Archaeology of Iron Metallurgy in Sri Lanka

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This article provides an overview of the archaeology of iron technology in Sri Lanka. Data on ancient iron metallurgy provided here are based on the data revealed from recently excavated iron production sites in the island and data from literary, ethnographical and metallurgical studies through other sub-disciplines of anthropology, which are strongly linked to the practice of archaeology of ancient iron technology.

Studies of Iron Metallurgy

The study of pre-modern iron metallurgy in Sri Lanka that had been started in the 19th centuryindicated that Sri Lankan iron and steel occupied a significant place in the south Asian iron technology complex. Although Sri Lanka's ancient chronicles and numerous epigraphs on stones provide evidence for using iron from early historic times, the ancient metallurgical knowledge of Sri Lanka is essentially incomplete due to the scarcity of research material published on archaeometallurgy. During the last decades of the 20th century, the archaeological discipline gradually shifted from an empirical and descriptive academic tradition which mainly focused on great monuments, ephigraphical works and art, to a discipline of archaeological material and analyses based on a multidisciplinary research approach connected with social sciences, natural sciences, and theoretical frameworks. As a result of new academic traditions, in the late 1980s major discoveries in the archaeological investigation of this subject were made at Dehigaha-ala-kanda (Alakolavava) and Dikyaya-kanda (Vavalavava) along the Kiri Oya Basin (KOB), in the Sigiriya-Dambulla Region of the dry zone, and at Samanalaweva on the banks of the upper Walave River in the intermediate zone. In Samanalaweva, the west-facing smelting site, was identified as using a wind-pressure technique without bellows for the smelting process. Evidence revealed from Dehigaha-ala-kanda and Dikyaya-kanda suggests that the smelters used a multiple/poly-tuyere system with bellows. However, in addition to these two sites, the existence of iron slag mounds throughout the island bear testimony to the fact that this technology was widespread. (Figure 1: Please see the back inner cover). The common indicator for smelting sites is the existence of iron slag, which is the main waste product of the smelting process.

Chronology

Until recently, the earliest known dates for the iron smelting technology was 10th-9th century BC, which was established through C^{14} dating from a slag sample extracted from an excavation in a protohistoric context, immediately above the Mesolithic layer from Aligala (998-848 BC) in Sigiriya, and from the excavation inside the citadel (930-800 BC)in Anuradhapura. Both samples indicated that the earliest archaeological evidence for the use of iron technology in the island which began with the agrarian protohistoric period in the Pre-Vijayan period. Slag samples dated 2400 BC, unearthed from recent excavations conducted in Beragala, pushes back the earliest date of the smelting technology in the island beyond the first millennium.

Radiocarbon Dating

Radiocarbon dates of excavated iron smelting sites in the Kiri Oya Basin; Dehigaha-ala-kanda, and Dikyaya-kanda have provided almost parallel data. Dikyaya-kanda samples were analyzed and calibrated at the Beta Analytic Radiocarbon Dating

Laboratory using latest INTCAL98 Radiocarbon Age Calibration database and the mathematical Pretoria calibration Procedures in C^{14} dates calibration for converting radiocarbon BP result to calendar years.

According to data, it seems that the main activities of iron smelting was conducted during Reigns of King Mahasen (269-296 A.D.) and his son King Kithsirimevan (269-324 AD), who ruled the area before King Kasyapa, the founder of the main construction period of Sigiriya Royal City of 5th century AD (477-495 AD). The period somewhere around 10th regnal year of King Kithsirimevan (296 AD) that is represented by the Vavalavava monastery rock inscription is also compatible with radiocarbon dates with main activity periods of both iron smelting sites.

Table 1: Radiocarbon dates for Dikyaya-kanda in the KOB.

