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An Experimental Study of Iron-Smelting Techniques Used in the Nathara-Ki-Pal and Iswal, India: Results for the Reconstruction of Ancient Metallurgical Processes

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Abstract: *This paper is an attempt to explain the theory and principles involved in the experiment of the iron smelting process. In the process of iron smelting, furnaces are broken, and the tuyeres are removed to recover the bloom. New furnaces may then be constructed either on the same spot as the previous one or adjacent to it. In the context of archaeological sites, several overlapping sequences of furnaces may be interpreted in diverse ways, e.g. successive cultural phases, different phases of occupation, etc. Here, we examine this question by looking at the process of furnace construction and destruction in ethnographic and experimental studies. This is then contrasted with the furnace distribution pattern at the early historic site of Iswal and Nathara-ki-Pal, Rajasthan. The study revolves around the number of furnaces and correlation with each other in terms of spatial distribution and furnaces versus demography. It also probes into the relationship of furnaces to tuyeres and the importance of the latter in terms of use/reuse.*

Keywords: *Archaeo-metallurgy, Experimental Archaeology, Slag, Iron Ore, Bellow*

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Introduction

The term 'experimental' carries multiple connotations. It suggests something provisional, 'being tested', perhaps not yet ready for release to a wider public. Experimental archaeology has been explained as a science, defined as a 'controllable imitative experiment to replicate past phenomena [….] to generate and test hypotheses to provide or enhance analogies for archaeological interpretation' (Mathieu 2002:1; Christopher B 2013). During the excavation it was very difficult to find the complete structure of the furnace; instead, we found the base of the furnace, broken parts of the furnace spread throughout the site, tuyeres of different sizes, slags, ashes, charcoal and iron artefacts, with the help of available data from excavation, we have attempted to reconstruct iron technologies that have been practised by the ancient iron smelters at Iswal and Nathara-ki-Pal. The purpose of this experimental study is to design an experimental method based on the structure of the furnace obtained from the excavation at the sites of Iswal and Nathara-ki-Pal (NKP). To propose hypotheses to the method used for iron smelting, and to enable interpretation of processes such as collecting ore, reconstruction of furnaces, making of a bellow, a requirement of charcoal, collecting clay, preparation of tuyeres and crushing of ores, nature of slag obtained, the timing involved for each stage, the labour involved and other details. This experimental study involved 3 phases of iron smelting experiments, based on replicating the nature of furnaces noted Iswal, Further, a comparison was made between experimental and archaeological slags and bloom iron. The methodology described below was formulated to ensure a thorough and comprehensive investigation of iron smelting processes and to provide the opportunity for comparison between earlier studies and this new experimental research.

Purpose and Scope of Experiment Study

The only way of obtaining detailed knowledge about the traditional technique is by archaeo-metallurgical investigation and by the construction of models. These methods permit interpretation of the available archaeological material in terms of analyses, analogies or model and so contribute to comparative studies of technology and culture history (Friede H. M. 1977). The production of iron from an ore seems to be a simple reduction process: the iron oxide of the ore (Fe_2O_3) is reduced to elemental iron by the carbon monoxide (CO) produced by the burning of charcoal ($Fe_2O_3 + 3CO= 2Fe + 3CO_2$). However, there are several difficulties in this process: one is the tendency of the reduced iron to re-oxidize at high temperature, and another is the possibility that an excessive supply of air may produce carbon dioxide instead of carbon monoxide. This excess carburization may give undesirable properties to the iron produced. Furthermore, it may often be difficult to separate the reduced metallic iron from the slag and other impurities. The smelting process must be regulated in such a way as to create optimum condition for reduction, carburization and separation. There are a number of factors that influence the process (Friede H.M. 1977).

Study Area

Iswal: Iswal village (24°44'N; 73°37'E) (Tehsil-Girva, Udaipur district) is located about 20 km north-west of Udaipur city. The ancient site located to the South-West of the village is spread over of one kilometre square, comprising several iron slag mounds. The site is close to the source of raw materials (Pandey *et al* 2006). Except for the Abu Block, the highest part of the main Aravalli range lies northwest of Udaipur between the village of Gogunda and Kumbhalgarh which is known as the Bhorat plateau, with an elevation of 1,225m. The Aravalli are important owing to the richness of the mineral deposits found there. The Department of mines and geology of Rajasthan has reported the iron ore deposit at Nathara-Ki-Pal, Dangio-Ki-Pancholi and Iswal (Pandey *et al*. 2009: 201) (Fig.1).

Furnace: Chronologically the remains of the earliest furnace were encountered in SE and NE quadrants of HG4, within the close proximity of a structural complex at a depth of 10.82m. It was semi-circular in shape and was made of stone and bricks. The surrounding floor of it was made of fine clay and slag material. A huge amount of fine ash was also recovered from it. Its total depth was approximately 52 cm and its measurement was 34 cm (NS) and 48 cm (EW). It appears that it was used for the forging purpose. A rotary quern was also found at a depth of 11.42m in trench HD4 which had two transverse slots at each side for the insertion of the handle. The two other furnaces were exposed in SE quadrant of trench HAB5. These were at a distance of around 70 cm from each other. One of them was measured 80 cm in height (N-S) and 60 cm (EW) in width. Its shape was roughly triangular; three

