Indian Journal of History of Science, 16 (2) ; 189—201. November 1981

SCIENTIFIC BASIS AND TECHNOLOGY OF ANCIENT INDIAN COPPER AND IRON METALLURGY*

K. T. M. HEGDE

Department of Archaeology and Ancient History
Maharaja Sayajirao University of Baroda, Vadodara 390 002

(*Received 27 February 1980 ; after revision 26 May 1980*)

When we visit Ellora, Konarka, Khajuraho or Mahabalipuram, we marvel at the artistic calibre of our ancient sculptors. There are a number of other monuments in our country that are equally marvellous to behold. These monuments have inspired art historians to speak eloquently of our great cultural heritage. That is rightly so. What might however prove equally interesting is to pause a little to think of the infrastructure that was necessary to build or carve these magnificent works of art. It will not take us long to realise that our cultural heritage reflects the strong base of our ancient technology. Along with our cultural heritage we have also inherited a technical heritage.

How shall we understand the details of this heritage ? We are aware, for example, that among the necessary tools that the ancient sculptors used was a set of chisels of varying strength, size and shape that had such sharp and enduring cutting edges as could be used with ease and precision on marble, sandstone, basalt or granite, rocks of different hardness and texture. How were those chisels made ? To seek an answer to that question, we have to consider the origin and development of ancient indian metal technology.

Preceding the advent of metallurgy, ground stone axes were the most dominant tools of man. Stones are brittle and they are easily blunted or broken. Using ground stone tools, man had to contend with a serious limitation to his production in agriculture and animal husbandry. Metal tools have harder, stronger, keener and more enduring cutting edges. Metals are also malleable. Therefore, when the cutting edges of metal tools are blunted, they could be easily made sharp by the simple process of cold or hot forging. Metals can be melted. Therefore, old, broken or otherwise unserviceable tools could be fabricated afresh into new ones. Archaeological records tell us that it was only when metal tools came into use that man was able to expand agriculture and stockraising.

*The paper is based on a series of three lectures delivered at the University of Mysore on 13, 14 and 15 September, 1979 under the auspices of the Indian National Science Academy.

This expansion brought in much greater prosperity and economic well-being. His family multiplied manifold. Prosperous villages changed into towns. A new way of life with new ideas and new cultural patterns set in.

Copper was the first metal to bring about this change, for, it was the first metal to be extracted from its ores. Copper metallurgy in India dates back to the beginning of the Chalcolithic cultures in the sub-continent. The term Chalcolithic is derived from two Greek words, *chalcos* and *lithos*, meaning copper and stone respectively. The Chalcolithic cultures used copper and stone as raw materials for making tools and weapons. These cultures occupy an important position in our history. They date from the time of the pre-Harappans who lived in the early centuries of the third millennium B. C. to the emergence of the Iron Age in the early centuries of the first millennium B. C.—a long span of over two thousand years. They lived in villages and well-laidout towns and cities. Their settlements were widely distributed from the foot-hills of the Himalayas to the Deccan plateau in the south, from the Arabian Sea coast to the plains of the Ganga and Yamuna rivers in the east. Over this very wide area of several hundred thousand square kilometers they successfully established an advanced cultural life and laid the foundation of Indian Civilisation.

The pre-Harappans did not use metal tools so extensively. Yet, the few artifacts that we have of their time show evidence of advanced metal technology. The Harappans made much use of copper and bronze. In fact, the large number of wide-ranging metal objects that they used is an index of their technical advancement and at the same time, a witness to their economic wellbeing. The successors to the Harappans, the most widely distributed Chalcolithic peasants, also used quite a number of wide-ranging implements, weapons and ornaments made of copper and bronze. These included axes, chisels, knives, daggers, arrowheads, bangles, bracelets and beads.

