© 2001 NML Jamshedpur 831 007, India; Metallurgy in India: A Retrospective; (ISBN: 81-87053-56-7); Eds: P. Ramachandra Rao and N.G. Goswami; pp. 1-24.

1

Minerals and their Exploitation in Ancient and Pre-modern India

A.K. Biswas

Professor in History of Science, The Asiatic Society, Calcutta, India.

ABSTRACT

The paper highlights the archaeological and literary evidence corroborating ancient India's primacy in the field of mineralogy and metallurgy. As we knew mineral is a naturally occuring crystalline element or a compound having definite chemical composition, and formed as a product of inorganic processes. The synthesis of new 'minerals' at high pressures and temperatures, discovery of new amporphous forms, biologically precipitated materials have put mineralogy at a cross-road. Both the scientist and archaeologists have legitimately taken broader interest in 'materials'. The paper gives stress on India's primacy in lapidary art, chalcedony, conch-shell, pearl, diamond, beryl, emerald, many other gems, and metallurgical practices related to laminated and forged iron, brass, zinc, crucible steel etc. Further, it has been attempted to trace the history, technology and occurrence of various minerals from evidence excavated by archeologists. The sample has been taken from the various periods right from pre-Harappan civilisation of India to modern India.

Key words : Indian Minerals, Materials, Lapidary art, Chalcedony, Conch-shell, Pearl, Diamond, Beryl, Emerald, Indian-metallurgical practices, Forged iron, Brass, Zinc, Crucible steel, Pre-Harappan civilization.

INTRODUCTION

The history of human civilization is replete with instances of use of diverse minerals, gems and various end-products manufactured therefrom. Associated with this ancient tradition have been the gradually evolved technical knowledges regarding fire, furnaces and mining. The earliest technologies related to potteries, ceramics and metals involved surface and sub-surface mining followed by thermal and metallurgical techniques.

Archaeological excavations unearth minerals, gems and metals, but do not prove whether these materials were locally manufactured, or imported from the neighbouring civilizations. Therefore, to establish primacy of a particular civilization, very careful C-14 and other kinds of dating are necessary. Existence of slags and positive metal/artefact-local ore correlation in terms of trace elements are also very useful. In the historical period, ancient literary evidences often clinch the issue. In this article we would highlight the archaeological and literary evidences corroborating ancient India's primacy in the fields of mineralogy and metallurgy[1].

Dana's System of Mineralogy[2] defined a mineral as a 'naturally occurring crystalline element or a compound having definite chemical composition, and formed as a product of inorganic processes'. The definition is now considered to be too restrictive. The synthesis of new 'minerals' at high pressures and temperatures, discovery of new amorphous forms, biologically precipitated materials etc., have put mineralogy at a cross-road[3]. Both the scientists and archaeologists have legitimately taken broader interest in 'materials' all of which are not covered under the title 'mineral'.

Hemley marked Theophrastus, the author of 300 BC text-book *De Lapidibus* introducing 16 minerals, as the founder of the science of mineralogy, but we believe that India (not Greece) was the first country where precious stones and minerals were studied in great depth. Similarly, in metallurgy also, Indians were the pioneers during the ancient and medieval periods. In this article, we would stress on India's primacy in lapidary art, chalcedony, conch-shell, pearl, diamond, beryl, emerald, many other gems, and metallurgical practices related to laminated and forged iron, brass, zinc, crucible steel etc.

Based on a series of articles and books by the present author and several other scholars. The present article is structured chronologically:

- The ancient civilizations including the Pre-Harappan.
- Minerals and metals in the Harappan era (3200-1800 BC)
- The transitional period and the Vedic literatures on minerals and metals.
- The Iron Age in India (1200 BC to 600 AD)
- Mines, gems and minerals (600 BC to 600 AD).
- Taxila and the primacy of India in brass and zinc metallurgy.
- The *Ratnaśāstra* texts and the Indo-Roman Trade on gems.
- The *Rasaśāstra* texts on other minerals and metals.
- Medieval zinc technology in India.
- Minerals in pre-modern India.
- Iron and crucible steel in pre-modern India and lastly
- Factors underlying medieval stagnation in the Indian science and technology.