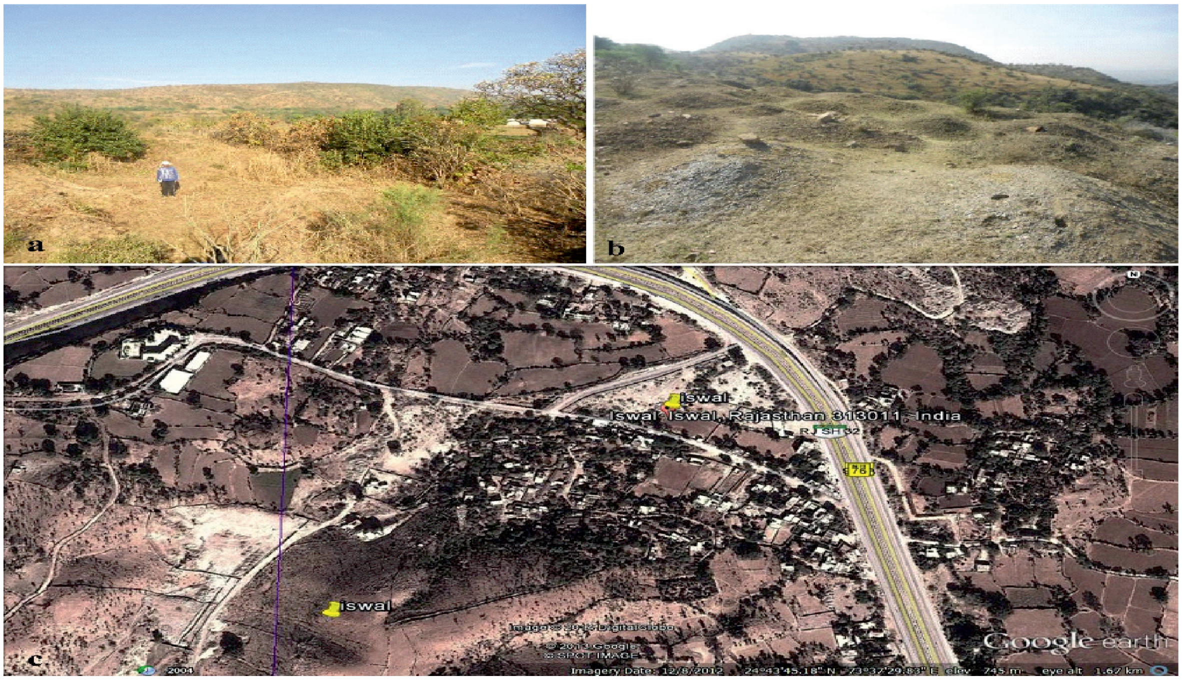

Fig. 1. a & b): General View of Iswal and C) Google Image of Iswal

broken retorts were also noticed at the upper part of the furnace. These retorts were 12 cm in length with a width of 8cm and with a hole of 1 cm. The other one was 90 cm (EW) in length with a width of 70 cm (NS). It was roughly oval in shape. The later walls of both the furnace were about 2.4cm thick and these were full of slag and ash. A square-like structure in SE quadrant of HB18 was also exposed at a depth of 12.50 m. It was made of compact mud and was spread in EW and NS directions. Its total measurement was 75 cm (EW) and 60 cm (NS). The central part of the structure was full of loose soil. It was spread to an area of 16 × 30 cm. A stone of 25 × 21 cm was close to the structure aligned to N-S. Besides, all the corners of the square-like structure had been strengthened with bricks and pebbles. Thus, the complete structure was spread over an area of 82 × 53 cm, the upper surface of the whole area was covered with a layer of red thick soil which is an indication of burning ore large scale (Fig.2).

Fig. 2. a).The Trench HG4 **Square like structure in SE quadrant of HB18**

Nathara-Ki-Pal: In 1994 the site Nathara-Ki-Pal was discovered by L.C. Patel of the Institute of Rajasthan studies, Udaipur. Later on, during the course of the systemic survey of the region Dr.V.S.

Shinde, Deccan College Post graduate Research Institute, Pune and Dr. Lalit Pandey, the application, re-examined the site and it was observed that it was a potential centre of iron metallurgical activities during the Early Historical to the medieval period. The evidence of broken retorts and the remains of the broken furnace were significantly visible on the surface of the mould. The village Nathara (73°47'E; 24°16'N) is located about fifty-seven km southeast of Udaipur. The site Nathara-Ki-Pal is at a distance of 4km northeast of Chavand, the famous capital of Maharana Pratap. Geographically, the village Nathara-Ki-Pal is a located on the foot hills of Aravalli. The village is located close to Gargal River, which originated from Manda-Dhawaraghatas; it is a seasonal river. The total area of village 5,527 hectares and spatially it is not only the largest 'Pal' (Tribal village) but also the largest village in Magra (hilly tract). The site of Nathara is spread in an area of 1 km (NS) X1/2 km(EW). The various heaps of iron slags can be seen on the surface of the mound which shows that it was a major centre of iron metallurgical activities. The site is on the close vicinity of iron ore. The iron ore is located on a hill at a distance of 1½ km, in the northwest direction. Locally, the hill is called Beda-ghata. According to the report of Dept. of Mines and Geology of Govt. of Rajasthan, Nathara has a good amount of iron deposit and the iron content in ore range from 48% to 62% (Pandey 2013) (Fig.3).

