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THE PRIMACY OF INDIA IN ANCIENT BRASS AND ZINC METALLURGY*

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The Indian sub-continent enjoys the unique distinction of being the first to introduce brass and zinc metallurgy to the world. Summarising the recent research and current literature on the subject[1-26], the present author claims that the earliest brass in the world was in the Harappan site of Lothal and then in the early PGW-site of Atranjikhera. The primacy of zinc metallurgy in India is established by three kinds of evidences: (a) second millennium BC radiocarbon dating of zinc ore mine in Southern Rajasthan, (b) fourth century BC brass vase in Taxila assaying 34% zinc, and (c) second century AD literature of Nāgārjuna describing distillation of zinc. This paper also documents the uninterrupted tradition in India on brassware, the details of the spectacular and large scale zinc manufacture in medieval Zawar, and the unique phenomenon of a technology transfer from India to the western world. After a decade-long painstaking research programme at I.I.T., Kanpur, H.Z.L., Udaipur, University of Baroda and the British Museum, London, an attempt has been made to summarise the present state of our knowledge on the subject.

INTRODUCTION

The earlier occurrence of zinc in man-made artifacts is in the form of the copper alloy known as brass. Ever since the discovery of copper and the alloying elements of tin, arsenic, lead, etc., different materials, including zinc, were used to alloy and harden copper.

The earliest method of making brass was possibly the cementation process in which finely divided copper fragments were intimately mixed with roasted zinc ore (oxide) and reducing agent, such as charcoal, and heated to 1000°C in a sealed crucible. Zinc vapour formed dissolved into the copper fragments yielding a poor quality brass, zinc percentage of which could not be easily controlled.

Fusion of zinc with copper increases the strength, hardness and toughness of the latter. When the alloy is composed of 10-18% zinc, it has a pleasing golden yellow colour. It can also take very high polish and literally glitter like gold. For this property, brass has been widely used for casting statuary, covering temple roofs, fabricating vessels, etc.

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*This paper is dedicated to the loving memory of Late Prof. K.T.M. Hegde, a pioneer in ancient Indian metallurgy, whose 'goat-path discovery unlocked secrets of medieval zinc'.

Reduction of zinc oxide around 1000°C is crucially important; below 950°C no zinc is produced. Zinc is obtained in the vapour form at this temperature, since its b.p. is 913°C. With trace of oxygen, the zinc vapour would be reoxidised and hence the successful operations in the past must have been done in closed crucibles. If the temperature were higher than 1083°C during brass-making, then copper would melt and flow down to the bottom of the crucible forming a puddle there, exposing a very small surface area of the metal for alloy formation.

Brasses containing up to 36% zinc are known as α-brasses, which undergo easy cold work. Brasses containing more than 46% zinc are brittle. With zinc content between 36 and 46%, we have $\alpha + \beta$ brasses which are lighter, harder and more suitable for casting statuary.

Werner[27] and Haedecke[28] demonstrated experimentally that brass produced by the cementation process could not contain more than 28% zinc. Brass founders trying the cementation process have verified this observation.

The materials of antiquity containing more than 28% zinc in copper matrix must have been prepared by mixing the two metals, which could have been possible only after the discovery of zinc as a separate metal and its preparation by a process such as distillation. The antiquity of brass artifacts can, therefore, be divided into two eras, one preceding, and the other following the discovery of zinc as a separate metal.

Brass Before the Discovery of Zinc

We claim that the earliest artifact noted so far containing an appreciable amount of zinc anywhere in the world is from India. Lothal (2200-1500 BC) showed one highly oxidized antiquity (No. 4189), which assayed: 70.7% copper, 6.04% zinc, 0.9% Fe and 6.04% acid-soluble component (probably carbonate, a product of atmospheric corrosion)[29]. The material could have been prepared through smelting of zinc-bearing copper ore or the cementation route described earlier. The raw materials might have come from the Ahar-Zawar area. The Harappan site of Rosdi, also in Gujarat, has yielded a few samples of chisel, celt, rod and bangle, made of brass and assaying up to 1.54% zinc[30].

Similar materials might have been used for making the brass-bronze items of Atranjikhera during the PGW era (1200-600 BC)[31]. One copper-based item contained 11.68% Sn, 9.0% Pb and 6.28% Zn, while another item assayed 20.72% Sn and 16.20% Zn. Both the samples contained traces of iron and sulphur, indicating the possibility of chalcopyrite and sphalerite-galena having been the source materials, which could easily come from the Ahar-Zawar area. Most of the brass samples in ancient India contained variable proportions of Zn, Sn and Pb (Table 1).

We have drawn attention to the brass items of Lothal and Atranjikhera and their possible link with the 1260 ± 160, 1136 ± 160 BC and 1050 ± 150 C-14 dates of the

Table 1. Analysis of Some Brass Objects in Ancient India

Sl No.	Date and site	Object	Analysis (%)				Remarks
			Cu	Zn	Sn	Pb	
1	~ 1500 BC Lothal	No. 4189 Copper object	70.70	6.04	-	-	Ref. 29
2	Harappan, Rosdi	Chisel, Celt rod, bangle	95.5-98.5	Up to 1.54	Up to 1.23	Up to 1.20	Ref. 30, pp. 36-37
3	~ 1000 BC Atranjikhera	No. 1	70.99	6.28	11.68	9.00	Ref. 31
		No.2	52.42	16.20	20.72	9.77	
4	4th century BC, Taxila	Vase Bm 215-284	55.39	34.34	4.25	3.08	Ref. 32
5	2nd century BC, Taxila	Bangle	73.72	19.70	0.10	5.84	Ref. 32
6	2nd century AD, Gujarat	Female figure carrying flower-container Indo-Parthian	88.60	7.60	0.13	2.49	Ref. 30, pp. 56-57
7	5th century AD	Gandhara Buddha	68.50	20.25	3.86	3.62	Ref. 37
8	6th century AD, Akota	Ambika	76.70	16.32	1.61	4.04	Ref. 30, pp. 104-105
9	7th century AD, Mahudi	Rishabhanatha	66.00	12.80	5.90	2.50	Ref. 30, p. 66
10	8th century AD, Kashmir	Shiva	82.00	17.00	1.00	-	Ref. 38
11	9th century AD, Nalanda	Buddha	78.95	15.15	0.74	3.03	Ref. 39
12	11th century AD, W. Tibet	Mañjuśri	65.50	30.40	0.30	1.70	Ref. 40

timber samples in the Rajpura-Dariba silver-lead-zinc mine near Udaipur[4,20].

During the Harappan era, copper used to be alloyed with tin and arsenic; since these were scarce commodities, alternative alloying elements had to be looked for. Artisans in the Rajasthan-Gujarat region might have stumbled on to zinc ore deposit as a new source of alloying element.

Craddock *et al.*[6,7] surveyed the evidences of early brass artifacts in the West. The earliest brass artifacts known in the West come from excavations at the Gordion Tomb in Phrygia, dating from the 8th and 7th centuries BC onwards. These came after the Lothal and Atranjikhera traditions. From the 7th century BC, the Greeks commented upon brass or oreichalkos, but always as an expensive, exotic metal not produced in Greece. There was no zinc in the early Greek bronzes. Etruscan bronze of the 5th century BC contained 11% zinc.

Zinc Metal and High-Zinc Brass

The earliest brass containing more than 28% zinc, which could be made only after the isolation of pure zinc metal[27,28], came from Taxila[32]. Craddock[8] pointed out the overriding importance of the vase (BM 215-284) excavated from the Bhir Mound at Taxila and dated to the 4th century BC. This brass sample contains 34.34% zinc, 4.25% Sn, 3.0% Pb, 1.77% Fe and 0.4% nickel[32]. This is very strong evidence for the availability of metallic zinc in the 4th century BC. Possibly India was the first to make this metal zinc (*rasaka*) by the distillation process, as practised for the other metal mercury (*rasa*).

There are references to zinc and brass in the lost (4th century BC) text *Philippica* of Theopompus, quoted by Strabo in his *Geography:*

"There is a stone near Andreida (north-west Anatolia) which yields iron when burnt. After being treated in a furnace with a certain earth it yields droplets of false silver. This, added to copper, forms the so-called mixture, which some call *oreichalkos*" (Strabo, *Geography*, Book XIII, Sec. 56).

