

IRON AND STEEL IN PRE-MODERN INDIA – A CRITICAL REVIEW

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We concentrate here on the 18th and 19th century pre-modern traditions in iron and steel. The most salient feature in our critical and up-to-date review is the diversity of ore bodies treated, mineral beneficiation techniques and smelting patterns in the Southern, Central, Eastern and Western India. The recent replication experiments and theoretical studies have thrown considerable light onto these pre-modern smelting and crucible steel making techniques.

We have reviewed the different types of enterprises, the charcoal crisis and the various factors which led to stagnation and atrophy in the iron industries of pre-modern India. There were many noticeable foreign influences but not enough in quantity or quality to prevent the atrophy which could not be overcome without an input of modern scientific knowledge.

INTRODUCTION

There exist several critical reviews on iron and steel in ancient India.¹⁻⁷ The dates of the earliest iron age sites in India show that the discovery and use of iron started around 1200 B.C. indigenously and independently in at least three nuclear zones – Karnataka in the south, U.P.-Rajasthan in the north, and West Bengal-Bihar area in the north-east⁶. In terms of surface carburization, forging and lamination techniques, the Indian tradition has been as ancient as any other outside India². The 7th-6th century B.C. smelting traditions at Ujjain, Dhatwa and Naikund have been remarkable^{3, 5}. At Naikund, carburization of iron used to be done to the extent of 1 p.c. carbon in the ingot^{4, 5}.

The earliest evidence (obtained so far) of hardening through quenching and tempered martensitic structure, pertains to a 3rd century B.C. iron sickle from Pandu Rajar Dhibi. Ghosh and Chattopadhyaya have dated a sample of hardened steel at Barudih in Bihar to be 810 B.C. (MASCA Journal 2, 2, 63, 1982). The issue raised by Bronson⁷ as to whether India produced crucible steel before 16th century A.D. has been contested by Prakash⁶. The subject is wide open for further research.

How exactly the corrosion-resistant forge-welded structures like the Delhi Iron Pillar, Dhar pillar or the Konarak beams were made, is not well-understood. The roots of the tribal traditions of iron-making in India, reported by several scholars⁶, must have originated in the ancient period before 1200 A.D.; but the exact dates

are problematical to find. Before we critically examine the late 18th/early 19th century scenario, a few historical facts related to the medieval India may be noted.

IRON AND STEEL IN MEDIEVAL INDIA

The historical records pertaining to iron and steel in medieval India are scanty. Ray Chaudhuri and Irfan Habib have provided some information in this regard⁸. The mining areas lay scattered in the hilly region beginning with Gwalior and extending to the tip of southern India. The Geniza records of the eleventh and twelfth centuries show that the Deccan exported iron and steel to the Middle East⁹. Fakhr-i-Mudabbir thought the Indian swords to be the best, and writes that the damascened sword (*maujdaryā*) was the rarest and fetched the highest price. Another kind was made of soft iron alloyed with copper and silver, and still another, from Kurij in Cutch was made of steel¹⁰. *Rasa Ratna Samuccaya* of the 13th century A.D. described different varieties of iron and steel, which shall be presented later.

Manucci reported that iron ore from Gwalior mines was smelted and the metal was finally processed in different Mughal provinces such as Bengal, Allahabad, Agra, Berar, Gujarat, Delhi, Indalvai, Indur and Kashmir. India exported over 10000 pounds of steel in 1657 and over 5 lakh pounds of ironware in 1667. The 'Dutch Establishment shipped in the 17th century from India 20000 ingots of 'wootz' steel.

During the 1660's the Dutch were active in developing the iron industry in the Godavari delta. They were in such an urgent need of pig iron, iron bands, iron bars and cannon balls, that they organized a manufactory system of production for these items in their factories. Varied iron products such as nails, cannon balls, iron bars iron bands etc. used to be exported from Coromandel to Batavia. Spikes, bolts and anchors were produced in India for shipyards at Narasapur, Masulipatam, Pulicat etc. In the Qutbshahi kingdom Indalwai (near the modern Nizamabad) was the centre of the manufacture of swords, daggers and lances which were made from iron that was mined in the Kalaghat hills¹¹⁻¹³.

Mining was widespread in Golconda, Karnataka and Mysore, Whereas Mysore iron and steel were of average quality and used mainly for ploughshares, horseshoes, nails etc. for local consumption, Golconda steel was famous all over India and even outside the sub-continent^{12, 14}. Another important area of iron ore mining and ferrous metallurgy in medieval India was Assam. The craftsmen supervising smelting were known as *ojhās*. Double-bellowed furnaces in Jaintia and other parts of the Khasi hills were more efficient than those in other parts of Assam. The Mughal India used to import iron hoes and bell-metal vessels from the Ahom state¹⁵.

Ever since Babar invaded India in 1526 A.D., artillery and gun founding started in the sub-continent. Most of the earlier cannons were made of cast bronze and brass. Some of these, such as *Malik-i-Maidan* used in 1564 A.D. were excessively

heavy and difficult to transport. The Bijapur kings requisitioned the services of many technicians from Turkey¹⁶. Gradually attention shifted towards the fabrication of iron cannons.

Amir Fathaullah, a reputed mechanical inventor, had come from Shiraz in Persia to assist Adil Shah of Bijapur. During 1584-1590 A.D. he served Akbar's foundry establishment with great distinction. New types of portable iron guns and match-locks, *bandūks* were made. A mechanically driven wheel was invented by the motion of which sixteen gun barrels could be cleaned in a very short time¹⁷.

Despite the presence of Turkish and European gun-casters in India, cast iron cannons were never introduced. During Akbar's regime the gun-barrel was made up of discs of wrought iron through which holes had been punched using hammers and chisels. These perforated discs were joined together by forge-welding and the joints were reinforced by slipping red-hot iron rings into these, so that on cooling, these rings contracted tightly onto the joints. 'The expertise in forging techniques was, therefore, diluting the need for casting technology'.^{17, 18} It is strange that despite the knowledge of refractory clay and the presence of foreign technicians there was so much sluggishness in medieval India to pass on from bronze casting to the casting technology of molten iron (higher melting point of 1535°C).

THE 18TH/19TH CENTURY SCENARIO: DIVERSITIES

Now we proceed to record and critically review the writings of the European travellers on the iron and steel scenario in the 18th/19th Century India. This information can partially, though not fully, compensate for the miserable lacunae in the medieval literature on the subject. One is immediately impressed with the diversities in ores processed, smelting techniques, furnaces, and products obtained in different geographical sectors of Pre-Modern India.

Valentine Ball recorded the diversity of iron ores mined, purified and processed by the Indian iron smelters¹⁹, mentioning the reports of the earlier workers²⁰⁻²⁶. We have briefly reviewed the literature regarding the mineralogical characteristics of different ore-bodies indigenously processed. Table 1 contains a summary.

In India three types of furnaces were used : bowl-shaped open hearths, small blast furnaces and tall blast furnaces²⁸⁻³¹. The Chota Nagpur small blast furnaces were typically 4'6" high, the blast being introduced by a single tuyere. The Malabar district Stückofen type tall blast furnaces were typically 10 ft high. Several furnaces were built together over a common platform. Charcoal was the only fuel used and flux was rarely used. India produced three kinds of product : crude wrought iron, pure wrought iron and wootz steel. Kathiawar furnace was exceptional insofar as it resembled the European reverberatory furnace and was probably a technological import/adaptation. Flame produced by the blast over the burning charcoal played over the ore which was kept in a separate compartment, instead of being mixed with

Table 1 Indigenous Processing of Iron Ores in Pre-modern India (Reproduced from Biswas⁴⁹)

Location	Type of Ore	Comments	References
Assam (Upper)	Clay ironstone	3000 smelters in 16th/17th centuries	Hannay in JASB, 25, 330
Khasi and Jaintia Hills	Titaniferous magnetic oxide	Beneficiation by raking	Yule. ^{24, 26}
Birbhum in West Bengal	Partly earthy, partly magnetic	Early production of <i>molten</i> iron-early 18th century	Hamilton ²⁰
Balasore, Orissa	Lateritic ore	Some collaboration with the Dutch in 17th century	Hamilton ²⁰
Palamu, Bihar	Three types of ore, Agarias preferring the magnetic type	Details on smelting by the Agarias.	Mem. GSI, Vol. XV, part 1, p. 112. Ref. No. 19, pp. 376-381
Sambalpur	Magnetite in metamorphic rock	Use of <i>Śāl</i> wood charcoal	Res. GSI, Vol. X, p. 182
Tendukhera Madhya Pradesh	High grade, slightly calcareous	Production of <i>kāchā</i> iron and <i>pakkā</i> steel	Franklin ²⁵ . Ref. 19, p. 386 Ref. 27, pp. 269-294
Gwalior	Rich deposits, now deserted	Very ancient tradition	Hackett, Records GSI, Vol. III, p. 42 Ref. 19, p. 394.
Nimar and Malwa in Indore Territory	Barwai deposit is chiefly brown hematite	Mentioned in 'Ain-i-Akbari'	Ref. 19, p. 397
Kathiawar and Cutch	Laterite of Subnummulitic group	Reverberatory furnace Production of wootz (1838-40)	Ref. 19, pp. 400-402
Hyderabad	Two kinds of ore – lateritic and magnetic sand	Steel mines of Nirmal mentioned in <i>Ain-i-Akbari</i>	Voysey ²³
Cuddapah and Kurnool	Siliceous hematite and also lateritic	Series of iron-smelting villages	1795 report of Heyne ²¹
Mysore	Black sand iron ore in Venkatagiri	Manufacture of Steel	Buchanan ²²
Chitaldrug in Salem	Non-magnetic ochrous limonite	Manufacture of wootz	Heyne ²¹
Malabar or Kerala	Black magnetic sand	Rock 'laterite' – term first coined.	Buchanan ²²

fuel. Thus reduction of iron oxide was by carbon monoxide rather than carbon.