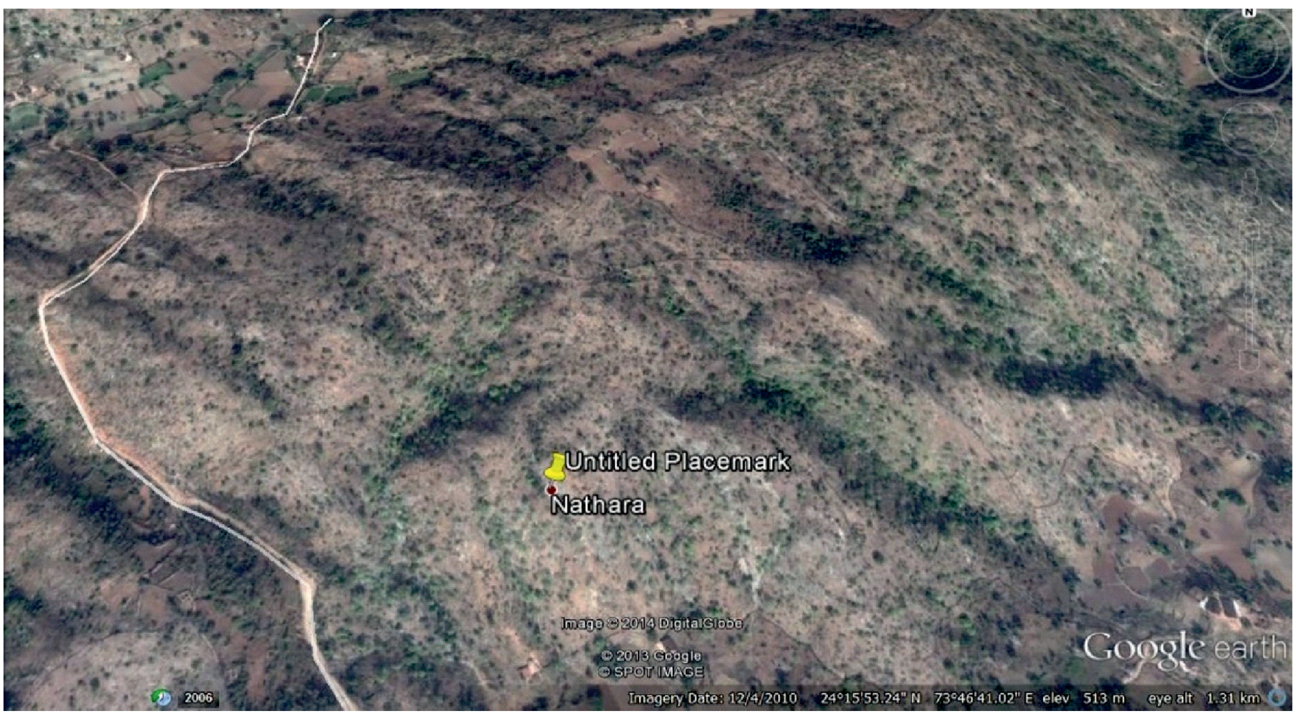

Fig. 3: Google image of Nathara-Ki-Pal

Furnace: The remains of a furnace were recovered in SE quadrant of trench TT2 at a depth of 3.10m in layer 6. The furnace was totally broken; therefore, it is not possible to predict its shape. During the course if excavation, only the base of the furnace could be recovered which is 15m thick and it is circular in shape. During the cleaning of the TT2, a broken retort is recovered from layer 6; it is noteworthy that the base of the furnace was also recovered from layer 6. The total length of the retort is 26cm and the width of 11cm. There are two holes on both ends; one is larger (4.5cm) and the other smaller (3cm). The larger holes run along the length of the retort. In course of it, the narrow hole of the retort is horizontal (Pandey *et al* 2008) (Fig.4).

Fig. 4: Furnace Structure, NKP

Methodology of Experimental of Iron Smelting Process

- Information collection
- Ore collections and preparation
- Collecting clay
- Preparation of tuyeres
- Air leather bellows
- Reconstruction of furnace
- Smelting process
- Scientific analysis

Information Collection*:* Data collection of the previous work on experimental of smelting process studies in a different region worldwide. "Perhaps the first were carried by Gilles in Germany (1958 and 1960), who being convinced that the earliest furnaces were blown by induced draught, erected a shaft furnace 1.72m height with a diameter of 0.9m. There was single (30 cm diameter) entrance for air at the bottom which could be controlled. Experiments were continued and shaft and hearth furnaces were reported in 1958 and 1960. Fayalite slags containing iron inclusion were produced. The maximum temperature reached was 1400°C" (Tylecote *et al* 1985: 8). Len Pole (2013) had worked on, iron working traditions in Ghana during 19th to 21st century of Mawu (Aptapu) iron workers. (Nadel 1942; Pole 2008) He has reconstructed a smelting operation in 1973. Keen (2013) conducted an experimental study of iron smelting in Madhya Pradesh, India. He had given a detailed description iron smelting operations of Agaria people who occupy a large territory in Madhya Pradesh; he has mentioned the smelting operation on diurnal basis. Juleff (2013) discussed the technological change in Sri Lanka's archaeological record. She had excavated a site named Samanalawewa (Galewalahinna), with a furnace of semi-permanent elongated C-shape clay furnace and the function of the furnace has been carefully studied through archaeological reconstruction work (Tabor *et al* 2005; Juleef 2013: 139). Tripathi (2013) Tripathi and Misra 1997: 56-67--- had also experimented on iron smelting processes. The study concludes that the furnace used by the living tradition of the Agrarians and the ancient furnace exposed during excavation shows some kind of similarity with the experimental work. Thiele (2010) discussed smelting experiments in the Early Medieval Fajaszi type of bloomer furnace (Theiele 2013: 100).

Ore Collection and Preparation*:* The iron ore available in Nathara-Ki-Pal comprises mainly haematite (Fe_2O_3), limonite-geothite ($2Fe_2O_3$-$3H_2O$) and magnetite (Fe_3O_4). The ores used for smelting process should have iron content between 48% to 52%; too low a content may give a low smelting yield of iron and too high a content of impurities cause difficulty in smelting (Pandey *et al* 2006). It is likely that the ancient mines of Nathara-Ki-Pal were the source of iron ore. We would find the iron ore in the site, which is approximately 2 to 3 kg of each iron lump. For the purpose of experimental work, author has collected almost 87 kg of iron ore from Nathara-Ki-Pal (Fig. 5). The iron ore is cursed or pounded into small bit or powder; this ore preparation will help during the smelting process.

Fig. 5: Ore Collection and Preparation

Clay Preparation*:* The clay for building furnace and preparation of tuyeres was collected from Buckingham canal, Chennai, Tamil Nadu and later the clay was mixed with red soil. The clay from the Buckingham canal is light brown in colour and mixed with shells and texture of clay is fine. The clay was found to be in lumps and the clay was soaked in to water for 3 days and then the clay was filtered to remove impurities (Fig.6).

Fig. 6: Clay Preparation

Preparation of Tuyeres*:* The tuyeres was made of the above-mentioned clay and were not mixed with any other materials, First 2cm diameter and 10cm wooden rod was taken and then covered with clay; waited for 15-20 minutes to dry up in the hot sun. Then slowly the wooden rod was removed from the clay module, so the clay can be moulded as tuyeres structure. After one day when the mould has dried up completely again it was smoothened with thin layer of same clay. Each tuyere took approximately 15 minutes to fabricate. The tuyeres are shaped to have a narrow end, so each of the tuyeres can fit into them gently into the furnace. For the first phase of experimental work, author has made up of six tuyeres of same size. The bottom of the tuyeres is made flat to fit the ground level and to connect the furnace and this aspect, we could see in the archaeological context of excavated tuyeres from Iswal and Nathara-Ki-Pal (Fig. 7).