Sample # & Beta Lab #	Measured Radiocarbon Age	Conventional Radiocarbon Age	2 Sigma Calibration (95% Probability)	1 Sigma Calibration (68% Probability)
SIT-22/04-01 201941	1900+60 BP	1860+60 BP	Cal AD 30 to 260 and Cal AD 290 to 320	Cal AD 80 to 230
SIT-22/04-02 201942	1780+40 BP	1780+40 BP	Cal AD 130 to 370	Cal AD 220 to 260 and Cal AD 290 to 320
SIT-22/04-03 201943	1790+40 BP	1760+40 BP	Cal AD 150 to 390	Cal AD 230 to 340
SIT-22/04-04 201944	1630+60 BP	1620+60 BP	Cal AD 260 to 290 and Cal AD 320 to 570	Cal AD 390 to 530

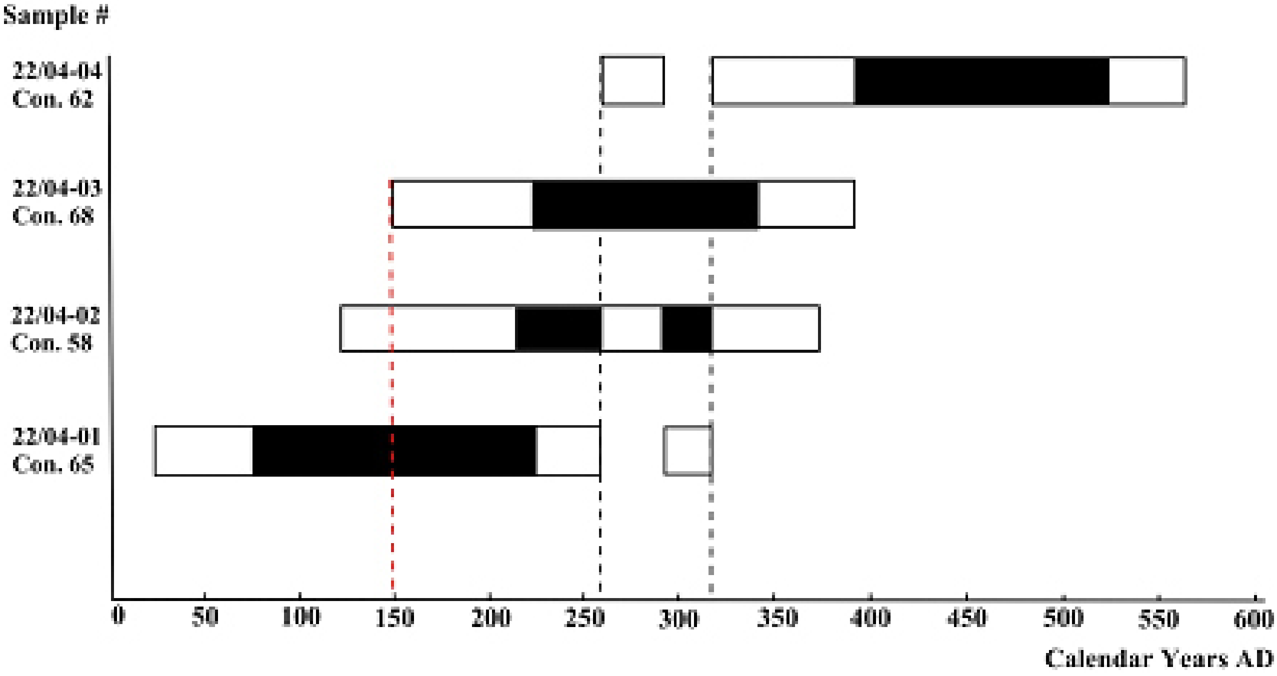

Figure 2: Diagram for Radiocarbon dates at Dikyaya-kanda in the KOB. Calibrated age ranges from cumulative probability, two sigma (95%) & one sigma (68%). INTCAL98 While hollow bars represent two sigma limits, solid bars represent one sigma limits.

Raw Materials: iron ore

The ancient iron smelters used haematite (Fe_2O_3), limonite ($Fe_2O_3.nH_2O$) and to a lesser extent magnetite (Fe_3O_4) ores as the principal raw material for their smelting process. Iron smelters at Samanalaweva also used limonite and haematite iron ores for the production process. The Anuradhapura Gedige site yielded some pieces of iron slag and limonite nodules indicating that these iron smelters also used limonite ore. But the X-ray diffraction confirmed that iron ore samples unearthed in the Kiri Oya Basin (Figure 3) are magnetite and the iron oxide content is around 90 wt.% (Table 2). The chemical analysis revealed all ore samples to have a very high purity.

