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Burning heat of charcoal</td>
<td>4,018,950</td>
<td>95.5</td>
</tr>
<tr>
<td>Reduction heat of iron ore</td>
<td>28,000</td>
<td>0.7</td>
</tr>
<tr>
<td>Production heat of “Noro”</td>
<td>160,740</td>
<td>3.8</td>
</tr>
<tr>
<td>Total</td>
<td>4,207,690</td>
<td>100.0</td>
</tr>
<tr>
<td><strong>Output heat</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latent heat of “Noro”</td>
<td>459,250</td>
<td>10.9</td>
</tr>
<tr>
<td>Latent heat of “Zuku”</td>
<td>21,530</td>
<td>0.5</td>
</tr>
<tr>
<td>Decomposition heat of H$_2$O in air</td>
<td>114,760</td>
<td>2.8</td>
</tr>
<tr>
<td>Latent heat of out gas</td>
<td>2,180,350</td>
<td>51.8</td>
</tr>
<tr>
<td>Radiation heat from furnace wall</td>
<td>240,410</td>
<td>5.7</td>
</tr>
<tr>
<td>Heat loss from bottom furnace</td>
<td>598,560</td>
<td>14.2</td>
</tr>
<tr>
<td>Heat in furnace and “Kera”</td>
<td>592,830</td>
<td>14.1</td>
</tr>
<tr>
<td>Total</td>
<td>4,207,690</td>
<td>100.0</td>
</tr>
</tbody>
</table>

**Conclusions**

“Noro” is fayalite slag and consists of around 35 mass% of silica and about 55 mass% of FeO, including about 10 mass% of TiO$_2$. About 40% of the silica came from iron sand and about 60% from the clay of the furnace. In the lower part of the furnace the clay was eroded by “Noro” and the thickness of the lower part of the wall was gradually reduced. After about 70 hr, the furnace was broken.

About 50% of iron from the iron sand became pig iron and bloom and the rest became “Noro”. Almost 50% of oxygen in the blown air passed through the furnace without burning charcoal. About 50% of the heat produced from charcoal burning was wasted as gas emission, about 20% was radiated from the furnace wall, around 10% was the latent heat of slag and about 10% was that of pig iron and bloom. The fuel ratio was about 4 and the heat efficiency of Tatara was almost the same of a European charcoal blast furnace of the 18th century.

Tatara is the only smelting furnace in the world that produces molten pig iron and a large bloom from fine powder of iron sand by using a soft blow of air. The flame of the Tatara is a very important signal that allows the control of the operative condition, as are also the fluidity of slag, the sound from the furnace and the round shape of the tuyere.

**References**

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Manufacture, use and trade of late prehistoric iron billhooks from mainland Southeast Asia

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ABSTRACT As part of ongoing research, this paper focuses on the billhooks from Ban Don Ta Phet, a protohistoric cemetery in West Central Thailand. The tools are of such a distinctive type, that it was felt that they could provide an opportunity to track their occurrence over a broad area thus helping to place BDTP within a wider context. Their shape suggests a specific function which might help to increase the understanding of the activities practiced by the individuals buried at the cemetery, be they farmers or merchants from a settled community within close proximity or perhaps a travelling community of traders or migrants. Questions were therefore: What were these billhooks used for? Who were they used by? Where were they made?

Introduction – Archaeological background

Distinctive iron billhooks (Fig.1), dated to the 4th century or early 3rd century BCE were among the 350 identifiable iron tools and weapons excavated in the 1980’s at the protohistoric Iron Age cemetery of Ban Don Ta Phet (BDTP) in Kanchanaburi Province in west central Thailand (Glover et al. 1984; Glover 1990a, Natapintu 1976). The site has produced by far the largest corpus of iron objects from any protohistoric site in mainland Southeast Asia and because virtually all of the objects were derived from a controlled archaeological context (Fig.2), which clearly places them firmly at the beginning of the Iron Age, the site has provided ideal material to:

- Document the technology used in the 4th century BCE or early 3rd century BCE.
- Investigate whether the raw iron material was produced using fairly standardised manufacturing techniques.
- Assess to what degree the manufacture of the objects was consistent within each of the different categories and between them: - socketed digging sticks, bill hooks/ sickles, axes, flat chisels, hollow based arrowheads, socketed arrow heads, tanged arrowheads, harpoons, fish hooks, tanged spearheads, socketed spearheads, tanged knives, tanged rods, ferrules and nails (Bennett 2013a Table 10.1).
- Determine whether the objects which appeared visually similar, were indeed manufactured in the same manner.
- Determine whether the socketed and tanged tools of a particular type, such as the digging sticks, were manufactured in different ways.
- Document whether the more sophisticated and rarer weapons such as the socketed spears were manufactured with a greater degree of skill than the simpler and commoner digging sticks.
- Determine whether there was any evidence of hardening of the working edges or of any heat treatment of the metal.
- Determine whether the objects showed evidence of having been used over prolonged periods of time prior to burial.
- Document the deliberate mutilation which was undertaken of certain objects.
- Assess any evidence as to whether the smelted iron was traded as a raw material, which was then locally forged into the desired tools and weapons.
- Assess the evidence as to whether the smelting and the smithing were both undertaken at central locations with the finished objects being traded to the surrounding areas.
Technology and manufacturing techniques

Because of the long-term preservation problems, the iron objects were carefully documented using photography, illustration and x-radiography. Since it was acknowledged that there were not the resources to allow for long-term preservation of all the material, generous permission was granted by the Thai Fine Arts Department to undertake an extensive sampling program for metallography. Thirty objects were chosen for study either because they were highly representative of a category of object or because they were highly unusual.

Based on this detailed metallographic study, Bennett concluded that the tools and weapons were all forged from good quality bloomery iron. The iron was composed of a piled structure consisting of layers of carbon free ferrite and layers composed of ferrite surrounded by pearlite containing up to 0.7 % carbon (Fig. 3). Regularly aligned slag stringers which ran the length of the samples clearly indicated the direction of working and in some of the more complicated shapes, such as the spearheads, the orientation of the layers and the elongated slag filaments had become contorted during forging (Bennett 2013b Fig. 7).

The manufacture of all of the objects investigated was fairly standardized. The objects which appeared visually similar, were indeed manufactured in the same manner and although the more sophisticated and rarer weapons such as the socketed spears were manufactured with a greater degree of skill than the simpler and commoner digging sticks, the quality of the iron and method of forging remained essentially the same for the whole range of implements.

The carbon present in the finished objects was undoubtedly derived from the charcoal fuel used as a reducing agent during the smelting operation and there was no evidence of any attempt to carburise the working edges of the tools or the weapons. Rather, what seems clear from Bennett’s metallographic study, is that a certain amount of decarburisation during forging was routinely accepted. During hot working some decarburisation would invariably have occurred at the surface of the objects due to the oxidising conditions in the forge and the location and depth of the decarburised surfaces have provided some information as to the manner in which the
objects were manipulated during the smithing. Hammering appears to have been most frequently undertaken from one side, causing the hammered surface to become decarburized (Fig. 4). Where both surfaces of the object had become decarburized, one surface was invariably more depleted in carbon than the other. The outer edges of the decarburised surfaces were usually composed of distorted, ragged ferrite grains with spheroidised pearlite at the grain boundaries, a structure typical of material forged in a falling temperature and left to cool very slowly from about 450°C, possibly in the hot ashes of the forge or at the edge of the smith’s fire. In other samples, Bennett observed austenite grain boundaries and Widmanstätten plates indicating that the objects were forged at a temperature above 850°C and subsequently rapidly air-cooled from this temperature (Fig. 5). Since the working edges of the finished items are invariably thinner than the main body of the objects, these edges would naturally have cooled more rapidly than the matrix. During the final stages of manufacture the thinner edges appear to have been reheated for short periods and worked at a temperature below 723°C with the reheating time being sufficiently short to cause the pearlite in the worked areas to spheroidise, while leaving that in the unworked areas intact.

Evidence of use prior to burial

The comparison of the metallographic structures of the samples removed from the working edges of the objects to those removed from the non-working areas, indicate that the soft wrought iron which was invariably present in the non-working areas was notably absent from the samples removed from the working edges. This absence may be the result of an intentional sharpening of the tools. Alternatively the objects may simply have been used over a sufficient period time so as to afford complete removal of the decarburised zone from the working edge, thus exposing the harder more carbon-rich material.

While it has not been possible to confirm that there was no intentional hardening of the working edges of the objects, the hardness values of Hv 165 - Hv 191 in the main portion of the metallographic sections and Hv 102 - Hv 125 in the lower carbon areas suggests that no significant work hardening was undertaken. A certain amount of cold working and a corresponding increase in the hardness of the metal was recorded in some instances where hardness values of 140 in the decarburized areas were higher than the hardness in the body of the sample. This increase reflects a degree of work-hardening, which probably occurred during the normal use of the tool.

Deliberate mutilation

Evidence of the mutilation of objects from BDTP included 2 out of 23 arrowheads, 15 out of 41 blades, 1 out of 92 digging sticks, 1 out of 8 rods, and 13 out of 23 spearheads (Bennett 2013a Fig.10.8). This mutilation,
which involved folding the iron back on itself may have
been undertaken as a way of preventing looting by grave
robbers or was perhaps associated with religious beliefs.
Examination of the metallography of a selection of these
items has helped to determine that the objects were used
prior to the mutilation rather than, as practiced in the
European Viking period, manufactured purely for ritual
purposes and never intended for use. Iron blades and
spearheads are the two major artefact types that were
mutilated, indicating that this was a practice largely
reserved for the more prestigious objects rather than
the more utilitarian ones. Glover (1990a) and Woods (2002)
have identified possible groupings of the BDTP graves
into kinship links, which may be seen as the beginnings
of social hierarchy and they have documented mortuary
differentiation in terms of the variety of materials used
within the burials.

The metallographic structures of the samples removed
from these deliberately “killed” objects indicated that
the bending back process was undertaken in the hot
state, rather than in the cold state, suggesting that the
people undertaking the mutilation had some knowledge
of and access to forging facilities. However because
BDTP cemetery is a secondary burial site, where the
burials were re-interred with their accompanying objects
in a manner to imitate primary burial, the deliberately
“killed” objects may have been mutilated before being
brought to the area for deposition. Excavations were
able to identify a bank and ditch enclosure of the site
and C14 dates indicate that all the reburials occurred
either as a single event or were undertaken within a
short period of time (Glover 1990a, Glover and Bellina
2012).

Evidence as to whether the finished objects
were traded to the surrounding areas

In view of the large numbers of iron artefacts recovered
at Ban Don Ta Phet, it is tempting to envisage a local
smelting and smithing centre. However, since its
discovery in the late 70’s and repeated excavations
between 1980 and 2000, there is no evidence of any
associated settlements or manufacturing sites in the
surrounding areas. Since the smelting of iron necessarily
generates substantial quantities of waste products in
the form of slag, refractory furnace wall and tuyère
fragments, any smelting sites within the vicinity should
be reasonably easily identifiable. Further, although
iron minerals in the form of lateritic stones are found
abundantly throughout Thailand, these have a low iron
content and Pryce and Natapintu (2009) have argued that
such an ore resource would not have proved sufficient
for successful smelting. However, based on the analysis
of the large amount of smelting slag excavated from
seventeen insitu furnaces at the 4th – 2nd centuries BCE
moated site of Ban Don Phlong in the Mun valley in
Northeast Thailand and at excavations at Non Ban Jak,
a late prehistoric cemetery close to Phimai in Northeast
Thailand this view is not necessarily accepted (Nitta
source might be the rich iron ore deposits of the Wong
Prachan valley in the central plains of Thailand, 200
kms Northwest of BDTP which has significant deposits,
although there is as yet no evidence of any iron smelting
at this date (Bennett 1989; Pigott, Weiss and Natapintu,
1997).

Based on ethnographic parallels our present
understanding of the organisation and division of labour
in the iron industry is that in many societies, smelting
and smithing did not occur in the same production
centre. Rather, the customer needing an object acquired
the raw iron and supplied it to the smith who contributed
his skill in return for part of the raw material as payment
(Marschall, 1968, 150). Raw iron may have been
imported to the BDTP surrounding area and the objects
forged locally according to particular requirements or
alternatively, the iron objects themselves may have
been imported to the region in the same manner as the
sophisticated and rare artefacts such as the high tin
bronze bowls, which are thought to be the result of trade
with India (Rajpitak and Seeley 1979, Srinivasan and
Glover 1995, Glover and Bennett 2012, Glover I.C. and

The earliest written evidence of maritime trade
between India and Southeast Asia comes from an ancient
Chinese text known as ‘The History of the former Han
dynasty 206 BCE – 25 CE which was written in 32 –
92 CE and which contains a passage describing Han
envoys sailing from the modern province of Guangdong
to India with the aim of buying luxury goods such as
pearls and opaque glass. Another passage in the same
text describes the Han court’s failed attempt to open
the overland trade route leading to Daxia (Bactria) by
pacifying the southwestern barbarians. Still another
Chinese account written before 91 BCE clearly indicates
that the Sichan –Yunnan – Burma – India overland trade
route was in use in the 2nd century BCE (Laichen 1997).
It therefore seems possible that the techniques of iron
working may have been introduced to Southeast Asia via
these merchants who were seeking raw materials, such
as the plentiful gold ores (Bennett 2010a and 2010b).

The reburial of the individuals at BDTP belongs to
a period of transition between the Bronze Age tradition
of inhumation burial in Southeast Asia and cremation,
which marks the adoption of Indian ritual culture
(Glover and Bellina, 2012). A period which coincides
with the first appearance of iron in Southeast Asia’s archaeological record (Higham and Higham 2009:table 2) and is also about the time that gold, semiprecious stone polishing and glass working first appear. Since no significant numbers of iron artefacts have been found anywhere else in the area in the last 30 years, and given BDTP’s geographical location, close to the Myanmar border and the overland trade route through the Three Pagoda Pass and to India beyond it seems quite possible that some of the iron objects found at BDTP could have been imported along this route. Indeed socketed iron spearheads, which are very similar in appearance to those excavated at BDTP, have been found in the Samon Valley in Myanmar (Bennett 2013a: Fig. 10.17, Htin 2007) and indeed Myanmar has very extensive resources of viable iron ores.