Fig. 7: Preparation of Tuyeres

Leather Air Bellow*:* It would seem likely, therefore, that the earliest method used in antiquity to increase the intensity and effectiveness of fire in a controlled way was using a blowpipe. A hollow red will do, but its distal end and nose quickly becomes charred by heat radiated from the fire, so in practice, a short, hollow clay tip is added, which becomes baled by the heat and provides a much longer use-life. In the absence of tuyeres or bellow, such tips would be the earliest archaeological evidence of blowpipe use. They would tend to be short, characteristically of smaller interior diameter than tuyeres of bellows, and possibly fragile because of only a moderate firing temperature. The "tuyeres" of 2000-1800 B.C. found at Kalinovka in Russia with internal diameters of 6mm (Gimbutas 1965: 345). Bellows are devices constructed to furnish strong blasts of air into the hearth or furnace, resulting in the fuel burning more intensely and with a brighter flame. Although the use of bellows is a crucial aspect of metallurgical processes, this is one area that does not lend itself to easy study in the archaeological record since bellows are made of perishable materials. Although fragments of furnaces and other forms of Archaeo-metallurgical debris such as tuyeres, crucible and moulds are known, bellows are rarely reported from archaeological contexts, particularly from India (Udayakumar 2020). For the second and third phase of experiment of iron smelting, we have used leather bellows from Solapur. Bellows-making in Solapur involves a variety of techniques and processes including preparing the goatskin, shaping the wooden components, making the desired outline for the bellows length and size and creating the designs to decorate the wooden frame. Indian smelters and smiths regarded the bellows as the most important element of their work. In many parts of India, the iron-smelting process was simply known as 'blowing the bellow' and competent smiths were referred to as 'men skilled in bellow'. Iron smelting and forging technology has a long history and is practiced even today. Despite this, we have no evidence for bellows in the archaeological assemblage. However, in ethnoarchaeology we have important information on the making of bellows fro smithies (Udayakumar 2020) (Fig. 8).

Fig. 8: Leather Air Bellow

Reconstruction of Furnace*:* The constructional features of the smelting furnaces are shape, dimension, construction material, insulation characteristics etc. are most important for the iron smelting process. The oval shape furnace found at Iswal has a major axis of 90 cm (WE) in length with a width of 70 cm (NS). The furnace was constructed in an open ground. The area for the furnace was marked out with white powder with the reference of excavated furnace from Iswal. The furnace pit was 9.5 cm deep and 74 cm in diameter and the pit was then lined with clay. After completing the clay line of the bottom portion of the furnace and author has kept two wooden rods to the ground level of the furnace. author has started to raise the furnace slowly. Clay was mixed with bunch of rice grasses (*Oryzopsishymenoide*). Over the wooden rods, author has started to build the furnace. The furnace wall was 16cm thick at the base and 8 cm thick at the top of the shaft. From the bottom of the furnace pit to the top of the shaft was 63cm. Overall approximately 250 kg of clay was used to construct the furnace, which took two days to complete the furnace. After the furnace was built the wooden rod had been slowly removed from the furnace and then we have small arch at the base of the furnace. This arch is used for two purposes-----one is air bellow, and another is to trap out the slags (Fig.9)

Fig. 9: Reconstruction of Furnace, Experimental Work

Data Recording during of Experimental Work

Preparation of the Clay for the Furnace

1.	Weight of clay
2.	Materials mixed with clay
3.	Duration of soaking of clay in water
4.	Composition of the clay (Pass through sieves)

Construction of Tuyeres

1.	Length of tuyeres
2.	Circumference of tuyeres at the top
3.	Circumference in middle
4.	Circumference at point of contact with furnace
5.	Height of tuyeres
6.	Weight of tuyeres
7.	Time required for construction of 1 tuyere
8.	Method for building of tuyeres

Building of the furnace (West facing)

1.	Height of furnace
2.	Circumference of furnace
3.	Direction of outlet
4.	Thickness of furnace at the base
5.	Thickness of furnace at the middle
6.	Thickness of furnace at the top
7.	Mode of construction of the furnace
8.	Time taken for construction of the furnace
9.	Number of people involved in making furnace

Experiment of Iron Smelting Process

First phase of experiment of iron smelting process (Fig. 10)

The six tuyeres were attached into the furnace, protruding approximately 10cm inside the structure at roughly 30° downward angles to the ground level. The bellow was placed in front of the tuyeres following this over a period of two hours, approximately 15 kg of charcoal and nearly 4 kg of iron ore was added for the iron smelting process.

Following are Descriptions of Various Stages in the 1st Phase of Smelting Processes

10.26 AM. The small wooden pieces and dry grasses as lighted into the furnace. At same time my assistant started to pump ait into the furnace. He pumped 37 stroked a minute. This is an easy rate to maintain as the bellow needs little effort to operate (keen 2013: 101).

11.00 AM. First interval of charcoal of 2kg was charged into the furnace

11.45 AM. Second interval of charcoal of 2kg was charged into the furnace

11.45 AM. After rising the temperature at first round of smelting process of 3kg of iron ore was charged into furnace.

12.23. PM. Second round of 1 kg of iron ore was charged into the furnace.

With the interval of each half hour, we need to spread the charcoal into the furnace and keep checking the temperature of the furnace with the help of iron rod. In the first phase of experiment work four person was involved and the pumping of bellow has shared of timing with the four people up to they get tried pumping the bellow.

1.00 PM. Third interval of 2kg charcoal was charged into the furnace.

1.30 PM. We can see the red and blue flames on the top of the furnace; this indicates that iron ore has started to smelt.

1.35 PM. The leather bellow has stopped working due to overheat and it was affected the bellow, then we decided to remove the leather bellow from the tuyeres. Later to increase we have used hand steel bellow; author's assistant was continuously pumping the bellow to raise the temperature.

2.00 PM. The bellow was removed from the furnace, and then we decided to break the furnace to recover the iron lumps and iron slags. While smelting we could not see any kind of indication that slag is coming out from the furnace. We have started to beak the furnace from the top with the help of a wooden stick which has sharp and narrow edge. The furnace was broken into small pieces and the broken pieces were kept away from the furnace. When we reached to the base of the furnace, we would see small pieces of iron lump or iron lump mixed with the slag, it didn't melt completely due to lack of raising temperature.

The First Experiment was partially successful Owing to the Following Reasons

- The bellow was not operated properly, and small leather bellow was insufficient for raising the temperature of the furnace
- Tuyeres were not placed correctly into the furnace
- The furnace was not dried properly.

Fig. 10: 1st Phase of Smelting Iron Processes

Second Phase of Experiment of Iron Smelting Process (Fig.11)

In 2nd phase of iron smelting process same methodology has been followed which was practiced during 1st phase of experiment. The shape and size of the furnace has been changed according to the amount of iron ore used.