The use of magnetite in bloomery furnaces has so far been identified only in a few exceptional cases in the world. Modern archaeometallurgists assume that the dense magnetite ore would be difficult to be reduced using this technique, because it would be impossible to attain the flame temperature high enough to reduce magnetite in these furnaces.

Before the production process, the pre-modern smelters roasted the ore to convert it into hematite, by removing much of the water content together with carbon dioxide and other volatile components like sulphur in the ore. The smelters also ground or pounded the ore making it suitable for putting it into the furnace.

A frontal bone, the bone of the human cranial vault, smeared with red ochre, which was found from Ravana Alla cave and two fractional human bones which were also coated with red ocher (haematite) and unearthed at Fa Hien cave (ca 5400 cal BP) are the earliest examples of the use of iron ore in Sri Lanka. This evidence suggests that iron ore was used in the lithic societies for ritualistic or funerary purposes even before identification of the metallurgical value of iron ore.

Furnace Construction

The most valuable part of studying the iron smelting process is to understand the structure of the furnace. The technological efficiency of the production process dependeds mainly on the furnace construction. Three factors are the basic requirements of the smelting process:

1) the speed of increasing the temperature;

2) attaining the temperature, and

3) the oxidation and reduction conditions inside the furnace, which depend on the furnace construction. The major raw materials used for the construction of furnaces excavated from smelting sites are clay, quartz grains and stone slabs. The height of a furnace when reconstructed with the remaining fragments seems to be about 2 m, while the thickness of the side walls was about 20-40 cm at the lower half, which decreased to about 3-4 cm at the top (Figure 4).

Table 2: Analysis chart of the iron ore samples at Dikyaya-kanda (Vavalavava) in the KOB.

		Atom%	
	SIT22-01	**SIT22-02**	**SIT22-04**
Fe	93.721	0	91.046
Na	0*	64.908*0*	
Mg	0.815*	0*	0*
Al	2.833	0*	0.919
Si	0.597	1.756	3.735
P	0.108*	5.322	2.771
S	0.243*	1.079*	0.017*
Cl	0.077*	7.177	0*
K	0.159*	0.762	0.017*
Ca	0.082*	0.402	0*
Sc	0.055*	0.231*	0.178*
Ti	0.72	4.715	0*
V	0*	6.768	0.111*
Cr	0.081*	0.178*	0.136*
Mn	0*	0.334*	0.11*
Sr	0.265*	0.144*	0.269*
Co	0*	6.226	0*
Ni	0244*	0*	0.158*

Area scan * = less than 2 sigma. Analyses report was done at the Arrhenius lab at the University of Stockholm under the supervision of Prof. Dag Noreus.

Taking into consideration the above as well as the height of the furnace, the furnaces appeared relatively broad, and had the shape of a rectangular bottle. The height and shape of the shaft showed its capability to control the

Figure 3: Iron ore samples found in the KOB. A) Pieces of iron ore unearthed at Dikyaya-kanda. B) Block of iron ore collected at Dehigaha-ala east. Scale is given in inches.

temperature, while at the same time ensuring the strength of the furnace construction. The stone slabs also ensured the strength of the furnace by supporting the weight of the superstructure that was made of clay. The other probable reason is to determine the breaking margin of the front wall without harming the rest of the furnace construction when taking out the iron bloom (the final product) after the production process is completed. The furnace superstructures at both smelting sites can be categorized as bloomery furnaces.

Furnace Operation

Although the technique used in the smelting process varied greatly from area to area, the basic principle remained the same. The operation of the furnace depended mainly on the scientific basis of the iron metallurgy. The success of the furnace operation or the smelting process depended mainly on the presence of carbon monoxide (CO) which acted as an active reducing agent in the furnace. The extraction of iron from the ore occurred through reduction with charcoal at a high temperature, where charcoal acted as a fuel and a reducing medium. According to the characteristic atmospheric conditions and chemical reactions of the bloomery process, the features inside of the furnace can be divided into three major zones, namely, combustion, solution and reduction. According to the general method of furnace operation, the furnace is preheated at first and then filled with ore and charcoal in alternate layers. The air is supplied through tuyeres (clay nozzles/pipes attached to the furnace wall to direct the air produced by bellows) blown by bellows or natural draught for the process. The oxidation zone is created near the tuyeres. At a temperature between 1100°C-1300°C, carbon monoxide is formed by the combustion of particles of charcoal with the air blown through tuyeres. The main reaction of the combustion zone is the reaction of oxygen with carbon (C) produced from charcoal, and conversion of it into carbon dioxide (CO_2). This