The billhooks and their archaeological context

As part of ongoing research, this paper focuses on the billhooks from BDTP (Figs. 1, 2, 6). In the first instance because they are such a distinctive object type, it was felt they would provide an opportunity to track their occurrence over a broader area and help place the site within a wider context. Further, since their shape suggests a specific function, ethnographic analogies could increase our understanding of the activities practiced by the individuals buried at BDTP, be they farmers or merchants, from a settled community within close proximity of the cemetery or a travelling community of traders or migrants. Questions were therefore: What were these billhooks used for? who were they used by ? and where were they made ?

Billhooks occur in abundance at BDTP and were present in 23 out of the 53 excavated graves. Statistical analysis of the grave goods has indicated a relationship in their distribution with that of spindle whorls (Woods, 2002). Whether this distribution is reflected in a correlation between gender and billhooks is unclear since poor preservation of organic material made sex determination of the burial remains impossible, and in any event in this period of Southeast Asian prehistory both men and women appear to have been buried with spindle whorls (O’Reilly 2000). The burials with spindle whorls invariably contained agricultural tools, and were present in eight out of twelve graves with arrowheads, one out of the ten graves with harpoons and two out of four graves with fishhooks (Glover 1990a, 175; Woods 2002). The billhooks in the BDTP burials invariably occurred with agricultural tools, which suggests that perhaps they were used as a form of agricultural sickle. More than thirty years after the initial excavations at BDTP only a few other examples of this tool type have been recorded anywhere in Thailand. There have been a few surface finds from Old Kanchanaburi, from near Chansen and from Lopburi. A few examples can be seen in museum collections in both Kanchanaburi and Ratchaburi provinces (Glover 1990a: 160-165) and there is one in the collection of the National Museum of Chumphon (Fig. 7) (Pryce et.al 2006, Bennett 2013a Fig.10.10) which comes from the contemporary river port site of Kao Sam Khaeo in eastern peninsular Thailand some 800 kms to the south of BDTP (Bellina et al. 2006). Bennett documented a handful of these billhooks, during survey work of the tin mining areas towards the Myanmar border (Fig. 8) (Bennett and Glover 1992). The tools had been recovered by tin miners at Khao Chamook (nose mountain), also known as Huai Suan Plu - west of Chombung and at Khao Kwark in Ratchaburi Province, perhaps suggesting that these tools were mining / digging tools.

Figure 6 Drawing of Billhook 73 (3263) sampled in 2 areas. Drawing Anne Farrer reproduced courtesy of Ian Glover

Figure 7 Billhook from Kao Sam Kao, in eastern Peninsular Thailand which is similar to those from BDTP

The name billhook was initially assigned to this tool type by Ian Glover, director of the BDTP excavations throughout the 1980’s, due to its resemblance to a modern billhook/sickle. However, the billhooks from BDTP differ
importantly from traditional billhooks in that their handle has a socket at a 90-degree angle to the blade. The BDTP billhooks occur in three basic sizes and are not dissimilar in shape to the *boti* or *boothi* used for cutting in Bengal and Bihar today (Figs. 9 and 10). The *boti* comprises a vertically positioned iron blade attached to a wooden board placed on the ground and is used in the kitchen to cut vegetables, fish and meat. The person cutting sits on the floor pressing their feet on the board with their hands on either side of the blade holding the food being cut and moving it against the blade. In an attempt to explore further ethnographic analogies to explain the function of the BDTP billhooks, Kathryn Bonnet undertook field studies in Sri Lanka where a kitchen cutting tool similar to a hand held boti is also still fairly common (Bonnet forthcoming). Other tools encountered in Sri Lanka, which resemble the smallest of the BDTP billhooks, are blades used for bark stripping on cinnamon farms, an important economic activity on the island.

Figure 8 Billhook and digging sticks similar to those from BDTP found by local tin miners in Ratchburi Province

Figure 9 Photograph showing the three sizes of *boti* from India. The two on the left are used for meat and vegetables. The small one on the right is for ceremonial use to cut fruit. Photo courtesy of Tathagata Neogi and Kathryn Bonnet

Figure 10 Photograph showing the use of a large *boti* and a wooden mallet to cut the bone section of a fish. Photo courtesy of Tathagata Neogi and Kathryn Bonnet

**Metallographic examinations of the billhooks.**

In an attempt to resolve some of the questions surrounding the manufacture and use of these billhooks, three of examples were sampled in either 2 or 3 areas; 46 (547)(Fig.11) (weight: 169 grams; length: 15 cms), 73 (3263) (Fig.6) (weight: 460 grams; length: 23 cms) and 43 (350) (weight: 350 grams; length: 22 cms).

Figure 11 Photograph of Billhook 46 (547) extensively sampled in 3 areas

Sample 1, taken as an entire cross section of the blade of 46 (547), through the area of the cutting edge
and mounted to expose the lateral direction indicated that the cutting edge was largely composed of acicular ferrite with a high carbon content in the form of spheroidised carbides, a structure indicative of rapid cooling from a high temperature, followed by reheating to, and maintaining at a temperature below 723°C (Fig. 12). A small area of the working edge and the sample removed from the blunt end of the tool were composed of large ragged ferrite grains (ASTM 4) (Figs. 13 & 14) indicating a degree decarburization. The hardness of the cutting edge (Hv 167) was twice that at the blunt end (Hv 86) (Fig. 15). Sample 2, a cross section through the area near the socket where the thickness of the metal was at its greatest, indicated that the shaft has been forged by lapping over a tongue of metal and forge welding it onto the blade, although the welding was not complete. The main portion of the sample was composed of equiaxed α grains (ASTM 4-5) surrounded by lamellar pearlite, which showed the beginnings of spheroidisation. The carbon content in this area was 0.2% while the external surfaces and those on either side of the weld have been completely decarburized and the α grains were significantly larger (ASTM 1) (Fig. 16). The absence of a decarburized zone along the cutting edge of the blade, may perhaps be best explained by the tool having been repeatedly sharpened during use. The other billhooks examined, 73 (3263) and 43 (350), had similar structures although because of corrosion it was not possible to determine whether the blades had been used and / or sharpened.

In order to verify the interpretations derived from the metallographic examinations and to understand the skills of these ancient smiths, Bonnet (2014) worked with two blacksmiths, one in UK and the other in Sri Lanka. Using the information outlined in Bennett’s metallurgical study the procedures to replicate the manufacture of the billhooks were documented using video and written field notes. The aims of the project were to:

- Verify the interpretation of the technology used to produce the billhooks
- Understand the skills needed to manufacture the tools
- Explore how these tools could have been hafted
- Explore the function and potential uses of the BDTP billhooks

Bennett had assumed that the blade of the BDTP billhooks was forged first and that then the socket was formed. However, both blacksmiths found such a
procedure made the forging much more difficult than forging the socket first, which allowed them to hold the socket with tongs while forging the blade. The unusual socket of the billhooks, set at a 90-degree angle to the blade, led Bonnet to instigate a series of trials to investigate how the tools could have been used. The replicated billhooks were hafted using different lengths and types of wood and their effectiveness on different materials evaluated. These will be described by Bonnet in a future publication.

Figure 15 Drawing of the cross section through the billhook 46 (547) showing the hardness of the cutting edge (Hv 167) which was twice that at the blunt end (Hv 86)

Figure 16 Photomicrograph of the sample removed from the socket end of billhook 46 (547) showing the decarburized surface and the large α grains (ASTM 1)

Conclusions

Biggs et al (2013:327) have recently concluded that “Although copper based technologies seem to have become reasonably well developed in mainland Southeast Asia by the mid-first millennium BCE, it seems that there was a clear disconnect in the level of skill displayed in this new material, iron “. The iron from BDTP however, clearly shows that by the 4th century BCE, this metal had in some instances completely replaced bronze for the manufacture of tools and weapons. The present study has demonstrated that these protohistoric smiths were able to produce a wide range of very good quality tools and weapons. They appeared to have paid little attention to the amount of decarburation which occurred during forging since they were able to readily remove the decarburized surfaces from the blade edges during use and or sharpening.

The archaeology of the billhooks indicates that they were a very important element of the material culture assemblage at BDTP and smithing experiments (Bonnet 2014) have clarified the complexity of their manufacture, which had previously been ignored. The high level of skill required to forge the billhook shape might suggest that this tool had a particular use or special role. While it has not yet been possible to identify an obvious use to match this apparent importance, it seems quite possible that these tools were so well adapted as to be suitable for many purposes. The non-standardisation of size of the BDTP billhooks had suggested to Bennett (2013a) that the objects were either forged in a large workshop with many individuals undertaking the smithing, or that they were forged in a variety of smaller independent workshops. Current ethnological observations suggest rather that this variation, which is also apparent in the botis from India, may be due to the adaptations of the tools for different functions (Bonnet forthcoming).

All of the objects examined metallurgically showed evidence of use, and the metallographic structures of the samples removed from the bent sections of the “killed” objects, indicated that the people undertaking this mutilation had some knowledge of forging. The question of where this early and rather sophisticated iron was made however remains unresolved. BDTP is not a primary burial site and the objects may therefore have been imported into the area, having already been used and mutilated.

Iron working could well have followed the trade route from India into Myanmar and Thailand - BDTP is not only close to the tin rich belt near the Myanmar border but is strategically close to the overland trade route of the three pagoda pass which in the 4th century BCE would probably have been accessible by river. Current research – both archaeology and technology, points clearly to a strong link to the Indian sub-continent at this time in prehistory (Bellina 2014, Glover 1990b, Glover and Bellina 2012, Glover and Shahaj Husne Jahan 2014, Higham 2002, 2004, 2014, Manguin 2004, Ray 1994). Noteworthy is that over the last thirty years, the only other examples of these characteristic iron billhooks have been found in the tin mining areas to the west of BDTP and from the ancient port site of KSK on the southern peninsula. Further, both KSK and the area of tin mining at Khao Chamook have also produced rare examples of the characteristic decorated high tin bronze bowls of the type abundantly found at BDTP (Glover and Bellina 2011, Glover and Bennett 2012).
Acknowledgments

Firstly, I would like to express my thanks to Kathryn Bonnet for her interest in the billhooks. Kathryn undertook experimental smithings and hafting trials as part of her MSc in Experimental Archaeology at the University of Exeter under the supervision of Dr. Gill Juleff and these will be published in detail elsewhere. I extend my grateful thanks to Ian Glover for so many useful discussions and for always being willing to help.

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Crucible steel at Hattota Amune, Sri Lanka, in the first millennium AD: archaeology and contextualisation

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ABSTRACT The discovery of a crucible steel manufacturing site and iron smelting sites of the first millennium AD during the survey of an area bordering the Knuckles range of hills in central Sri Lanka is described. The nature of the evidence for both smelting and crucible steel technologies is discussed and comparisons made with earlier published fieldwork at Samanalawewa. The excavation of the crucible steel site is presented along with a discussion of the interpretations drawn from the field evidence.

KEYWORDS: crucible steel, crucibles, Sri Lanka, iron smelting, Middle Historic,

Introduction

The gradual increase in archaemetallurgical fieldwork in South and Central Asia is bringing to light more field evidence for crucible steel manufacturing technologies and with each report our understanding of the nature and extent of this significant technology improves, reducing our over-reliance on documentary sources, many of which are secondary re-workings of a limited number of primary sources. This report describes one such site in Sri Lanka and an outline is given here of the main findings of the Hattota Amune survey in advance of

Figure 1 Map showing location of Hattota Amune survey area relative to the Knuckles and Samanalawewa
more comprehensive treatment of the data and scientific analysis of the crucibles themselves.

The site at Hattota Amune was discovered in 1996 during a reconnaissance survey of the eastern flank of the Knuckles range of hills of central Sri Lanka (Fig. 1). The purpose of the survey was to test the long range continuity of the field evidence for iron production witnessed and recorded at Samanalawewa on the southern edge of the central highlands (Juleff 1996, 1998). The aim was to sample the archaeometallurgical record of a region distant from Samanalawewa and therefore not culturally contiguous but which had similar characteristics and resources in terms of geology and ores, climate and environment. To contextualise the findings of the survey it is necessary to first briefly review the main characteristics of the Samanalawewa record.

Samanalawewa revealed previously unknown evidence of industrial-scale seasonal iron production during the second half of the first millennium AD, based on a low, linear furnace design that was driven by directionally-constant, high-velocity monsoon winds. The many sites of this industry are all located on the leading western edges of hills and ridges with uninterrupted westerly aspects, which is the direction from which the monsoon wind blows, and hence have become known as the west-facing sites and furnaces. Experimental re-enactment of the smelting process established that the furnace was capable of sustaining temperatures in excess of 1400°C and smelting directly to high-carbon steel (Juleff 1996, 1998). The late Middle Historic period of this industry coincides with the Early Islamic period of Western Asia and documentary reference by the contemporary commentator, al-Kindi, to the superior properties of Sarandibi steel (Sarandib being the Islamic name for Sri Lanka) (Hoyland and Gilmour 2006) and it was postulated that the steel being referred to was that produced in the wind-powered furnaces (Juleff 1998, p. 218). The origins of this unusual technology lie in a smaller, multiple-tuyere, proto-linear-design furnace, also from the Samanalawewa area and dated by radiocarbon to the 4th century BCE (Juleff 1998; 2009).

The wind-powered west-facing technology disappears from the archaeological record at Samanalawewa in the 11th century and is replaced by bloomery smelting in small, bellows-driven shaft furnaces located within valley-bottom settlements. Current evidence suggests there is no dynamic chrono-cultural relationship between the disappearance of one technology and the emergence of another. Village-based smelting continues into living memory (Coomaraswamy 1956) and was last practiced in the mid-twentieth century (Juleff 2009a).