Day 1*:* A common processing task is roasting, involving the heating of ore in an open fire to drive off water and volatile compounds. The ore is enriched in Fe and made more porous through micro-cracks created by the escaping gases. This makes it more friable and reducible due to a greatly increased surface area to volume ration. Roasting converts the iron hydroxide into Fe_2O_3 giving it a bright red colour, though it may also oxidise to magnetite, creating a black colour (Humphris J 2008). Roasting a lump or iron ore and the timing of roasting of iron ore started from 11.00. Amand ended at 1.30 pm. The purpose of roasting is to change the physical and chemical composition of ores and it converts the useful components and removes the moisture from iron ore.

Day 2: The structure of furnace was being built, from 12.12 PM. And before starting to build the furnace the bottom of the furnace or floor have to be flat. It was plastered with same clay, which was used to build the furnace, so in this case author started to dig a small pit measured around ½ inch to make a floor of the furnace. The pit must be filled with clay and plastered well and above the floor; the measurement of the floor in North direction was 30 inches and South direction 36 inches. Author has started to build furnace structure. The measurement of furnace was 9.5 inches in length, 19 inches in breath, and the top view of the furnace's diameter was 9.55 inches and thickness of furnace was 2 inches.

Day 2 to 5*:* Breaking of iron ore: Iron oresmust be crushed in powder stage, after pounding it has been sieved thoroughly, so in this case author has used sieve BSS 0.85 and 0.15. The pounding makes iron ore to melt faster.

Following is the Description of Various Stages in the 2nd Round of Smelting Processes

10.00 AM. The small wooden pieces and dry grasses were lighted into the furnace.

10.30 AM. First interval of charcoal of 1 kg was charged into the furnace.

10.46 AM. Second interval of charcoal of 2kg was charged into the furnace.

10.50 AM. First interval of iron ore of 1 kg was charged into the furnace.

11.24 AM. Second interval of iron ore of 1.852 kg was charged into the furnace.

11.24 AM. Third interval of charcoal of 2kg was charged into the furnace.

12.30 PM. Third interval of iron ore of 0.828kg was charged into the furnace.

2.00 PM. Fourth interval of iron of 2 kg was charged into the furnace.

Fig. 11: 2nd Phase of Iron Smelting Processes

3.15 PM. Same as the first round of experimental work---- breaking process was followed in the second round of experimental work. The bellow was removed from the furnace, and then author has decided to break the furnace to recover the iron lump and iron slags. While smelting author couldn't see any kind of slag coming out from the furnace. The researcher has started to break the furnace from the top with the help of wooden stick which has sharp and narrow edge. The furnace was broken into the small pieces and the broken piece was kept away from the furnace. When researcher has reached to the base of the furnace, author has found a few slags and some of the melted metal which had started to melt but due to lack temperature, it couldn't smelt completely.

In second round of experimental studies has done the scientific analysis with the collaboration with Prof. Jang-Sik Park from Hongik, University, Korea.

Analytical Procedure (Scientific Analysis of Second Phase of Experimental Study)

The analytical work begins with preparation of specimen, taken from metallic and non-metallic object, following the standard metallographic procedure of mounting, polishing and etching. Microstructures are then examined using an optical microscope and a scanning electron microscope (SEM). The chemical composition of specimen is measured using dispersive X- ray spectrometer (EDS) includes within the SEM instrument.

Results

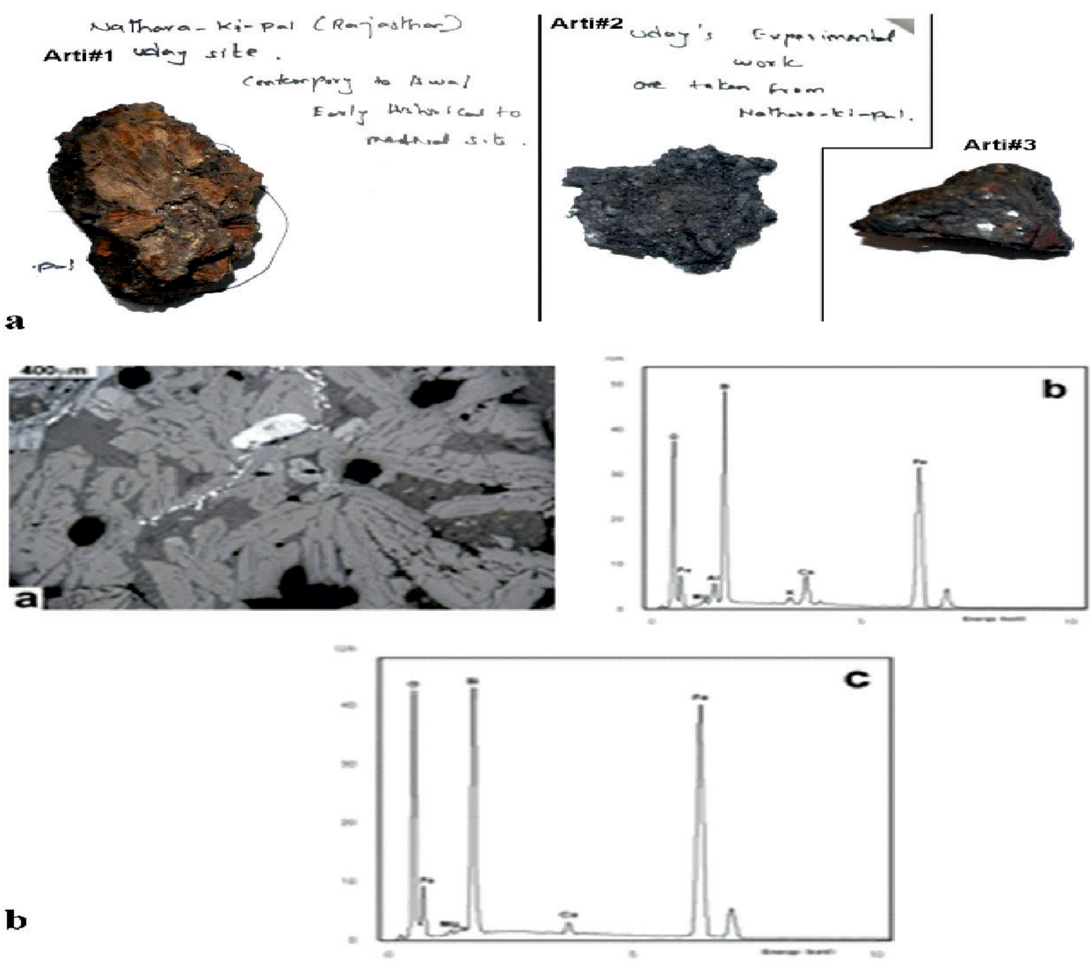

Fig. 12: a) General picture of iron ore from experimental work & b) micro-structural and chemical composition of object #1