MATERIALS IN THE PRE-HARAPPAN CIVILIZATIONS OF INDIA

Till the early part of the twentieth century, the knowledge of Indian history hardly went before the period of Gautama Buddha, and then came the discoveries at Mohenjo-Daro and Harappa when the clock went back to 3000 BC. Soon after independence in 1947, the Indian archaeologists discovered archaeological sites of Kalibangan etc. on the extinct river of Sarasvati. These were the Ṛgvedic sites of the Harappan civilization which should be re-named as Sarasvati-Indus Valley Complex. The Ṛgvedic war was a civil war amongst tribes speaking the same language in different dialects. The Rgvedic civilization was indigenous and the theory that the so-called 'Aryans' came from Central Asia and invaded India is an unacceptable myth[4]. During the 1980's, further archaeological discoveries have shown that there were many pre-Harappan sites in India, such as 7000 BC Mehargarh[5], which contributed to the build-up of the Harappan civilization[6].

Mehargarh in Baluchistan, Pakistan has revealed a eighth-sixth millennium BC pre-ceramic neolithic culture showing flint tools, grinding stones, barley, wheat, cereal cultivation, cakes of red ochre, beads of shell, turquoise, lapis lazuli and a cylindrical shaped copper bead (MASCA C-14 date 7786 $\pm$ 120 BC). Phase II (6^{th}-5^{th} millennium BC Culture) has revealed soapstone beads, flint drills and copper ring and bead. The first half of 5th millennium BC showed crucibles used for melting copper, some metal still adhering (4745 $\pm$ 90 BC MASCA C-14 date). The Mehargarh evidences have negatived the earlier view expressed by Agarwal[7] that the metallurgical know-how had diffused to India from Tal-i-Iblis, Iran for which Caldwell[8] provided a date of 4000 BC. It may now be safely asserted that copper metallurgy was developed indigenously in the Indian sub-continent and well before 4000 BC. There had been sizeable copper ore deposits in the Zhob district for the people of Mehargarh to smelt.

The clearest evidence about the Pre-Harappan chalcolithic culture in India has been obtained in the Ganeshwar-Jodhpura area near Jaipur, Rajasthan[9]. This site yielded huge quantities of copper objects such as blades, arrowheads, fish-hooks used in the Pre-Harappan Sothi culture and later in the Harappan culture. Deeper digging has shown earlier stone age culture, proving that Ganeshwar gradually moved from the neolithic to the chalcolithic stage before the Harappan era.

Mehargarh was connected through trade routes with the southern Nal and sea-coast site of Balakot (near Karachi) and in the north-west with the site of Mundigak in Afghanistan providing access to Iran as well as Central Asia. Shell bangles, rings, beads and pendants, prepared from the Indian variety of *śankha* (*Turbinella pyrum* Linn.) or conch-shell, were used in all the successive periods of Mehargarh and in almost all other pre-Harappan sites. Dales[10] has reported shell beads in Balakot Period I and working floors in Period II, covered with large quantities of shell bangles in all stages of manufacture. Conch pearl or *Kṛśan* was recognised as an important gem in the Rgvedic culture. Lapis Lazuli and turquoise came from Iran but were processed in Mehargarh and Nal. The find of unpolished, unpierced and roughly modelled as well as the finished lapis beads

— cylindrical, discoid and irregular hexagonal — at the site of Nal proves that the imported raw meterial was locally processed. Most of the lapis collected by the Harappans used to be exported to Mesopotamia through the Makran coast. Cuneiform texts from Mesopotamia lists lapis as one of the commodities apart from copper, ivory etc. coming from Meluhha or Mohenjo-Daro, India[11]. This pattern of pre-Harappan trade continued very vigorously during the Harappan era.