In places of large scale production such as Mysore or Birbhum, the refining forges were separate and the refiners bought the iron blooms from the smelters. Steel was made either by carburizing wrought iron in crucible (wootz) or by decarburizing cast iron.

Recently some studies have been made on the pre-modern technology by reconstructing ancient furnaces with the aid of the aged rural artisans, and measuring operating conditions and analysing raw materials and products^{6b, 32-35}. These replication experiments and data have helped in quantification of the pre-modern technologies. Now we proceed to describe specific regional patterns in iron/steel technology specifically in the Southern, Central, Eastern and Western India.

PRE-MODERN IRON TECHNOLOGY IN SOUTHERN INDIA

During his famous journey through Mysore, Karnataka and Malabar (Kerala), Buchanan noted²² several places where lateritic (the term coined by Buchanan himself: lateritis = brick) iron ores were processed and smelted. At Colangodu in Malabar, four furnaces smelted black magnetic sand. At Velater there were 34 furnaces which belonged to a Mopla.

The lateritic ore was beneficiated by washing in a trough, open at both ends, which was placed in a running stream. The washed ore was largely magnetic. Buchanan provided admirably drawn sketches-sections and elevations of twin-shaft (250 Kg iron per day) furnace which according to Prakash 'conform to the design parameters of the modern 1000 TPD furnaces'^{6b, 29}. We do not know whether the local artisans had been assisted during the earlier centuries by some Portuguese or Dutch travellers. These 10' ft tall furnaces were provided with bellow – pairs, peep holes, hearth and slag pit. Dirar and others have recently attempted to revive the ancient process in Kerala^{33, 34}.

A report on the manufacture of bar iron in the Salem region of South India was recorded by Campbell³⁶ in 1842 reproduced by Rahman, Subbarayappa³⁷ and Dharampal³⁸. The furnace was constructed with common red potters clay. On a platform of about 2' square and 5" thick the furnace wall was 4"-6" thick. The annular space inside was partly cylindrical (9" diam. 18" ht.) and above conical (18" ht. and diam. tapering 9" to 3") and then expanding like a funnel upto 9" diam. The blast pipe was a cylinder of dry clay 14" long, about 4" thick, pierced with a hole of one inch in diameter. It was introduced into the furnace 5" above the bottom. The blast pipe was connected to the bellows made of two whole goat skins.

The furnace was filled to the neck with charcoal, about 26 pounds and fire introduced. Then the common magnetic iron of Salem (about 5 lb.) was mixed with charcoal (10 lb) and introduced into the furnace.

Normally one 11 lb. lump was obtained as the product, one fourth of it being recovered in the forge as iron. 'As regards their quality', wrote Campbell, 'the worst of them is as good as the best English iron and its supposed defects arise from its almost always containing a considerable portion of steel..... A fractured end of a bar of iron presents a very different appearance – no glistening portion like English bar iron : it is granular or an aggregation of crystalline grains'.

Campbell specifically mentioned that the South Indian iron-making furnaces resembled the 10-15 ft. high, 3 ft. diam ancient Stückofen furnaces in Germany. Thus some Dutch influence in the design of this kind of furnace cannot be ruled out.

Buchanan made frequent allusions to the manufacture of iron in different parts of Mysore, and gave detailed accounts of the process. Many of his observations²² as well as those of Heyne²¹ were made in connection with the manufacture of steel, and hence shall be described later. In the Shimoga district, iron ores were worked in some parts. magnetic ore occurred at Kodachadri in which is located the famous 10 m. iron pillar. An effort was made during the middle of the 19th century to tabulate the number of mines and furnaces for iron working in the districts of Shimoga, Kadur and Chitaldrug. Ball commented that 'it is incredible that in the years between 1872 and 1875 there were upwards of 1400 mines'³⁹.

In the Andhra Pradesh area, Cuddapah and Kurnool districts had many iron works. A series of iron-smelting villages lay along the eastern side of the Khundair valley (8 miles north of Dhoor). At a small village called Colapetta there were ten furnaces. In other parts of the Cuddapah district there were furnaces, and itinerant blacksmiths carried their implements and wandered over the district seeking for employment.

Manufacture of iron in the Krishna and Godavari districts attracted notice for many years. In September 1795, Benjamin Heyne referred to his visits to Lutchmiporum (Laxmipuram) and Ramanakapettah iron works, the latter being very close to Noozed and the diamond mines of Mallavilly⁴⁰. Before the terrible famine of 1790-92, Ramanakapettah was in a state of affluence with a great number of silver and coppersmiths and 40 iron – smelting furnaces; after the famine the number came down to ten. Each furnace required nine men, chiefly employed in working the bellows, 'an operation which might be easily improved by a proper mechanical apparatus, through the medium of fire or water, or both'. Preparation of steel at Nirmal and Konasamudram in the Nizam's territory would be discussed later.

IRON IN THE PRE-MODERN CENTRAL INDIA

Several ancient iron ore mines were known to exist in the districts of Jabalpur, Baragaon, Panna, Katola and Sagar. Franklin described in around 1827 these mines

and the mode of manufacturing iron in Central India⁴¹. The Tendukaira or Tendukhera mine and iron works in the Sagar District were described in great detail.

The smelting furnaces were 'very exact in their interior proportions and constructed with precision'. Franklin observed that the production of four furnaces (per week) was 71 maunds or 2.25 English tons, cost of production being two pounds six shillings per English ton.

Part of the bloom used to be forge-hammered just short of fusion, then 'rolled in the ashes of burnt cowdung, previous to fresh hammering, heated red-hot and plunged into water'. It was then an excellent steel. Franklin made suggestions with reference to the introduction of simple machinery in the works. In the years 1830, Colonel Presgrave opened a suspension bridge over the Bias river in Sagar, the iron for which had been all smelted at Tendukhera.

In 1857 there were about 70 to 80 furnaces in Tendukhera. The charcoal was made in the jungle and *kachchā* iron blooms made in Catalan type furnaces. The *pakkā* iron was made in a different form, from which it came in the condition of crude steel, which was hammered for making edge-tools.

Ball recorded that the 250 ft. high hill Khandeshwar (near Dewalgaon) in the Chanda district was wholly laden with iron ore and in view of the abundance of fuel available, 'this hill alone might furnish the whole of India with iron'⁴². P.N. Bose the first Indian geologist of the modern era recorded good quality iron ores in the Chanda district. Bose saw ancient mines in the Western portion of the district at Raipur : mine of Magarkund, furnaces at Kondkasar, Dalli, Nandgaon, Khairagar etc. Flux was never used in the furnaces and wooded forests near Dalli were so plenty that large charcoal furnaces seemed to be quite viable for long-term operation. The Agarias who were working the furnaces were 'a very unsettled people, leaving a place as soon as the neighbouring jungle failed to satisfy their requirements, or the Zamindar enhanced the duty levied on their furnaces'⁴³.

Elwin surveyed the whole of Central India and made ethno-technological studies on the iron-making by the Agarias⁴⁴. Krishnan has also reviewed the status of iron-making in ancient India⁴⁵. The Mundia and Halbi tribes of Bastar were well-versed with the iron-making technology and they were capable of producing forgeable iron from their tiny furnace. The region of Bastar could not earlier be surveyed and included in the 'Agaria' belt 'because of the inaccessibility of that region or due to the traditional self-containment of these tribes'.