Object #1: Fig. 1a presents an optical micrograph showing the typical structure of the specimen taken from object #1 in the photo 1. Fig. 1a consists of the fayalite phase ($Fe_2Si_2O_4$). Precipitated in plates with the area between them being filled with small crystallites. Fig. 1b, an EDS spectrum taken in a raster mode from an area of approximately 0.64 X 0.45 mm, shows that the specimen is primarily made of oxide of silicon (Si), iron (Fe), calcium (Ca) and aluminium (A1) along with trace amounts of potassium (K) and magnesium (Mg) oxide. Fig. 1c, an EDS spectrum representing those taken in a point mode from the arrow in Fig. 1a, which is in the form of plates, is the fayality phase composed of silicon oxide and iron oxide contaminated with oxides of calcium and magnesium. The microstructure and chemical composition as illustrated in Fig. 1a are typically observed in slag objects from the smelting of blommery iron, indicating that object #1 was the by-product of the bloomery process in which blommery iron was smelted as target material (Fig.12)

Object# 2: Fig. 2a is an optical micrograph showing the structure of the specimen taken from object #2 in photo 1. The micrograph is seen to consist primarily of angular particles of two different kinds distinguished by their brightness. Those appearing bright found mostly in the left-hand side show great variation in size. In contrast, the angular particles appearing gray are distributed over the entire micrograph with those in the right hand side are much coarser than those in the other. Fig. 2b, an EDS spectrum taken in raster mode from an area of approximately 2.6 X 1.8 mm containing the area of Fig. 2a near its centre, shows that this specimen is made of oxide of silicon (Si), iron (Fe) and aluminium (Al) along with trace amounts of calcium (Ca) and potassium (K) oxide. Fig 2c, an EDS spectrum taken in appoint mode from the dark arrow in Fig. 2a, indicated that the larger bright angular particle marked by the arrow is iron oxide. Given that object #2 is strongly magnetic, one may conclude that the particle and the other smaller particle mostly located in the left-hand side of Fig. 2a represent the magnetite phase. In contrast, EDS analyses on the gray angular particles produced EDS spectra like the presented in Fig. 1c, indicating that they are fayalite. Fig. 2d is an optical micrograph showing the structure of another specimen taken from object #2. The left-hand side of this micrograph is mostly covered with the bright areas, which were found in EDS analyses to correspond to magnetite, while the right-hand side consists of structure that are clearly distinguished from those in the left. Fig. 2e, an optical micrograph providing a magnified view of the right-hand side, shows numerous angular dendrites precipitated in the gray background. Fig. 2f, an EDS spectrum taken from the dark arrow in Fig. 2e, reveals that the dendrites are made of iron oxides. Fig. 2g, an EDS spectrum taken in a raster mode from the area containing the entire dendrites marked by the arrow, shows that the background in which the dendrites is included consists of silicon oxide. The result observed in the two specimens above suggests that object #2 is a piece of slag produced in reactions similar tothat place in the smelting of blommery iron. The great variation in microstructure, however, indicates that the reactions were highly heterogeneous, causing structural variability to be pronounced even within a small specimen (Fig.13).

Object #3: Fig. 3a is an optical micrograph showing the structure of the specimen taken from object #3 in photo 1. Fig. 3b, an EDS spectrum taken in a raster from near the central part Fig. 3a, showing that this specimen is made primarily of iron oxide, likely magnetite, containing a substantial amount of silicon, aluminium and potassium oxide. Fig 3c, an EDS spectrum taken in a point mode from the dark arrow, represent the silicon oxide phase (Fig.14).

Third Phase of Experiment of Iron Smelting Process (Fig.15)

In 3rd phase of iron smelting process same methodology has been followed which was practiced during 1st and 2nd phase of the experiment with little changes and understanding. The shape and size of the furnace has been changed according to the amount of iron ore used in the smelting process.