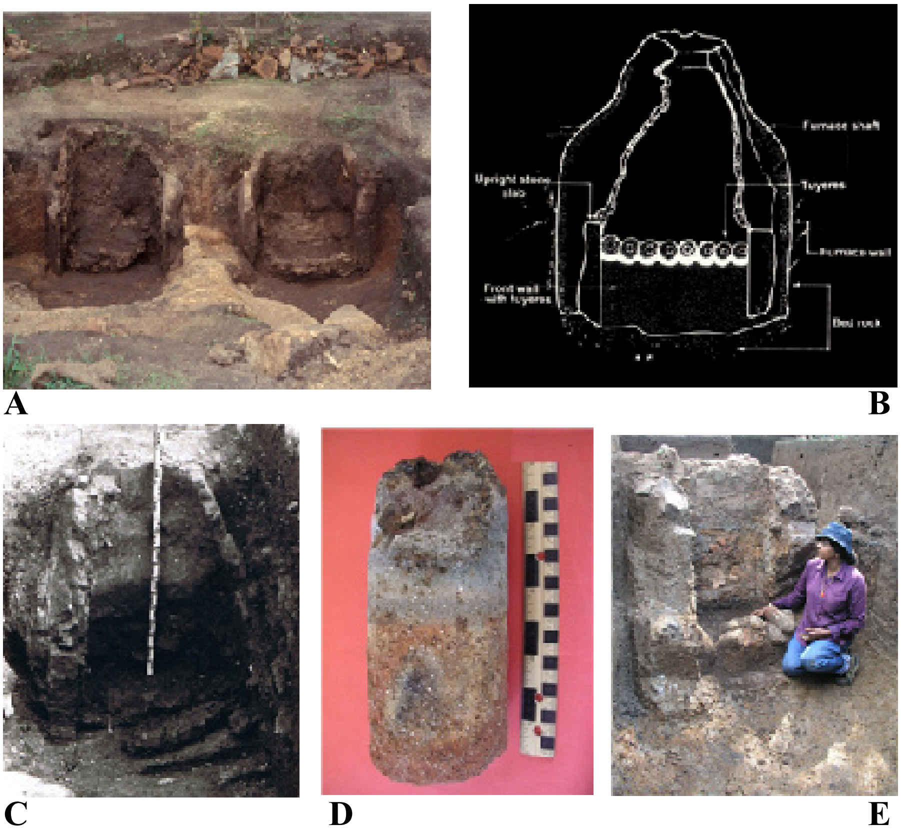

Figure 4: Furnaces in the KOB. A) Unearthed two furnaces at Dehigaha-ala-kanda. B) Reconstructed drawing of the furnace at Dehigaha-ala-kanda. C)Well-preserved furnace at Dehigaha-ala-kanda;presently exhibited at the Sigiriya archaeology museum. D) A tuyere unearthed at Dikyaya-kanda.E)Furnace at Dikyaya-kanda.

carbon dioxide reacts with more charcoal to form the reduction gas, carbon monoxide (CO) in the solution zone.

Heat is the most important factor of the iron smelting process. In pre-modern furnaces, the ore was incompletely reduced because the temperature did not reach 1100°C-1300°C. Therefore reduction was completed in two stages. In the reduction zone ferrous oxide (FeO) was formed at first as a result of the ore (eg. Magnetite Fe_3O_4) reacting with carbon monoxide (CO). Secondly, ferrous oxide was partly reduced to iron as a result of the reaction with carbon monoxide, and partly turning the melt to slag together with the gangue or mainly silicates as fayalite (Fe_2SiO_4).

The fayalite compound melts at 1170°C absorbing the oxides of manganese, magnesium and aluminum present in the gangue. In some parts of South Asia there is evidence for the use of lime ($CaCO_3$) as a flux. In such cases the resulting slag also contains calcium silicate.