The above reference pertains probably to the process of downward distillation of zinc ('droplets of false silver') and its subsequent mixing with copper to make brass *oreichalkos* (*ārakūṭa* in Kautilya's *Arthaśāstra*) described in detail in the post-Christian era Sanskrit texts.

It is quite possible that the zinc-making technology travelled west from India during 6th-5th centuries BC, as it did later again in the 18th century AD. The pseudo-Aristotelian work *'On Marvellous Things Heard'* mentioned:

"They also say that amongst the Indians the bronze is so bright, clean and free from corrosion that it is indistinguishable from gold, but that amongst the cups of Darius there is a considerable number that could not be distinguished from gold or bronze except by colour" (quoted by Craddock[6]).

The Indian emphasis was on the 'gold-like' brass and not on the zinc metal. The Greeks, however, used zinc metal as such in a few cases. In the course of the excavation of the Agora in Athens, a roll of sheet zinc was found in a sealed deposit dating from the 3rd or 2nd century BC[33]. Analysis showed it to be nearly pure zinc with 1.3% lead, 0.06% Cd, 0.016% Fe and 0.005% Cu with traces of Mn, Mg, Sn, Ag and Sb (quoted by Craddock[6]). Although Needham and Forbes doubted the above evidence on the ground that 'the pieces were beyond the contemporary technology'[8], Craddock certifies this to be a genuine sample[8, 24]. It is quite possible that the Greeks had carried the material or the technology which had existed in Taxila as early as 4th century BC and possibly much earlier in Rajasthan.

Mining Archaeology and Smelting Related to Indian Zinc Ore

The recent pioneering work on the zinc-lead-silver mining archaeology in the southern part of Rajasthan by Willies *et al.*[12,20,21] and the relevant C-14 dates have firmly established India's primacy in non-ferrous ore mining in the ancient world.

The ancient workings in the South Lode (100 m depth) of Rajpura-Dariba mine (80 km north-east of Udaipur) have been C-14 dated as 1260 BC, 1130 BC, 1050 BC and the East Lode workings as 375 BC, 360 BC, 250 BC, 120 BC, 150 AD, etc. Thus, it is clear that the tradition of underground mining in India goes back to the thirteenth century BC, if not earlier. The earliest emphasis was possibly on copper ore; at Rajpura-Dariba, the other targets were lead, silver and possibly zinc ore, which is strongly suggested by the brass artifacts of Lothal and Atranjikhera.

The art of smelting zinc ore and recovery of zinc metal by distillation must have been discovered before 4th century BC when Taxila produced the brass vase containing 34.34% zinc[32]. This possibility is reinforced by the facts of mining archaeology. Starting from the 5th century BC, we have many C-14 datings in Rajpura-Dariba, Rampura-Agucha (40 km south of Ajmer) and most crucially, in the Zawar mine systems.

Zawar (24°21'N, 73°41'E) is about 30 km south-west from Udaipur, where the ancient mines (earliest C-14 date obtained so far is 430 BC) are found, both opencast and underground. Zawar Mala, Mochia and Balaria are some of the specific mines in this area.

The host rock of the Zawar mines is sheared dolomite, the result of metamorphism of sedimentary dolomites. The ore was geologically deposited syngenetically as disseminated lenses within the dolomite beds. Zinc occurs as sphalerite or as marmatite in which zinc sulphide is in solid solution with iron sulphide. Also associated with the rock are galena, hydrozincite, pyrite, silver, etc.

Ancient workings are found at outcrops on the ridge of Zawar Mala, and as deep as the 470 m (above sea) levels of the modern Zawar Mala mine, some 120 m below surface. The upper parts accessible from there were a few tens of metres below surface, isolated by a roof fall. At the surface, mine openings occur at intervals of 50 m or so. Willies[20] investigated one mine of more commodious proportion – Pratapkhan or Pratap's mine – in which Rana Pratap Singh, rival of Akbar, took refuge during 1595-1600 AD. A flat 'room' floored with phyllite slabs is inferred as Pratap's refuge. The quarried materials used to feed a zinc smelter just below the narrow valley.

The earliest C-14 datings in the Zawar mines are 430 ± 100 BC of the PRL 932 sample from the Zawar Mala mine and 380 ± 50 BC of the BM 2381 sample from the Mochia mine[17]. Similar datings from Rajpura – Dariba (e.g. 375 BC), Rampura-Agucha (370 BC), etc. confirm widespread underground mining of lead-zinc ores in the southern Rajasthan during the fifth-fourth centuries BC onwards.

Subsequent C-14 datings in the said mining area are: 250 BC, 200, 170, 140, 120 BC, 60 AD, 110 AD, 150 AD.

As regards the recovery of zinc from the ore, the crucible reduction/distillation method was put to large scale commercial practice in the 13th century AD; this will be described later. Indirect and circumstantial evidences suggest that distillation method was in vogue much earlier, probably from the 4th century BC onwards, although not on a large scale, as we find in the 13th century AD context.

In this connection, we recall the evidence from Rampura Agucha[17,34]. The zinc-lead-silver ore at the site was selectively mined at least as early as 370 and 250 BC. An appreciable amount of zinc must have been separated from the zinc-rich ore (present-day ore in the site contains 13.5% zinc), as revealed from the low-zinc content slag. One sample of slag assayed as low as 0.01% zinc[34]. Near the slag dump area several retort-like pieces were reported. When assembled, their appearance suggested a cylinder approximately 20 cm long with walls 4-5 cm thick and an innermost pipe – like feature with a coating of dirty white material, mainly zinc sulphate. They could be mistaken for tuyeres but for their closed pointed ends. This is highly suggestive of a used retort. Along with this, some thin-walled tube-like object containing a thin coating of blister type material was also found[17].

It is conceivable that the retorts were being used in the said context for roasting zinc ore to obtain the light, white, smoky zinc oxide, which the ancient Greeks called pompholyx or philosopher's wool. In the modern zinc plant at Udaipur, roasting of zinc sulphide concentrate produces not only zinc oxide (and sulphur dioxide gas) but also some zinc sulphate, which was detected in the 4th-3rd century BC retort in Rampura-Agucha.

The said retorts, already found sealed at one end, must have been closed or sealed at the other and also to prevent the escape of smoky zinc oxide into the atmosphere. The retorts were possibly modified to serve as reduction distillation chambers (to produce metallic zinc), the final version of which, notified in the 13th century AD context, would be described later. Very significantly, Tiwari *et al.*[34] noted that the slag sample from Agucha containing only 0.01% zinc but as high as 9.30% lead, was 'attached to baked earthen materials which could be part of the earthen appliance used for smelting'. We suggest the possibility that the earthen appliance was a zinc distillation retort. Remains of zinc furnaces have been found at Sojat in Jodhpur also.

Brass and Zinc in Ancient India

We may now turn our attention to the antiquity of brass in ancient India. Before the discovery of zinc metal in India (made by the distillation route) sometime during the fifth-fourth century BC, brass could be made*, as in Lothal and Atranjikhera, only

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*The 2nd century AD text *Rasaratnākara* of Nāgārjuna mentions (1.3): "What wonder is it that calamine (zinc ore) roasted thrice with copper converts the latter into gold". This is an allusion to the making of yellow gold-like cementation brass. The same text (1.31-32) also refers to the reduction-distillation of calamine yielding zinc: "an essence of the appearance of tin".

by the cementation route in which one of following was smelted along with copper ore: zinc ore, sphalerite concentrate or the roasted product, philosopher's wool or zinc oxide. The traditions of making philosopher's wool and cementation brass could have persisted even after the discovery of the distillation process of making zinc. We invite attention of the readers to the analysis of some Indian brass objects made before 4th century BC (Table 1).

As we have indicated earlier, the distillation route of making zinc and alloying this with molten copper was the only way of making high-zinc (more than 28%) brass, such as the 4th century BC Taxila vase (34.34% zinc). The said vase (BM 215-284), excavated from the Bhir Mound site, was made before the Greek settlement in Sirkap[32].

One bangle from the second century BC Sirkap settlement assayed 19.70% zinc. The Dharmarajika settlement of the post-Christian era produced brass objects like bangle and pot with controlled compositions 77-79% Cu, 12.88-13.07% Zn, 2.5-3.5% Sn and 3-6% Pb.