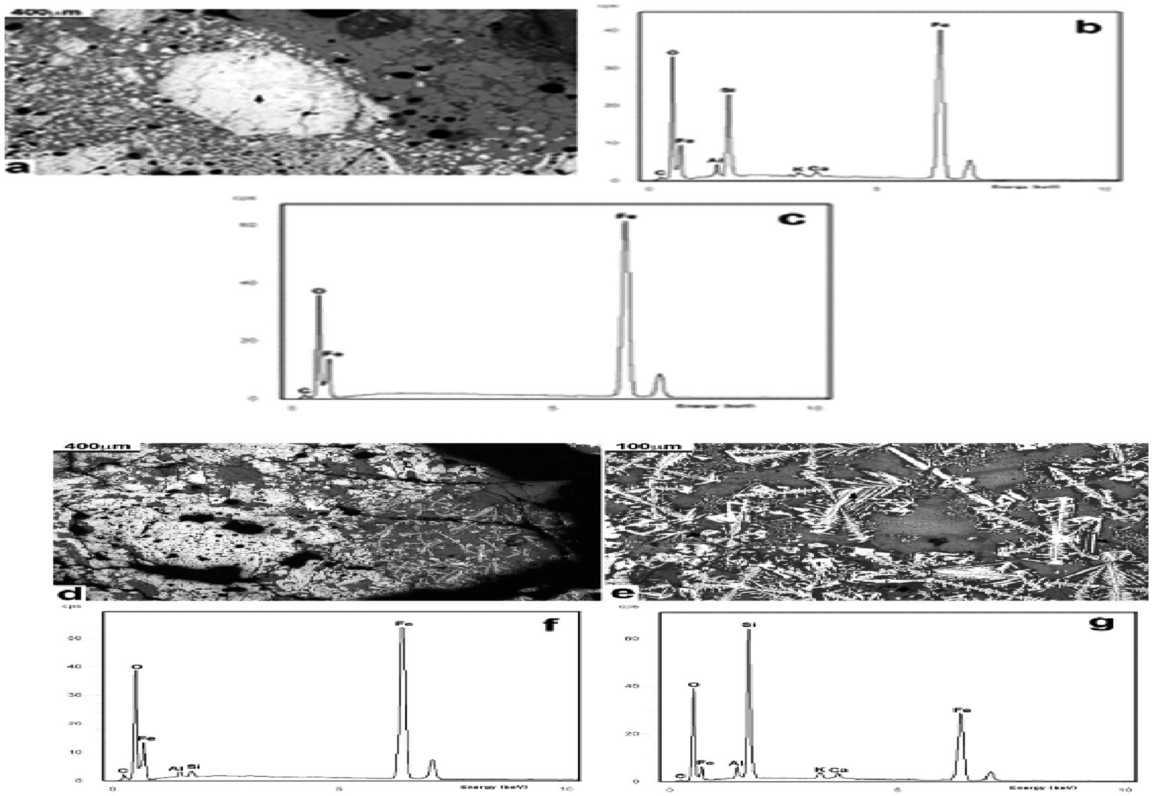

Fig. 13: Optical micrograph& EDS spectrum of the experimental sample

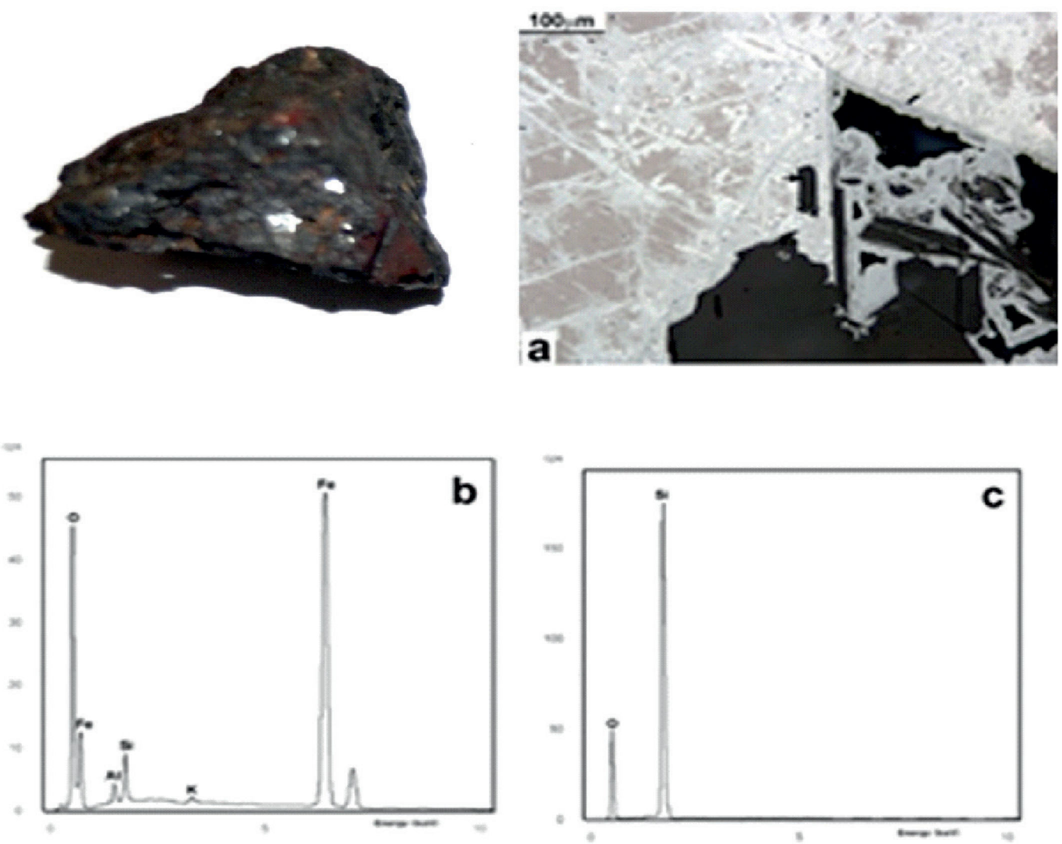

Fig. 14: Optical micrograph & EDS spectrum of the experimental sample

Preparation of the Clay for the Furnace: For the 3rd phase of experimental work, author has collected more than 75kg of clay and the composition of clay is fine and brown in colour. The clay was soaked in water for 4 days and filtered to remove impurities.

Construction of Tuyere*:* The tuyeres were fabricated from the same clay which was used to build the furnace. The clay was not tempered with any other material. The length of tuyeres is 12 inches, circumference of tuyeres at top is 3 X 5 inches, circumference in middle is 15 X 15 inches, height of tuyere is 2.5 inches and weight of the tuyere is 4.5 kg. Each tuyere took approximately 15 fabricate; tuyeres were left to dry in shade for 2-3 days.

Constructing the Furnace*:* The area for the furnace was marked out with white powder to have control over constructing the furnace. The height of the furnace was 11 inches; circumference of the furnace was 7.5 X 7.5 inches (inner part of furnace) and 10 X 10 inches (outer part of furnace). The furnace wall was 4 inches thick at the base, 2 inches thick at the top of the furnace and 3.5 inches at the middle of the furnace. Overall, 75 kg of clay were used to construct the furnace, and it took 3 hours to complete the whole process and the number of people involved in constructing the furnace was 2 people. The furnace was then left to dry for 5 days.

Pre-heating*:* The purpose of pre-heating is to remove moisture and make the furnace dry completely. The material used for pre-heating was wood and dry coconut shell and duration of pre-heating the furnace took place from 4 hours (2.30. pm to 6.30. p.m.)

Procedure for Fixing Below*:* Steps taken to adjust the bellow and furnace position has been enumerated below. Several experimental stages were followed to understand the iron technologies of the ancient time; with repeated adjustment of the position and angle of the bellow; measuring distance from the furnace; arranging shape and length of the tuyere; adjusting to the stand and nail on which the bellow were fixed; establishment of the framework on which the pale with the rope to pull the bellow was fixed; weight and length of the pole on which the rope to pull the bellow was attached were the steps taken for experimental work.

Important Points: Difficulties in achieving sufficient air pressure from below; that is distance between furnace and bellow; length of tuyere; weight attached to the back and position of restraining bar in front. Here is the question that arises related to the range of arch structure in the tuyeres found, in term of the diameter of the hole and their presumed total length and breakage patterns.

Rate of Pulling Bellow*:* Total number of strokes of pulling the bellow average time we could spend around 2 Mins to 5 Mins per person.