Figure 2 Early 20th century crucibles from Samanalawewa. Arrows indicate the positions of vertical and horizontal slag ‘fins’. Enlarged cross-section through crucible shows a rare fragment of an ingot in its horizontal solidification position (from photo by T. Milton, British Museum Photographic Service).
In a further twist of complexity, a very small number of crucible steel sites were also identified at Samanalawewa. These date not from the period of the west-facing industry and Sarandibi steel as might be expected but from the 19th and 20th centuries, and are recorded in contemporary literature (Ondaatje 1854; Coomaraswamy 1956). The five crucible steel making locations recorded fall within two larger extended village settlements and represent separate family-based workshops. By comparison with the industrial-scale crucible steel sites of Karnataka (Anantharamu et al 1999), Andhra Pradesh (Jaikishan 2009) and central Asia (Herrmann et al 1995), these sites are small. The crucibles they used are elongated tubes, c. 187mm length and 34mm diameter, with lids that show perforations and a uniform course brown/black fabric heavily tempered with rice husk (Fig. 2). The ‘fins’ of slag, left adhering to the internal crucible wall, that mark the position of the upper surface of the steel ingot, in these examples indicates that the crucibles were held vertical when in the furnace and then horizontally during cooling so that the final ingot form was of an elongated bar (Fig. 2) (Wayman and Juleff 1999).

One significant absence in the Samanalawewa record is the occurrence of crucible steel sites in the Middle Historic period (defined by Deraniyagala (1992, p.707) as c. 300-1250AD) when the west-facing industry was at its height. This observation, and the interpretations that could be drawn from it, along with the unequivocal dominance of the record by the west-facing technology provided the motivation for sampling a comparable landscape to help to contextualise Samanalawewa.

**Location and setting**

The Knuckles are a range of hills extending as a broad spine northwards from the Central Highlands (Fig. 1). Like Samanalawewa, the Knuckles fall within the Intermediate Zone which means its climate and ecology lies between the extremes of the Wet Zone to the south and west and the Dry Zone of the east and north. Climate and topography suggest that it too would experience high velocity dry winds during the monsoon (June – August) and this was confirmed by local inhabitants. Its vegetation cover is comparable with Samanalawewa and thus likely to support populations of tree species suitable for charcoal fuel. While deposits of iron ore are not geologically recorded for the area, small-scale surface occurrences of good quality mixed oxide ores, formed as a result of tropical weathering, are ubiquitous across much of the island and can be found with relative ease.

The area selected for survey comprised undulating flat land extending north from Pallegama and sandwiched between the eastern flank of the Knuckles and the Kalu Ganga river (Fig. 3). Unlike the Knuckles interior, which is thinly populated with scattered traditional villages akin to those of Samanalawewa, the survey area was uncultivated and devoid of settlements until the mid-20th century when colonisers from all parts of the island were encouraged to the area to reinstate rice cultivation and create new communities. However, the landscape is dotted with archaeological evidence for settlement and monastic sites of the Early and Middle Historic periods and the lack of later villages indicates that this area was one abandoned in the 11th-12th centuries during the demographic shift to the Wet Zone at the end of the Middle Historic (de Silva 1981). One of the first activities that new settlers to the area engage in is gem mining, as the deep alluvial deposits of the flood plain of the Kalu Ganga are regarded as a rich source of precious and semi-precious stones. The process of gem mining is simple with square-sided pits of c. 3-6m dug several meters deep into the alluvium. These are only back-filled when the ground is instated for cultivation and consequently the landscape is dotted with old gem pits that allow a convenient window into underlying deposits.

**Survey**

Slags, indicating the presence of smelting sites, had been reported from the area by P.B. Karunaratne, a collaborator on the Samanalawewa project, and in November 1996 the first rapid survey was conducted.

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**Figure 3** Two views of the survey area with distant view the Knuckles range (top) and low forested hills and paddy field terrain, with local guide (bottom)
Although only a few days in duration, following as it did in the wake of the Samanalawewa experience, the survey was carefully targeted. Reconnaissance-style survey was used, which meant making enquiries and then being lead to possible sites by local informants (Fig. 3). Extensive narrative field notes were taken, recording landscapes, locations, features and conversations. In all, seven smelting sites, a possible ore deposit and one crucible steel site were located and interviews conducted with two traditional blacksmiths. Further survey in the same area in 1999 and 2000, including that conducted by the Archaeological Survey Department of Sri Lanka, ultimately took the total number of archaeometallurgical sites to 32 in a tract of land extending northwards from Pallegama to Elahera, bordered by the Kalu Ganga to the east and straddling the Hattota Amune irrigation canal to the west (Fig. 4).

Concentrating here on the seven smelting sites located in 1996, five of them fall convincingly within the west-facing technology type on the basis of the macro-morphology of their slags. The unusual design of the west-facing furnaces at Samanalawewa produced a distinctive array of slag morphologies that have been described in detail elsewhere (Juleff 1998, 55-63). Particular amongst these are tuyere-line and tuyere-plug slags. These slag types form inside the furnace when slag builds up against and fills the line of reused tuyeres used to create the foundation of the straight front wall of the furnace. Both forms evidence the use of multiple tuyeres and the tuyere plugs, fragments of cylindrical slag, some tapering, made up of repeated flows, can only form when slag solidifies inside a tuyere. Abundant fragments of tuyeres are also strong indicators of a west-facing-type technology. A further feature of the slags of the west-facing sites at Samanalawewa is the extensive occurrence of pseudomorphed impressions of paddy straw and paddy husk used to line the base of the furnace. At all five Hattota Amune sites assigned as west-facing type tuyere-plug slags were recorded. Distinctive impressions of paddy straw and husk were also recorded at all sites. Tap slags were abundant on all sites and fragments of furnace wall that were flat and without curvature, both also attributes of the west-facing assemblages. On one site a definitive fragment of furnace wall with multiple tuyere slots was observed (Fig. 5). Interestingly, despite being a small sample of sites, there was variation in the degree of taper of the tuyeres, from parallel-sided through slight to noticeable taper. Variation in tuyere taper was present but not a strong feature of the Samanalawewa assemblages which
are dominated by tapering tuyeres. The five sites share sufficient traits with the Samanalawewa west-facing material to be classed as part of the same technological tradition.

Figure 5 Fragment of furnace wall with multiple tuyere slots recorded during survey

In contrast to slag morphology, the locations of the Hattota Amune sites do not follow the Samanalawewa pattern of being on exposed west-facing hills. Here they are on flat or gently undulating ground within or close to the edge of the flood plain of the Kalu Ganga. While most demonstrated thick deposits of slag, occasionally mounding to c. 1m, most did not exceed c. 20m in diameter with one exception comprising at least four loci of activity within an area of over 75m. None are in sheltered positions but equally they are not in particularly exposed positions. Local inhabitants report that the area is subject to very strong dry winds during the monsoon to the extent that roofs need to be weighted with sand bags and tyres. Furnaces could thus be wind-powered but whether they were designed and operated in precisely the same manner as those at Samanalawewa, or also relied on a degree of natural draught induced by increased shaft height, is unclear and requires further investigation. It is possible that they were more akin to the furnaces excavated at Dehigaha-ala-kanda, near Sigiriya, due north of Hattota Amune (Fig. 1). The Dehigaha-ala-kanda furnaces are straight-fronted, use multiple tuyeres, although don’t appear to reuse tuyeres in furnace wall construction, and have substantial superstructures, up to 1.6m in height. They were excavated in 1990-91 and described by Forenius and Solangaarachchi (1995), and further discussed in relation to the west-facing furnaces and a postulated wider technological tradition of linear furnaces (Juleff 2009b). They are earlier than the main industrial activity at Samanalawewa, having given seven radiocarbon dates between the 2\textsuperscript{nd} century BC and the 4\textsuperscript{th} century AD.

The five west-facing type smelting sites at Hattota Amune remain undated as they were recorded only from surface survey and thus it is not certain whether they are contemporary with either the earlier Dehigaha-ala-kanda furnaces or the later Samanalawewa furnaces, or possibly intermediate between them. However, pottery collected at several of the sites included types which are generally regarded as typical of the Middle Historic period. Given the pottery evidence combined with the general settlement pattern of the area in terms of the 11-12\textsuperscript{th} century abandonment described above, it is reasonable to suggest that the sites date no later than the Middle Historic period.

The two further smelting sites of the 1996 Hattota Amune survey presented slags that were very different in morphology to those described above. At these two sites the slags were more massive and comprised course-textured furnace slags in block-like forms. Little or no tap slag was observed and tuyeres and other refractory materials were absent. These slags bear no resemblance to either the west-facing or the later village smelting shaft furnaces types of Samanalawewa. The sites are undated but both are located in a more isolated area of hilly terrain were the few sparse settlements are older than those in the flood plain and thus it could be postulated that these smelting sites are contemporary with the settlements and belong to the Later Historic period.

The two remaining sites included a possible small ore deposit comprising a weathered lateritic outcrop with ferruginous gravel and the crucible steel site that will be the focus of the remainder of this paper.

Hattota Amune Wallewala (HAW'96)

The site at Hattota Amune, Wallewala, (HAW’96) lies at lat. 07°36'16" and long. 80°49'46" and c. 150m msl. It is c. 500m from the nearest west-facing type smelting site and is located in the compound of No. 14 Wallewala, which is situated immediately east of the track that follows the course of the Hattota Amune irrigation canal. The 50m wide compound comprises a traditional house and a semi-wild garden used for fruit and vegetables, and immediately adjoins on its eastern side a wide tract of paddy land that stretches c. 500m to the Kalu Ganga. Slags were clearly visible embedded in the trampled and swept surface of the compound and increased in the vegetable growing area (Fig. 6) where an abandoned gem pit of c. 5x5m and 2m depth exposed a thick deposit of slag and pottery. It was here that the first few fragments of crucible were collected.
Excavation

With the discovery of crucible fragments it was decided that the site would be suitable for an exploratory excavation to determine the nature and possible date of the metal working activity. The excavation took place in December 1996 over 4 days and was led in the field by Nerina De Silva and Tom Dawson. The objective was to cut back the exposed sections of the gem pit to record and sample the deposit of debris which varied in depth along the sections from 0.50m to 0.70m. In the time between the survey and the excavation rain had flooded the gem pit to half its depth making it impossible to access the sections from inside the pit so it was decided to concentrate on the north section only.

A shelf was cut to create a working platform from which an area 5.5m in length and 0.40m wide, designated trench I, was excavated stratigraphically (Figs 7&8). All excavated material was weighed and sorted. Pottery and crucible fragments were retained and charcoal was sampled following the established procedure of the Archaeology Department. After cutting back and recording the section a further 1x1m test pit, designated trench II, was excavated into the section to increase the amount of charcoal retrieved for dating. A new series of context numbers were given to the excavated layers in trench II.

The stratigraphic sequence in both trenches was the same, with the uppermost topsoil (context 1) overlying a layer (context 2 in trench I and 7 in trench II) containing large amounts of slag (c. 82 kg in total) and some crucible fragments. This layer was up to 0.3m thick and overlay a further layer (context 3 in trench I and 8 in trench II), 0.2m thick, which contained crucible fragments, tapped slag and abundant pottery but far fewer large cakes of slag than context 2/7. The total weight of slag recorded for context 3/8 was 10kg. Below context 3/8 lay context 4, 0.1-0.2m thick, which contained only a few fragments of tap slag and pottery sherds. The final layer excavated, context 5, contained no slag and infrequent pottery. Excavation was halted before the bottom of this layer was reached.

Context 2/7 contained the bulk of the slag and appeared as a dumped layer, visible in all four sections of the gem pit and indicating an active workplace in close proximity. Context 3/8 contained slag but in much reduced quantities. The difference between contexts 2/7 and 3/8 was the absence of large slags in the latter and, as the soil matrix in both is the same, the conclusion drawn was that the smaller size material in 3/8 had worked its way downwards due to the action of roots and insects. The landowner reported removing large trees from the site when he first occupied the site and there was evidence of termite activity. The interface between contexts 2/7 and 3/8 was diffuse with clear evidence of bioturbation. However, it is also possible that the lower layers relate to a phase when metal working was less...
intense. No evidence for working surfaces or structures was found.

**Dating**

The pottery from the excavation was examined by S.U. Deraniyagala and given a tentative Middle Historic date range of 5th-8th centuries. The study of local pottery typologies at the time of the excavation, and still today, is in its infancy and only broad date ranges can be applied to known and recognisable types. The abundance of pottery at a metalworking site indicates sustained domestic activity in proximity with metal working.

The charcoal collected was submitted for dating and the results obtained are presented in table 1. Two observations are immediately apparent. All the dates fall within the Middle Historic period and that they are inverted in terms of the stratigraphic sequence. Possible reasons for the inversion have been considered by the excavation team and mis-labelling of samples has been ruled out, as has inversion of the stratigraphy due to secondary dumping. The remaining explanations are bioturbation, which was noted during excavation, allowing smaller material to migrate through loosely-packed larger slags and the possibility of old heartwood being included in the sample from context 2/7. Setting aside the uppermost early date as possibly anomalous, the dates for contexts 3/8 and 4 could be regarded as most reliable, in particular 3/8 which contained the majority of the crucible fragments. The pottery evidence and the radiocarbon dates combined place crucible steel making at the site in the second half of the first millennium AD, beginning at least in the 7th century.

**Slags and crucibles**

The large quantities of slag suggest a well-established and long-lived workplace. Morphologically, the assemblage is not of the west-facing type and is dominated by large and irregular plano-convex cakes and fragments thereof. These are interpreted as smithing slags, probably derived from primary forging of slag-rich iron direct from local smelting. Fragments of tap slag may seem to contradict the smithing interpretation and imply smelting but, although tap slag is in reasonable abundance, it does not occur as large agglomerations of multiple flows. It is likely that it derives from flows of liquid slag produced in a smithing hearth at high temperatures. The observation that the slag cakes are dense and well-consolidated, suggesting they formed from low viscosity slag, reinforces this. No hearth or furnace lining material was observed or collected.