MINERALS AND METALS IN THE HARAPPAN ERA

Considerable information[12-16] on the Harappan civilization in India (3200 to 1800 BC) has been obtained from the works of John Marshall, E.J.H. Mackay, M.S. Vats, S.R. Rao, the multi-authored volume edited by G.L. Possehl etc. Mohenjo-Daro, Harappa and Kalibangan were the principal metropolis towns. Mohenjo-Daro, was definitely the grandest, exhibiting a bewilderingly large variety of materials. We may list some of them. Semi-precious stone bead industry was widespread in the Harappan civilization which used rock crystal or quartz (SiO_2) and varieties of chalcedony (SiO_2, nH_2O, sometimes waxy) such as: carnelian (sard pale to deep red, reddening due to dehydration of yellow hydrated ferric oxide in the industrial process), chrysoprase (apple-green due to nickel), plasma (bright to emerald green), heliotrope or blood-stone (plasma with red spots), agate (banded, different coloured chalcedony), onyx (agate with straight bands, even planes), felspar/microcline ($KAlSi_3O_8$), amazonstone (green, twinning striation microcline), nepheline or sodalite. Lapis lazuli, turquoise and jadeite were probably imported. Amongst other materials found were: potteries, clay, brick, limestone, lime and gypsum as mortar, faience and vitreous paste suggesting the use of *reh* or alkaline river incrustation and colouring flux, sandstone, steatite or soapstone containing talc, basalt, bitumen, *silajit*, a black coal-like organic medicine, pigments such as white gypsum, red/yellow ochre, purple-black manganiferous oxide, green *terre verte* or green earth (glauconite or chlorite, an iron silicate found in the basalt of Bhuswal in Central India) etc. Whereas the city of Harappa did not show as many varieties of materials as in Mohenjo-Daro. Some of the special materials found there were: coral, mica, yellow arsenic or lollingite ([illegible]) for bronze metallurgy, scrap bronze used as source of tin, yellowish limestone, grey granite, terracotta animal toys, finer textured potteries etc. Harappa was an important manufacturing centre, there being many more furnaces[16] than in Mohenjo-Daro. Fa, Fe and Fj furnaces definitely produced metals, since crucibles and slags were found there. Crude copper ingots found at Harappa probably came from Rajasthan and Hakra (Sarasvati river bed now in Pakistan) areas.

Chanhudaro was an important workshop centre producing seals and beads made of steatite or soapstone, the main constituent of which is talc $Mg_3Si_4O_{10}(OH)_2$, which is one of the softest materials known. Gujarat steatite contains some kaolin-type aluminium silicate, which is also soft. Hegde[17] has demonstrated that when this material is heated, it is hardened (Moh's scale of hardness rising from one to seven) on account of formation of silica (crystobalite) and enstatite (anhydrous magnsium silicate).

To produce the steatite seals, steatite rock was cut and then often coated with steatite paste. Hegde[17] has conjectured the following method of preparation for hollow steatite micro-beads: A paste of finely ground talcose steatite was probably squeezed through 1mm. diameter perforations having 0.5 mm. diam copper or bronze wires in centre to produce hollow tubes. These were then cut into small pieces, dried and hardened by firing above 900°C. The Harappans did not know chemistry or material science, but their empirical technology nevertheless be spoke of ingenuity!

A variety of gold ornaments were used by Harappans. The prolific use of silver was confined to the Late Harappan era. Lead was used for plumb bobs and even for better fusibility in copper casting. Copper technology was of course the most noteworthy. Arsenic, tin and nickel were used to alloy copper, but their sources are difficult to locate. Löllingite (Fe_3As_4) and scrap bronze (source of tin) have been obtained as archaeological specimens. Agrawal[17,18] analysed some 177 copper artefacts of which 8 p.c. contained arsenic and 4 p.c. contained nickel. Only 30 p.c. contained any tin, and 20 p.c. artefacts assayed 8-12 p.c. tin, suggesting some standardisation in the proces of alloying.