Person	*Age*	*Time*	*Strokes per minutes*	*Type of bellow*
Person1	27	10.05 am.	63 strokes per minutes	Large size bellow
Person 2	27	10.10. am.	75 strokes per minutes	Large size bellow
Person 3	47	10.11. am.	75 strokes per minutes	Large size bellow
Person 4	24	10.20. am.	99 strokes per minutes	Large size bellow
Person 5	37	10.45. am.	37 stokes per minutes	Large size bellow
Person 6	47	10.50. am.	47 stokes per minutes	Large size bellow
Person 7	27	10.50. am.	50 stokes per minutes	Large size bellow

Question- How many strokes can one person do without a break?

Around 100 strokes are possible, but it varies with work experience,

Those working with hand blower, for e.g. Person 4 could do around 5 minutes without a break.

Note: Again, the experimental work began at 10.00. a.m., further clay and sand packing for content joint between bellow and tuyere were done.

Smelting Process*:* The weather condition while smelting process were partly sunny, temperature ranged from 25°c to 32°c and the wind direction was SE-NW.

The single tuyere was inserted into the furnace, protruding approximately 12 inches inside the structure at roughly 30° downward angle to the ground level. The bellow was placed with clay and sand to prevent them moving around when the operation began.

Step: 1. Burning of grass within the furnace: this process is initiated to ignite the charcoal and continue heating of the furnace. The author took handful of dry grasses and dry leaves to light the fire, along with dry grasses some wooden pieces were lighted. The smelting process began at 10.00. a.m., after 10-15 minutes, the charcoal of 550 grams were charged into the furnace to increase the temperature. The total number of people involved for the third round of smelting process was 5 persons.

Step: 2. charging the furnace with charcoal and iron ore.

The charging of charcoal for smelting process began at 10.0. a.m

10.20. A.M. First interval of 1 kg of charcoal and 550 gm of dried grasses and dried wooden pieces were charged into the furnace.

10.25. A.M. Second interval of 1 kg of charcoal was charged into the furnace.

10.30. A.M. First interval of 2 kg of iron ore were charged into the furnace.

10.45. A.M. Third interval of 1 kg of charcoal was charged into the furnace.

11.00. A.M. Fourth interval of 3 kg of charcoal was charged into the furnace.

11.00. A.M. Fourth interval of 3 kg of charcoal was charged into the furnace.

12.45. P.M. Fifth interval of 1.5 kg of charcoal was charged into the furnace.

1.33. P.M. Sixth interval of 750 gm of charcoal was charged into the furnace.

2.10. P.M. Seventh interval of 250 gm of charcoal was charged into the furnace.

2.15. P.M. Eight interval of 250 gm of charcoal were charged into the furnace.

2.50. P.M. Ninth interval of 500 gm of charcoal was charged into the furnace.

3.45. P.M. The bellow and tuyere were removed, and the author started to break the furnace to recover the blommery iron and slags.

Checking the Slag: Around 3.45.pm. it was first noted as the tuyeres to large bellow was blocked by charcoal ashes and small pits of iron slags. To clean blocked the charcoal was removed but this did not help, so we have removed the main tuyere and the large bellow from furnace. While breaking the furnace we could find small fragment which was around 2-3 inches in size and it could be blommery iron (bloom iron nothing but mixture of slag and wrought iron).

Additional important point of bellow which were noticed during smelting process:

1. Lid was put prior to charging iron at 10.20.A.M.
2. A second hand-bellow (small) was attached to the 2nd exit at the furnace at 10.20.A.M
3. At 11.05 AM; the small bellow was heated and had to be replaced with the 2nd small bellow.
4. At round 1.00.P.M; a vertical crack was seen in the furnace. Important reason why furnace was not reused
5. At 1.55.P.M; tuyere for slag recovery and attached to small bellow had slightly broken and was replaced with another one.
6. At 2.30.PM; 2nd tuyere which was a small bellow was broken and replaced.

7. Owing to the brakeage of air source from the main bellow; the charcoal and the ash were cleaned and resumed the bit slag from the furnace. The main tuyere was then remanded, and slag was noticed while breaking the furnace.

Fig. 15: 3rd phase of Iron Smelting Processes

Discussion

Through the experimental study author has understood different pattern and arrangement of iron smelting process, which can be enumerated as follows:

1. The first involves the accurate reconstruction of ancient furnace using archaeological remains as a guide. This is the research most clearly associated with archaeologists working from the archaeological record toward conjectural reconstruction that is then 'tested' during experimental smelts.
2. The one followed by the workshop organizers-involves learning in practical terms the mechanics of how to smelt.

3. Tuyeres placed at different angles are favorable so the arrangement of tuyeres in the furnace plays a very important role during smelting process.
4. Smelter should know number tuyeres should be used during the smelting process.
5. The speed of bellow operation with two genders and age plays importation role to raise the high temperature during the smelting process.

Through the experiment study, the author brought the light to the overlapping of the furnace, so here author could give an address that in archaeological excavation we could see overlapping furnaces sometimes, by mistake some excavators push the furnaces into the different time periods, but the fact is that furnaces are constructed in the same time period to make use of the space which smelter has rebuilt the furnace or build the new furnace near the old furnace. In the author's experiment, there were two furnaces builtnear to by because the experiment space is very limited. The overlapping furnace could see current ethnography survey of bronze casting artisans from Tamil Nadu, the artisans use very small space for years and years for the smelting or casting process, they break the furnace and again rebuild the new furnace. The author observes that the overlapping furnace from the archaeological assemblage is not only a different period but it's also the usage of space by smelters or artisans.

As Lee Saudar explains,

> "We can't say that (the way smelt in our experiments) is the way they did it, but if you don't get iron (in your experiment), we can certainly say this *isn't* the way they did it. "So, the key for them is to understand how to make useable iron and then to experiment from there using archaeologically relevant materials and evidence to better approximate ancient smelting. "We haven't discovered *the* way (to make iron), we've discovered *a way*," say Darrell Markewitz (Elizabeth G. Humilton 2007).

The scientific analysis shows that the iron ore which was collected from Nathara-Ki-Pal for experimental work is of better quality for smelting and it's smelt around 1500°c to 1800°c. And it is better quality to make iron implements through forging method. The scientific analysis results prove that the material which was collected during experimental iron smelting process, it is absolutely ironslag, and it shows that it is typically observed slag object from the smelting of blommery iron.

It appears from the result of the analyses, tests and experiments that, in the Nathara-Ki-Pal (Early historical to Medieval period), the smelting operation were complex processes such as from collecting iron ore to smelting the iron ore and it is much to the credit of the smelters of that time that they could turn out, with the simple means available to them.

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