It is interesting to know how these objects were made. But that interest raises a number of questions like what was the source of their metal ? How was the metal extracted from the ore ? Was the ore roasted before it was fed into the smelting furnace ? In the furnace was it fluxed ? What was the furnace like ? What was the quality of the extracted metal ? In the productions of useful objects was the metal used in unalloyed form or was it alloyed ? How were the objects made ? Were they cast or wrought ? If cast, what were the casting moulds like ? Were they open moulds or properly ventilated closed ones ? If wrought, were they forged above the recrystallisation temperature of the metal or below it ? Answers to these questions will reveal the scientific basis and technical skill of the early Indian copper smelters and smiths. It is their knowledge and skill that brought about the earliest economic development and urbanisation in our country. It is therefore worth while to investigate and know the history of this technology and its scientific basis.

But our ancient metal workers did not leave any written records of their activity. It is therefore none too easy to reconstruct the progress of their technical skills in a sequential order All that we have are the metal objects recovered in stratified excavations and from one site metallurgical slags. We are yet to recover their metal smelting furnaces. Let us see if we can deduce any worthwhile information from these few material remains of the past.

As noted above, we have copper and bronze objects of the Pre-Harappan, Harappan and post-Harappan Chalcolithic periods, recoverd in that chronological order from archaeological excavations. These metal objects contain within them records that can shed a ray of light on the above questions. We have only to train ourselves to read these records. The training is simple. It includes chemical and spectrometric analysis of ore, slag and metal objects recovered in the excavations and metallo-graphic examination of the artifacts.

First of all, let us examine the question whether the technology of copper metallurgy originated in India. Very probably not. At least the odds are against such a supposition. Pre-Harappan peasants, settled in Baluchistan and the Indus Valley, were the earliest people to use copper implements in the Indian sub-continent. The archaeological records, unearthed at Nal, Mehi and Kot Diji, all pre-Harappan settlement sites, have revealed a small number of axes, chisels and mirrors. The small number of objects may suggest that these communities did not use metal tools so extensively. Yet, the few objects that we have of their time are very well made and finished artifacts. One of the objects recovered from Mehi is outstanding. It is a copper mirror, 12.5 cm in diameter, with a handle, also made of copper, representing a stylized female figure, in the manner of terracotta female figurines, excavated at the site, with breasts and conventionalized arms akimbo, but with head provided only by the reflection of the user of the mirror! A chemical analysis of a fragment of an axe recovered from Nal showed that it was made of 94 per cent pure copper with five per cent of nickel in it[1]. It is therefore clear that these earliest metal artifacts of the Indian sub-continent were made by smelters and smiths who possessed a full knowledge of copper metallurgy. None of the early Chalcolithic sites in our sub-continent has revealed any evidence of experimental and developing stages of copper metallurgy. Such stages are recorded at sites in Iran.

In Iran, at Tepe-sialk and Tal-i-iblis, archaeologists have unearthed much useful evidence for reconstructing the sequence of developing stages in copper metallurgy dating from the 5th millennium B. C. Excavators of Tal-i-iblis have indicated that the Kerman mountains, rich in copper ore deposits, played an important role in the dissemination of metal technology to Afghanistan, Baluchistan and the Indus Valley[2]. Thus, it is possible to infer that our earliest metal workers received their technical know-how from Iran. There is, however, no evidence to support the view that the early Indian copper and bronze objects were imported from Iran. They appear to have been made indigenously. We have now archaeological and analytical data to prove that at least those objects excavated from the later Chalcolithic sites were made in India. Let us turn to those data.