Prakash and Igaki surveyed actual performance of the ancient iron making in the Bastar district⁴⁶. The furnace used by the tribes was essentially of the same type as that used in the Chiglabecha area of Koraput⁴⁷. The bowl-shaped furnace was built below the ground level by digging a square pit of about 2000x2000 mm and 500 mm. depth and with steps on one side to go down. The furnace had a total

height of about 800 mm. and the diameter of the furnace at the throat 200 mm. The shaft of the furnace was 600 mm. in depth and had a tapered wall. It ended into a bowl-shaped hearth having about 240 mm. maximum diameter and 100 mm. depth. A hole was provided in the bowl to tap out the slag. The furnace was made below the ground level to cut down the access of air and inner wall was coated with a layer of refractory clay.

The air blowing rate was adjusted to maintain a temperature of around 1150°C. The whole operation took 5-6 hours producing one Kg of iron. The semi-fused mass of the sponge iron block mixed with slag was taken out and separated from the solidified bottom charge. The sponge iron block was forged on an anvil to flatten it and squeeze out the slag, the response to forging giving an idea of its carbon content⁴⁶. The Mundia and Halbi tribes have been living a life of self-sufficiency and making iron by the ancient method to prepare arrowheads, axes and hoe which form a part of their routine life.

Recently, Balasubramanian, Ballal et al. have documented³³ some typical ancient iron-smelting furnaces in Madhya Pradesh – used by the Lohra family at Ghatgaon (Dist. Raigarh) and Wadruffnagar (Dist. Sarguja). The smelting furnace in the unbroken tradition of Ghatgaon is a cylindrical clay structure 600 mm. in diameter and 950 mm in height on the outside. The shaft inside extends 150 mm. below ground level so that the total shaft height is 1100 mm. The shaft can be divided into 3 sections : (a) lowermost cylindrical portion of 250 mm. diameter and 550 mm. height (b) the next section a truncated cone with a base diameter 250 mm, top diam. 100 mm. height 250 mm. and (c) top cylindrical section of 100 mm. diam. 300 mm. height.

The furnace used by the Agariayas from Wadruffnagar is a squat structure, 600 mm. above the ground level. The shaft extends to 270 mm. below the ground. The diameter is 120 mm. at the top. The shaft runs straight down at the front but opens out at the side and rear to a diameter of 300 mm. over a length of 450 mm. The lower portion is a cylinder of diameter 300 mm.

Locally available clay is used for the construction of the furnace. Vegetable matter like Kodon chaff, rice husk or hay may be mixed with the clay for reinforcement and stabilisation. A sloping pan is used for beneficiation of ferruginous sand from the river bed by gravity separation. The lighter siliceous particles are washed away with water and the heavier black ore particles, left behind, contain higher p.c. of iron. These are sun-dried and put into the furnace with local charcoal.

PRE-MODERN IRON MAKING IN EASTERN INDIA

There were certain specific features in the ironmaking traditions prevalent in the Eastern India. The smelting of iron was an important industry in Upper Assam, specially in the Naga Hills. According to Colonel Hannay (*Journal of Asiatic*

Society of Bengal, Vol. XXV, p. 330), there had been at one time 3000 smelters and smiths in Upper Assam. The principal centres of their operations were at Tirugaon and Hattigar, where the remains of their slag heaps and furnaces are still to be seen. During the 16th and 17th centuries, Assam was famous for the manufacture of big iron guns; one at Rangpur fort measured 17 feet 3½ inches and the metal was 7¾ inches thick. This casting technology could have been borrowed from the Chinese. This tradition died down on account of the Burmese incursions and competition from the Khasi Hill technology. Hydraulic mining and beneficiation of the iron ore sands in the Khasi and Jaintia Hills have been described earlier^{48, 49}.

F.R. Mallet observed⁵⁰ that the smiths of the Upper Assam used contrivances quite different from those used in India proper. In most parts of the sub-continent bellows were used: the supply of air to the furnace was provided by alternate expansion and contraction of a flexible material, like leather or raw skin. The contrivances used in Upper Assam were made of blowing cylinders – single-acting or double-acting made of rigid material such as solid piece of wood, turned or bored. Into the ends, discs of wood were fitted by rough dove-tailing, the circular joints between discs and cylinder being rendered air-tight with clay. In the centre of one disc is a small hole in which the piston rod works; the latter is made from a slip of bamboo split from a large-sized piece. Close to each end of the cylinder there is a hole of an inch or so in diameter, which allows the air to pass into the tubes or the tuyere. Thus the system worked like a blowing machine which substantially raised the temperature of the charcoal-fired furnace.

The double-cylinder machines were observed at Burhāt on the Disāng. Modifications were noted in the Naga Village of Ranckatu, 11 miles south-east of Mākum. Quoting Percy²⁸, Mallet noted that the wooden blowing machines were common amongst the Chinese and the Burmese, and it is probable that the Assamese had acquired a knowledge of the principle from them⁵⁰.

The existence of iron in the districts of Balasore in Orissa and Birbhum in West Bengal seems to have been known at the earliest period of British rule in the country. Captain Alexander Hamilton narrated in 1708 how he found on his way from Bhadrak to Balasore ‘iron so plentiful that they cast anchors for ships in moulds’⁵¹. Is this occurrence of cast iron attributable to the earlier Dutch influence?⁵³

In Birbhum, Hamilton found ‘iron ores carried by the *beparries* to established markets called *aurangs*, where it was purchased by the smelters, whose furnaces or *saals* adjoined the *aurang*’. The Rajah’s officers supervised the operations and products of the *loha-mahal* having *kot-saal* or roasting furnace and *khamar-saal* where the iron was finally prepared for use.⁵¹

Sanyal reviewed⁵⁴ two types of indigenous pre-modern iron industries operating in Birbhum during 1843-1881. The first type (I) had small furnaces operated by the itinerant tribal people like Santals/Munda Kols.

The second type (II) of manufacture was carried out by the Bengali-speaking people in the north-western part of the district, where ore as well as timber for charcoal fuel were easily available. Large scale furnaces being operated here were not to be found anywhere else in India. 70 furnaces in the centres of Ballia, Narainpur, Deocha, Dumra, Ganpur (Chowdhuries were the proprietors) etc. produced in 1852 (when Oldham visited the area) more than 2380 tons of *kachchā* iron. At Deocha itself there were 30 furnaces; average annual output from one furnace was 34 tons. In these furnaces the *kachchā* iron, 'unlike that produced in other parts of India, formed at the bottom of the furnace in a *molten condition*, and resembled good pig iron' (Engineers' Journal, Calcutta, Vol. III, 1852, p. 112). The refining was really a sort of puddling process, which induced a pasty condition admitting of the iron being drawn out and hammered until it became thoroughly malleable. The Muslims supervised the production of the *kachchā* iron and the Hindus refined them to *pakkā* iron.

Oldham observed that this soft charcoal iron had its uses on account of malleability, but in price it could not compete with English iron at the prices then prevailing in Calcutta. Absence of economical fuel (forest wood charcoal) made the future of the process quite bleak⁵⁵. During the previous century, Indranarain Sarma, an Indian, wanted to produce iron⁵² at a large scale in Birbhum (1774). During 1777-1789, Farquhar had used the indigenous process – not the European method – to cast shot and shells and hook iron and supply them to Fort William⁵⁵ prior to switching over to the gunpowder manufactory at Phulta (1789).

Hamilton's 1708 note on iron in Orissa has been already mentioned^{51, 53}. Not much detail is available regarding the late 17th century foreign influence in the local technology. In 1964, Moni Ghosh submitted his report on the primitive iron making in the Koraput district of Orissa⁴⁷. These furnaces are about 30 inches high, height of the semi-spherical dome from the bottom of the furnace is 17 inches, height of the chimney 13 inches, and the internal diameter of the chimney 5.5 inches. Ghosh noted two types of furnaces in the area. The first is a shaft furnace and is fully subterranean. The second, which is partly subterranean is constructed over a rectangular pit.

Ball recorded the richness of the iron ore deposits in the Palamu sub-division of the Lohardaga district – three distinct types (a) magnetite (b) siderite and hematite and (c) red and brown hematite – and the large variations in the smelting techniques adopted by the Agarias. One typical account was described⁵⁶.

The furnaces of the Agarias were built of mud and were about 3 to 4 ft. high, tapering from a diameter of about 2½ ft. at base to 1½ ft. at the top. The hearth was a rounded cavity, which was about 10 inches in diameter, and the circular shaft above it is 6 inches in diameter. A bed of charcoal having been rammed down the hearth, ignited charcoal was placed above it, and the shaft was filled with charcoal. The blast was produced by a pair of kettledrum – like bellows, consisting of

hollowed drums of wood, with goats' skins attached, and nozzles of bamboo. The bamboos which convey the blast were luted into clay tuyeres, which were themselves luted into the front of the furnace. The blast used to be kept up for six hours.