The Harappan tool repertoire comprises of razors, knives, chisels, thin arrow-heads and spear-heads, axes and fish-hooks. Metallographic examination of the artefacts indicated knowledge of slow-cooling of the cast, annealing and cold work etc., possessed by the Harappans[18]. Even lost wax or *cire perdue* process of casting was known to them as shown by the dancing girl figurines from Mohenjo-Daro.

The indigenous nature of the Harappan copper industry has been specially investigated. Both the sulphide and oxide ores were used for reduction to copper metal. Large quantities of copper oxide ore were discovered from a brick-lined pit at Mohenjo-Daro. Agrawal[17,18] has conducted very useful ore-artefact correlation. He suggested that Chanhu-Daro celt and Mohenjo-Daro spearheads were made from Khetri chalcopyrite ore, since all the three materials contained trace impurities of Sb and Pb but not Fe and As.

Similarly, Hegde[19] performed spectrographic analysis of two copper samples (an axe and a sheet) from Late-Harappan site of Ahar and of the Khetri copper ore, all the three from Rajasthan. The samples showed traces of elements such as Pb, Ni, Co, Fe, Mn, Zn etc. and absence of elements such as Au, Ag and Sn. This positive ore-artefact correlation suggested that the Ahar metal might have been made from Khetri ore.

The present author has however argued that even such correlations are not conclusive[1]. For conclusive evidences on indigenous technology, we should look for mines, metallurgical production units, artefacts at different stages of manufacture, heaps of slags and slag-ore correlation. Fortunately, several such evidences for indigenous metallurgy in India have been obtained from Mehargarh, Ganeshwar-Jodhpura, Chanhu-Daro, Ahar, Khetri (for copper), Atranjikhera, Ujjain (for iron), Zawar (for zinc) etc. Ahar for example has shown heaps of slags which have been analysed (Hegde, 1969).

THE TRANSITIONAL PERIOD AND THE VEDIC LITERATURES

The transitional period between the Harappan to the Historical eras namely 2000-800 BC has been characterised by several interesting features. A number of experts[16] have concluded that the collapse of the Harappan civilization was not on account of any 'foreign invasion' but essentially due to repeated floods, tectonic movement leading to the drying up and disappearance of the Sarasvati river, civil war, loss of trade etc. The Ṛgvedic civilization, which was most probably the Sothi Culture on the Sarasvati river, and very much a part of the wider Indus-Saraṣvati Valley civilization, moved eastwards in the search of perennial water. Harappans also moved to the southern India. During the said transitional period we come across two chalcolithic cultures: 'Copper Hoard' in the east, alloying copper more with arsenic, and Peninsular' in the south preferring tin and lead as alloying elements. In quest of fresh raw materials and alloying elements, chance discoveries had been made. The Rangpur, Gujarat, a Post-Harappan (2000-1300 BC) site showed copper objects containing nickel: a celt assayed 2.1p.c. nickel and a pin 5.88pc. nickel. Nickel in these samples was probably derived from the Rupavati ore in the neighbourhood and not an intentional addition[1].

The story of zinc also started during this period. The present author has claimed[20] that the earliest brass anywhere in the world is from the Harappan site of Lothal: No. 4189 copper object at 1500 BC. Lothal assys 6.04 p.c. zinc[18]. Harappan Rosdi also produced chisel, celt, rod and bangle containing up to 1.54 p.c. zinc. A part of a chariot in submerged Dwarka circa 1500 B.C. assays 10.68 p.c. zinc, 1.32 lead, 0.43 iron and rest copper. The Iron Age site of Atranjikhera (ca. 1000 BC) produced heavily alloyed copper objects : one asayed 6.28 Zn, 11.68 Sn, and the other 16.20 Zn and 20.72 Sn. The present author has drawn attention to these early samples of cementation brass and their possible link with the 1260 ± 160, 1136 ± 160 and 1050 ± 150 BC, C-14 dates of the timber samples in the Rajpura-Dariba silver-lead-zinc ore mine near Udaipur[20]. We would continue to describe the saga of bronze and zinc in India later.