In 1962, Professor H. D. Sankalia of the Deccan College, Pune, leading an excavation of the Chalcolithic site at Ahar, near Udaipur, in the Aravalli Hills, discovered heaps of semifused glasslike material together with copper tools and Quartz in stratified layers, dated from 1800 to 1600 B. C. by radiocarbon[3]. Professor Sankalia sent the glasslike material and the copper tools to us for their examination. The analysis of the glasslike material revealed that it was copper metallurgical slag—a waste product of copper smelting industry[4]. This identification is significant. It established the slag as an evidence for copper smelting activity at Ahar during the Chalcolithic period. Ahar therefore was a Chalcolithic period copper smelting centre. Probably one of many such centres, for, more than fifty sites yielding the distinctive white painted Black and Red Ware, referred to by the archaeologists as the Ahar Ware, have now been found in the Aravalli Hills. Important among these sites are Gilund, Meroli, Kumaria and Kadukota. The excavation report on Ahar includes a map showing the distribution of these sites[5]. Identification of Ahar slag also led to an important corollary, namely, that the Indian Chalcolithic metal objects were in all probability indigenously made. In order to gain a degree of certainty for this hypothesis, it was necessary to link the Chalcolithic copper objects with Indian copper ore deposits.

Ancient metal objects contain a large number of elements, many of them in minute traces, as impurities. It is obvious that these elements could not have been deliberately fused into the metal. The impurities must have got into the metal from the ore from which the metal was extracted. These impurities therefore can serve as valuable clues in tracing the source of the metal. Spectrometric analysis, in which small samples cut from the ancient metal objects are exposed to an intense light source and the spectrum they emit is analysed for their composition, reveals the impurity elements present in the samples. These can be compared with the impurity elements present in the likely ore deposits and in this way, the source of the metal can be determined.

Within the area inhabited by the Chalcolithic communities, extensive copper ore deposits are located in the Aravalli Hills. At many places these deposits are dotted with deep mining shafts and slag heaps—marks of ancient mining and smelting activities. Aravalli copper ore deposits were therefore considered as the likely source used by the Chalcolithic metal workers. We therefore carried out spectrometric studies on copper ore samples obtained from the ancient mine pits at Khetri and on metal samples cut from representative Harappan artifacts recovered from Mitathal in Haryana and post-Harappan Chalcolithic artifacts recovered from eight sites distributed in Rajasthan, Gujarat, Madhya Pradesh and Maharashtra. Impurity patterns of the artifacts and the ore samples showed an agreement of over 92 percent[6]. Much work is yet to be done on pre-Harappan and Harappan metal objects. All the same, we have considered it reasonable to observe, on the basis of this analytical study, that the Indian Chalcolithic copper objects were in all probability indigenously made and that their metal was extracted from the chalcopyrite ore deposits in the Aravalli Hills.

How was the metal extracted from the ore ? Though chalcopyrite deposits in the Aravalli Hills occur in fair abundance, the percentage of copper in the ore is rather poor. After mining it has to be crushed and dressed. Golden yellow colour of chalcopyrite lends itself for dressing by hand picking of crushed ore pieces. Chemical analysis of the Chalcolithic metal samples has revealed that they contained only traces of arsenic, antimony and sulphur[7]. This is significant. The Aravalli Hill copper ore contains these elements in considerable proportions. These elements are volatile. Their presence in the metal in proportions higher than two per cent renders it brittle—a condition none too desirable in a metal intended for producing cutting implements. The Chalcolithic metal smelters appear to have eradicated the injurious volatile elements from the ore by roasting it. Roasting ore is simple. If chalcopyrite is heated over a charcoal fire at 500° to 600°C in a large container, open to the atmosphere, a considerable portion of sulphur in the ore is oxidised and removed as sulphur dioxide. At the same time the arsenic and antimony present in the ore are removed as their respective volatile oxides. Chalcopyrite is converted in the process into a mixture of cuprous and ferrous sulphides :

$$2\,CuFeS_2 + O_2 \rightarrow Cu_2S + 2FeS + SO_2.$$

Further prolonged roasting of the ore would lead to oxidation of the sulphides :

$$2\,Cu_2S + 3O_2 \rightarrow 2Cu_2O + 2SO_2.$$

$$2\,FeS + 3O_2 \rightarrow 2FeO + 2SO_2.$$

Similarly, chemical analysis of the slag samples recovered from Ahar showed over 68 per cent of silica in it while percentage of silica in the Khetri ore sample was found to be less than 27[8]. This is also significant. High percentage of silica in Ahar slag suggests the possibility of deliberate addition of crushed quartz to the smelting charge. Silica acts like a flux and reduces the fusion temperature of the ore and also facilitates the separation of the smelted metal from the gangue in the furnace. The occurence of quartz in the excavation together with the slag at Ahar lends support to this observation.