Powdered ore was sprinkled in alternate layers with charcoal – on the top of the ignited charcoal in the shaft. The slag formed was tapped through a hole. During the end of the process, the clay-luting of the hearth was broken down, and a *giri*, or ball of semi-molten iron, including slag and half-burnt charcoal was taken out. This was hammered to squeeze out the molten slag. The iron was then either refined by the Agarias or sold to the *lohars* who worked it up into bars⁵⁶. If the hearth were larger, bloom produced would also be large and unworkable. Such a big piece (156.5 lbs.) was worshipped for many years by the people of the Kharakpur Hills in the Monghyr district!⁵⁷.

Moving west from Bihar, we find ancient ironmaking traditions existed in Gurgaon District, Haryana. In 1831, the Ferozpur/Narnul ores were being smelted in the smelting furnace called *Māndarī* which was merely a square receptacle leaving an opening both above and below; the dross ran out from the lower orifice into a hollow sunk into the ground. Two bellows were used for each furnace. Iron obtained as an imperfectly melted conglomerate was forged for heavy wedge-headed hammers⁵⁸.

IRON IN PRE-MODERN GUJARAT AREA

In the year 1840, Captain Grant described the manufacture of iron in Cutch which was conducted according to the ordinary Indian method. It was reported that *wootz* or steel used to be produced there formerly.

The iron industry in Kathiawar was described by Captain G. Legrand Jacob in 1838 (Selection from Records, Bombay Government, No. XXXVII, p. 465) and this description was quoted by Ball⁵⁹. There were six groups of furnaces, of which two, situated respectively at Ranawao and Ranpur, were visited by Captain Jacob.

The lateritic ore was smelted in the furnaces of unusual shape; these were 'something of the nature of a reverberatory furnace, except in the essential particular that the ore was placed in partial contact, though not mixed with the fuel'. The furnaces were long and narrow (dimensions not given), and were built of brickwork lined with clay. At one end there was a chimney, and close to the other extremity there were two apertures on opposite sides; through one of these the blast from the bellows was driven over the ignited fuel, and by the other the slag was withdrawn. The ore was placed in hollows on a bed of charcoal, and was covered with a layer of the same, but was so arranged to be on either side of the stream of air.

The bellows consisted of two bullock hides sewn round bamboo hoops in vertical rings and worked alternately by downward pressure, the operator closing

the mouth of the sack with his hands as he weighed upon it with his chest and arms. The furnace held little more than seven Bombay maunds (1 maund = 40 seers), which took from six to eight hours to melt.

Captain Jacob calculated that the metal recovery was about 40 per cent. The workmen said that the direction of the wind affected the outturn, 'five maunds being obtained from a double charge of the furnace, during westerly winds, and seven maunds when it blew from the east'. 'This they accounted for by saying that metals were like mortals, some climates agreeing with them better than others'. Jacob and Ball attributed the difference to the comparative vigour of the men who worked the bellows under the influence of moist and dry winds. It is equally possible that moist wind resulted in lowering the furnace temperature.

Captain Jacob wrote that 'it was difficult to witness without pain the struggles of these men for a subsistence, which, owing to competition, was yearly becoming more arduous'. He predicted rapid extinction of this industry which actually took place in a few decades since 1838. Ball reported in 1880 the *new modern* blast furnaces in India started by the Governor General for the Raja of Sirmur at Nahan.

REPLICATION EXPERIMENTS AND THEORETICAL STUDIES ON THE PRE-MODERN TECHNOLOGIES

Moni Ghosh reported operations on the ancient Koraput furnaces in Jiragora (Bihar) and Chinglebecha and also in Kamarjoda near Jamshedpur⁴⁷. The ironsmelting practice at Bishunpur has been simulated by Vikas Bharati, a voluntary organisation with the help of Nagu Birjia, an old technician of this area. Prakash has compared the operating parameters of Jiragora and Bishunpur (Dist. Gumla, Bihar) iron-making furnaces and also compiled composition of iron produced by ancient Indian furnaces^{6b}. The compiled data are reproduced in Tables 2 and 3. Balasubramanian, Ballal et al. have described³³ the operating features of the ancient furnaces at Bishunpur (Bihar) as well as at Ghatgaon (Dist. Raigarh) and Wadruffnagar (Dist. Sarguja) in Madhya Pradesh.

We have noted that most of the indigenous furnaces have varied in height between 0.6 to 1.2 m and diameter 0.25-0.5 m. Charcoal from hard woods like sal, teak etc. were used. Normally no flux was used and the blast air was at room temperature. Vivek tried to simulate this process at IIT, Bombay and we quote some of his experimental results and theoretical calculations³⁵.

Vivek constructed the clay furnace 1.2 m high and the diameter varying from 0.3 m at the bottom to 0.15 m at the top. Air was supplied by simulated bellows, and charcoal from the local market was used. The experiments were conducted in summer months with 30°C temperature and 50-60% relative humidity.

The Raceway Theoretical Flame Temperature (RAFT) was calculated to be 1500-1510°C if the input dry air temperature varied between 20 to 30°C. The effect

Table 2 Comparison of operating parameters of Jiragora and Bishunpur iron making furnaces (Taken from Prakash, Ref. No. 6b)

Operation	Time	Material Charged Ore	Coal	Blowing Rate	Remark
JIRAGORA FURNACE					
1. Furnace preheating	1h	—	8 kg	Faster than 87 strokes/min	
2. Reduction stage	4h	—	14 kg	87 strokes/min	Sequence of ore and coal charging not available
3. Consolidation stage	1h	—	8 kg	Vigorous blowing	
4. Total operating time	6h	—	—	—	—
5. Total material charged	—	24 kg	30 kg	—	5.6 kg of iron
BISHUNPUR FURNACE					
1. Furnace preheating	1.25h	2.5 kg	3.25 kg	40-50 strokes/min	Fce Temp. 550°C
2. Reduction stage	4h	8 kg	16 kg	60-70 strokes/min	950°C
3. Consolidation stage	0.5h	1 kg	2 kg	110 strokes/min	1500°C
4. Total operating time	5.75h	—	—	—	—
5. Total material charged	—	11.25 kg	21.5 kg	—	2.5 kg of iron

Table 3 Chemical composition of iron produced by ancient Indian furnaces^{6b}

Source	C%	Si%	Mn%	P%	S%	Others
1. Delhi Iron Pillar	0.23	0.066	—	0.18	Traces	N ₂ = 0.0065%
2. Bhubaneswar Iron Beams	0.27 to 0.45	0.05 to 0.11	Traces to 0.04	0.015 to 0.018	0.006 to 0.015	Cr = 0.9% Ni = 1.6%
3. Bastar Iron Axe (100 years old)	0.25 to 0.45	—	—	—	—	Other elements in traces
4. Jabalpur Iron (recent)	0.59	110 ppm	40 ppm	—	—	Cu = 340 ppm Ni = 353 ppm Others in traces
5. Bishunpur Iron (recent)	0.016 to 0.043	—	0.057	0.02 to 0.2	0.007 to 0.013	—

of humidity on the RAFT was considerable. During summer, 30°C air with 50% RH is supposed to give RAFT of 1400°C whereas during winter, 20°C air with 25% RH would give a RAFT of 1475°C. (This also corroborates Captain Jacob's observation at Kathiawar⁵⁹). Using a pyrometer 2 hrs. after starting the furnace, the maximum temperature was found to vary between 1400-1475°C. Through temperature measurements at different parts of the furnace, a thermal profile was constructed.

Significant reduction of the ore commenced only after it descended about half the height of the furnace. The particle of iron was molten for a very short time and that too on the surface. 'Bloom' is the aggregate of iron particles sintering into a highly porous mass with interstices filled with molten slag. In the modern blast furnace the liquid metal product picks up large proportions of C, Si, P etc. In the

ancient process, carbon content in the solid metal was low (α -ferrite has m.p. 1410°C) unless larger proportion of charcoal was used. Silicon, sulphur and manganese pick-up were also little. Charcoal being much purer fuel, impurity pick-up in the malleable metal was very low. Only the phosphorus part went into the metal, providing corrosion – resistance to it.

Since the lime-flux was rarely used, the slag was often fayalite, 2FeO , SiO_2 , melting in the range $1150\text{-}1200^{\circ}\text{C}$. The slag coating the metal further retarded carbon pick-up. In the ancient process considerable amount of iron oxide remained in the slag unreduced, iron recovery was low, but the purity of the metal was high.

Bloomgren and Tholander have shown⁶⁰ that high oxygen activity of the fayalite slag acted as a control parameter in lowering the carbon content of the metal. They have also shown that in the modern blast furnace, productivity and temperature being high and limestone being used as flux, fayalite concentration in the calcium silicate/calcium aluminosilicate goes down, oxygen potential decreases and hence the carbon pick-up in the metal is increased⁶⁰.