Some of the other early brass samples from ancient India have been reviewed by Neogi[35] and Ray[36], an extract of which is presented below.

Brass articles of the 1st century BC or AD have been found on excavation of some ancient stupas. General Ventura executed operations for the examination of the stupas at Manikyalaya in 1830. Three deposits were obtained, of which the third, at a depth of 64 ft, consisted of a copper box enclosing a brass cylindrical box cast and beautifully turned on the lathe. The lid of the brass casket was found on cleansing to be inscribed. From the inscriptions on the various articles of this deposit and the accompanying Indo-Scythian coins, the great tope at Manikyalaya has been identified to be a mausoleum of the Indo-Scythian king Kanishka (1st century BC or AD).

Another inscribed brass urn of the same date as the former has been discovered in a tope about 30 miles west of Kabul in Wardak district. This urn, which in shape and size approaches closely the ordinary water-vessels in use in India to this day, was originally thickly gilt and its surface has in consequence remained well-preserved.

As regards coins, both brass and bronze were used in ancient India for coinage. Circular punch-marked brass coins of Dhanadeva and Aryavarmā of Ayodhya (*c.* Ist century BC) have been found. Brass coins of kings of several other dynasties living at that time have also been collected. From these archaeological and numismatic evidences it is clear that brass was in common use in ancient India during the first century BC. A small number of die-struck coins of the Pre-Gupta and Gupta periods, including a piece attributed to Chandragupta II, are considered to be made of brass.

Table 1 features some of the typical brass objects in ancient India up to 11th century AD, before the advent of Muslims in the country. In his masterly treatise[30], Swarnakamal highlighted the continuing role of Gujarat in brass technology ever since the Harappan era. The discovery of three important hoards of metallic art objects at Mahudi of north Gujarat, Lilvadeva (north-east) and Akota of central Gujarat, dated between 6th and 11th centuries AD, proved that the artisans there had developed four varieties of alloys: (a) bronze, (b) zinc-bronze, (c) lead brass, and (d) conventional brass. Apart from Zawar ore, the copper-zinc ore deposit of Ambamata (north Gujarat) was also used for smelting. A large number of brass coins of India dated 5th-12th centuries AD have been analysed by other workers[37-40]. A few of these are listed in Table 1. The data are impressive enough to justify the primacy of India in brass and zinc metallurgy.

Literary Evidences on Zinc and Brass in Ancient India

We have mentioned earlier the pseudo-Aristotelian work *'On Marvellous Things Heard'* referring to 'gold-like bronze' or brass of the Indians during the reign of Darius, The Greeks' 'oreichalcos' was equivalent to Kautilya's *ārakūṭa (Arthasāstra,* 2.12.23, 2.17.14, 4.1.35). Both Kautilya and the earliest Indian brass of Taxila belonged to 4th century BC, while the earliest C-14 dating of the Zawar mine is 430±100 BC.

The technical term *ārakūṭa* for brass persisted through centuries and we find this mentioned in the 4th century AD Jaina text *Aṅgavijja* (as *hārakūḍa*) and also in *Amarakośa* (450 AD).

A more popular name for brass in the ancient India has been *rītī* or *rītikā*, which also meant calx of brass. The word was probably derived from *harita* or yellow, which had been a synonym for gold in the Vedic literature. The word was chosen on account of the yellow colour of gold-like brass. *Caraka Saṁhitā* refers to *rīti* (Sutrasthān, 5.26) and *rītikā* (Siddhisthān, 3.4) amongst other metals and alloys. *Pushpānjan* mentioned in *Caraka Saṁhitā* as well as in *Suśruta Saṁhitā* and used in treatment of eyes and open wounds, is probably zinc oxide. The writings of Manu, Yājñavalkya and Patanjali of the pre-Christian era sometimes refer to bronze (*Kāṁsya*) and brass *(rītikā)* almost synonymously.

During the first century AD, the Roman traders wrote about Indian brass. While the Periplus used the Greek term oreichalcos (mountain copper) for brass, Pliny mentioned the Latin term *aurichalcum* (golden copper), made in India from *cadmia*, identified as calamine or the zinc ore. Samuel Beal suggested that the name *cadmia* came from Calamina, a port at the mouth of the Indus, which negotiated the export of the ore or the alloy of zinc. Ball[41], however, suggested that the port was Calliana or Kalyan near Bombay. The sixth century AD traveller Sopater had mentioned Calliana exporting brass.

Philostratus of Lemons, writing around 230 AD, mentioned a shrine in Taxila (presumably Buddhist) in which 'the various figures were portrayed in a mosaic of orichalcum (brass), silver, gold and oxidized copper'. A much more significant fact related to Indian brass of this era is the advent of the alchemist Nāgārjuna.

THE EARLIEST LITERARY REFERENCE TO ZINC METAL – NĀGĀRJUNA'S DATE

The earliest reference to zinc as a metal is found in Nāgārjuna's *Rasa-Ratnākara* (RR). In one passage (RR 3) it was mentioned: "What wonder is that *rasaka* (zinc or zinc ore) roasted with three parts of *śulva* (copper) converts the latter into gold". Actually, this was gold-coloured 25% zinc brass, also known as *pīta-tāla (pitala)* or yellow alloy. The description given above could have corresponded to mixing of metals or the cementation process. Another passage (RR 31-32), however, leaves us in no doubt that zinc metal was obtained as a reduction product of *rasaka* when roasted with a reducing agent and borax in a covered crucible:

> mūkamūṣāgatam dhmātam ṭaṅkaṇena samanvitam satvam kuṭilasaṁkāśam patate nātra saṁśayaḥ – 'there is no doubt that this (process) yields an essence (metallic) of the appearance of tin'.

Albiruni of the 10th century AD wrote that 'Nāgārjuna lived nearly a hundred years before our time'. On this basis, Ray put Nagarjuna in the eighth/seventh century AD[42]. Filliozat[43] has, however, pointed out that Hiuen Tsiang attested in 630 AD that the alchemist Nāgārjuna had lived much before his time. When his contemporary '*Sadvaha-raja*' fell short of gold, Nāgārjuna Bodhisattva, by moistening all the great stones with a divine and superior decoction, changed them into gold; then raja used this to make four golden statues of Buddha'[44]. *Rasa-Ratnākara* itself mentions '*Śālivāhana*'. Evidently, what Nāgārjuna did was to suggest the preparation and use of gold-like brass.

Nāgārjuna, the alchemist, was born in Karhād (17°7'N. and 74°11'E) of Satara district in Maharashtra (parents: Trivikrama and Savitā)[45]. Al-Biruni put him as a native of Daihak near Somnath. Nāgārjuna was a contemporary and friend of Yajñaśrī Gautamīputra Sātavāhana or Sātakarṇi (174-203 AD). His friendship with the powerful Sātavāhana king, who had ousted the Scythians from the Central and Western India, is attested by his famous work *Suhrillekha* ('Letters to a Friend').

In another text, *Kakṣapuṭatantram*, Nāgārjuna[46] mentioned the levitating pressure of mercury vapour and an alloy *trilauha* of three metals, gold, silver and copper (5:8:6). Presumably, Nāgārjuna's alchemistry, which later influenced many other workers in the sub-continent from Kerala in the south to northern Bengal in the east[45], was directed towards the substitution of gold. Nāgārjuna might have been aware of the Indo-Parthian tradition on brass in the 2nd century AD Gujarat (vide item 6 in Table I) and Yavaneśwara's Greek book (150 AD) on mineralogy[47]. The secret art of zinc distillation, practised in Rajasthan and Gujarat, and utilised by Kushans, Parthians and Scythians in brass technology, was passed on to the Sātavāhana civilization by the knowledgeable alchemist Nāgārjuna. Although Ray thought that the compilation of *Rasa Ratnākara* in the present form took place in the seventh century AD[42], the events narrated and the personality of Nāgārjuna clearly belonged to the latter half of second century AD (Furthermore, the alchemist Nāgārjuna is not to be confused[48] with the equally famous Madhyamika philosopher Nāgārjuna, who was probably a contemporary of king Kaniska, 78-102 AD).

Thus, it may be submitted that the proofs of the earliest (in the world) discovery and use of zinc as a metal in India are of two types: (a) use of brass containing more than 28% zinc in Taxila (reference 32 and data in Table 1), and (b) literary reference of Nāgārjuna belonging to the second half of second century AD.