The crucible fragments form a minor component of the excavated assemblage and, despite a total sampling strategy, only 44 possible crucible fragments were recorded. Examples of the crucibles are illustrated in figures 9 and 10. They are thin-walled (c. 3-5mm) with a dark brown/black, slightly coarse but uniform-textured fabric. Their external surfaces are coated with uneven blue-green glassy vitrification products which accumulate towards the base of the crucible. Internally, the more complete fragments preserve a glassy ‘fin’ marking the top of the ingot space when the crucible was positioned vertically. The second ‘fin’ observed
at Samanalawewa indicating a horizontal position during cooling is absent here. The most complete profiles indicate that the crucibles are small, narrow-necked rounded flasks. The rim of the crucible is neatly finished and closed with a separate plug of clay, although no full examples of lids remain. The diameter of the neck is c. 15mm while the body expands to 45mm and the internal depth is at least 65mm. It is important to note that, given the small number and size of the crucible fragments, these dimensions are drawn from a very limited sample. From the few fragments of possible crucible lid there was not sufficient survival to determine whether the lids had been pierced as at Samanalawewa and elsewhere in South Asia, however, one example preserved a definite and deliberate perforation of the side wall of the crucible (Fig. 10), a feature which has not been recorded previously. Also within the debris assemblage at HAW’96 are fragments of amorphous glassy slag/vitrification (Fig. 9). This is often blue/green in colour but can also be pale cream. It is clearly the same material as adheres to the exterior of the crucibles.

Discussion

The first observation that can be made of the Hattota Amune crucibles is that, while they share fabric traits, they are unlike the tubular forms of those from Samanalawewa. This is hardly surprising in that they are separated in time by over a millennium. From their size, they would produce only small button-like ingots and their neck diameter suggests that charging the crucible would be challenging. The feedstock would have to be in the form of narrow and short bars or small diameter fragments or prills. However, there are some interesting similarities in context between Hattota Amune and Samanalawewa. In both cases crucibles occur alongside plano-convex cakes of smithing slags, although at Samanalawewa the proportion of crucibles to slags is far higher (Juleff 1998, 93). This suggests crucible steel manufacturing was not a sole occupation but one element of a wider repertoire being practiced. On current evidence, crucible steel production at Hattota Amune is minimal, although it is remotely possible that another part of the site could reveal higher concentrations of crucibles.

While it is not the intention of this paper to review the evidence for crucible steel in Asia it is notable, from the growing gallery of crucible forms from across south and central Asia, that although there are similarities in fabric and features such as closed lids, with or without perforations, and co-occurrence of coloured glassy slag across macro-regions, no two areas are alike. Until more forms are recorded and dated it is not possible to compile a typology that allows the development, transmission and adaptation of crucible forms to be traced. What can be interpreted is that all the forms known are effective and that crucible steel is a resilient technology able to tolerate a high degree of variation. This implies a high degree of technological competence and knowhow, which brings the discussion back to the issue of context. All too often crucible steel is studied in isolation as a specialist technology. In contrast, being able to examine crucible steel within wider, regional patterns of ferrous metallurgy, adapted to supplying a wide range of end-users, will afford a better understanding of the technocultural role of crucible steel. Like Samanalawewa, using this approach at Hattota Amune a pattern has emerged. Iron was smelted extensively across the area during the mid- to late Middle Historic period, using a technology that is part of the same tradition as the wind-powered furnaces of Samanalawewa. While there are shared traits in terms of furnace design and operation, including use and reuse of multiple tuyeres, there also differences which represent adaptations to local conditions or stages of development. The smelted metal was processed at local smithing sites that also had a minor capacity to refine high carbon steel in crucibles. The level of crucible steel production at HAW’96 would fall short of that for Sarandibi steel implied by al-Kindi. At Samanalawewa, the pattern is different. There is no crucible steel manufacturing contemporary with the smelting industry and this is interpreted as implying that the substantial output of the west-facing furnaces was itself Sarandibi steel. These Sri Lankan patterns are distinct from those of other areas in southern India in the later second millennium AD when crucible steel became an important economic industry with specialised sites and practitioners focussed exclusively on steel ingot production (Juleff et al 2011).

Table 1. Radiocarbon dates for HAW’96

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Site</th>
<th>Context</th>
<th>C14 date b.p.</th>
<th>Calibrated date range (2σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beta 101297</td>
<td>HAW’96</td>
<td>2/7</td>
<td>1430±60 BP</td>
<td>530-680 cal AD</td>
</tr>
<tr>
<td>Beta 101298</td>
<td>HAW’96</td>
<td>3/8</td>
<td>1170±60 BP</td>
<td>680-990 cal AD</td>
</tr>
<tr>
<td>Beta 101299</td>
<td>HAW’96</td>
<td>4</td>
<td>1060±70 BP</td>
<td>810-1160 cal AD</td>
</tr>
</tbody>
</table>
Acknowledgements

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A New Discovery: Manganese as a Flux Agent at the Song Dynasty [960 -1279 A.D.] Iron-Smelting Sites in Xingye County, Guangxi, China.

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ABSTRACT This paper offers a recent study on iron-smelting sites and slag of the Song dynasty found in Xingye County, Guangxi Zhuang Autonomous Region, southern China. Archaeological fieldwork was conducted in Xingye County in November 2006 and August 2008. The ancient iron smelting sites are distributed through an area of about 20 km² in the vicinity of Long’an town. Ten iron smelting and casting sites were investigated. A dozen shaft furnaces and the bottom of one destroyed shaft furnace have been found, as well as a lot of slag heaps, broken tuyère, casting moulds and pottery.

Pre-modern texts indicate the presence of such sites in the Southern Song dynasty, though local archaeologists consider that the sites started in the Tang dynasty. The patterns of pottery shards unearthed from the Gaoling site possibly belong to a much earlier period.

Preliminary analysis using SEM-EDS of 23 smelting slag samples collected from 4 sites are presented. It is noted that all the samples of slag are composed of MnO-SiO₂. Analysis of the microstructure of the metallic droplets in the slag by metallographic microscopy shows that all were the product of cast iron smelting. This is the first time that the use of manganese as a flux agent in ancient cast iron smelting has been confirmed in China.

The typology of the remains of straight-round-shaped tuyère indicates a shared tradition with earlier copper and iron-smelting finds in the Guangxi area, resembling closely those from South and Southeast Asian ancient iron-smelting ruins.

Introduction
Iron has been a fundamental material for promoting the progress of human civilization since the second millennium BCE when iron smelting technology was invented (Tylecote 1992, p. 3). Bloomery iron smelting technology was the predominant technique used throughout most of the world in pre-industrial times. However, cast iron smelting technology was developed in central/north China by 800 BCE (Han 2000, p. 1178), and from then on became the main technique within China’s cultural area. Guangxi Zhuang Autonomous Region, located in southern China, an important region connecting central China with Southeast Asia, has been a frontier for cultural contact and exchange from ancient times. Archaeological excavations and preliminary studies indicate that iron artefacts began to be used in the Guangxi region at the latest in the Warring States period [475-221 B.C.] (Lan 1989, p. 77; Guangxi Cultural Relics Team, 1978, p. 211). According to extant pre-modern texts, the Guangxi region began iron smelting in the Sui [581-618 A.D.] or early Tang [618-907 A.D.] dynasties, and the earliest records of ancient iron smelting sites situate them at Huaiji (present-day Guangdong province) and Guiling (present-day Hexian County in Guangxi region). (Wu 1935, p.2; Li, Xu 1943, p. 5; Li, Huang 1941, p. 12; Xia, Li, Wang 1986, p.70)

A Song dynasty work Yudi Jisheng (Records of popular places) by Wang Xiangzhi indicates the presence
of iron smelting sites in Xingye County, Guangxi during 1131-1173 A.D (南宋绍兴－乾道年间) (Xia, Li, Wang 1986, p.99, 143, 166), and these were discovered during the National Survey of Cultural Relics in the 1980s.

Studies on their remains offer the possibility for discerning the characteristics of the Song dynasty iron smelting technology in the region, as well as its spread and exchange locally and to neighbouring areas, such as central China, Southeast Asia, and the Indian subcontinent. This paper describes a part of our research achievements in the Guangxi region since late 2006.

Background of the sites

Xingye County is located in the south-eastern part of Guangxi Province. At the time of the Qin dynasty invasion from the north of the Lingnan area in 214 B.C., the aboriginal nations of the region were known in Chinese literary sources as the Xiou 西呕 and Luoyue 骆越 (Huang, Huang, Zhang 1988, p. 3). At that time, the Qin emperor established three administrative regions or Commanderies (jun 郡) in the Lingnan area, namely Guilin Commandery, Xiangjun Commandery and Nanhai Commandery. The area of present-day Xingye County was under the jurisdiction of the Guilin Commandery. During the early Western Han dynasty the region was controlled by the Nanyue Kingdom [203-111 B.C.], and subsequently became part of the Yulin Commandery or Yuzhou Commandery. From 561 to 665 A.D the region was controlled by the Shinan Commandery, and thereafter became a County, variously named or Shinan, Nanliu and Xingye (Wang, 1992, p. 3500).

Aims

This paper presents archaeometallurgical studies on the Song dynasty iron smelting sites and slag found in Xingye County. The research had three major goals: to conduct archaeological fieldwork on the ancient metallurgical sites of the region; to appraise its iron smelting technology mainly through the scientific analysis of slag; and to try to reconstruct the history of the indigenous iron-smelting technology, discussing connections with neighbouring areas from the point of view of technological and cultural exchanges.

Fieldwork

With the instruction and help of Professor Jiang Tingyu of Guangxi Provincial Museum, Professor Wan Fubin of Guangxi University for Nationalities, Liang Chan of Xingye County Museum, local cadres and villagers of Long’an town in Xingye County, archaeological fieldwork was conducted in Xingye County in November 2006 and August 2008. The geographical coordinates of the investigations are between 22°30′N ~ 22°48′N, 109°35′E ~ 110°02′E (GPS measured data).

The ancient iron smelting sites are distributed throughout an area of about 20 km² in the vicinity of Long’an town. The Yaqiao River, which flows down to Beibu Gulf (Beibawan), runs through the sites. The fieldwork yielded 10 iron smelting sites at Qiyangling nanpo, Chongtangling, Liuxicun, Shandiling, Shenguoci, Jialing, Niulanchong, Juecaichong, Dapitou, and Gaoling (Fig.1).
All of the ancient remains were at the foot of hills of less than 100m in altitude, and located in the upper regions of the Nanliujiang River. A dozen shaft furnaces and the bottom of a destroyed shaft furnace were found, as well as a lot of slag heaps (Fig.2), eroded iron blocks, intact and broken fragments of tuyère, and casting moulds (Fig.3). In addition, large quantities of pottery shards, identified by typology and pattern as dating from the Tang [618-907 A.D.], Song [960-1279 A.D.] and Ming [1368-1644 A.D.] dynasties, were found on the surface of the sites. As a result, the local archaeologists consider that the sites started in the Tang, flourished during the Song, then came to an end in the Ming dynasty (Xingyexian Bowuguan, 2006, p.1). Pottery shards possibly belonging to a much earlier period (before 220 A.D.) have also been found at the Gaoling site (Fig.4), but the relation between these pottery shards and the smelting activities requires further study.

![Figure 4](image) The patterns of pottery shards possibly date to the Han Dynasty (before 220 A.D.) unearthed at Gaoling site.

All the slag found and collected was broken tapped slag of black and brown colour (Fig.5). Slag heaps more than 2m high, much higher than those at any other site, and covering an area of about 1000m² were found at the Juecaichong site (Fig.2).

![Figure 5](image) Broken tapped slag of black and brown colour remained at the Gaoling site.

Many almost intact tuyères were collected at all the sites during our fieldwork. They are of a round-straight shape, about 45cm-50cm in length, with an inner diameter about 4cm-5cm, an outer diameter about 12cm-15cm and made of white mud and sand (Fig.6). We found a little charcoal in the slag heaps at some sites, but we did not find any remains of iron ore.

![Figure 6](image) An almost intact and broken fragments of Straight-round shaped tuyère remained at the Juecaichong site.

An intact shaft furnace was found at the Chongtangling site. Its remains are more than 2.5 meters high.

![Figure 7](image) An intact shaft furnace found at Chongtangling site. Its remains are more than 2.5 meters high.

An intact shaft furnace was found at the Chongtangling site. Its remains are more than 2.5 meters high (Fig.7). It has an outer diameter of about 40cm at the upper rim, 110cm at the middle and 120cm at the bottom. The thickness of the shaft furnace wall is
about 10cm-15cm, and is made of white mud and sand. There is also an opening for tapping slag of about 20cm width at the bottom of the shaft furnace in its northwest face. The bottom of a destroyed shaft furnace with an inner diameter about 112cm (Fig.8) was also found at the Shengguoci site. Several other almost intact shaft furnaces found underground at other sites during our investigation are also to be excavated to discover their structure (Huang, Li, Wan 2007, p. 23).

Scientific examination methods

In order to determine the smelting technologies employed, slag from 4 sites, namely Gaoling, Shengguoci, Juecaichong and Liuxicun, were examined and analyzed using metallographic microscopy, mineralographic microscopy, and scanning electron microscope with energy-dispersive spectrometry (SEM-EDS).

Scanning electron microscopy (SEM) was used to observe the microstructures and compositions of polished sections of the samples. SEM with energy-dispersive spectrometry (EDS) was used to carry out the non-sampling quantitative analysis. This research was undertaken using a Cambridge S-360 SEM-EDS at the School of Materials, University of Science and Technology Beijing. The excitation voltage was 20 Kv. Since light elements, such as carbon and oxygen, with atomic numbers less than 11 could not be detected, only a qualitative analysis of the corroded objects or occluded trace elements could be given. Oxidised components could not be determined. To determine the average components, surface scanning was used with multifaceted scanning on different parts of the samples to discover the precise composition of each sample. Based on previous analyses, the lower confidence limits for this instrument may be established at 0.3 wt%; values below this limit can be taken as indicative only.