Thus the indigenous technology had low productivity and thermal efficiency and yet produced pure malleable metal which was used to forge a large number of locally useful materials such as arrowhead, dagger, knife, spade etc., and preferred over hard but brittle high carbon imported iron.

THE CHARCOAL CRISIS AND THE ATROPHY OF THE INDIGENOUS INDUSTRIES

Various reasons have been ascribed to the atrophy and the extinction of the indigenous iron industries in India. Neither the Mughal government nor the people in the country were aware of the new technological developments in the field of mass production of iron and steel, which were spreading fast in Europe³¹. The 19th century European observers consistently remarked about the lack of innovation in the Indian industries, the persistence of charcoal furnaces, the non-use of mineral fuels, the non-use of flux etc. On the other hand, some scholars believe that the most important factor has been the British competition, intrusion into the Indian market and ruthless elimination of the Indian industries. Dharampal has written: 'The disappearance seems to have resulted mainly from large-scale economic breakdown and hostile state policy'²⁷.

The phenomenon was indeed complex. One technical factor was the charcoal crisis which Bhattacharyya has deliberated upon in his masterly paper³⁰.

Enormous quantities of charcoal was needed in the indigenous processes. The proportion of charcoal to that of iron yielded was often 5:1. Considering the refining stage, all told about 14.5 tons of charcoal was used to produce one ton of refined wrought iron. It has been estimated that to produce 2500 tons of refined wrought iron, 140,000 tons of wood were required which could be obtained from 437 square

miles of heavily wooded land! Production of charcoal from green wood was so wasteful. Bhattacharyya rightly commented that ‘the rapid depletion of fuel source seems to have been one of the causes of the atrophy of the iron-smelting industry in the nineteenth century’³⁰.

Europe had faced similar problem in the 16th century when forests were being depleted on account of the charcoal-based process in the iron industry. An acute shortage of timber threatened the ship-building industry in England. The legislative restrictions on waste of timber and high price of fuel charcoal led to technical experiments with coal as a substitute for charcoal. Abraham Darby introduced coke for smelting iron in 1709. The use of coke spread rapidly in England, but it is noteworthy that as late as 1806, 11 out of 173 pig iron furnaces were still using charcoal.

One reason why coal or coke could not replace charcoal as fuel readily, was that the conventional bellows were not sufficient to bring the mineral fuel to the required temperature. The coke furnace needed an engine two and a half times more powerful than that needed for a charcoal furnace for iron smelting. Charcoal could not be replaced with mineral fuel without auxiliary innovations such as superior blasting machines in place of the low-powered bellows.

At this stage, we may record a brief note on the use of coal and coke in ancient China. The Chinese people had been using efficient double-acting bellows since 4th century B.C., the hydraulic bellows from the 1st century A.D., and good refractory clay and surface coal from c.A.D. 400. Thus, efficient use of coke or coal demanded powerful and mechanised bellows which India did not have, except in the Chinese border of Eastern India. China could develop furnaces having higher temperatures which melted iron, but they were aided by their possession of high-phosphorus iron ore which substantially reduced the melting point of iron and enabled production of cast iron⁶¹.

Thus, the Indian persistence of charcoal furnaces and the non-use of mineral fuels, the non-use of flux, non-availability of mechanised bellows, non-development of high-grade refractories represented different aspects of a complex phenomenon resulting in stagnation and atrophy of the indigenous craft. When the Western visitors attributed the atrophy to the Indian artisan’s indolence, indifference and resistance against technological improvements, they were a bit too harsh and uncharitable. There were several examples when the British entrepreneurs tried coal or coke in indigenous furnaces and failed on account of the technical reasons cited earlier.

On the question of improving iron manufacture in India during the 19th century, there emerged two schools of thought. One view, supported by Bhattacharyya³⁰, and now endorsed by the present author, was that new technology had to be introduced – employing coke, good refractory, flux, mechanisation etc. – *all at once* instead

of making piece-meal improvements in the indigenous method of production. The other view propounded by M. Fryar etc. was that the better method was 'to gradually engraft improvements on the native methods of manufacture'³⁰. Dharampal felt that indigenous technology was hurt by 'unthinking transplanting of European sciences' and that the disappearance of the indigenous iron industries in India was on account of unequal British competition, 'large-scale economic breakdown and hostile state policy'²⁷. Dharampal hardly attended to the technical considerations of the charcoal issue (as Bhattacharyya did). His observations had political overtones and would be discussed at the end of this article.

IRON-CARBON ALLOYS IN INDIA

The 13th century A.D. text *Rasa Ratna Samuccaya* (RRS) contains a section (5.69-5.96) on the different varieties of iron⁶². The descriptions clearly indicate that Indians were familiar with iron-carbon alloys and different phases.

Kānta loha is soft wrought iron with five sub-varieties of different magnetic properties.

The name *Munda loha* (second major variety) probably originated from *Mundia*, one of the metalsmith tribes in the district of Bastar whose ancient iron-making process has been scientifically observed and recorded by Prakash and Igaki⁴⁶. *Munda loha* had three sub-varieties: *mṛdu*, soft which is *drutadrāva* 'melting or softening quickly' and could be low m.p. grey cast iron; *Kuntha*, expanding with great difficulty on hammering, could be mottled grey iron; and *Kaḍāra* sub-variety which 'breaks on hammering' could be white cast iron. The indigenous metalsmiths produced the last two brittle varieties unintentionally, when temperature of the furnace rose high and amount of charcoal used was large, resulting in high-carbon iron. They preferred the first variety *mṛdu* which had smooth surface, did not contain fissures and was adjudged to be 'the best of the three'.

Tikṣṇa loha or carbon steel had six sub-varieties. These appreciably hard materials were carburised iron which could be hypo-eutectoid (less than 0.83 percent carbon) or hypereutectoid (more than 0.83 percent carbon) steel. 'Pogaras' mentioned in the text (RRS, 5.77-83) meant hair-like lines which may be surmised as white cementite streaks, coarse enough to be seen by the naked eyes.

The *khara* sub-variety of *tikṣṇa loha* is free from *pogaras* (or has *pogaras* too fine to be seen), breaks on bending and has 'mercury-like shining fracture surface'. The *sāra* sub-variety looks fibrous. The other four varieties were probably the products of hot forging and quenching. *Hṛnnāla* looked whitish black and contained *pogaras*; this was '*Chedane atiparuṣam*', very hard to pierce. *Vājira* looked bluish black and was 'full of hard *pogaras* and overspread by dense thin linings'. *Tārāvatta* developed good cutting edge. *Kālāyasa* was described as 'bluish black in colour, dense, smooth, heavy and bright in appearance, whose sharpened edges do not get

spoiled even by hammering'. This description is close enough to that of the damascened steel swords 'of a dull blue colour marked with ten millions of meandering lines' which are compressed and elongated cementite grains or streaks in pearlite - graphite - martensite matrix.

WOOTZ, A CRUCIBLE STEEL OF INDIA

The Indian crucible process for making high quality steel might have started before the Christian era as evidence by the excavations of crucibles dated 250 B.C. in Tamilnadu⁴⁶. Even earlier, quality steel of India was presented by King Porus to Alexander (323 B.C.) and Kauṭilya's *Arthaśāstra* referred (2.17.14; 4.1.35) to *vṛtta* or steel. The word *vṛtta* means circle or disc, and could denote crucible-molten steel, *ukku* in Telugu or Kannada, *wuz* in Gujarati or *wootz* which was the term used, and spread all over the world by the traders from the Middle East.

In his excellent review⁷, Bennet Bronson grudgingly concedes that 'India may have invented or perfected from the second century A.D. the idea of crucible steel making, but that should not be accepted as a given in medieval studies'. Bronson felt that 'wootz' was merely carburised iron showing brittleness; there were several processes for making it, some practised outside India; the art of converting wootz to steel objects such as Damascus sword was known and probably perfected outside India.

Prakash has contested⁷ Bronson, and has recorded circumstantial evidences, such as the texts of *Bṛhatsamhitā* of Varāhamihira and *Rasa ratna samuccaya* (quoted by us earlier) etc. to prove that India was indeed the pioneer in producing different kinds of wootz and the end products of malleable steel. We also feel that *Rasa ratna samuccaya*'s 'bluish black' *kālāyasa* (5.82) which had been mentioned much earlier in Kauṭilya's *Arthaśāstra* (2.17.14), corresponds beautifully with the Damascus sword, 'the sharpened edges of which do not get spoiled by hammering', and thus establishes India's primacy not only in *wootz* but also in the finished steel. We have discussed our views on iron and steel in ancient India elsewhere¹.