Nāgārjuna boosted the tradition of brass which had originated in India as early as the second millennium before Christ. After Nāgārjuna, we find an extensive proliferation of brass-trade in Central India[49], Gujarat and the rest of the sub-continent. An inscribed brass statue of Buddha, 30 cm high and 13.5 cm wide, of the sixth century AD, has been discovered in a dharmaśālā at Fatehpur, a village 20 miles due west of Kangra-Kot.

The early sixth century AD text *Bṛhatsaṁhita* of Varāhamihira (BS 57.1-7) described several *vajra-lepa* or cement recipes, one of them containing *rītikā* or calx of brass. During the same century, Sopater, a traveller, mentioned the port of Kalyana exporting brass.

When Hiuen-Tsiang visited India (629-645 AD), he found many statues made of *teou-shih* or brass: standing Buddha at Bamiyan, cast in small pieces and then joined together, the image of sun-god in Multan, statues in the kingdom of Takka on the river Vipāśā, some near the Kulu province, Māyāpura or Haridwara, Garhwal and Kumaun areas, brass statues of Śiva in Varanasi, of Buddha in Bodh-Gaya, 'ornamented with rare jewels', and lastly the brass vihāra of Nālandā: 'being built by Śilādityarāja (Harshavardhana 606-647 AD) not yet finished, when finished would measure 100 feet'.

Thus, it is clear that by the seventh century AD, India had well-established pre-Muslim traditions in brass-making.

Pre-Muslim Era Tradition at Zawar

One small slag heap in the Zawar area is dated to the 7th century AD[50], and this is contemporary with the date of the earliest historical references to Zawar. This reference is on an inscription found at Sanoli, well to the south of Zawar, which refers to the arrival of a merchant who had a mine at Zawar, then known as Aranoyagire or hill of wells (indicating earlier mine-shafts in the hilly area)[17,50]. There are similar inscriptions on old temples constructed in and around old Zawar during this period.

While Gujarat and other parts of India were making brass icons out of distilled zinc during the period 5th-11th centuries AD continuously (vide reference 30, also Table I), the Muslim world made zinc oxide but not the metal itself. The Iranian Abu Dalaf, writing in the 10th century, describing zinc oxide and its use in brass-making (evidently by the cementation route), stated that in India "it is made from the vapour of tin"[51]. Al-Biruni of the 11th century and the Italian traveller Marco Polo of the 13th century described the Iranian process of obtaining zinc oxide (sublimate deposited on pegs or bars) but not the metal itself.

The earliest evidence for zinc smelting in medieval Zawar is the C-14 date of 840 ± 130 BP (around 1150 AD) for one of the heaps of white ash removed from the zinc-smelting Koshthi furnaces[50]. The main expansion of the industrial phase of zinc production was executed by Rana Lakha of Mewar (1382-97). Even after the 12th century AD, the local rulers at Udaipur retained the control of zinc and brass technology at Zawar. Rana Pratap Singh (1572-1597) was forced to hide from the armies of Akbar in one of the spacious mines on Zawar Mala, now known as Pratap Khan. In *Ain-i-Akbari* completed in 1596, Abul Fazl admitted his ignorance about *jast* (derived from Sanskrit *jaśada* or zinc): "according to some this is *ruh-i-tutiya** (the metal of *tutiya* or zinc oxide): it is nowhere mentioned in the philosophical books (Persian and other Islamic works); there is a mine of it in Zawar"[52].

DISCOVERY OF THE MEDIEVAL ZINC SMELTING OUTFIT

It is amazing that nearly seven centuries long (1150-1810 AD) medieval or pre-modern tradition of zinc smelting at Zawar was nearly forgotten. Evidently, much secrecy was maintained there. Only the iatro-chemist authors of the *Rasaśāstra* texts, such as the 13th century *Rasa Ratna Samuccaya*[3], had some access to the details and described a part of the same.

Colonel Tod, the great historian of Rajasthan, wrote[53] in 1829 that as recently as 1760, the Zawar mines had been in full production. The mines were abandoned during the reign of Maharana Bhim Singh (1778-1828), when the State of Mewar was repeatedly plundered by the Maratha invaders. In 1850, Brooke[54] mentioned the ancient art of zinc distillation and an old man who claimed that he knew the technology.

In the neighbouring villages, the used brinjal-shaped retorts have been utilised as components of building-walls and this has always been a familiar sight, although people forgot how and where these retorts were used. Attention has been drawn to the ancient deep mine shafts[55] and the huge quantity of zinc extraction debris at Zawar[56].

Straczek *et al.*[56] pointed out that there are two distinct types of smelter residues. One is a sinter or clinker intermixed with fragments of fired clay pots or retorts and contained in unbroken retorts; the retort residue and wall contain substantial amounts of zinc, showing that these retorts are possibly zinc smelting crucibles. The other kind

*The referee commented that *tutiya* is copper sulphate and not zinc oxide. The word *tutiya* is actually a generic name like vitriol, which can be blue (copper sulphate), green (iron sulphate) or white (zinc sulphate). In India, *tutiya* commonly represented copper sulphate. Colonel Yule and V. Ball, however, noted that *tutiya* was the ancient Persian word for zinc oxide. Therefore, the Persian *ruh-i-tutiya* or essence of *tutiya*, as mentioned by Abul Fazl, has been rightly translated by Blochmann as the metal from zinc oxide or zinc itself.

of residue is normal glass slag left after the recovery of lead and possibly silver.

In April 1980, the Hindustan Zinc Limited (HZL) sponsored a three-year research project on recovery of zinc from the ancient slags which was successfully conducted at the Indian Institute of Technology (I.I.T.), Kanpur by the present author[57]. In 1982, HZL collaborated with British Museum Research Laboratory (P.T. Craddock, Lyon Willies, etc.) and the Department of Archaeology, M.S. University of Baroda (K.T.M. Hegde) on archaeological investigations, and this led to the spectacular discovery of the zinc distillation outfit, including furnaces and retorts showing the production strategy, Craddock described the exciting discovery:

"On the third day of the excavation (December 1983), one of the Baroda team (Hegde) spotted the corner of a refractory plate sticking out from a heap of spent retorts beside a goat track in a valley on Zawar Mala ... With mounting excitement we cleared a small area above and around it to reveal first, the edges of furnace walls, and then the tops of retorts still *in situ*"[10].

Extensive archaeological and archaeo-material investigations followed[1-26]; we now present the summary of the results of the historical experiments performed in two continents.

Ancient Retorts and Furnaces at Zawar

During the 1983 excavations, two groups of furnaces were uncovered. A single bank of seven furnaces upon Zawar Mala contained small retorts 20 cm long and 10 cm in diameter. In old Zawar, there was a more extensive arrangement of furnaces using larger retorts (30-35 cm long and 10-15 cm diameter). In both groups, 36 retorts in a 6 x 6 arrangement were contained within the truncated pyramid of each furnace. Thus, no less than 252 retorts were fired simultaneously in a single bank. The retorts were supported vertically on perforated bricks through which the condenser tubes passed into the cooler zinc collectors beneath (Figs. 1-3).

The furnaces are in two parts consisting of a zinc vapour condensation chamber at the bottom and a furnace chamber at the top. The two chambers are separated by a perforated terracotta plate. The condensation chamber measures 65 $\times$ 65 cm and 20 cm in height. The perforated terracotta plate that separates the two chambers is a composite unit made up of four equal segments of 35 cm^2. It is 4 cm thick, well-baked, and sturdy. Its perforations include circular holes of two sizes: larger ones of 4 cm diameter, each of which is surrounded by a number of smaller holes of 2.5 cm diameter. Within the furnace, the composite terracotta plate was found to be supported on a ledge in the furnace walls on all four sides and a single solid terracotta pillar placed below the junction of its four segments[16,22].