Metallographic microscopy was used to observe the microstructures of the iron prills in polished sections of samples of the slag and iron products, and this research was undertaken using a German LEICA DM4000M at the Institute of Historical Metallurgy and Materials, University of Science and Technology Beijing, and at the School of Archaeology and Museology, Peking University.

Mineralographic microscopy was used to observe the microstructures of polished sections of samples of the slag and iron ores, using a German LEICA DM4000M at the Institute of Historical Metallurgy and Materials, University of Science and Technology Beijing.

Figure 8 The bottom of a destroyed furnace at the Shengguoci site.

Microstructural and chemical analyses

The compositional analysis of the slag, iron products’ inclusions and ores is significant for our understanding of the smelting techniques employed and the sources of the ores used. The microstructure of the iron prills in the slag and iron products is also very important for determining the smelting techniques (Tholander 1989, p. 35).

Figure 9 SEM backscattered electron image of the matrix of the tapped slag No. XS001 from the Shengguoci site (voids are black). The phases present include glassy (c: Mn 59.71% (wt%), Si 22.47% (wt%), Al 11.99% (wt%), Ca 1.65% (wt%), K 2.35% (wt%)), iron prill (a: Fe 89.17% (wt%), P 9.90% (wt%), Mn 0.56% (wt%); b: Fe 97.11% (wt%), P 2.04% (wt%), Mn 0.54% (wt%)). Iron droplet (white phase): point a, the inner bulgy part, higher phosphor; point b, the outside lower part, lower phosphor. Glassy phase (point c), the basic elements of the slag.

The 23 tapped slag samples from the 4 sites were selected at random. The SEM-EDS results show that the microstructure and composition of polished sections of the slag samples can be of one type only. The phases present include glassy, iron prills (Fig.9), and tephroite in some samples (Fig.10). Their composition is almost the same. Their average composition (adding oxide) of FeO was 3.08% (wt%), SiO\(_2\) about 32% (wt%), Al\(_2\)O\(_3\) about 14% (wt%), K\(_2\)O about 2.5% (wt%), CaO about 2% (wt%), S about 0.3% (wt%), MgO about 0.09% (wt%), MnO about 46% (wt%) and P\(_2\)O\(_5\) about 0.01%
In addition, we found droplets of iron prills in all of these tapped slag samples.

**Figure 10** SEM backscattered electron image of the matrix of the tapped slag No. XL004 from the Liuxicun site. The phases present include glassy, iron prills (white phase: point a), and tephroite (black-grey phase: point b, Mn 79.45% (wt%), Si 16.10% (wt%), Fe 3.42% (wt%)). Point c (grey-black phase) in the tephroite may be spessartite (Mn 57.74% (wt%), Al 37.67% (wt%), Fe 1.87% (wt%)).

The composition of all the iron prills in these samples was fairly high in P (Fig.9), the average composition of P being 3.53% (wt%), while Mn was either not detected or low. Their microstructure also showed white cast iron (Fig.11), as observed by metallographic microscopy.

**Figure 11** Optical macrograph of the metallic iron prill of tapped slag No. XL003 at the Liuxicun site. Cast iron, nital etch.

All of the 23 samples were well-melted, as observed under the mineralographic microscopy.

**Discussions**

**Smelting techniques**

We did not find Cu, Pb, Zn or Ag and relevant metallic particles among the basic components of the slag samples matrix surface using the SEM-EDS method. Based on current archaeological research about ancient non-ferrous metallurgical slag and iron-smelting slag classification criteria (Li 1995, p. 23; Craddock, Freestone, Gale, Meeks, Rothenberg and Tite 1985, p. 199; Rothenberg, Blanco-Freijero 1981, p.312) we may exclude the possibility that they are copper smelting slag, lead smelting slag, zinc smelting slag or silver smelting slag.

The characteristics of the 23 tapped slag samples, which showed phases of glassy, iron prills and tephroite sometimes, and the microstructure of their iron prills showing white cast iron, is certainly typical of cast iron smelting technology.

**Furnace**

Based on the morphology of the furnaces and slag found at the sites, we can conclude that there was at least one type of shaft furnace for tapped slag. The structure of these shaft furnaces has yet to be determined by further excavation and research.

**Ore**

*Ming Tongyizhi (A History of the Ming Dynasty)* records that the local people at Luya Mountain, located in northwest Nanliu County, Yuzhou Commandery, dredged and got green and yellow mud there, smelted them and cast woks (郁林州南流县绿鸦山在州西北三十五里. 州人于此淘取青黄泥炼成铁. 铸成锅) (Zhang 1954, p. 270). We did not find any fragments of iron ores at the sites during our investigation. So we consider that the iron ores (green and yellow mud) used should be sand iron ores, though further evidence is required to confirm this.

**Fuels**

During the National Survey of Cultural Relics in the 1980s, local archaeologists found a lot of charcoal in the furnace hearths at some sites. We also found a little charcoal in the slag heaps at some sites, and based on the potassium content in the slag samples, we consider that the fuel used should be charcoal. However, determining which timber they used to make the charcoal for smelting still needs further research.

**Production**

According to the text mentioned above, *Ming Tongyizhi*, one of the products made at the sites was cast iron
works. This was confirmed by the discovery of moulds for casting woks at the sites (Fig. 3), leading us to conclude that there were also cast iron foundries at the sites, besides the smelting workshops.

The *Yudi Jisheng*, also mentioned above, indicates that the iron smelting factory at Luya, Nanliu County, yielded iron production of about 64700 (Jin) (32,350 kg) per year, which was delivered to Censhui factory, Shaohou (present-day Shaoguan, northern Guangdong province) (绿鸦场在南流县, 岁收铁六万四千七百斤, 往韶州涔水场库交) (Wang, 1992, p. 3505). So, we may conclude that the iron smelting factories at the sites were important for China, during the Southern Song dynasty at least.

**Flux agent**

Based on the slag samples analyzed, we can conclude that the local people used manganese as a flux agent during cast iron smelting.

Usually, the slag from traditional cast iron smelting will be mainly composed of Al$_2$O$_3$-CaO-SiO$_2$, according to existing data of ancient cast iron smelting slag in central/north China. In other words, they used limestone as a flux agent during the smelting process. However, the slag discussed here definitely does not indicate the addition of limestone as a flux agent. Where did the manganese in the slag come from? We consider that there may be two possibilities: one is that the ore used could be a multi-mineral orebody or paragenetic mineral mainly composed of Fe and Mn; the other is that the craftsmen deliberately added manganese ore as a flux agent, mixing the iron ore and manganese ore together during the smelting process.

This raises further questions. For instance, limestone is common in the region, so why did not they choose limestone rather than manganese as a flux agent? Why did they use manganese while limestone was still the norm in central/north China? How did they know to use manganese as a flux agent? Is it the result of innovation or invention? If the ore they used was a multi-mineral orebody consisting of Fe and Mn, where is the mining site for such a multi-mineral orebody? If the craftsmen deliberately added manganese ore, where are the mining sites for the iron and manganese ores? These questions still need further study.

**Smelting temperature judged from slag composition**

Based on the analysis using SEM-EDS of the 23 smelting slag samples, we know that all the slag is mainly composed of Al$_2$O$_3$-MnO-SiO$_2$. According to the Al$_2$O$_3$-MnO-SiO$_2$ diagram, the liquid temperature of the samples was about 1200°C (Fig. 12), judging from the average composition of the slag. However, these results do not take into consideration other factors. In practice, the temperature of cast iron smelting when using limestone as a flux agent is above 1400°C, so we consider that it was easier to extract cast iron from iron ores when manganese rather than limestone was used.
“silk route” requires considerably more interdisciplinary study and international co-operation.

The dates of the finds

Dating the finds and sites discussed above is still an issue. The Yudi Jisheng indicates the presence of such sites during 1131-1173 A.D in the Southern Song dynasty. Based on finds of large quantities of pottery shards, local archaeologists consider that the sites started in the Tang, flourished in the Song, then came to an end in the Ming dynasty. The patterns of pottery shards (Fig. 4) unearthed at the Gaoling site, however, have led some archaeologists to consider that they date to the Han dynasty [before 220 A.D.] at the latest. Examination with AMS-14C of the charcoal samples directly related to the smelting activities found at the sites should help to clarify some of these issues.

Conclusions

The slag samples analyzed were cast iron smelting slag. This is the first time that the use of manganese as a flux agent in ancient cast iron smelting has been confirmed in China.

The typology of the remains of the straight-round tuyère indicates a shared tradition with earlier copper and iron smelting sites in the Guangxi region, South and Southeast Asia.

Acknowledgements

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Metallurgical Innovations and Pattern of Adaptation of Iron in Early Cultures of India

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ABSTRACT Iron appears in India in a Chalcolithic context during opening centuries of 2nd millennium BCE without bringing about much change in material milieu. The efficacy of iron as an agent of change has been therefore questioned. The present paper examines the issue of technological innovation and pattern of its adaptation in the early cultures of India.

The Issues

The advent of iron and steel provided a great impetus to human civilization, though the metallurgical process took a long time to evolve and mature to be truly effective. A comparative assessment of iron objects vis-a-vis the status of material remains at particular stages of culture may provide a clue to the degree of impact of technology on society. The present paper proposes to trace the stages of development of iron technology and to assess the role of iron in cultural change. Iron is supposed to be a utilitarian metal with superior strength than copper. Why is it that its impact was so gradual? An answer to such an anomaly lies inherently in the metallurgical development of iron. Firstly, copper is easier to produce on larger scale through casting. Secondly, any bronze even with ten per cent tin alloying is superior to wrought iron as initially produced. Therefore the change from bronze to iron was slow as aptly explained by Taylor and Shell (1988:205-221) in Chinese context, “Two misunderstandings regarding the change over from bronze to iron plague archaeological literature... they are that iron is better than bronze and that the difficulty in smelting iron lies in the high temperature required. In fact it is only steel that is consistently stronger than bronze... Furthermore, a usable bloom, or molten iron, if it contains a large amount of carbon or other impurities can be produced at temperatures close to or even below those needed to melt copper or gold... the difficulty with iron lay not in obtaining high temperatures but in developing the new techniques necessary to hot forge the bloom...” Thus iron required a new kind of technological configuration that necessitated a much longer process of experimentation through trial and error. Iron at early stage remained scarce and of uncertain nature. This resulted into a slow pace of production and adaptation of iron. This issue has been examined in detail by many like Tylecote (1962), Maxwell Hyslop (1974) and Waldbaum (1980: 90-91). They observed that the iron metallurgy initially was more suitable for bronze. This explains a rather slow adoption of iron and the continued use of copper-bronze even after the advent of iron. We propose to examine this at three stages of techno-cultural development in India.

Early Iron Age

Recent radiometric characterizations suggest that iron first appeared in the Indian subcontinent between 1800-1200 BCE (Table.1). The Early Iron Age (EIA) cultures located in different ecological and geographical parts of the Indian sub-continent may be classified in several zones (zones A to F, Fig.1). These are: (a) the North-western region with cairn burials (b) the Painted Grey Ware (PGW) culture (c) the pre-Northern Black Polished Ware (NBP) culture with BRW-BSW (Black and Red Ware-Black Slipped Ware) pottery traditions (d) Early Iron Age cultures in Madhya Pradesh (e) Megalithic culture of Vidarbh (f) Megalithic culture of peninsular India. We have sites like Noh, Jodhpura in Rajasthan (belonging to PGW cultural phase (1100-600 BCE) in Indo-Gangetic divide; Prakash, Bahal in Deccan and Kaytha in M.P. (Chalcolithic level); Chirand in Bihar; Dadupur, Raja Nal-ka-Tila, Malhar,
Koldihwa, Kausambi, Jhusi, Rajghat and Narthan in Uttar Pradesh, (18/1700-600 BCE); Hatigra, Mangalkot, Mahaisdal, Pandurajar Dhibi (1200-600 BCE) in West Bengal; Naikund, Takalghat-Khap, Mahurjhari, Hallur, Tadkanhalli, Komaranhalli (1400-6/500 BCE) in Vidarbha and Tamil Nadu (for details see Tripathi 2001, 2008).

Figure 1 Map Showing Zones of Iron Using Cultures in India

Figure 2 Electron micrograph of celt, Tadkanhalli

Figure 3 Tempered martensitic structure of sickle, Pandurajar Dhibi 1000X 15 KV.
An elementary type of iron with slag inclusions was being produced by bloomery process at this stage. The furnaces were not efficient enough to generate sufficient temperature. Hatigra, Pandurajar Dhibi in district Burdwan (West Bengal), have yielded iron in the second phase of the Chalcolithic culture (Period II, Figs. 2, 3, respectively) datable to 2940±55 BP (1048 BC) and 2870±30 BP. 970 BC, Period III is dated to 2580 BP (630 BC). The analysed objects of Hatigra (Bengal, 1100-1000 BCE) had Widmanstätten structure due to prolonged exposure at a temperature of about 1200°C followed by slow cooling (Ghosh and Chattopadhyay 1987 p. 88). It is said to be a ‘low carbon hypereutectoid steel’. The concentration of carbon on the edges visible in some of the micrographs shows carburization. It may have been incidental due to the technique of repeated heating and hammering in contact of charcoal. The evidence of a dish shaped object from Period II from Pandurajar Dhibi in district Bardwan (West Bengal) is noteworthy in this regard. On analysis, it has been described as a ‘dark brown object with yellowish tinge that could easily be confused with copper based objects as work of a copper smith who accidentally seems to have worked it’ (De and Chattopadhyay 1989:34). “The specimen could not be sliced with a hacksaw blade as it is extremely hard at the same time brittle’. The chemical analysis (wet method) revealed only silicon and iron (De and Chattopadhyay 1989 34, Tripathi 2001, Table 6, 184). They further observed that it is very hard and ‘could not be sliced with a hacksaw blade. EPMA revealed cobalt, oxygen, ruthenium, alumina and silica.’ The fayalite in large quantity suggests the elementary stage of metallurgy. No carbide or pearlite structure could be detected on etching. High potassium content indicates use of charcoal as fuel.