The earliest Western report on pre-modern Indian iron and steel was recorded by Havart⁶³. Some of the earliest writings by the British travellers²⁰⁻²⁶ have been already quoted. A few researchers specifically investigated wootz and Indian steel-both the processes and the products⁶⁴⁻⁶⁹. Stodart for example, sustained his interest on wootz right from 1795 to 1820, collaborating with Michael Faraday. These two collaborators tried to prove that 'wootz was in reality an alloy of iron with aluminium or various other metals'⁶⁸.

It appears that there were *two* distinct processes for making wootz. The South Indian processes (there were minor variations), practised at Mysore and its surroundings, Tamilnadu and Sri Lanka, corresponded to carburisation of wrought iron in crucibles. On the other hand, the Hyderabad process probably involved co-

fusion in crucible of wrought iron and white cast iron.

SOUTH INDIAN PROCESSES

Heyne²¹ and Buchanan²² described several pre-modern South Indian processes for making steel. Heyne witnessed a process starting with ochreous limonite in a small village among the hills south-west of Chitaldrug. He also saw steel being made at Kakerahally, on the road from Bangalore to Seringapatam, using magnetic sand. Buchanan gave detailed accounts of steel-making processes in different parts of Mysore. He saw furnaces at Venkatagiri, Ghettipura (two *cos*s from Magadih), Madhugiri, Chinnarayandurga, Hagalawadi and Devarayadurga. The Sri Lanka version of the process was described by Coomaraswamy⁷⁰.

The crucible was usually made from locally available clay, mixed with carbonaceous materials like the rice husk (charred or uncharred) in equal proportions. CVB mentioned⁷¹ the use of red clay, strained and purified by sedimentation. After moistening, the mixture was well mixed 'under the feet of oxen'²² or by pounding in a stone⁷¹. The well-mixed clay was fashioned into crucibles of conical shape, size ranging between 250 ml. to 500 ml. Coomaraswamy gave⁷⁰ the dimensions of the crucible as 200 mm. long x 50 mm. diam x 6.25 mm. thick.

The crucible was filled with 250-500 g. of bloomery iron, wood chips from *Cassia Auriculata* (*Awaram* in Tamil), leaves or creepers of plants, rice husk etc. The crucible was then sealed with a sun-dried clay lid or a ball of moist clay. Coomaraswamy mentioned a hole in the cover for the gases to escape.

The closed crucibles were allowed to dry and then heated in a charcoal fire. The details of the furnace were given by Buchanan²². The furnace consisted of a horizontal ash-pit and a vertical fire-place, both sunk below the level of the ground. A row of crucibles was first laid round the sloping mouth of the furnace; within these, another row was placed, and the centre of the dome so formed, was occupied by a single crucible, making fifteen in all.

Air was blown with hand bellows usually made from buffalo skins; Coomaraswamy's report shows however foot-operated drum bellows as used in Central India. The number of crucibles fired at a time varied between 6 and 59.

The crucibles were then covered with charcoal and the fire started. The fire was kept up for about 5-6 hours, till the contents were molten. Charcoal was replenished periodically both above and below the crucibles. At the end of the operation, the crucibles were allowed to cool by throwing water over them or in the furnace itself. The contents solidified inside, taking the conical shape of the crucible. The top surface showed striations indicating crystallisation from the liquid state.

Rao, Mukherjee and Lahiri found⁷² that the unused crucibles in the South

Indian sites such as Salem consisted mainly of aluminium silicates and free quartz. The fired crucible was found to be porous and contained mineral mullite, indicating that it had been heated to a temperature not less than 1300°C. Presence of cristobalite showed that the temperature might have occasionally risen over 1470°C.

In the ingot, the carbon content in the periphery was around 0.8 p.c. and the value decreased towards the centre. This indicated diffusion of carbon from the organic content of the crucible and incomplete fusion. Bronson commented on the 'somewhat slapdash nature of the South Indian process by comparison with the rigorously controlled methods in use in Hyderabad'⁷.

THE HYDERABAD OR DECCANI PROCESS

Wootz from Hyderabad was better suited for making Damascus blade and prepared by a different method, namely co-fusion of two different kinds of iron – one low in carbon and the other a high – carbon steel or cast iron. We present a suitable extract from Voysey's manuscript²³ describing the process:

"Konasamudram, situated about 12 miles south of the Godavari and 25 from Nirmal (mentioned in *Ain-i-Akbari*) is celebrated for its manufacture of steel, the chief part of which goes to Persia; the following are the chief details of the place, and personal inspection of the process.

"The furnace is a temporary circular structure of clay, from four to five feet in height, and five feet in diameter. It is sunk two feet below the surface of the ground. The fuel is charcoal. The granitic clay of the furnace is infusible. In making the pine – shaped crucibles, the same granitic clay, containing some quartz and felspar, is ground to a fine powder along with the fragments of old furnaces and crucibles, and the whole kneaded together with the chaff of rice and oil.

"No charcoal is put into the crucible, but small pieces of *kānch*, or the glass formed in the process, are put at the bottom as flux. The materials used in the preparation of the steel are two different kinds of iron: one from Mirtpalli – the other from Kondapur, in the proportion of three parts of the former to two of the latter. The Mirtpalli iron, derived from iron sand (magnetite), is sent in the state of large amorphous masses of a reddish grey colour, extremely porous in texture and having iridescent internal fracture. The Kondapur iron is procured from an ore found amongst the iron clay (laterite), at a place about 20 miles distant. It is said to be of a dirty brown colour, and very frangible. The iron is, however, moderately compact of a brilliant white fracture. Occasionally, it contains some ingredient which spoils the steel, rendering it excessively brittle; the natives assert that the adulteration is copper, but it is more probably arsenic.

"The mixture being put into the crucible, the fire is excited and kept up for 24 hours. The degree of heat, reckoned at 130° of Wedgwood, could fuse steel in

3 hours. The bellows made of bullock skins are plied incessantly day and night. During the operation the men are relieved every four hours, each being engaged to work 12 out of the 24. They are partly protected by a screen of mud between them and the furnace, but the heat and exertion render their task sufficiently laborious. After the operations, the crucibles are taken out and placed on the ground to cool.

“When quite cold, a crucible is opened, and a cake of steel of great hardness is found, weighing on an average about a pound and a half. The cake is covered with clay, and annealed in the furnace for 12-16 hours. It is then taken out and cooled, and again annealed, and this may be repeated a third or fourth time until the metal is rendered sufficiently soft to be worked. The steel is known by the name of Wootz.

“The export of this metal to Persia must be profitable. We found at the village, in 1820, Hājī Hosyn (Hussain?) from Ispahan, engaged in the speculation, here again in 1823. He informed us that the place and the process are both familiar to the Persians, and that they have attempted to imitate the latter without success”²³.

RECENT INVESTIGATIONS BY LOWE

Following Bronsons' intelligent interpretation⁷ of Voysey's Report²³, additional knowledge on the Hyderabad or Deccani process of the production of wootz has been gained through the recent investigations by Thelma Larson Lowe⁷³⁻⁷⁶. She has identified in her extensive field work 74 sites of ore smelting, of which 14 were crucible production centres, 8 sites of historical mining activity and 17 probable ore sources.

The map (Fig. 1) shows the area of Andhra Pradesh bounded by 78° to 79°E and 18°10' to 19°10'N providing two types of iron ore. South of Nizamabad there were laterite-smelting sites exploiting lateritic hardcaps around Inparattigutta. Shafts less than one meter in diameter and perhaps more than 4-5 meters deep were excavated. A transect walked across the approximate one-half kilometer width passes near 44 shafts. The debris around the shafts consisted of the redeposited alkalis leached from the siliceous rock-cap, and this could have served as a flux.

East of Nizamabad and south of the Godavari river lay the magnetite banded iron formation (BIF) sites around Regunta – Rangaraopet – Konasamudram. Lowe noted⁷³ shallow cups carved into the surface of fine – grained granite which concentrated the heavier fraction of crushed magnetite – quartzite. A slurry of crushed ore was flushed over the cupped surface creating an uneven, swirling flow gradient that removed the lighter fraction, the quartz and other gangue minerals, and the magnetite accumulated in the cups. Havart recorded⁶³ the practice of roasting magnetite ore in Andhra Pradesh.