Up above the perforated terracotta plate is the furnace chamber, in which 36 charged retorts (Figs. 1-2) were arranged, inverted vertically; it may be presumed that

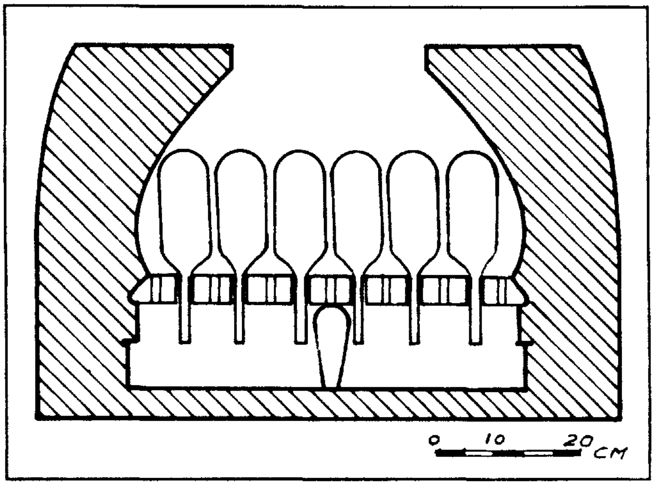

Fig 1 Midpoint vertical section through a zinc reduction - distillation furnace at Zawar Mala (Craddock *et al.*[13])

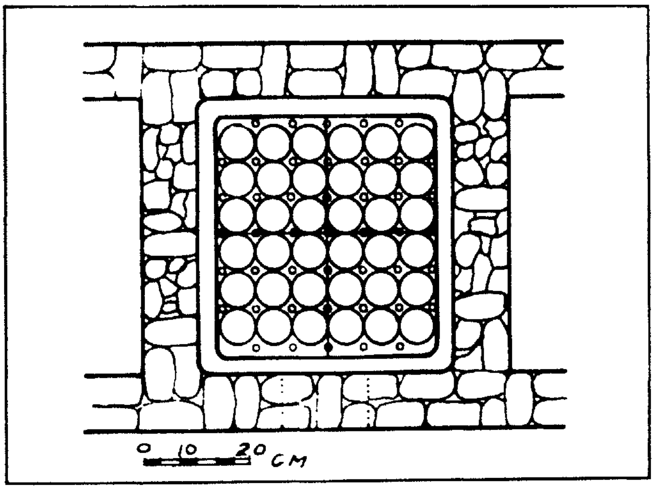

Fig. 2 Horizontal section through the furnace in Fig 1 at perforated plate level (Craddock *et al.*[13])

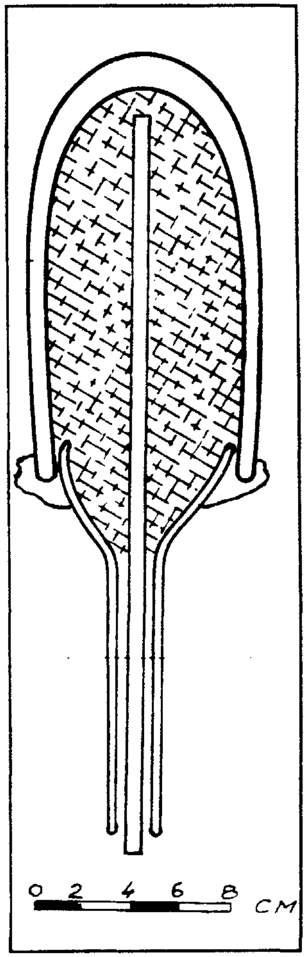

Fig. 3 Section through small charged zinc reduction - distillation retort with stick still in place (Craddock *et al.*[13])

36 vessels were placed, one underneath each retort, to collect the condensed zinc vapour. This arrangement of downward distillation retort with the condensing unit underneath or '*distillation per descensum*', is precisely what had been described in *Rasaratnasamuccaya* text (2.157-166; 9.48-50). The brinjal-like retorts in Zawar (Fig. 3) are also similar to the *vṛntākamūṣā* described in *Rasaratnasamuccaya* (10.22-23).

It appears that a cylindrical reed of 1.5 cm diameter was inserted into the retort after it was charged and the funnel part was luted on it (Fig. 3); this is evident from the central hole which is preserved in many retort residues[13]. The reed helped to keep the charge within the retort when it was inverted and placed in the furnace. When the furnace was fired, the reed burnt away leaving behind a cylindrical flow channel for the zinc vapour to flow freely out of the retort.

An Outline of the Medieval Process

In the Zawar mines, the host rock is dolomitic and arkosic (quartz and felspar) containing a variety of sulphide minerals, such as sphalerite (ZnS) (the principal zinc-bearing mineral), galena (PbS), sulphides of iron, copper, silver, etc.[56].

In Table 2 are presented analytical data on Zawar ore, tail, concentrate from the modern plant and the ancient retort residue. Craddock *et al.*[15,24] suggested on the basis of 'similar Fe/Pb/Ag ratios in the retort residues and in the modern concentrates' that substantial upgradation or beneficiation was done by the ancient smelters by hand-picking or winnowing, so that the retort charge assayed more than 30% in zinc. Then to explain the high proportion of calcium and magnesium in the retort residue, Craddock *et al*[15,24] suggested that additional materials like dolomite were added in the charge. This hypothesis may be contested on the basis of the data in Table 2 compiled by us. The insoluble silica/Ca/Mg ratios are quite similar in the ore, tail and retort residue. Therefore, we suggest that zinc mineral was not highly beneficiated and not substantially freed from silica, Ca, Mg, Na, K moiety while being charged in the retort.

Table 2. Analysis of Zawar Ore, Tail, Zinc Concentrate and Retort Residue, and Relative Proportions of Constituents

	Mochia Ore[1]		Mochia Tail[1]		Zinc Conc.[1]		Retort Residue	
	%	Relative	%	Relative	%	Relative	%	Relative
Fe	3.00	1.00	3.10	1.00	8.00	1.00	5.7	1.00
Zn	3.50	1.17	0.35	0.11	52.00	6.50	3.04[3]	0.53
Pb	1.40	0.47	0.22	0.07	1.30	0.16	1.55	0.27
Mn	0.35	0.12	–	–	0.035	4.4×10^{-3}	1.03	0.18
Ag (ppm)	40.00	10^{-3}	–	–	140.00	1.7×10^{-3}	114[4]	2×10^{-3}
Insoluble (silica)	30.00	10.00	33.20	10.70	1.25	0.16	42.5	7.45
Ca	13.00	4.33	14.00	4.50	1.00	0.125	17.2	3.00
Mg	7.5	2.50	8.50	2.70	1.20	0.15	6.7	1.18

Notes: 1. The data for the ore, tail and concentrate in the modern plant are taken from Chatterjee and Agarwal[58].
2. Elemental percentages calculated from oxide compositions given by Hegde[22].
3. From Hegde's data, elemental zinc in the retort residue comes out to be low (1.82%), whereas Freestone[15] gives the figure 3.85%. Our estimate (Biswas)[1] is 3.04%.
4. Average of the values for silver quoted.

The ore must have been roasted before smelting, since reduction of zinc sulphide to the metallic state is very difficult. It is doubtful whether the ore was dead-roasted above 1000°C for complete conversion to oxide; we detected in the retort residue not only a little sulphur (0.35%), but also the specific phase of goslarite or zinc sulphate[1].

The smelting charge must have included a small quantity of common salt (as surmised from the chlorine and sodium contents in the retort residue) and an adequately large quantity of carbonaceous matter, apart from the calcined ore, and then rolled into pellets of 1 cm^3 volume (*Rasa Ratna Samuccaya* or RRS 2.163-164 refers to the *guṭikākṛti* pellets containing sodium bicarbonate and borax). The charge (about 1.5 kg per retort) was loaded into clay retorts fitted with funnel-like condenser tubes, as described before (Fig. 3). These were indeed the brinjal-shaped crucible or *vṛntāka mūṣā*, as described in RRS (2.157, 2.163, 10.23-24, etc.). On heating in the furnace, zinc oxide was reduced by the carbonaceous matter to zinc vapour. The reducing blue flame of carbon monoxide was observed to be substituted by white flame of zinc vapour, indicating that reduction had taken place (*bhavet nīlā sitā yadi* – RRS 2.159-160).

Using a scanning electron microscope and observing the vitrification textures of the Zawar retort and clay materials, Freestone and Middleton[18] estimated that the temperature reached in the Zawar zinc distillation furnace was of the order of 1150-1200°C, and that this temperature was maintained for 5 hours or more. The highly endothermic reduction of zinc oxide must have been achieved at a very low partial pressure of oxygen (less than 10^{-20} atm) to prevent re-oxidation of the metal. Zinc vapour condensed in the tube, the temperature being around 500°C, and collected in the vessels placed below. This kind of downward distillation or *tiryakpātana* of zinc vapour, produced under a highly reducing atmosphere, has been described in RRS (2.163-168, 10.48-50).