So far no furnace has been found in India, which can be said to have been used for smelting copper during the Chalcolithic period. This is because no metallurgical site like Ahar has been horizontally excavated. We can therefore only try to infer the broad outlines of this smelting device.

The following are the minimum requirements of a copper smelting furnace : (1) An enclosed space where heat could be raised to 1200°—1250°C and also retained at that temperature until the charge inside it is smelted. Copper melts at 1083°C. A higher temperature than this will bring about effective separation of the molten metal from the slag while smelting chalcopyrite. (2) The heat generated by an ordinary charcoal fire may reach up to 700°C. The furnace therefore should have facilities either of natural draught or forced draught to raise the temperature to 1250°C. A natural draught of air through a furnace is induced by a high chimney. A forced draught furnace will have provisions for an air blast blown in by bellows through a tuyere. Such forced draught furnaces may be divided into the primitive type which do not tap slag and a slightly more developed type in which slag is tapped.

The Ahar slag samples sent to us were fragmentary. It was not possible to discern in them any telltale evidence for their ejection from the furnace through a tap. When slag is tapped, it sometimes retains the cylindrical structure in which it emerges from the tap. The slag melts at 1170°C. If the tapping temperature is higher than this, it may not retain this structure. The Ahar slag is of the fayalite ($Fe_2 SiO_4$) type. It shows that the roasted ore was smelted directly at about 1200° to 1250°C. The Chalcolithic metal smelting furnace therefore was probably similar to the one that was used to smelt iron in the Iron Age. We have found indirect evidence to support this view[9]. The structure of an ancient iron smelting furnace is described below.

Nearly all of the Chalcolithic copper objects examined by us were found to be made of either more than 98 per cent pure copper or low tin bronze[10]. 98 per cent purity in copper is equivalent to the purity of the present day 'blister copper', which is extracted after Bessemerisation of the matter. Evidence of ore dressing, roasting, fluxing and extraction of copper that was consistently above 98 per cent in purity—all bear out the fact that an advanced stage in extractive metallurgy was reached and maintained in India during the Chalcolithic period.

Some of the Chalcolithic artifacts were made of bronze. Out of the 38 objects analysed by us 7 were found to be made of bronze. Their tin content varied from 3.12 to 12.82 per cent[11]. Bronze is much harder and stronger than copper. Bronze tools have keener and more enduring cutting edges than copper tools. Besides, alloying copper with tin facilitates casting and forging operations. It is clear that the Chalcolithic metal workers knew the advantages of allowing copper with tin. But the fact that there were only a small number of bronze objects suggests that tin was probably scarce.

How were the useful objects made from the extracted metal or its alloy ? To seek an answer to this question, we carried out metallographic examination of the artifacts. Metallographic examination reveals many important features of the smithery. For example, it can tell us whether an object was cast or wrought. If cast, what was the casting mould like ; if wrought, what was the nature of the thermal treatment that the object was subjected to during its manufacture. And, it will also reveal whether the metal is porous or brittle or it contains nonmetallic inclusions. There will be defined on the polished and etched surfaces of the metal such structural characteristics as grain size, distortion of the grains, sliplines, cross sliplines, twinning of the grains, pattern of distribution of the secondary phases, segregations and other heterogeneous conditions—all that would help us to understand the quality of the metal and the smithery techniques that were used in the production of artifacts.