Lowe specially studied the Deccani crucibles⁷⁴⁻⁷⁶ consisting of refractory vessel

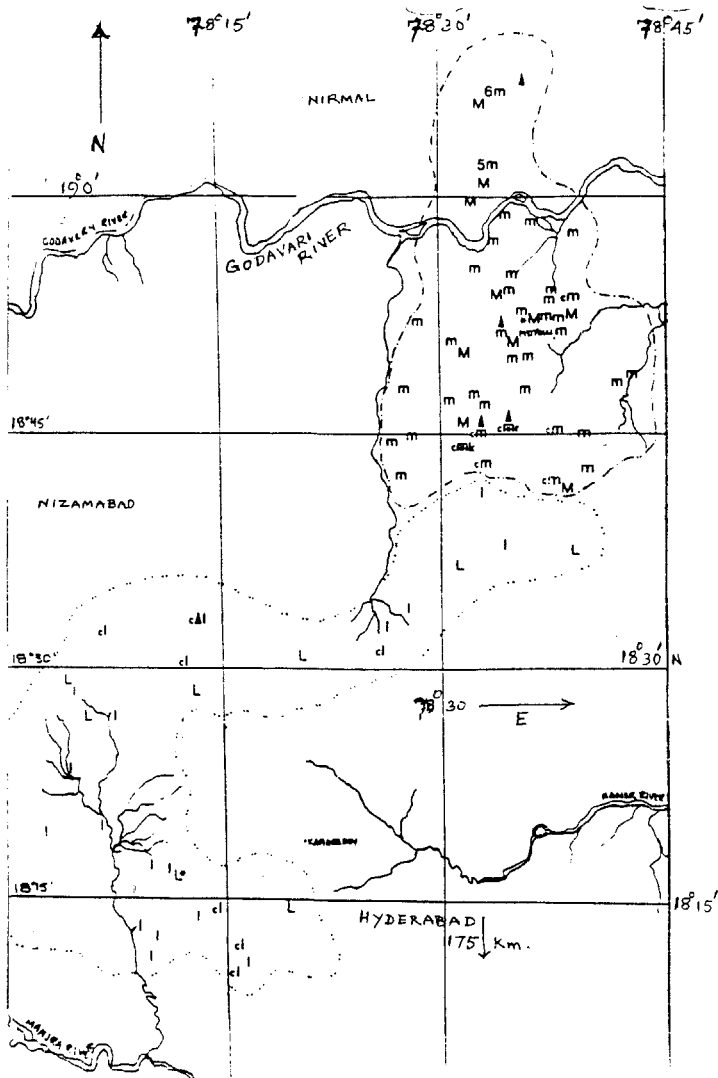


Fig. 1 Sketch map – summary field survey results: smelting sites, crucible production sites, magnetite BIF and lateritic iron ore mining sites and forts. (Ref. No. 73)

KEY

- l laterite smelting
- m magnetite smelting
- L lateritic ore deposits
- M magnetite BIF deposits
- c crucible production site
- f forts

Sites mentioned in one text.

- L* Inparattigutta
- *M Regunta
- c * r Rangaraopet
- c * k Konasamudram

to hold the high-carbon iron charge and a cover of an appropriate geometry. The size of the crucible varied from 2.5 cm. to 12 cm. interior diameter. The Voysey account stated that for making the crucibles, charred (coked) rice hulls were mixed with clay and oil. It is known that during ignition, the surfaces of the polysilicic form of silica become partially dehydrated and are more compatible with oils than with water. This specific property of the surface of charred rice hulls was apparently exploited by Deccani refractory ceramicists⁷⁴.

The charged crucible was fired at high temperature (1150-1250°C) in a strongly reducing atmosphere. Lowe et al found through optical microscopy, XRD, SEM, TEM, HREM techniques that in the used crucibles there were two phases reinforcing the glassy matrix – cristobalite relics of rice husks and a network of acicular alumino-silicate mullite crystals⁷⁶.

Thermal properties controlled by high porosity and by orientation of the rice husks during fabrication favoured slow cooling and controlled crystallisation⁷⁵. Konasamudram ingots examined by Lowe clearly showed the dendritic lath cementite crystals⁷⁵ of Vickers Microhardness 450 in the matrix of lamellar pearlite HV 235-250.

CARBURISED IRON TO MALLEABLE STEEL

Bronson has made it clear⁷ that Voysey's report refers to a process of co-fusion in which 'moderately compact' cast iron 'of a brilliant white fracture' probably having more than 3 p.c. carbon is converted to steel with less than 2 p.c. carbon by melting it with wrought iron. Occasionally 'excessively brittle' product used to be obtained – not because of copper or arsenic, as Voysey surmised, but simply on account of high carbon. Prolonged fusion for 24 hours and repeated annealing were observed and reported by Voysey indicating that the end product was not simply carburised iron but malleable steel 'sufficiently soft to be worked' like Damascus sword. This contradicts Bronson's notion⁷ that wootz was merely carburised iron.

Tavernier provided very useful description about wootz in 1679:

"This steel (used by Persians) is brought from Golconda, and is the only sort of steel which can be damasked. For when the workman puts it in the fire, he needs no more than to give it the redness of a cherry; should he give it the same heat as to ours (higher temperature), it would grow so hard that when it came to be wrought it would break like glass.

"This steel is sold in pieces as large as our one-sou loaves or the size of a half-penny cake. In order to know that it is good and that there is no fraud involved, they cut it in two, each fragment being enough to make one saber I speak thus to undeceive the people *there being no steel in the world but that of Golconda (Hyderabad) which can be damasked*".

Verhoeven has suggested that wootz metal with as-cast carbon composition of around 1.6 p.c. could have been made in the 1400-1450°C temperature range⁷⁷. Verhoeven and Jones have suggested that high phosphorus impurity levels of Damascus steels could have controlled the mechanism of cementite formation⁷⁸.

Sherby and Wadsworth studied⁷⁹ how Damascus swords containing more carbon than most modern steel (vide Table 4) could have been prepared from Indian wootz. High-carbon wootz cakes were probably forged at a not-too-high temperature in the range of 650-850°C (between 'blood-red' 650° to 'cherry-red' 850°C) and then heat-treated by quenching.

The European smiths failed to reproduce the results, probably because they were familiar with only low-carbon steel having a higher m.p., and tried to forge wootz at a white heat, when the cementite phase dissolved in the austenite, and the brittle structure 'crumbled under the hammer'.

Table 4 Composition of Wootz Steel and Damascus Blades³³

		C %	Si %	Mn %	P %	S %	Others %	Ref.
1.	Wootz (Royal Sch. of Mines, London)	1.34	-	-	-	-		78
2.	Wootz (Sri Lanka)	1.97	0.007	0.007	0.002	0.007		70
3.	Wootz, Indian	1.642	0.045	-	-	0.181		7
4.	Wootz, Indian	1.682	0.042	-	-	0.17		7
5.	Wootz, Mysore	0.963	0.127	0.097	0.007	0.02		7
6.	Wootz, Mysore	0.45	0.14	-	0.27	0.01		7
7.	Damascus blade	1.49	0.005	0.08	0.1	0.05		78
8.	Dagger	1.677	0.015	0.056	0.086	0.007		78
9.	Dagger	1.575	0.011	0.3	0.104	0.018		78
10.	Sword	1.874	0.049	0.005	0.127	0.013		78
11.	Sword	0.596	0.119	0.159	0.252	0.32		78
12.	Sword	1.342	0.062	0.019	0.108	0.008		78
13.	Sword	1.726	0.062	0.028	0.172	0.02		78
14.	Sword	1.62	0.027	trace	0.087	0.007	Ni, Cr traces	78
15.	Sword	1.42	0.11	0.13	0.035	0.038		78
16.	Sword	1.42	-	0.015	0.206	-	Ni:0.016; Cu:0.056	78
17.	Sword	1.42	-	0.14	0.05	-	Ni:0.008; Cu:0.041	78
18.	Sword	1.1	-	0.071		-	As:0.005; Cu:0.034	78

Sherby and Wadsworth have shown⁷⁹ that high-carbon (1.3-1.9 p.c.) wootz can be satisfactorily forged upto a temperature of 850°C without producing brittleness; slow cooling allowed a coarse, continuous and white cementite network which could be seen after selective etching, preferentially attacking the ferrite background. These damask patterns of cementite network have been poetically described as 'ten millions of (white) meandering lines in the dull blue sword'.

Heating and quenching produced martensitic structure providing additional hardness. If the Damascus blade were heated to *only just above* 727°C before being quenched, it would have been hard as well as tough (non-brittle). On the other hand, heating to much above 800°C before quenching would endow brittleness to the sword, thereby giving a bad reputation to Indian wootz!

Although the Nirmal-Konasamudram area in Andhra Pradesh was the most famous steel-making site in Pre-Modern India, there were other places where such art prospered. At Tendukhera in the Narasinghpur District, Madhya Pradesh, *pakkā* iron or crude steel used to be made and converted to edge tools by case hardening, during the middle of the 19th century. Before 1827, hot carburising and quenching gave steel in the iron works of Sagar and Bundelkhand. During this period, Cutch steel was famous. Abbott described in 1847 how cast steel (wootz type of material) was being converted in Gujarat to sufficiently elastic (Damascus type) sword blades⁸⁰. The edge of the damask was not sufficiently malleable but 'seemed specially suited to the fabric of razors, penknives and surgical instruments, in which keenness of edge is of the first consequence and elasticity of none'⁸⁰.