Unless the charcoal is broken into small pieces before charging, the distribution of carbon in the charge may not be sufficiently uniform, and unless the ore is adequately porous, it will not be completely reduced because the carbon monoxide will not be able to reach all parts of the ore. These two reasons caused the production of a small quantity of low quality output relative to the amount of raw material used. The other important point is that when too much enthusiasm is shown for the use of the bellows, or as another reason if too much oxygen is produced inside the furnace, especially due to the local absence of carbon, the already reduced iron may become reoxidized. This causes the whole process to be a failure.

As discussed above, the iron smelting process requires more critical conditions than copper, for a successful production. At least it requires a temperature of 1250°C to separate the useless gangue from the smelting charges in the furnace. Therefore it needs a good supply of oxygen to reach this high temperature. It is very difficult to maintain a reducing condition with a good supply of oxygen.

Ancient smelters were capable of controlling these critical points and complicated demands, and were able to produce high quality iron with the sustained experience of technological knowhow. They knew how to produce the desired quality of metal with their long experience, even though they may not have had a clear understanding of the chemical and metallurgical principles involved is the smelting technology.

Iron slags

An iron rich wüstite phase (FeO) was not found in the slag samples collected in the Kiri Oya Basin (Figure 5). But only the usual

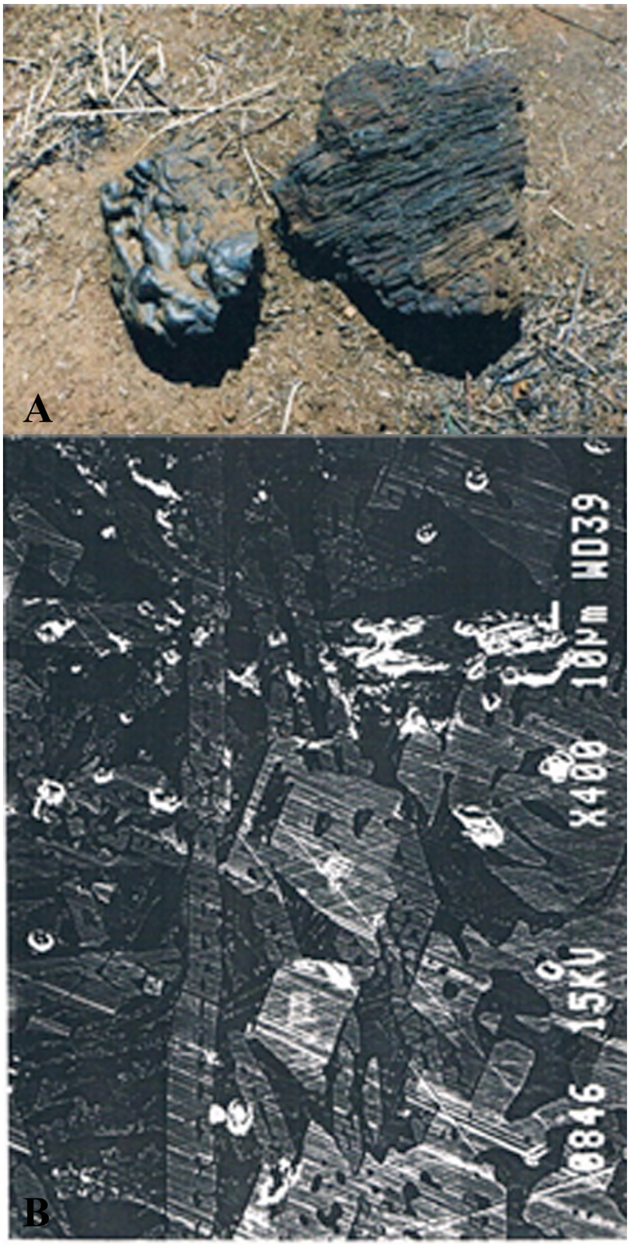

Figure 5: A) Different types of iron slag samples collected in the KOB.
B)Electron microscopy picture of a typical reduction slag at Dehigaha-ala-kanda.