Table 1: Radiocarbon Dates from Iron Age sites

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Sites</th>
<th>Radiocarbon dates in BP/BC on the basis of half life 5730 ± 40 years</th>
<th>Calibrated Dates- B.C.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>BS-1578 1996-97 Trench No. U - 19 (6) 1.95-2.00#m With iron</td>
<td>2626±110 BP 676±110 BC</td>
<td>822 (773) 486 BC</td>
</tr>
<tr>
<td>4.</td>
<td>BS – 1300 1995-96 Trench No. A-1 (6) 2.00#m With iron</td>
<td>3150±110 BP 1200±110 BC</td>
<td>1423 (1307) 1144 BC</td>
</tr>
<tr>
<td>5.</td>
<td>PRL-2049 1996-97 Trench No. T-19 (6) 2.00#m With iron</td>
<td>3150±90 BP 1200±90 BC</td>
<td>1406 BC-1198 BC 1186 BC-1164 BC 1143 BC-1132 BC</td>
</tr>
<tr>
<td>6.</td>
<td>BS - 1623, MLR II Trench No. XAl, Layer No. (3) Depth 0.55 cm</td>
<td>3550 ± 90</td>
<td>1886, 1664 1649, 1643 BC</td>
</tr>
<tr>
<td>8.</td>
<td>BS-1590 MLR II Layer No. (4) 80 cm</td>
<td>3850 ± 80</td>
<td>2283, 2248, 2233, 2030 BC</td>
</tr>
<tr>
<td>9.</td>
<td>BS-1822 Trench No. DDR-3, A-1</td>
<td>3368± 80 BP 1420± 80 B.C</td>
<td>1679 (1522) 1422 BC</td>
</tr>
<tr>
<td>11.</td>
<td>BS-1825 (Pit sealed by (12)</td>
<td>3532 ± 90 BP 1580 ± 90 BC</td>
<td>1739, 1706, 1695 BC</td>
</tr>
</tbody>
</table>

Table 1: Radiocarbon Dates from Iron Age sites
Iron first appeared as shapeless bits at Noh in Rajasthan. Within a span of half a century of EIA, finished iron objects appear in several sites. The number gradually increased over the period. In a thick deposit of 2.50 m PGW culture dated between 1100/1000–600 B.C. at Atranjikhera (Gaur 1983) yielded 7, 46 and 81 iron objects, at its three sub-periods, respectively (Table 2). Jakhera, another site nearby has yielded an iron ploughshare along with pieces of slag in the Pre-PGW- Black and Red Ware (BRW). In the PGW the number and type of objects multiply manifolds yielding hoe, sickle, spearhead, arrow-head, dagger, chopper, chisel, axe, nails, rods etc. (Sahi 1994). At Hastinapur (Lal 1954-55) and Alamgirpur in Meerut district iron appears for the first time during the PGW cultural period (Tripathi 2001, fig. 12) A somewhat similar evidence comes forth from Mangalkot (West Bengal) in an otherwise Chalcolithic cultural milieu dominated by Black and red ware. It has been dated to 1300 BCE (Dutta 1992). The iron samples analysed from the site of Hatigra dated 1100-100 BC as noted earlier had Widmanstätten structure due to prolonged exposure at low temperature producing a ‘hypo-eutectoid steel’. The analysis indicates carburization (Ghosh and Chattopadhyay 1987).

Table 2: Iron Objects of PGW at different sub-phases (Atranjikhera)

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Objects</th>
<th>Lower</th>
<th>Middle</th>
<th>Upper</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Arrow-head</td>
<td>-</td>
<td>7</td>
<td>14</td>
<td>21</td>
</tr>
<tr>
<td>2.</td>
<td>Spear-head</td>
<td>-</td>
<td>3</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>3.</td>
<td>Shaft</td>
<td>2</td>
<td>5</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>4.</td>
<td>Tongs</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>5.</td>
<td>Clamp</td>
<td>-</td>
<td>10</td>
<td>11</td>
<td>21</td>
</tr>
<tr>
<td>6.</td>
<td>Nail</td>
<td>2</td>
<td>4</td>
<td>14</td>
<td>20</td>
</tr>
<tr>
<td>7.</td>
<td>Bar/Rod</td>
<td>-</td>
<td>2</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>8.</td>
<td>Hook</td>
<td>-</td>
<td>2</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>9.</td>
<td>Borer</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>10.</td>
<td>Chisel</td>
<td>-</td>
<td>4</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>11.</td>
<td>Needle</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>12.</td>
<td>Axe</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>13.</td>
<td>Knife</td>
<td>-</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>14.</td>
<td>Bangle</td>
<td>-</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>15.</td>
<td>Lumps</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>15.</td>
<td>Indeterminate</td>
<td>2</td>
<td>3</td>
<td>9</td>
<td>14</td>
</tr>
<tr>
<td>Grand Total</td>
<td>8</td>
<td>46</td>
<td>81</td>
<td>135</td>
<td></td>
</tr>
</tbody>
</table>

The megalithic burials of southern India at EIA are rich in iron yielding swords, spikes, tridents, horse’s bits, and also utensils are found along with usually used shapes found at this period, i.e. arrowhead, spearhead, chisel, axe, fish hook and bangles (Fig. 4). Iron objects from Tadkanhalli, a megalithic site dated by TL to 14th-13th BC show steeling with pearlite at grain boundaries (Hari Narain et al. 1998). The megalithic tools from Mahurjhari show high carbon content with evidence of carburization and quenching (Deshpande et al., 2010).

Middle Iron Age (900 to 200 BCE)

A culture designated as Northern Black Polished Ware (NBPW) culture dominates this stage. This was a period of consolidation of iron technology with steeling and deliberate carburization. A relative increase is recorded in the number and types of iron objects. We see javelins, lances, daggers, blades, and elephant goads along with the earlier types (Tripathi 2001, Figs. 20-24). Agricultural implements become common at this stage.

Though solid-state reduction of iron continues to be the norm of smelting, improvisation in metallurgical technique is clearly perceptible. An iron sickle of Pandurajar Dhibi pertaining to NBP Period was examined. “Electron micrograph obtained at a magnification of 100 X clearly represents its tempered martensitic structure”. De and Chattopdhya (1989, 37; Fig. 4.C.) observed, ‘it shows non-uniform structure and retained acicularity at certain places, especially around large patches of ferrite areas. Carburization was done during smithy in course of heating and forging of objects. Inside the core, the carbon content that is retained is only 0.22%. But the high level of corrosion that took place over the time must have caused depletion of carbon. There is also an uneven distribution of carbon concentration. It indicates that carbon was more than 0.4% initially.’ There are also indications of quenching and tempering. Such conditions were noticed in iron from Senuwar, Narhan, Chirand and Taradih. (Singh and Merkel. 2001-02; Tripathi 2001, PL.X.C, Figs. 24C, and D). Lamination technique was also in practice as seen at Sringverpur (Tripathi, 2001, Fig. 23 A).
Late Iron Age (C.E.100-600 and beyond)

At stage III, there is not only a proliferation in tool types including some armour grade weapons of high carbon steel at Taxila (Fig.5, see Table 3). A greater proficiency was attained in iron metallurgy. Techniques like lamination and quenching were employed frequently. Hadfield (1913-14) noted high carbon in Taxila iron. He further observed an affinity between Delhi iron and tribal iron objects produced at Mirjati showing continuity in technique. Sisupalgarh in Orissa (datable to 2

<table>
<thead>
<tr>
<th>Tool Type</th>
<th>Name Of Tool</th>
<th>Early Stage</th>
<th>Middle Stage</th>
<th>Late Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hunting Tool</td>
<td>Spear heads</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Arrow heads</td>
<td>*</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td></td>
<td>Points</td>
<td>*</td>
<td>o</td>
<td>o</td>
</tr>
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<td>Household objects</td>
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<td>Discs</td>
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<td>Chisel</td>
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<td>Pipes</td>
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<td>Sockets</td>
<td>x</td>
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<td>Plump bob</td>
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<td>Door handle</td>
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<td>Tweezers</td>
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<td>Anvils</td>
<td>x</td>
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<td>Hammers</td>
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<td>Scissors</td>
<td>x</td>
<td>x</td>
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<td></td>
<td>Saw</td>
<td>x</td>
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</tbody>
</table>

Table 3. Relative Position of Iron Objects at Different Cultural Periods

At stage III, there is not only a proliferation in tool types including some armour grade weapons of high carbon steel at Taxila (Fig.5, see Table 3). A greater proficiency was attained in iron metallurgy. Techniques like lamination and quenching were employed frequently. Hadfield (1913-14) noted high carbon in Taxila iron. He further observed an affinity between Delhi iron and tribal iron objects produced at Mirjati showing continuity in technique. Sisupalgarh in Orissa (datable to 2

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1963; Ghosh, 1963; Lahiri, 1963; Balsubramaniam, 2002, 2008). The quality of iron is so good that even after standing in the open for more than sixteen hundred years it still maintains its anticorrosive property. These studies show that ironsmiths had attained mastery over cementing and forge-welding small rods of iron, and strongly forging them to shape such large objects. It also indicates that the ancient craftsman had mastered the operation and technique of control over temperature in furnaces to produce iron of uniform composition on such a large scale. The question that arises at this juncture is about the efficacy of iron technology in bringing about socio-cultural changes.
Discussion: Pattern of technology adaptation and culture change

The interface of iron utilization and material prosperity may help establish a relationship between the two. A brief review of Iron Age Cultures and pattern of utilization of iron at specific stages is called for here.

Stage I: Age of Commencement

The Early Iron Age settlements are modest sized habitations of thatched roofed huts or sun-baked structures made of mud-bricks. At sites like Kausambi (Sharma 1960) and Hasinapura (Lal 1954-55) towards the later part of this period, rammed roads have been located. Protective bunds and embankments or moats have also been found at sites like Atranjikhera, Jakhera, Kausambi, Sonkh and Eran. It suggests emergence of an organized socio-political system by 8th-7th BCE.

The economy was predominantly agrarian with cultivation of a variety of grains (Saraswat, 2010). Atranjikhera yielded wheat, barley and rice. In absence of suitable tools and techniques the yield must have been inadequate, as evidenced by cattle rearing and hunting. A near absence of iron ploughshares suggests the use of wooden ploughshare. (The later Vedic texts attest this). Common occurrence of bull figurines and toy carts indicate the significance of cattle.

In the absence of coinage a simple barter system must have been in vogue. Small weights of chert and jasper have been found at Hastinapur which implies some sort of commerce, but what merchandise required such weights is not clear (Ghosh 1973, 10 ). Minor antiquities of this stage are beads of terracotta and objects like points, styli, beads and bangles, stone balls, ivory shell and horn objects. Glass is used for the first time at PGW level, beads and bangles are fashioned with glass.

Stage II: Middle Iron Age: The Period of Fluorescence

The NBP Ware had a distribution extending from Taxila andCharsadda (now in Pakistan) in the North to Brahmangiri in Karnata and Anuradhpur (Sri Lanka) in the south; from Prabhas Patan in Saurashtra, in the west to Mahasthangarh in Bangladesh, in the east. Chronologically, NBP overlaps with PGW on the one hand, and the Sunga-Kusana period on the other. The earlier chronological bracket of 700/600 to 200 BCE is modified by radiometric dates of 1000 BCE if not earlier, for the beginning of NBPW culture. The culture is harbinger of the second urbanization in ancient India. For the first time, we come across evidence of coinage and writing. The settlements expand with rising population (Fig. 7). Use of baked bricks - haltingly first and more commonly later - fortification of settlements and sanitary arrangements mark the structural activity. At important sites like Hastinapur and Kausambi, remains of larger houses have been unearthed. Kausambi had a double storied house measuring 28’ x 15’ and 16 steps, while in Hastinapur, a long wall has been traced. Lined and unlined drainage system, wells and ring wells have been introduced. Rajghat excavations also revealed a rammed road having a thickness of 33.1 cm. It was made at the late NBP level (Roy 1983, 138). Pataliputra yields a pillared hall with colossal stone pillars, fortification, and drains etc. at the relatively later phase of this period. The Asokan pillars with glossy finish and elegant capital-heads dated to 4th-3rd BCE are found across the country. Excellent quality iron implements were indeed inevitable in modelling and chiselling of these majestic edifices.

The sophistication in pyrotechnology reached a high standard – the ceramic art specially evolved in the form of NBP Ware having a typical metallic finish. A double chambered kiln was unearthed at Khairadidh (Ballia), (Tripathi and Singh 2004). Terracotta figures
and pottery are handiworks of specialist class, so are glass, ivory and beads of precious and semi-precious stones. A bead making workshop was discovered at Agiabir, near Varanasi. The Buddhist literature makes frequent references to flourishing trade, both overland and marine. The occurrence of inscribed NBPW at Sri Lanka in 5th century BCE reiterates the growing international trade by 5th-4th BCE.

The political history is witness to rise of historical age marked by rise of Mahajanapadas (states) across India. The fall of Nandas and rise of Mauryan dynasty synchronizes with this period. It hardly needs to be underlined here that the rise of an organized socio-political system had its mark on every sphere of life. Rise of Buddhism and Jainism left a deep mark on every sphere of life.

Stage III: Late Iron Age: Age of Culmination

This was the era of cultural culmination. The pace of innovations started earlier gained momentum as testified by literary as well as archaeological evidences. The victory pillars being commandeered by the power centres exhibit prowess and technological acumen at the same time. The mighty Kusanas had established themselves in large part of India. The Guptas took India to greater heights subsequently.

The state provided patronage to art-architecture, literature, music, craft, trade and commerce during the Gupta-period. The guilds of traders were well organised and wielded great power in society. It was an era vibrant with activities that took India to unprecedented heights in every sphere of life. How much in it was the contribution of technology may be a debatable issue. It is however, undisputed that science, technology and ‘industry’ had reached an all time high during this period described by many as Golden Period of Indian history.