All the fifteen axes that we studied were cast in closed moulds. However, while twelve of them were made in well ventilated moulds we found three of them cast in not too well ventilated moulds. This had resulted in entrapment of gases within the metal and had given rise to porosity and formation of cuprous oxide in the metal. On account of poor casting the metal was brittle. Proper ventilation of the mould is the secret of successful casting in copper. After casting, the cutting edges of the axes were bevelled by hot and cold forging. Chisels, knives, daggers, bangles and bracelets were all found to be shaped by forging the metal both above and below its recrystallisation temperature (500°C)[12].

To sum up, from our study of the Chalcolithic period copper and bronze objects and slag samples from Ahar, we have been able to observe that these objects were not imported but indigenously made. Their metal was extracted from chalcopyrite deposits in the Aravalli Hills. The technique of smelting and smithery practised by the ancient metal workers were advanced and beyond the stages of uncertain experimentation. We have stratified evidence to believe that these techniques were well maintained all through the long span of the Chalcolithic period. This copper technology ushered the iron technology into our country.

There is now much archaeological evidence to support the view that the Indian iron-working technology developed indigenously. This was not so a couple of decades ago. For example, Banerjee and the Allchins expressed the view that India obtained the technical know-how for iron smelting through her north-western neighbours : Iran and Afghanistan. According to this view, the smelting of iron ore was first discovered in Asia Minor and that between 1800 and 1200 B.C. It remained virtually a monopoly of the Hittites. The breakdown of the Hittite empire was the stimulus for the diffusion of iron-working towards the east as well as the west [13,14]. Lallanji Gopal expressed the view that it was the Aryans who introduced iron technology into our country[15], Banerjee while supporting this view has gone a step ahead. Accepting the hypothesis put forward by Lal that the users of the Painted Grey Ware, who lived in the plains of the Sutlej, Ghaggar, Yamuna and Ganga were the Aryans[16], Banerjee has observed that it was the painted Grey Ware people who introduced iron technology into India[17]. He also observed that the Aryans passed through Iran in the course of their movement towards India and while doing so picked up the techniques of iron metallurgy[18]. But the archaeological records unearthed so far in Central Asia, Iran, Baluchistan and Sindh do not lend much support to these views. On those records the Aryans have remained as elusive as ever. What evidence then we do have to support the view that the Indian iron-working technology originated indigenously ?

First of all, we have noted the evidence for a long tradition of advanced copper technology in the country. This technology will have provided the most essential infrastructure for smelting iron ore, that is, the furnace. Secondly, the earliest levels of the Iron Age sites, like Hastinapura[19] and Atranjikhera[20] in the Ganga valley, dated to the earliest centuries of the first millennium B.C., have yielded only a few, small, fragmentary, unidentifiable iron objects. This evidence suggests that at this stage the Indian iron industry was in an uncertain, experimental stage. We have seen the absence of such an evidence in the case of copper objects in our subcontinent. Even at the earliest levels of pre-Harappan sites like Amri, Nal and Kot Diji, the copper and bronze objects recovered represented a wide range of finished, well made artifacts. In contrast, in the case of iron, we have evidence of an incipient industry in the ninth and eighth centuries B.C. There is a reason for that.

The technique required for smelting iron is a litte more difficult than that is required for smelting copper. Iron melts at a much higher temperature, (1534°C) than that of copper (1083°C). Also, affinity of iron to oxygen is much stronger than that of copper to oxygen. Iron ore is associated with more impurities than copper ore. Iron therefore requires more critical conditions for its successful smelting. A temperature of 1250°C is necessary in the furnace to achieve separation of the unwanted gangue minerals from the smelting charge. To obtain this high temperature the furnace will need a good supply of oxygen. With such a supply of oxygen it is difficult to maintain reducing condition in the furnace. The smelter has to know how to balance these conflicting demands. He has to maintain a strong blast of air through the furnace. To offset its oxidising effect, it is necessary to feed the furnace with an excess of fuel at regular intervals, so that the reducing gas, carbon monoxide, produced in the furnace, dominates over carbon dioxide. All such technical prerequisites appear to have been gradually understood by the early Indian iron smelters. We have evidence of their experiments in the form of small quantities of poor quality iron occurring at the earliest levels of the Iron Age sites. It is therefore clear that we did not receive the technical know-how of iron smelting and smithery from an outside source We appear to have slowly developed these techniques indigenously. Such development took place at more than one centre. The evidence from Hallur, a site in Karnataka, where the earliest iron objects are dated to 1100—900 B.C. supports that view[21].