A part of the zinc oxide was converted to well-identified silicate phases and thus could not be recovered as reduced metal.

Freestone *et al.*[14] estimated that 200-500 g zinc was extracted per retort, or 7-18 kg per smelt of 36 retorts. Each retort weighs about 3 kg. Thus, the debris of around 6 lakh tons of spent retorts corresponds to about 1 lakh ton of zinc, according to Freestone *et al.*[14], which might have been produced at Zawar during 13th-18th centuries AD. This has been indeed one of the most outstanding levels of industrial production in the medieval world.

Phase Studies on Zawar Slags at IIT, Kanpur

Six lakh tons of spent retorts contain two lakh tons of residues within, assaying about 3% zinc. Therefore, some 6000 tons of zinc metal remain within the retort residue, and probably another 1000 tons in the lead slag. Our research at the Indian Institute of Technology (IIT), Kanpur, sponsored by the Hindustan Zinc Limited, was directed towards the recovery of zinc from these two kinds of slags[57]. The first step in our work was characterisation of these residues, which turned out to be very useful and relevant to the archaeo-metallurgical problem.

The phases identified by X-ray and electron diffraction studies by Biswas *et al.*[1]

Table 3. Phases Identified in Zawar Retort Residue (Content), Wall and (Lead) Slag by X-ray and Electron Diffraction Studies (Biswas *et al.*[1])

Sample	Phases identified	
	X-ray diffraction	Electron diffraction
Retort content	$Zn_2P_2O_7$. $5H_2O$, goslarite $ZnSO_4$, $7H_2O$, hemimorphite, $Zn_4(OH)_2$ Si_2O_7. H_2O, esperite Ca_2Pb $(ZnSiO_4)_4$, sphalerite ZnS, Chalcopyrite $CuFeS_2$, larsenite, $PbZnSiO_4$	$Zn_2P_2O_7$. $5H_2O$, goslarite, hemimorphite, esperite, quartz, $Mg_2Al_4Si_5O_{18}$, hardistonite $Ca_2ZnSi_2O_7$, hydrozincite or aurichalcite, Zn_5 $(CO_3)_2$ $(OH)_6$
Retort wall	Goslarite, hardistonite, hemimorphite $Zn_2P_2O_7$. $5H_2O$ aurichalcite, quartz, sphalerite	Goslarite, hemimorphite, willemite Zn_2SiO_4, hardistonite
Slag	Quartz, goslarite, $Zn_2P_2O_7$. $5H_2O$, hemimorphite, aurichalcite, sphaleritte, chalcopyrite, hardistonite	Hemimorphite, goslarite, hydrozincite, quartz, sphalerite

are summarised in Table 3. The results show that in the roasting operation prior to retort distillation, a small part of sphalerite was not converted into oxide and remained in the retort as ZnS and $ZnSO_4$. The presence of goslarite or $ZnSO_4$, $7H_2O$ (hydraded at a later stage) was confirmed by the endothermic DTA peaks apart from X-ray and electron diffraction studies. Some ZnO might have remained unconverted in the retort to undergo atmospheric conversion to basic carbonate at a later stage. While most of the ZnO was reduced to metal, a part of it must have been converted at a high temperature to phosphate and silicates from which the metal could not be recovered. Biswas *et al.* detected a number of zinc, calcium-zinc, lead-zinc, calcium-lead-zinc and magnesium-aluminium silicates[1]. Later, Freestone *et al.*[15] reported that lead slag contained iron, calcium-iron, calcium-zinc, magnesium and calcium-magnesium silicates. The only silicate phase that Freestone *et al.*[15] could report in the retort residue was $CaMgSi_2O_6$ or diopside.

Biswas *et al.*[1] obtained secondary electron images of retort residue samples and found that the particles have a variety of morphology: plates, needles and spheres. Scanning electron microscopy and X-ray microanalysis showed characteristic peaks of many elements, the most prominent being those of silicon and calcium. Scanning was done by a fine electron probe on the zinc-containing particles in the size range 0.5-40 μm.

Several of the small particles (0.5-8.0 μm) show approximately constant values for the ratio of intensities corresponding to the elements Si, Ca, Mg, Fe, Al, Zn, Pb, Mn, Na, K and S (in decreasing order of occurrence), indicating that these particles containing a few of the above elements are homogeneous in nature. The larger particles show wide variation in intensity ratios and hence variation in the chemical composition of the grains from point to point. Thus, the approximate size of the zinc-containing and other homogeneous grains in the retort residue is in the range 0.5-8.0 μm.

The size of the particles in the lead slag sample was found to be lower than that in the retort residue. The size of the zinc-containing grains was estimated to be in the range 0.5-6.0 μm, by carrying out point to point analysis. The X-ray spectrum showed the presence of titanium apart from the other elements noted in the retort residue.

The work at IIT, Kanpur was directed primarily towards the recovery of zinc from the siliceous retort residue and slag at Zawar. We found (Biswas and Kumar[2]) that the non-silicate phase, such as hydrozincite $Zn_5(CO_3)_2(OH)_6$, could be easily leached by acid. A special 'fast leaching' technique, making use of the water-starved nature of the silicate-sulphuric acid system, could recover more than 80% of the zinc contained in the silicate phases, such as hemimorphite $Zn_4(OH)_2Si_2O_7.H_2O$, willemite Zn_2SiO_4, etc.

The characterisation work done at IIT, Kanpur[1,57] has established the existence of complex zinc-phosphate-silicate phases in the slag which could have been produced only by the above 1000°C pyrometallurgical smelting process. This corroborates the conclusions reached by Craddock *et al.*[6-26].

Table 4. Brass Icons in India (1350-1752 AD)

Sl No	Site	Item	Elemental percentages					Impurities
			Cu	Sn	Zn	Pb	Fe	
	Medieval Period							
1	Gujarat 1350 AD	Ambikā	68.4	1.6	18.5	9.5	-	Fe, Ag, Bi
2	" 1480 AD	Model Temple with four doors 10 × 24.5 cm	68.6	0.2	28.9	1.6	-	Fe, Mg, Bi
3	" 1485 AD	Vishnu-Nārāyana	58.9	0.5	36.8	2.1	-	Fe, Al, Ag, Si, Mg, Bi
4	Rajasthan 15th-16th centuries AD	Rajput Prince on Horse	72.9	0.4	21.8	2.7	1.0	Al 0.3, Ag, Mg
5	Gujarat 1554 AD	Kal Bhairava	76.7	1.2	13.8	6.3	1.5	Al, Mg
6	" 17th century AD	Chauri-Bearer	58.3	1.5	35.5	2.3		Fe, Ni, Al, Ag, Cd, Si, Mg
7	Rajasthan 17th century AD	Dīpalakshmī Rajput Girl	58.8	0.9	33.2	4.5	0.8	Al 1.6, Mg
8	Gujarat 18th century AD	Dīpalakshmī	52.8	1.1	39.9	2.9	-	Fe, Al
9	" 1752 AD	Tīrthankara-Seated	62.3	-	36.0	0.5	-	Fe, Ag, Bi
10	Nepal	Sadakasari Lokeśvara Form of Avalokiteśvara	60.5	2.75	35.3	2.37	-	Fe, Ni, As, Au

SCENARIO – 14TH CENTURY ONWARDS

The large-scale manufacture and widespread use of zinc and brass in medieval India need to be fully chronicled. Table 4 records a few brass icons of India for the period 1350-1752 AD; the high zinc content, sometimes in the range 35-40%, in these icons is particularly notworthy. Item No. 9 in Table 4 is dated 1752 AD – five years before the War of Plassey, and eight years before the Zawar production was slowed down on account of the Maratha invasions. During the medieval period, the Moghuls had used brass (as well as bronze) for manufacturing guns[35], and artisans of Bidar (83 km from Hyderabad) used high zinc (84%) brass or *bidri* alloy for ornamentation over it by gold or silver ware[59].