Conclusions

To summarise, we may state that technological skill contributed to economic prosperity. Talking specifically about iron metallurgy, we may say that it took a long time to evolve, as reflected in the scarcity and the elementary nature of iron objects produced in elementary furnaces at low temperature which had little advantage over a good quality bronze having even 11% tin, with a Brinell hardness of 60,000 per sq. inch (PSI.). The hardness increases up to 120,000 PSI after cold working. Wrought iron, on the other hand has the hardness of only 40,000 PSI. Repeated hammering and heating in contact with charcoal raises its hardness up to 100,000 PSI. The elementary level of metallurgical know-how, coupled with a conservative and sceptical temper of society, explains the reason of late adaptation of iron, for purposes other than weaponry or carpentry at the earliest level. The metallurgy had to attain a high level of efficiency to produce cheaper and affordable objects in sufficient quantity to be socially acceptable, operative and effective.

There appears to be syncretistic growth of technology and social affluence. It may be difficult to establish a direct link between the technology input and socio-cultural development, especially at relatively later stages of emergence with political system and state coming at the helm of affairs. However, at the relatively earlier stages, technology must have played a more crucial role
in bringing about prosperity by providing better tools and implements of production that strengthened the economic foundation for future growth. It was truer of iron, the utilitarian metal capable of making a difference in the production mechanism and thereby bringing about prosperity and affluence in society.

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Improvements in Traditional Indian Iron Making Technology

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&

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ABSTRACT
Iron has been produced and used in India for over 3000 years. Indian tribes preserved the technology of ancient iron making up to the 20th century. In order to reduce the cost and energy requirement and increase the yield of product several improvements were necessary to improve the basic process adopted by the tribals. The National Metallurgical Laboratory of Jamshedpur initiated investigations to understand the ancient iron making process and implemented a number of improvements to make the process a source of livelihood for tribals. Initially a prototype traditional furnace was established to study the effect of different process parameters. The foot driven bellows were replaced by a semi-mechanized air blower, and sal wood charcoal was replaced by charcoal made from eucalyptus or acacia. The ancient iron making process was scaled–up by incorporating the heat recovery system and three semi mechanized air blowers. Hot air was blown into the entire cross section of the furnace through three tuyeres positioned at 120° apart from each other with a view to increase the yield of product from 25 to 54 %.

Introduction
The Agarias were one of the major tribes of India engaged in the production of iron in central India, eastern Uttar Pradesh, Bihar, and Orissa. The whole family, including women, were engaged in this traditional trade and the technology was maintained as a family trade secret. They moved from place to place and produced iron deep inside jungles. During the 17th and 18th century the iron industry experienced a boost and artisans producing iron and blacksmiths making weapons were kept busy. Iron and steel produced during the 18th century in India were of very high quality and a regular item of export. Such people were called Lohars. This industry was active in various places in U.P., Jharkhand, Bengal, Orissa, Maharashtra, Chattisgarh, Mysore, Assam and Madras. The furnaces were small, up to 30 inches in height, and made of mud, with bellows being used to blow the air. The profile of a typical furnace used at Salem in the early 19th century resembles that of a blast furnace in miniature. The Travel records of Voysey (1823), Buchanan (1807), Hadfield (1912), and Verrier Elwin (1991) clearly show the supremacy of Indian iron and steel technology even in the 18th century.

Charles Wood, who was in charge of the Beypur Iron Works, as reported in a paper by Turner (1894), mentioned that his company could not produce a metal similar to that of the Indian swords used in the Indian Mutiny of 1857. The indigenous iron and steel industry started to decline because of various socio-technical reasons. Unfortunately this art disappeared after the development of a new technology during the 19th and 20th century. Indian metallurgical skills receded to the background, being restricted to the production of utensils, idols, ornaments, industries specializing in exquisite crafts of religious statuary jewellery. The industrial revolution in the 18th century led to Western predominance in materials development and utilization over the rest of the world. The Indian iron and steel industry began to decline in the last two centuries, under the impact of the British rule and the influx of mass scale produced iron and steel of European origin. With the establishment of the Tata Iron & Steel Company Limited (TISCO), there was a gradual extinction of the old indigenous smelting industry carried on by people known as Asur, Lohars, Birjias, Agarias etc. In 1960
Ghosh (1964) and Rao (1963), located a few families of Agarias near Jamshedpur and in Orissa. They observed the operation of three different furnaces at Jiragora and Chiglabecha in Orissa, and at Kamarjoda in Bihar. In 1963 a public demonstration of ancient iron making was organized at National Metallurgical Laboratory, Jamshedpur. Ghosh (1964) published a detailed report regarding the working of such furnaces and their products. In 1981, Prakash and Igaki (1984) located a family of the Mundia tribe at Loharpura in Baster that was smelting iron in that region until recently. In late eighties RDCIS, SAIL (Prasad et al 1990) with the assistance of Vikash Bharati, a voluntary organization at Bishunpur, Gumla District, Jharkhand, initiated investigations on the process of iron making practiced by the tribal artisans of Chhotanagpur Division of the then Bihar State and suggested several improvements to make the process a source of livelihood for them. The knowhow of ancient iron making still survives in some of the tribes in this country, especially in the regions of Central and Southern India.

The disadvantages of the old technology of iron making were critically reviewed and the design of the furnace was modified and improved accordingly, to make the process energy efficient, economical and eco-friendly. NML scientists (Vaish et al 1999) discussed the historical perspectives and technological considerations to make the ancient process of iron making economically viable and efficient. The kinetic study (Goswami, 2001) on the reduction of low grade iron ore used in tribal iron making by charcoal showed very good agreement with Ginstling-Bronstein model in which diffusion is considered to be the rate controlling step and charcoal is the appropriate selection as a reductant for reducing inferior iron ore. The National Metallurgical Laboratory, Jamshedpur attempted to develop a system to considerably improve the efficiency and yield of ancient iron making process. The incorporation of a heat recovery system and semi-mechanized blowers rendered the process more efficient and eco-friendly. Three tuyeres were positioned at 120° apart from each other for uniformly feeding hot air in the entire cross section of the furnace. The newly developed process was scaled-up and increased the yield of iron from 25 to 54%. Sal wood charcoal was replaced by charcoal made from acacia or eucalyptus, as this charcoal was found to be equivalent to that made with the more expensive sal wood. The improved process makes use of iron ore in the form of composite pellets made of char and ore fines with cowdung as binder. The process has a tremendous advantage for commercialization since the decorative articles made out of this product have a very good export potential.

Study the primitive technology of iron making

The tribal artisans generally used low grade iron ore (limonite / goethite) available on the surface of the hills (Fig. 1a), and charcoal made from Sal wood for making iron at the tribal site (Fig. 1b).

![Figure 1 Illustration of iron ore deposit and charcoal making](a)

Traditinal iron making activities at Hadup Village, Bishunpur, Jharkhand State (India)

The primitive iron-making required the construction of a furnace of stone and clay against a hillock or as a bowl. The open front bottom part of the furnace was closed after the placement of the air blast system and was finally broken when taking out the metal. Locally available iron ores, clay and charcoal prepared from sal wood were used for the production of iron. The furnace was filled with charcoal from the top, lighted up at the bottom, and air was blown through the tuyere by using...
foot-operated bellows. Bellows made of animal skins were used for air blasting. The charge was a mixture of ore and charcoal. During the air blowing operation the charge level diminishes. After the initial ignition the blowing of air through the charge continued until the operation was over. The dimension of a typical furnace was as follows: around 1 m deep and about two thirds of a meter in diameter. It was filled with iron ore and charcoal in several layers. A tuyere made of clay was inserted from the side or from the top and attached to the bellows. The temperature in the hottest part was around 1200 °C and although reduction took place due to low $P_{O2}$ and high CO/CO$_2$ ratio, the metallic product was not liquid but a spongy mass. The optimal conditions were maintained by empirical experience alone. The slag - mostly fusible ferrous silicate or fayalite (melting at 1170 °C) was caught up in the spongy solid mass, and tapped intermittently or continuously throughout the furnace operation. The measured temperature in front of the tuyere is about 1500 °C. After the completion of the reduction, the leather bellows were removed, the furnace mouth was broken, and the spongy bloom was taken out and hammered gently to squeeze out the slag. The reduced iron in form of porous lump was separated from the FeO rich fayalite (2FeO.SiO$_2$) slag. The iron bloom was then further reheated in a smithy forge to almost white hot (>1250 °C) condition and silica sand was sprinkled on it, to react with the remaining FeO, and to help the formation of 2FeO.SiO$_2$ which flows out of the iron block. The refined iron produced in this way could be shaped into the desired products by forging. The microstructure of refined iron consists of ferrite grains, a little pearlite and slag stringers. The traditional process seems to totally follow scientific principles.

### Treatment of sponge iron

The sponge iron retrieved from the furnace was subjected to hammering on a stone. The pieces of sponge iron were then once again reheated in a separate charcoal furnace of the type blacksmiths normally use. The slag had to be squeezed out of the sponge iron by hammering at or above 1250 °C, a process known as forging. About 30-50% of weight loss can be observed in this step, and the iron takes the shape of an implement. Table 1: Typical analysis of iron ore from Bishunpur and the metal and slag obtained in traditional Bishunpur type furnace

<table>
<thead>
<tr>
<th>Bishunpur ore lumps</th>
<th>Metal</th>
<th>Slag</th>
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<tbody>
<tr>
<td>Fe (T) %</td>
<td>56.35</td>
<td>C</td>
</tr>
<tr>
<td>SiO$_2$ %</td>
<td>2.84</td>
<td>Si</td>
</tr>
<tr>
<td>Al$_2$O$_3$ %</td>
<td>4.08</td>
<td>S</td>
</tr>
<tr>
<td>MnO %</td>
<td></td>
<td>Nf</td>
</tr>
<tr>
<td>S %</td>
<td>0.004</td>
<td>Mn</td>
</tr>
<tr>
<td>P %</td>
<td>0.119</td>
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</tbody>
</table>

The ancient iron making furnace at Hadup village, Bishunpur, Gumla district Jharkhand

### Traditional iron making activities at Kondagaon, Baster District, Chattisgarh State (India)

The furnace used at Kondagaon was similar to the Bishunpur furnace, but the charge is fed through a specially prepared charging bay (inclined at an angle with respect to the horizontal plane to facilitate the feeding of charge materials), and it has a separate slag spout on the side of the furnace. Locally available iron ores and sal wood charcoal were used in the process and clay was employed for the furnace. Initially the furnace was filled up to the top with charcoal, and the mixture
of ore and charcoal, in proportion of 1:2, was spread on the charging bay at 20–25 minutes time interval. Slag in the liquid state was removed several times through the slag spout. The front arch was broken and the lump of reduced iron was taken out with a wooden plank or a bamboo pole after the conclusion of the operation. Fig. 3. The chemical analyses of iron ore from Kondagaon as well as metal and slag produced in the primitive iron-making furnace are given in Table 2. The tribal artisans of the Bastar region have popularised the traditional iron making technology by organising live demonstrations at National and International conferences as well as at Pragati Maidan, New Delhi on special occasions.

Table 2 : Typical analysis of iron ore from Bastar, and metal and slag obtained in the traditional Bastar type furnace

<table>
<thead>
<tr>
<th></th>
<th>Bastar ore lumps</th>
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<th>Slag</th>
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</thead>
<tbody>
<tr>
<td>Fe (T) %</td>
<td>60.19</td>
<td>C</td>
<td>SiO₂</td>
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<td>SiO₂ %</td>
<td>1.97</td>
<td>Si</td>
<td>CaO</td>
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<tr>
<td>Al₂O₃ %</td>
<td>12.09</td>
<td>S</td>
<td>MgO</td>
</tr>
<tr>
<td>MnO %</td>
<td>n/a</td>
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<td>FeO</td>
</tr>
<tr>
<td>S %</td>
<td>0.005</td>
<td>Mn</td>
<td>Al₂O₃</td>
</tr>
<tr>
<td>P %</td>
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</table>

Mechanism of reduction of iron ore by carbonaceous reductant in the traditional iron making furnace

In the traditional iron making furnace, the hot ascending gas gives up its heat to the descending charge, while the CO portion of the gas reduces the iron oxides according to its reducing potential at the various temperature levels and is converted to CO₂. Considering the reduction reactions with CO at 900 °C in the reduction zone of the furnace, the equilibrium CO/CO₂ ratios, CO- utilisation factors η_{CO} will be as follows:

<table>
<thead>
<tr>
<th>Reactions</th>
<th>Equilibrium at 900 °C</th>
<th>η_{CO} %</th>
</tr>
</thead>
<tbody>
<tr>
<td>3Fe₂O₃ + CO = 2FeO₂ + CO₂</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Fe₃O₄ + CO = 2FeO + CO₂</td>
<td>0.25</td>
<td>80</td>
</tr>
<tr>
<td>FeO + CO = Fe + CO₂</td>
<td>2.3</td>
<td>30</td>
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</tbody>
</table>

The extent of utilisation, i.e. the percentage CO converted to CO₂ is denoted as

\[ \eta_{CO} \% = 100 \left( \frac{\%CO_2}{\%CO + \%CO_2} \right) \]

The traditional furnace is a counter current process. The tuyere gas with high CO content comes in contact with the wüstite which needs a very high reduction potential to convert into Fe. The resulting lower potential gas, as it ascends, encounters magnetite and hematite that require a much lesser degree of equilibrium CO/CO₂ ratio for reduction to lower oxides. The reaction product of indirect reduction is CO₂. If any wüstite remains unreduced in a zone where temperature is higher than 1000°C, the CO₂ is reduced by carbon, CO₂ + C = 2CO – 41.210

Advantages of the traditional ancient iron making process

(i) Locally available clay is mainly used for making the furnace and the tuyeres
(ii) The iron made by ancient process is a pure form of iron (wrought iron) with very low C (0.10 - 0.20%).
The process needs no electric power, no special refractory, no expenditure for the procurement of raw materials and furnace preparation as the entire family, including women, collect the iron ore and participate in furnace making.