DIFFERENT TYPES OF ENTERPRISES

Bhattacharyya identified three distinctly different types of economic organizations in the pre-modern iron and steel industries of India³⁰.

Type I. Tribal Household Industry:

The *Agarias* in the Central Provinces, the states of Rewa, Surguja, Udaipur and Jashpur, in the districts of Mirzapur, Uttar Pradesh, Ranchi and Palamau in Bihar etc. were iron-smelting tribes. In their smelting shop all labours were supplied by members of one family. The produce often passed to the *Lohars* or the ironsmiths of the nearby villages. The *Agarias* in the inaccessible regions had to market their produce through itinerant merchants.

Type II. Market-Oriented Craftgroups:

Skilled, free, specialist craftsmen operated centering local markets. In the district of Birbhum, West Bengal, there was a flourishing iron-smelting industry centering around Deocha⁵². The iron-smelters purchased ore in established market places called *aurangs* from *beparries* itinerant merchants. After smelting in the

kotsāls, the Muslim smelters used to sell the iron blooms to the *kāmārśāls* or the refineries where the refiners were from Hindu artisan castes.

Sanyal further subdivides⁵⁴ the manufacturing scenario at Birbhum into two subtypes: IIa and IIb. The first sub-type of manufacture was practised in the western-most part of Birbhum by the tribals: Santals and Munda Kols. The tribals were in the habit of migrating from place to place in search of spots where the timber and ore supply were readily available. This tradition of itinerant smelters was mentioned in the *R̥gveda* and has always been a part of the Indian heritage. In Maharashtra, Dhavads, a wandering Muslim class, specialised in smelting⁸¹. The furnaces used by the tribals were small in dimension and period of service.

The second sub-type IIb of manufacture was practised by the settled Bengali-speaking population concentrated in the north-western part of the district who had permanent kotsals and kamarsals as mentioned before. Their furnaces were much bigger, and iron formed at the bottom was in a *molten condition*. The refining was a sort of puddling process. The itinerant merchants carried the finished product, namely refined iron, to the accessory industries in Dubrajpur, Lokpur, Rajnagar, Rampurhat, Murshidabad etc., where knives, swords, daggers, axes, scissors, cooking utensils etc. were made.

Production for the market was not as highly developed (as in Birbhum) in places remote from the centres of commerce. In the Salem district of Tamilnadu, wrought iron, made in Catalan type furnace and high quality steel or *wootz*, made in crucibles, were sold in the local *bazaar*. Similarly, the smelters in the Jorhat district of Assam, supervised by an *ozha* or master craftsman, produced lumps of iron and offered their produce for sale in the local *bazaar*.

Type III. Protocapitalist Enterprises:

In the first decade of the nineteenth century, protocapitalist enterprises were already in existence in Mysore. Buchanan-Hamilton described the iron-smelting workshops in Mysore owned by proprietors who employed labourers, foremen and differentiated their wages according to their skills²². In certain places such as Madhugiri, Devarayadurga etc., money wages were not paid, but the physical produce was divided. In a typical case, ordinary workmen (numbering 20) received 3 p.c. each, the foreman of the smelting house 6 p.c., the foreman of the forging house 8 p.c. and the remainder 26 p.c. went to the proprietor. From the sale proceeds of his share, the proprietor met the expenses of the 'firm' such as customs duties, forest duties for charcoal smelting, payments to the village headman for permission to gather ore, furnace rent to the latter, charity for the Brahmins, etc.

Steel-making enterprises often received capital advances from merchants who would themselves borrow from 'some greater merchant'. Crucible steel of Mysore and Hyderabad was in great demand and 'almost the whole' was exported. In 1832

Voysey met in Konasamudram an Ispahani merchant who was in the business of exporting steel to Persia.

Capt. L. Jacob observed a similar structure of enterprise in Kathiawar (Saurashtra) in 1843. The proprietor employed about ten workmen in each smelting house, the collector of charcoal and ore and the master workman; he also paid taxes and material costs.

Certain features of the type of enterprise in Mysore, Hyderabad and Kathiawar may be summarised as follows: (a) higher level of physical output compared to type I; (b) a higher level of technology as evidenced by the production of crucible steel; (c) the proprietor in the role of a manager; (d) differentiation in functions and wages of labourers.

STAGNATION TO EXTINCTION: REASONS

In many ways, the iron and steel industries of India were leading in the ancient, medieval and even pre-modern world. The outstanding achievements were made in the areas of carburization of wrought iron and crucible steel making. Then why did the indigenous traditions stagnate and ultimately get extinguished?

There were two sets of factors which would explain the decline: (a) technical and (b) socio-political and intellectual. The second set was deeper in origin and more profound in results, affecting not only ferrous but also many other indigenous industries-in brief, science and technology in India as a whole.

The first set viz., technical factors were related mainly to the charcoal issue which we have deliberated upon earlier. We have emphasized that new technology had to be introduced all at once. Replacement of charcoal by coke was not the only issue. Even the British entrepreneurs failed, when they tried to introduce improvements in a piece-meal fashion. Thus, their criticism against the artisans' 'resistance⁶ towards technological improvements' was uncharitable³⁰.

The second set of factors may be listed as far as possible in a chronological manner.

(1) The Hindu-Muslim rivalry prevented free diffusion of technical knowledge to and from India.

(2) Neither the Mughal government nor the people in the country were awake to the new technological developments in the field of mass production of iron and steel, which were spreading fast in Europe. They were very slow in innovation and mechanisation.

(3) In Britain, the demand for cast iron cannon led to the sudden increase in

size and productivity of blast furnaces from 30 to 300 tons during the course of the 15th century. When the industry was rapidly burning up forests for fuel, the king intervened⁸². No such development took place in India on account of closed economy and lack of maritime adventure.

(4) During the Mughal period, guns were made mostly of bronze and brass. Cast iron cannon was never an article of urgent need⁶¹. The barrels of Akbar's guns were made of discs joined together by forge-welding. The expertise in forging techniques was, therefore, diluting the need for casting technology^{61, 83}.

(5) Since the middle of the 17th century, the Marhattas purchased cannons from the Europeans. The casting technology for iron was never learnt. By the close of the 17th century, the European experts grew reticent about disclosing technological information due to the fear of social ostracization as well as legal action which was becoming increasingly evident in the West⁸⁴. Later, this desire to isolate technology from the Indians became a part of the official colonial policy.

(6) The Britishers, who initially arrived as a trading company, started flooding the Indian market with cheap iron produced in Britain on a large scale. The rising cost of production by the indigenous methods forced the artisan families to quit their jobs for survival.

(7) The Britishers were very selective in extending the financial assistance to entrepreneurs interested in reviving Indian iron and steel industry. The proposal of Mr. Inder Narain Sharma for large scale production of iron in Birbhum in 1774 was turned down, whereas a few British entrepreneurs were granted the permission⁵².

(8) During the latter part of the eighteenth century, the number of iron and steel furnaces in India was in the region of 10,000, producing on an average 20 tons per year per furnace. From about 1800 A.D. onwards, India was treated as a consumer of British manufactures, and Dharampal has rightly commented that the disappearance of the indigenous industries resulted from 'large-scale economic breakdown and hostile state policy'²⁷.

(9) However, Dharampal overshot his point when he asserted that the sciences and technologies of India 'had reached a desirable balance before the eighteenth century' and 'were usefully performing the tasks desired by Indian society'²⁷. We wish we could accept his assertion.

Dharampal referred to the 'link' (?) between the practitioners of the various techniques and 'the professors of the theoretical knowledge'. The link, 'largely snapped in India by the end of the eighteenth century', could have been re-established, according to Dharampal, 'in a changed political climate'. These are indeed brave patriotic words!

We are not aware of any Indian 'professor of the theoretical knowledge' in the pre-modern era who could explain the extractive and physical metallurgy of iron and steel. As a matter of fact, the theoretical knowledge pertaining to chemistry and metallurgy was barely evolving at that time even in the West, and the Japanese people could easily see that this new knowledge had to be borrowed from the West.

When Dharampal opines that 'unthinking transplanting of European sciences and technologies in India resulted in retarding and blunting of indigenous innovation and creativity'²⁷, the topic certainly demands detailed discussion and debate. Of course there is a merit in systematic studies on the ancient technologies. The pre-modern iron and steel industries of India held certain promises which can be considered for exploitation in the modern context. Rice-husk reinforced refractory crucibles can still be tried for high temperature work. The ancient art of making wootz steel and Damascus blade can be simulated to make ultra-high carbon steel having strength as well as ductility⁷⁹. Some scholars believe that the pre-modern techniques of direct smelting of iron ore in small bloomeries and of crucible production of special steels may be revived with certain modifications³³.

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