In the levels dated to the seventh century B.C. at Hastinapura, Alamgirpur, Kausambi, Atranjikhera and Noh, all located in the Ganga Yamuna Doab, we see in the archaeological records, a clear evidence of progress of iron industry. These levels have yielded finished iron objects like arrowheads, spearheads, daggers and knives. But their number remains very small[22].

Between the sixth and fourth centuries B.C. there was an enormous increase in the production of iron weapons in the country. Archaeological records of the period unearthed at Taxila, Rupar, Hastinapura, Mathura, Kausambi, Rajghat and Ujjain have revealed a large number of arrowheads and spearheads together with daggers and knives. Evaluating this record, Subramanyam has rightly observed, that the industry was chiefly geared to meet the military requirements of the ambitious, warring Mahajanapadas at this time[23].

By the fourth century B.C. the knowledge of iron technology had diffused all over the country and the industry reached its mature stage. This is revealed from the wide distribution and extensive metallurgical activity in the country. For these we have definite evidence from excavations. In addition to the weapons mentioned above, a large number of wide ranging new weapons and implements appear on the archaeological records of the time. These included chisels with rectangular and square sections, straight sided knives, ploughshares, sickles, nails, parallel sided swords, spearheads with leafshaped blades and even bowls and dishes. At this stage Indian iron also became renowned for its quality. It was much appreciated by Herodotus[24]. Alexander[25] and Kauṭilya[26].

Thus we can clearly visualize the sequence of stages in the progress of iron technology in our country. A recent study has revealed some details of this technology.

This study was carried out on materials recovered in the excavation at Dhatwa. Dhatwa, an iron-working site dated to fifth and fourth centuries B.C., is located on the southern bank of the Tapi river in Gujarat. It was excavated by the M. S. University of Baroda.[27] The excavation revealed evidence of iron industry in the form of a number of iron objects like a ploughshare, chisels, nails and knives, heaps of metallurgical tap slag and pieces of iron ore, occurring in association with the crude Black and Red Ware, lead ear-studs, bone points and glass beads, all of which are dated to the mid-centuries of the first millennium B.C. An analysis of the metal, slag and ore samples and a study of the iron smelting furnaces recovered from Kumbhariya[28] have revealed that the technique employed by the ancient indian iron-workers was simple. It was direct reduction of the roasted ore followed by forging the metal into various useful shapes. The fame of ancient indian iron weapons was entirely due to the skill, perseverance and pains-taking labour of the ironsmiths. The following is a brief-description of the simple smelting process and the laborious smithery work as revealed from the study of the materials excavated from Dhatwa.

The Dhatwa iron smelters exploited the locally availabe limonite ore. They roasted the ore to convert it into haematite and expel much of the water content together with carbon dioxide and other volatile components like sulphur in the ore. Roasting the ore renders it more porous, fragile and hence easier to crush and more suitable for reduction in the furnace.

Their furnace was small, It was crucible-shaped, claylined and worked with a forced draught blown in from bellows through tuyeres. It had an outlet for tapping slag. In such a furnace they could have smelted about 2kg. of iron at a time. The slag produced at Dhatwa consisted mainly of the Fayalite compound. As noted above, this compound melts at 1170°C and it can absorb oxides of manganese, magnesium and aluminium present in the gangue. The main principle in iron smelting is the reduction of haematite with carbon monoxide :

$$Fe_2O_3 + 3CO \rightarrow Fe + 3CO_2.$$

The carbon monoxide is formed by partial combustion of charcoal with the air from the tuyere. The temperature of smelting was not more than 1250°C. This is not hot enough to melt iron but it is good enough to separate the gangue as slag and eject it out through the tap. In such a primitive smelting process it is also thought that a part of the slag forms a coat on the smelted metal and hence prevents carbon diffusing into it. The metal so formed is a spongy mass of pure iron with slag inclusions. Pure iron is soft. How did ancient ironsmiths produce hard and strong weapons and implements that could be used to carve hard rocks ?