Limitations of the process

The limitations of the traditional ancient processes are:
(i) Continuous air blasting by foot driven leather bellows for 4–5 hours is strenuous.
(ii) Large scale production is not possible since it can produce about 3.5–4.5 kg of metal per heat.
(iii) The productivity of the process is also very low since major loss of iron takes place in the form of FeO in slag.
(iv) A significant amount of heat energy and chemical energy are lost through exit gases from the furnace whose temperature is 550–600°C.
(v) The use of Sal wood charcoal is not suitable from the point of view of environmental management therefore it is advisable to use an alternative reductant namely acacia or eucalyptus charcoal
(vi) It is observed that the degree of ore reduction is less due to low shaft height of the furnace

Improvements in ancient iron making technology at NML Jamshedpur

Prior to incorporating several improvements in the traditional iron making process a prototype traditional furnace was constructed at NML Jamshedpur to optimize the process parameters.

Construction of prototype traditional furnace

A prototype traditional furnace was built at NML by using locally available clay. Extensive experiments were conducted to optimize the following process parameters: ● Type of ore (Bishunpur and Bastar) ● Form of ore (lumps or pellets) ● Type of reductant ● Air flow rate /volume of air blast per unit time ● Type of blower (leather bellows / mechanically driven hand blower)

<table>
<thead>
<tr>
<th>Metal Analysis</th>
<th>Sal charcoal</th>
<th>Tamarind charcoal</th>
<th>Jamun charcoal</th>
<th>Mahua charcoal</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.12</td>
<td>0.11</td>
<td>0.095</td>
<td>0.131</td>
</tr>
<tr>
<td>Si</td>
<td>0.045</td>
<td>0.038</td>
<td>0.039</td>
<td>0.042</td>
</tr>
<tr>
<td>S</td>
<td>0.031</td>
<td>0.034</td>
<td>0.028</td>
<td>0.026</td>
</tr>
<tr>
<td>P</td>
<td>0.041</td>
<td>0.038</td>
<td>0.046</td>
<td>0.043</td>
</tr>
<tr>
<td>Mn</td>
<td>0.0071</td>
<td>0.0069</td>
<td>0.0058</td>
<td>0.0069</td>
</tr>
<tr>
<td>SiO2</td>
<td>44.30</td>
<td>45.31</td>
<td>46.10</td>
<td>46.21</td>
</tr>
<tr>
<td>CaO</td>
<td>0.61</td>
<td>0.58</td>
<td>0.53</td>
<td>0.67</td>
</tr>
<tr>
<td>MgO</td>
<td>0.24</td>
<td>0.28</td>
<td>0.31</td>
<td>0.33</td>
</tr>
<tr>
<td>FeO</td>
<td>45.30</td>
<td>43.40</td>
<td>42.31</td>
<td>40.67</td>
</tr>
<tr>
<td>Al2O3</td>
<td>6.98</td>
<td>8.31</td>
<td>7.94</td>
<td>7.31</td>
</tr>
</tbody>
</table>

The iron making process in the prototype furnace at NML Jamshedpur is shown in Fig. 4. The degree of metallization of sponge iron is low. The metal is probably to some extent re-oxidised in the open atmosphere during the cooling phase. The sulphur and carbon contents in the product are low while Al2O3 and iron oxides are high. The typical analysis of metal and slag obtained in

Figure 4 The iron making process in the prototype furnace at NML Jamshedpur
Table 4: Theoretical & experimental CO/CO₂ ratio at different temperatures

<table>
<thead>
<tr>
<th>Location</th>
<th>Height from ground level</th>
<th>Range of temp (°C)</th>
<th>Theoretical CO/CO₂</th>
<th>Experimental CO/CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flame</td>
<td>--</td>
<td>500–600</td>
<td>1.20</td>
<td>Not measured</td>
</tr>
<tr>
<td>Upper</td>
<td>39 cm</td>
<td>750–850</td>
<td>1.85</td>
<td>3.0</td>
</tr>
<tr>
<td>Middle</td>
<td>26 cm</td>
<td>950–1050</td>
<td>2.60</td>
<td>4.0</td>
</tr>
<tr>
<td>Lower</td>
<td>11.5 cm</td>
<td>1050–1150</td>
<td>3.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Tuyere Zone</td>
<td>--</td>
<td>1425–1475</td>
<td>4.0</td>
<td>Not measured</td>
</tr>
</tbody>
</table>

the traditional Bastar type furnace, with a hand operated blower, iron ore from Kondagaon and charcoal made from Sal, Tamarind, Jamun and Mahua is given in Table 3. As the total iron percentage is low, more slag formation occurs and as a result the yield is decreased.

The exit gas from the furnace was analysed using Orsat Apparatus especially to determine the percentage of CO and CO₂ and to find out the ratio of CO/CO₂ at different heights in the furnace. A comparison of theoretical and experimental CO/CO₂ ratio at different temperatures along the height of the furnace is given in Table 4. The gas pressure was also measured at different heights in the furnace by using a U-tube manometer.

A thermo couple was inserted in the hole through which air is blown into the furnace. The temperature was found to be about 1450-1500 °C. The temperature in the reheating furnace was also found to be around 1300–1350 °C.

Analysis of Product

The iron made by the ancient process contains slag strewn all over the matrix. The slag content varies from 5-12 % as shown in Fig. 5. The iron contains low carbon and it is ductile in nature. Its hardness (VHN) is of the order of 200-230. The yield of metallic product made by the traditional process is only 20-25%. In the present investigation, an attempt has been made to enhance it up to 50%. Both polarisation as well as immersion tests show that corrosion rates of ancient iron and modern mild steel are almost similar.

Improved technology of ancient iron making at NML Jamshedpur

A comparison between primitive technology and improved technology for ancient iron making is shown in Table 5. After considering several disadvantages of the ancient iron making process (see previous section) several modifications were incorporated and the process was scaled–up by 5–6 times.

Table 5 : comparison between primitive technology and improved technology for ancient iron making

<table>
<thead>
<tr>
<th>#</th>
<th>Primitive technology</th>
<th>Improved technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>One tuyere</td>
<td>Three tuyeres at 120 degrees apart</td>
</tr>
<tr>
<td>2.</td>
<td>Sal charcoal</td>
<td>Acacia or eucalyptus charcoal</td>
</tr>
<tr>
<td>3.</td>
<td>Cold blast of air</td>
<td>Hot blast of air</td>
</tr>
<tr>
<td>4.</td>
<td>Leather foot-driven bellows for blasting cold air into the furnace</td>
<td>Semi – mechanized foot driven system for blasting hot air into the furnace</td>
</tr>
<tr>
<td>5.</td>
<td>No incorporation of waste heat utilization system</td>
<td>Incorporation of waste heat utilization system</td>
</tr>
<tr>
<td>6.</td>
<td>Charge mix comprised of ore lumps only</td>
<td>Charge mix comprised of composite pellets of even hematite ore and ore lumps</td>
</tr>
<tr>
<td>7.</td>
<td>The height of furnace shaft was low</td>
<td>The height of furnace shaft was considerably increased</td>
</tr>
</tbody>
</table>

Scale up criteria

The height of the furnace shaft plays an important role in the overall reduction process of iron ore. With very short height, the reaction equilibrium is rarely reached. The enhancement in shaft height increases the average residence time of the reactants and indirectly increases
the overall reduction of iron ore to metallic iron. The scale up criteria for the traditional iron making furnace at NML Jamshedpur included d/D ratio, H/D ratio, stack angle and volume/kg of iron as mentioned in Table 6. Based on this criteria the Bastar-type furnace was scaled up (up to 6 times) by incorporating a heat recovery system to improve its thermal efficiency. The volume of the furnace was enhanced to six times compared to a conventional furnace by incorporating the following features

- The traditional leather bellows were replaced by semi-mechanized blowers to introduce the required amount of air into the furnace.
- The height of the furnace shaft was almost doubled to increase the average residence time of reactants and the overall reduction of iron ore to metallic iron.
- The conventional salwood charcoal was replaced by char made from acacia and eucalyptus.
- The char made from acacia and eucalyptus was found to have a performance equivalent to that of the expensive traditionally employed salwood charcoal.
- The developed process can accept a wide range of raw materials in terms of their physico-chemical properties.
- Even hematite ore with Fe~58 to 60% was successfully used in the form of composite pellets.
- The scaled-up furnace can produce about 15 kg of wrought iron per each run, (total duration is around 4 hours).

### Experiments in scaled up furnaces

The details of the newly developed scaled up system without and with heat recovery are shown in Fig. 6a and Fig. 6b respectively. During the experiments in scaled up furnaces, it was well established that char made from both Acacia and Eucalyptus is a sustainable reductant and a renewable source of thermal energy for ancient iron making. Both Acacia and Eucalyptus are fast growing trees in dry lands and can be planted for making charcoal required for the tribal iron making process. The calorific value of char made from Acacia (7170 kcal/Kg) and Eucalyptus (6720 kcal/Kg) have a performance equivalent to that of sal char (6900 kcal/Kg). In view of heat loss, a heat recovery system has been designed to make use of the sensible heat of exit gases for increasing the blast temperature. This hot air is inserted into the furnace through

### Table 6: Scaled up parameters for prototype furnace (Bastar model) established at NML, Jamshedpur and demonstration sites.

<table>
<thead>
<tr>
<th>Sl No.</th>
<th>Type of furnace</th>
<th>Furnace cross section</th>
<th>d (cm)</th>
<th>D (cm)</th>
<th>H (cm)</th>
<th>d:D ratio</th>
<th>H/D ratio</th>
<th>Stack angle θ°</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Prototype furnace (Bastar model)</td>
<td>Circular</td>
<td>16</td>
<td>28</td>
<td>80</td>
<td>0.57</td>
<td>2.855</td>
<td>85</td>
</tr>
<tr>
<td>2.</td>
<td>Scaled –up (6 times) furnace I</td>
<td>Circular</td>
<td>28</td>
<td>48</td>
<td>127</td>
<td>0.58</td>
<td>2.645</td>
<td>85</td>
</tr>
<tr>
<td>3.</td>
<td>Scaled – up (6 times) furnace II at demonstration sites</td>
<td>Circular</td>
<td>23</td>
<td>46</td>
<td>127</td>
<td>0.50</td>
<td>2.76</td>
<td>85</td>
</tr>
</tbody>
</table>

### Table 7: Typical analysis of metal and slag obtained in scaled–up furnace, and scaled–up furnace with heat recovery system, by making use of charcoal prepared from eucalyptus and acacia

<table>
<thead>
<tr>
<th>Metal</th>
<th>Using charcoal prepared from eucalyptus</th>
<th>Using charcoal prepared from acacia</th>
<th>Using charcoal prepared from eucalyptus</th>
<th>Using charcoal prepared from acacia</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bastar ore I</td>
<td>Bastar ore II</td>
<td>Bastar ore I</td>
<td>Bastar ore II</td>
</tr>
<tr>
<td>C</td>
<td>0.095</td>
<td>0.135</td>
<td>0.11</td>
<td>0.143</td>
</tr>
<tr>
<td>Si</td>
<td>0.035</td>
<td>0.049</td>
<td>0.038</td>
<td>0.053</td>
</tr>
<tr>
<td>S</td>
<td>0.027</td>
<td>0.021</td>
<td>0.028</td>
<td>0.020</td>
</tr>
<tr>
<td>P</td>
<td>0.018</td>
<td>0.043</td>
<td>0.019</td>
<td>0.048</td>
</tr>
<tr>
<td>Mn</td>
<td>0.0018</td>
<td>0.0073</td>
<td>0.0019</td>
<td>0.0084</td>
</tr>
<tr>
<td>Slag</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO₂</td>
<td>38.75</td>
<td>39.35</td>
<td>39.40</td>
<td>40.15</td>
</tr>
<tr>
<td>CaO</td>
<td>8.75</td>
<td>10.10</td>
<td>8.74</td>
<td>10.15</td>
</tr>
<tr>
<td>MgO</td>
<td>2.40</td>
<td>1.89</td>
<td>2.45</td>
<td>1.82</td>
</tr>
<tr>
<td>FeO</td>
<td>35.3</td>
<td>37.3</td>
<td>34.8</td>
<td>36.95</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>11.45</td>
<td>10.10</td>
<td>11.34</td>
<td>10.35</td>
</tr>
</tbody>
</table>
the passage of tuyeres (Fig. 6b). Three semi-mechanized blowers were fitted and hot blast of air was blown at 125 °C into the furnace through three tuyers fitted 120° apart. The result was a uniform distribution of air through the entire cross-section of the furnace, the reduction of localized hot spots and increased yield of product. Also the flame temperature of exit gases was brought down to less than 450 °C. Further it is important to increase the air blast temperature by further modifying the heat recovery system and bring down the temperature of exit gas to around 300 °C. The product contains elongated slag as shown in Fig. 7. It is of non-corrosive nature and can be used for making several decorative articles as illustrated in Fig.8. The typical analysis of metal and slag obtained in the scaled up furnace, and scaled up furnace with heat recovery system by making use of charcoal prepared from eucalyptus and acacia is given in Table 7.

The scaled up process of ancient iron making with heat recovery system was successfully demonstrated at NML Jamshedpur to a large number of visitors and entrepreneurs. It was also successfully demonstrated at two tribal sites, namely Tribal Cultural Society, Jamshedpur and Technical Training Institute, Bahanaga, Balasore, Orissa. The product of the process is the value added wrought iron, extremely suitable for making decorative articles that have a good export market. The adaptation of this scaled up process with a heat recovery system shall raise the income and living standards of tribal and rural artisans of our country and preserve the age old technology of iron making.

Conclusions

- Important aspects of ancient iron making process employed at Hadup village, Bishunpur Jharkhand
and Kondagoan, Bastar, Chattisgarh have been highlighted.

- A prototype traditional furnace for iron making was built at NML and extensive experiments were conducted with a variety of charcoals in order to comprehend the effect of different process parameters on the yield of the product.
- For uniform distribution of air in the entire cross section of the furnace, three tuyers have been fitted at 120° apart to improve the yield of the product.
- A scaled up furnace with heat recovery system and semi-mechanized blowers was constructed at NML in order to improve the productivity of the furnace.
- It is expected that the improved technology of ancient iron making will generate enormous employment for the tribal and rural artisans. The export of decorative articles can boost up their micro – economy.

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