The etymology of the words denoting zinc became clearer. *Madanapāla – Nirghaṇṭu* of 1374 AD mentioned *yaśadam vaṅgasadṛśam* or the 'zinc metal (*yaśada*) like tin' (Table 5). *Yaśada* means that which gives *yaśa* or fame; the connection was clear insofar as zinc was known to produce the famous gold-like yellow alloy of brass (vide 2nd century AD text *Rasaratnākara* 1.3). The European word 'zinc' was probably derived from *yaśada*; the Sanskrit word became *jast* (Abdul Fazl) and *dastā* in several Indian languages.

In 1597, Libavius (AD 1545-1616) received Indian zinc, which he called 'Indian or Malabar lead'. He was uncertain what it was. Although Paracelsus (1616 AD) is generally credited to have given the name 'zinc' to the metal, large scale export of the metal from India to the West started later in the 17th century, and according to Roscoe, the identification of zinc as the metal from blende or calamine was

Table 5. Some Literature on Zinc (1374-1886 AD)

1374 AD	Madanapāla-Nighantu refers to *Yaśadam vaṅgasadṛśam* (zinc - tin like): *Yaśada* means that which gives *yaśa* or fame, converts copper into yellow gold-like brass.
1597 AD	Libavius receives a sample and calls it Indian or Malabar lead.
1616 AD	Paracelsus calls it *'zinc'* from *Yaśada*, in several Indian languages, *dastā*.
1695 AD	Homberg identifies Indian zinc as the same metal from European calamine.
Before 1730 AD	An Englishman transmitted Zawar technology to the West - identity not known.
1730 AD	William Champion's experiment at Warmley near Bristol; patent in 1738. Cost of metal £ 260 a ton, whereas calamine cost only £ 6 a ton.
1743 AD	Champion starts manufacturing zinc by distillation per descensum - process 'notoriously close to the Zawar process' (Morgan and Craddock).
1751 AD	Postlewayt's *Dictionary of Trade and Commerce* admits ignorance about zinc technology. India continues making high-Zn brass statues.
1800-1820 AD	Zawar zinc industry devastated by famine and Marhatta invasion.
1886 AD	V. Ball quotes Beckmann's *History of Inventions* (Bohn's Edition, ii, p. 32): "An Englishman went to India in the 17th century to discover the process used there in the manufacture of zinc, and returned with an account of distillation per descensum. I have not yet been able to identity this Englishman".

accomplished by Homberg[35] in 1695.

As late as 1751, Postlewayt's *Universal Dictionary of Trade and Commerce* had to admit ignorance of how the zinc was made in the East. In 1731, imported zinc commanded a price of £ 260 a ton on the London market, whereas the abundant calamine, used to make cementation brass, cost only £ 6 a ton[13].

Technology Transfer to the West

In 1730, William Champion of Warmley (near Bristol, England), started experiments on making zinc metal from calamine by the reduction-distillation route. In 1738, he applied for a patent and in 1743 he commenced production of zinc. Morgan, a modern expert of Imperial Smelting Processes (ISP) Ltd., wonders 'how such a remarkable achievement was completed in so short a time'[9]. Morgan and Craddock *et al.*[13] noted that: "Champion was notoriously close with details to Indian process at Zawar; possibly a third party described the general principle of the process to Champion".

The process at Warmley used the same arrangement of retorts and the same technique of 'distillation *per descensum*' as in Zawar and even included 1.5 weight % common salt in the zinc – smelting charge. The closeness was indeed 'notorious'! Craddock *et al.*[13] possibly overlooked the significant remark made earlier on the subject by Ball[60]. Mentioning Beckmann's *History of Inventions* (Bohn's Edition ii, p. 32), and his comments about the earliest efforts for making zinc in Europe, V. Ball wrote:

"Beckmann adds that an Englishman went to India in the 17th century to discover the process used there in the manufacture (of zinc), and returned with an account that it was obtained by distillation *per descensum*. I have not been able to identify this Englishman"[60]. Recently, Porter[61] has written: "A Dr. Lane seems to have smelted zinc ore at his copper works in Swansea as early as 1720". Had he visited Zawar?

It is thus established that there was a technology transfer from Zawar in India to Bristol in England sometime before 1730. The evidence contradicts the usual notion that the vector of science and technology transfer has always been from the West to the East. Indian traditions have frequently benefited the growths of the Greek, Arab and medieval European sciences. On brass and zinc metallurgy, the primacy of India in the ancient and medieval world is now beyond any dispute.

References and Notes

1. Biswas, A.K., Gangopadhyay, A. and Ramachandran, T.R., Phase Studies on Zinc Residues of Ancient Indian Origin, *Trans. Indian Inst. Metals*, **37** (3), 234-241, June 1984.
2. Biswas, A.K., and Kumar, Rakesh, Zinc Recovery from Zawar Ancient Siliceous Slag, *Hydrometallurgy*, **15**, 267-280, 1986.
3. Biswas, A.K., Rasa-Ratna-Samuccaya and Mineral Processing State-of-Art in the 13th century A.D.

India, *Indian J. His. Sci.*, **22 (1)**, 29-46, 1987.

4. Biswas, A.K., Biswas, S. and Chakravorty, N.A., Archaeo-material Studies in India and Literary Evidences, in *Historical Archaeology of India*, edited by A. Ray and S. Mukherjee, Books and Books, New Delhi, 1990, pp. 49-66.
5. Biswas, A.K., *Minerals and Metals in Ancient India – A Few Glimpses*, Centenary Lecture, Bengal Engineering College, 10 April 1992, pp. 1-15, discussed in the July 1992, p. 189 editorial of *Journal of Mines, Metals and Fuels*. The seminar lectures delivered at the Jadavpur University, Aligarh Muslim University and I.I.T. Kanpur have been widely appreciated.
6. Craddock, P.T., The Composition of the Copper Alloys Used by the Greek, Etruscan and Roman Civilization – The Origins and Early Use and Brass, *J. Archaeol. Sci.*, **5**, 1-16, 1978.
7. Craddock, P.T., Burnett, A.M. and Preston, K. Hellenistic Copper-Base Coinage and the Origins of Brass. In *Scientific Studies in Numismatics*, edited by W.A. Oddy, Occasional Paper No. 18, British Museum, 1980, pp. 53-64.
8. Craddock, P.T., The Copper Alloys of Tibet and Their Background, in *Aspects of Tibetan Metallurgy*, Occasional Paper No. 15, British Museum, 1981, pp. 1-31.
9. Morgan, S.W.K., William Champion as a Metallurgist, paper presented to Historical Metallurgy Society meeting at Bath, 20 September 1981; *Trans. Inst. Min. Metall. Assoc. Sect.* C, **92**, C 192-C 200, December 1983.
10. Craddock, P.T., Goat Path Discovery Unlocks Secrets of Medieval Zinc, *IAMS Newsletter*, No. 6, Institute of Archaeology, London, 1984.
11. Craddock, P.T., Gurjar, L.K. and Hegde, K.T.M., Zinc Production in Medieval India, *World Archaeol.*, **15 (2)**, 211-217, 1983.
12. Willies, Lynn, Craddock, P.T., Gurjar, L.K. and Hegde, K.T.M. Ancient Lead and Zinc Mining in Rajasthan, India, *World Archaeol.*, **16 (2)**, 222-233, October 1984.
13. Craddock, P.T., Freestone, I.C., Gurjar, L.K., Hegde, K.T.M. and Sonavane, V.H., Early Zinc Production in India, *Min. Mag.*, 45-52, January 1985.
14. Freestone, I.C., Craddock, P.T., Hegde, K.T.M., Hughes, M.J. and Paliwal, H.V., Zinc Production at Zawar, Rajasthan, *In Furnaces and Smelting Technology in Antiquity*, edited by P.T. Craddock and M.J. Hughes, Occasional Paper No. 48, British Museum, 1985, 229-244.
15. Freestone, I.C., Craddock, P.T., Gurjar, L.K., Hegde, K.T.M. and Paliwal, H.V., Analytical Approaches to the Interpretation of Medieval Zinc – Smelting Debris from Zawar, Rajasthan, *J. Archaeol. Chem.*, **3**, 1-12, December 1985.
16. Hegde, K.T.M., Craddock, P.T., and Sonavane, V.H., Zinc Distillation in Ancient India, *Proceedings of the 24th International Archaeometry Symposium*, Smithsonian Institution Press, Washington, 249-258, 1986.
17. Paliwal, H.V., Gurjar, L.K. and Craddock, P.T., Zinc and Brass in Ancient India, *Can. Min. Metall. Bull.* **79** (885), 75-79, January 1986.
18. Freestone, I.C. and Middleton, A.P., Mineralogical Applications of the Analytical SEM in Archaeology, *Mineral. Mag.* **51**, 21-31, March 1987.
19. Craddock, P.T., The Early History of Zinc, *Endeavour*, **11** (4), 183-191, 1987.
20. Willies, Lynn, Ancient Zinc-Lead-Silver Mining in Rajasthan, Interim Report, *Bull. Peak Dist. Mines Hist. Soc. Ltd.*, **10** (2), 81-123, Winter 1987.
21. Willies, Lynn, Ancient Lead-Zinc-Silver Mines in Rajasthan, *Min. Mag.*, 31-35, January 1989.
22. Hegde, K.T.M., Zinc and Brass Production in Ancient India, *Interdiscipl. Sci. Rev.*, **14** (1), 86-96, 1989.
23. Craddock, P.T., Freestone, I.C., Gurjar, L.K., Middleton, A.P. and Willies, L., The Production of Lead, Silver and Zinc in Early India, *Old World Archaeometallurgy*, edited by A. Hauptmann, E. Pernicka and G.A. Wagner, Der Anschnitt, Beiheft **7**, Bochum, pp. 51-69, 1989.
24. *2000 Years of Zinc and Brass*, edited by P.T. Craddock, British Museum Occasional Paper **50**, London, pp. 1-6 and 29-72, 1990.
25. Freestone, I.C., Middleton, A.P., Craddock, P.T., Gurjar, L.K. and Hook, D.R., Role of Materials Analysis in the Reconstruction of Early Metal Extraction Technology: Zinc and Silver-Lead Smelting at Zawar, Rajasthan, *Materials Issues in Art and Archaeology*, II, Materials Research Society, pp. 56-83, 1991.
26. Hegde, K.T.M., *An Introduction to Ancient Indian Metallurgy*, Geological Society of India, Bangalore, A special chapter on 'Zinc and Brass Production in Ancient India', pp. 56-83, 1991.