To seek an answer to this question we carried out metallographic examination and hardness tests of the metal samples cut from ploughshare, chisel and knife recovered in the excavations at Dhatwa. Hardness tests on the samples revealed that the metal was much harder near the upper and lower surfaces of the implements and the hardness varied from point to point on the cut and polished section of the metal. Metallographic examination revealed a closely welded laminated structure in the metal. From these observations it is possible to infer that the implements were made in three stages. First, the small bloom from the furnace was heated to redness in an open forge-fire, maintained at above 1000°C. with the help of a forced draught. The red hot metal was forged on an anvil kept close to the fire. In the forging process, the entrapped and adhering slag separated out and simultaneously, by the incorporation of fine particles of carbon flying in the air above the forge-fire, the surface of the metal was progressively carburised and case-hardened, imparting a steel-like quality in composition, strength and hardness to the forged surface of the metal. The bloom was beaten to a thin strip of metal. Secondly, a number of such strips were joined, laterally, one by one, by welding. To-day this form of welding is termed as smith-welding to distinguish it from the welding processes based upon fusion. Finally, the whole built-up mass of iron was further forged to shape it into a useful implement or weapon[26]. The strength, hardness and carburised, laminated smith-welded structure of the excavated objects suggest that the ancient indian blacksmiths had learnt the strengthening effect of minute quantities of carbon in iron. They also appear to have been well-versed in the technique of further enhancing the hardness of the cutting edges of iron tools and weapons to the required degree by heating the metal to attain a certain surface colour (colour of iron while heating from 200°C to 500°C changes from yellow to blue through various shades of brown and purple as temperature rises) and quenching it in cold water as soon as the specimen reached appropriate colour. It is with such skilful but painstaking and laborious smithing techniques that the ancient indian blacksmiths were able to produce hard, strong and sharp swords that earned the tributes of Megasthenes, the Greek ambassador to the Mauryan court and chisels that the ancient sculptors used to carve out such magnificent temples like Kailas at Ellora. Excellence in indian iron technology was continuously maintained until the eighteenth century, as long as there was demand for indigenous iron. The demand lessened progressively as the British consolidated their hold on our country and developed their trade through steamship and railways. As testimonies to the continued excellence of iron technology, one may cite the examples of fourth century A.D. massive iron pillar near Qutb Minar at Delhi, tenth century A.D iron beams useb in the construction of Konarka temple and twelfth century iron pillar at Dhar and a number of other large and small objects of iron in the country, including the famous 'wootz' steel that was exported from India to the Roman empire and became the forerunner of 'damask' steel that was used in the manufacture of damascenes[29].

The Delhi iron pillar is a masterpiece. It measures 7.50 m in height, 1.5 m in circumference near the base and weighs more than 6000 kg. An inscription near its base attests to its production in the fourth century A.D. It has remained for 1600 years exposed to sun, rain, wind and dust, successfully resisting the forces of corrosion. The pillar was built-up by smith-welding, one above the other, over 200 solid cylindrical lumps of wrought iron. The high purity of the metal (99.79%)[30] and presence of only traces of injurious elements like sulphur in it, suggests that the ore for the metal was well roasted and it was smelted with charcoal. The environment around Delhi, until recently, was free from sulphurous gases. Purity of the metal and the non-malignant environment that surrounded it, helped in establishing an early environmental equilibrium in the corrosion reaction of the metal. Corrosion came to a standstill with the formation of a thin film of rust on the surface of the pillar. Not many, however, seem to realise how delicate this environmental equilibrium is. Rapid industrialisation and the resultant enormous increase in traffic in and around Delhi is continuously raising the quantum of sulphurous gases in the environment. This, if allowed to grow unabated, may soon reach the optimum to offset the equilibrium, and corrosion of the metal will then manifest as ugly, moist, beaded rust and weaken the matrix of the pillar.