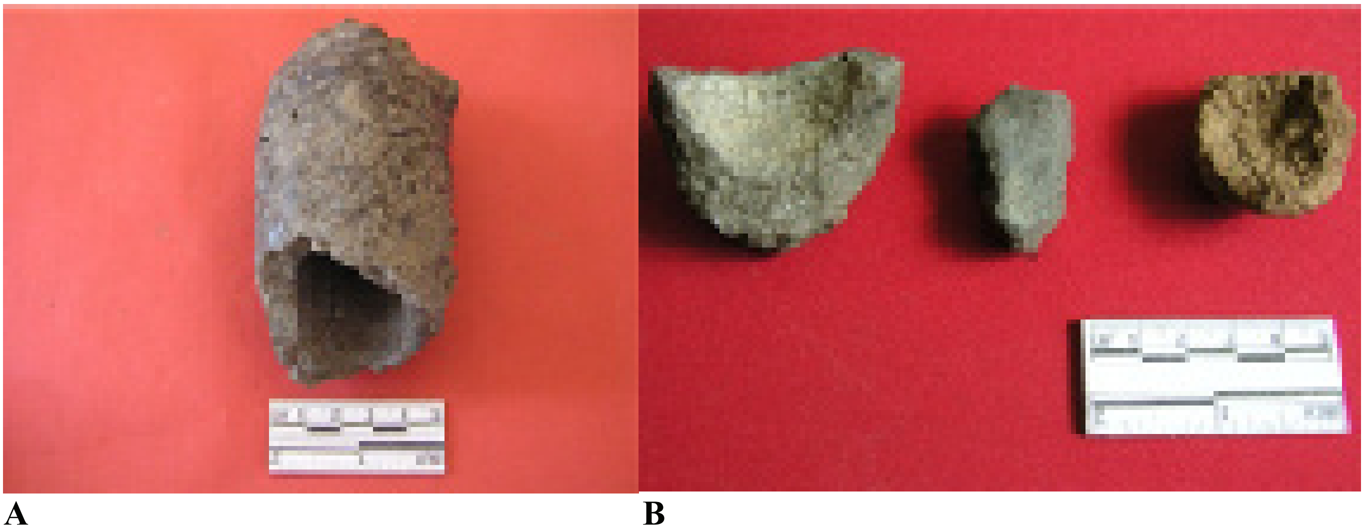

Figure 6: A)A crucible sample collected near paddy field near Balangoda Uggal Aluthnuwara Karagama Devalaya. (Presently exhibits at the Archaeology Museum of the Kelaniya University). B) Pieces of crucibles unearthed in the KOB.

fayalite phase (Fe_2SiO_4), which is an iron poor glassy phase. According to chemical analysis, the iron oxide contents in the slags in the Kiri Oya Basin were unusually low for bloomery slags.

Slags from both sites consisted of the lower iron oxide content of fayalite (Fe_2SiO_4) compound when compared with slag samples from other production sites which were situated around the area. This indicates that the yield of iron at the site had been very high. Considering the above data, it can be assumed that the smelters of KOB had the knowledge to select ore of good quality which could produce a high yield compared to the quantity of raw materials used, and the advanced smelting technology to achieve high quality

The brighter crystals with sharp edges are fayalite on a dark background of the glassy phase, and where the heavier elements are concentrated, will appear brighter on the pictures with this technique.

Crucible steel

The process of making steel was based on the principles of carburization of wrought iron in crucibles and these ingots were generally known as crucible steel or *wootz* steel. The ancient Islamic world used forged Damascus Swords from the high carbon crucible steel or Damascus Steel or *`Wootz Steel'* that was made in Southern India and Sri Lanka. Sri Lankan steel appeared in the book of al-Kindi who was a writer of the mid ninth century. According to him, four major sword-making centers of Yemen, Fars, Khorasan, and Mansura preferred using Serendib steel.

The procedure for producing steel from wrought iron is mostly recorded in most ancient smelting sites. The carbon content of steel is intermediate between that of cast iron and wrought iron. The percentage of carbon ranges from 0.1 to 2% in steel.

Very tiny (~ 10 g) piece of “steely iron” yielded at Dehigaha-ala-kanda confirmed that the furnaces at the site had fairly strong reducing conditions for producing `steely' iron and pieces of crucibles unearthed in the KOB also confirmed the existence of steel production in the region (Figure 6).Radiocarbon dating for the crucible pieces unearthed at the crucible steel site at Mamalgaha village near Balangoda Uggal Aluthnuwara Kataragama Devalaya, dated to 17 century AD which also confirmed Coomarswamy's eyewithness account for steel making technology around Samanalavava region in Sri Lanka.

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