27. Werner, O., *Spektralanalytische und Metallurgische Untersuchungen an Indischen Bronzen*, Leiden, Brill., 1972.
28. Haedecke, K., Gleichgewichtsverhältnisse bei der Messingherstellung nach dem Galmeiverfahren, *Erzmetall*, **26**, 229-233, 1973.
29. Rao, S.R., *Lothal – A Harappan Port-Town* (1955-62) in 2 volumes, Archaeological Survey of India, New Delhi, Vol. II, 1985 p. 660. Chemical analyses of the Harappan level samples were provided by B.B. Lal.
30. Swarnakamal, *Metallic Art and Technology of Gujarat*, Museum and Picture Gallery, Baroda, 1978, pp. 36-37, 56-57, 66, 104-105.
31. Gaur, R.C., *Excavations at Atranjikhera – Early Civilisation of the Upper Ganga Basin*, Aligarh Muslim University and Motilal Banarasidass, Delhi, 1983, p. 497.
32. Marshall, J., *Taxila*, 3 volumes, Cambridge, 1951.
33. Farnsworth, M., Smith, C.S. and Rodda, J.L., Metallographic Examination of a Sample of Metallic Zinc from Ancient Athens, *Hesperia* (Suppl. 8), 126-129, 1949.
34. Tiwari, R.K. and Kavdia, N.K., Ancient Mining activity around Agucha Village, Bhilwara District, Rajasthan, *Man & Envir.*, **8**, 81-87, 1984.
35. Neogi, P., *Copper in Ancient India*, 1917, reprinted in 1979 by Janaki Prakashan, Patna, pp. 40-42.
36. *History of Chemistry in Ancient and Medieval India*, edited by P. Ray, Indian Chemical Society, Calcutta. pp. 94-95, 1956.
37. Lo Bue, E., Statuary Metals in Tibet, in Reference 8, p. 38.
38. Werner, O., Spectro-chemical Analysis of Antique and Modern Bronzes, *Material Prüfung*, **7** (12), 463-470, 1965.
39. Lal, B.B., An Examination of Some Metal Images from Nalanda, *Anc. India*, **12,** 53-57, 1956.
40. Schroeder, U. Von., *Indo-Tibetan Bronzes*, Visual Dharma Publications Ltd., Hong Kong, 1981.
41. Ball, V., Zinc Ores, Their Mode of Occurrence, Metallurgy, and History, in India, *Scient. Proc. R. Dubl. Soc.* **5,** 321-331, 1886-87.
42. Ref. 36, pp. 116-118. We cannot accept this date nor the other suggestion of Ray that 'brass appears to have been introduced in northern India through Chinese trade' (p. 97).
43. Filliozat, J., Al-Biruni and Indian Alchemy, in *Al-Biruni Commemoration Volume*, Iran Society, Calcutta, pp. 101-105, 1951.
44. Beal, Samuel, *Buddhist Records of the Western World*, 1884, Reprint, Oriental Books, Delhi, p. 216, 1969.
45. Lévi, Sylvain, Un nouveau document sur le bouddhisme de basse époque dans l' Inde, *Bull. Sch. Orient. Afr. Stud., Lond.*, **VI,** 417-29.
46. Banerjee, Bireswar, Siddha Nagarjuna Kakshaputatantram, *Sci. Cult.*, **21**(4), 195-97, Oct. 1955.
47. Pingree, David (translated and edited), *The Yavanajataka of Sphujidvaja*, 2 volumes, Harvard University Press, 1978. Sphujidhvaja's Sanskrit text (270 A.D.) was a translation of Yavanesvara's Greek text (150 A.D.)
48. Majumdar, R.C., *The History of Culture of the Indian People – The Age of Imperial Unity*. volume II, Bharatiya Vidya Bhavan, Bombay, 1980, pp. 388-389. In this portion, the eminent scholar Nalinaksa Dutta writes on the 'confusion' created by an early Indian source, and sustained in Kumarajiva's biography on Nagarjuna (in Chinese, A.D. 405) and subsequent texts.
49. A.S. Bisht and R.C. Jain reported 5th century A.D. standing Buddhas in East Nimar, Madhya Pradesh, made of brass 'cast in hot molds by the lost wax process', and assaying 26-27 p.c. zinc. *Conservation of Cultural Property in India*, 1981-82, pp. 14-15 and 28-30.
50. Ref. 24, p. 49
51. Allan, J.W., *Persian Metal Technology* 700-1300 A.D., Ithaca Press, Oxford, 1979, p. 43, cited by Craddock *et al.* (ref. 23).
52. Abul Fazl, *The Ain-i-Akbari*, Vol I translated by H. Blochmann, New Delhi, 3rd edition, 1977, pp. 41-42.
53. Tod, J., *Annals and Antiquities of Rajasthan*, Smith and Elder, London, 1829; 1950 edition, Routledge and Kegan Paul Limited, 1950, Vol. 1, p. 399.
54. Brooke, J.C., Notes on the Zinc Mines of Zawar, *J. Asiat. Soc. Bengal*, **19,** 212-215, 1850.
55. Mookherjee, A., Geology of the Zawar Lead-Zinc Mine, Rajasthan, *Econ. Geol.*, **59,** 657-677, 1964.
56. Straczek, J.A. and Srikantan, B., The Geology of Zawar Zinc-Lead Area, Rajasthan, *Mem. Geol. Surv. of India*, **92,** 47, 1967.

57. Biswas, A.K., Annual Reports of Hindustan Zinc Limited, Udaipur: *'Studies on Recovery of Zinc from Flotation Tailings and Ancient Slags'*, Indian Institute of Technology, Kanpur, 1981-84.
58. Chatterjee, B.N. and Agarwal, B.L. How Zawar Beneficiates Low Grade Lead-Zinc Sulphide Ore, *Proceedings, International Seminar on Lead, Zinc and Cadmium*, New Delhi, Volume 1, Nov. 1981, pp. B72-B.97.
59. Jafar Mahmud, Syed, *Metal Technology in Medieval India*, Daya Publishing House, Delhi, 1988, pp. 115-126. Jafar Mahmud provides some details about the Bidri ware as well as the Zawar technology.
60. Ball, V., Ref. 41, p. 322.
61. Porter, Frank, *Zinc Handbook*, Marcel Dekker Inc., New York, 1991, p. 60