It is hoped that proper care will be taken to see that this does not happen to a great monument to our heritage of metal technology. It is important that we cherish our rich inheritance in art ; no less important is that we build on and continue our traditions of skill and labour. That is to say, if we will care to know what these have been.

REFERENCES

1 Piggott, S., *Prehistoric India*, 1952, pp. 66-131.

2 Lamberg-Karlovasky, C. C., Archaeology and Metallurgical Technology in Prehistoric Afghanistan, India and Pakistan, *American Anthropologist*, 1967, 67, pp. 31-8.

3 Sankalia, H. D., Deo, S. B. and Ansari, Z. D., *Excavations at Ahar*, 1969, pp. 8-12, 99.

4 Hegde, K. T. M., Technical Studies in Copper Artifacts from Ahar, in Sankalia *et al. op cit*, p. 225-29 plates XXVI-VIIII.

[5] Sankalia *et al. op cit*, p. 218.

[6] Hegde, K. T. M., *The Chalcolithic Period Copper Metallurgy in India*, 1965, Ph. D. Thesis, M. S. University of Baroda, pp. 49-73.

[7] Ibid, pp. 82-86.

[8] Ibid, pp. 74-78.

[9] Hegde, K. T. M., Ancient Indian Metallurgical Furnaces, in A. Ghosh (Ed.), *A Dictionary of Indian Archaeology*, (in Press).

[10] Hegde. K. T. M.. *The Chalcolithic Period Copper Metallurgy in India, op cit.* pp, 97-124.

[11] Ibid, pp. 120-166.

[12] Hegde, K. T. M., Sources of Ancient Tin in India, in T. Wertime and J. Olin, (Eds), *The Search for Ancient Tin*, 1978, pp. 39-42.

[13] Banerjee, N. R., *The Iron Age in India*, 1965, pp. 108-111.

[14] Allchin, B. and Allchin, F. R., *The Birth of Indian Civilisation*, 1968, p. 207.

[15] Gopal, L., Antiquity of Iron in India, *Uttara Bharati*, 1960, Vol. 9, No. 3, pp. 71-86.

[16] Lal, B. B., Excavations at Hastinapura and Other Explorations in the Upper Ganga and Sutlej Basins. *Ancient India*, 1955, Nos. 10 and 11, pp. 150-51.

[17] Banarjee, N. R., *Op cit*, pp. 77-96, 239.

[18] Ibid, p. 144.

[19] Lal, B. B., *Op cit*, p. 13.

[20] Gaur, R. C., in *Indian Archaeology*—A Review. 1963-64, p. 43.

[21] Rao, N. M. S., *Protohistoric Cultures of the Tungabhadra Valley*, 1971, p. 144.

[22] Subramanyam, B. R., *Iron age in India*, 1966, Ph.D. Thesis, M. S. University, Baroda, pp. 49-53.

[23] Ibid, p. 44.

[24] Forbes, R. J., *Metallurgy in Antiquity*, 1950, P. 435.

[25] Shamasastry, R. *Kauṭilya's Arthaśāstra*, 1929, p. 83.

[26] Mehta R. N., Chowdhary, S. N., Hegde, K.T.M., Shah D.R., *Excavations at Dhatwa*, 1975 pp. 4, 18.

[27] Hegde, K.T.M., A Model for Understanding Ancient Indian Iron Metallurgy, *Man*, 1973, Vol. 8, pp. 416-21.

[28] Forbes, R. J., Metallurgy *in* Charles Singer *et al.* (Eds), *A History of Technology*, 1956, Vol. 2, p. 57.

[29] Britton, S. C., Indian Iron, *Nature*, 1934, Vol. 34 pp. 238-40.