The most intersting feature of this transitional period is the emergence of the Vedic literatures. Biswas and Biswas[21] have highlighted the literary evidences pertaining to minerals and metals in India, and naturally they have started with the Rgveda, world's oldest literature. Max Muller[22] had arbitrarily proposed that the Rgveda was compiled around 1200 BC, but this view may be summarily rejected[4]. This literature vividly describes the second millennium BC. Harappan civilization on the bank of the mighty river Sarasvati which disappeared after 1800 BC.

The transition from the neolithic to the chalcolithic age has been subtly depicted in the Rgveda (RV). Cutting stone-tool is indicated in RV 1.191.15 and this is corroborated in the Pre-Harappan stratum of Kalibangan(I) where we find chalcecdony and agate blades. These were serrated, mounted on wooden handle and probably used for cutting and sowing. *Kārmāra* was originally a stone-worker (RV 9.112.2) gradually becoming a metalsmith. The *vāśī* in the Ṛgveda is probably an adze with a flat surface and a sloping edge whose modern equivalent is carpenter's *basulā* (Hindi). Mehta and Kantawala[23] have pointed out that whereas RV 10.101.10 refers to *aśmanmayī vasi* or stone-made adze, RV 8.29.3 mentions *vāśīm āyasīm* or a metallic adze or axe.

In the Ṛgveda we find some concern for digging and mines *(khanitra)*, mining treasure *(nidhi)* and gems *(mani, ratna)* etc. Conch-shell *(śankha)* and conch-pearl *(krśana)* were quite popular. *Ayās* in the Ṛgveda meant 'metal' in general and not 'iron' in particular which was not discovered before 1200 BC. *Āyasī* or metallic equipments in the Ṛgvedic era were probably made of copper and its alloys such as bronze. Gold and silver were mentioned as such, but we do not know whether these were recognised as gems or metals. Even in the modern parlance, gold and silver are considered both as metals as well as minerals since these occur as such in nature. The Vedic literatures described various artefacts made of copper and bronze, and ornaments made of gold and silver.

Ṛgveda described fire as a 'cradle of gems' melting gold, and the blower *(dhmātari)* or the metalsmith blowing to produce sharp flame (RV 5.9.5) in a furnace. Later, *Śatapatha Brāhmana* (1.1.2.7, 1.6.3.16) introduced the word *bhastrā* meaning the leather-bellow used to blow air into a furnace.

Śukla Yajurveda (S. YV) was probably the first Indian literature to mention *śyāmāyasa* or *Kṛṣnāyasa* which is black metal or iron specifically. We also find mentioned there *loha* or red metal copper, *sīsaka* or lead, *trapu* or tin (S.YV 18.13). *Chāndogya Upaniṣad* (Cha. Up) recognised that metals have intrinsic properties irrespective of the shapes that these may assume (Cha. Up 6.1.5 & 6). It stipulated that one can join gold with the help of borax, lead with the help of tin etc. (4.17.7).

In the *Atharvaveda* (4.10.1-7), the genesis of conch-shell and pearl were speculated upon. *Śatapatha Brahmana* (6.1.3.1-5) propounded a theory of material evolution. *Kaṭha Upaniṣad* (1.2.20) mentioned atoms and molecules. *Uddālaka Āruni*, a historical figure of the eighth century BC was mentioned in the *Chāndogya Upaniṣad,* as propounding that everything in the universe including man evolved out of three elements, and even mind is a product of matter. He preceded Ṭheles of Greece by nearly two centuries and has therefore been claimed by Chattopadhyaya[24] as 'the first scientist in the world'. Commenting on the passage 7.1.2 in the *Chāndogya Upaniṣad,* wherein several branches of knowledge such as *rāśi* or mathematics, *bhūtavidyā* or physics and *nidhi* or mineralogy were mentioned, the great commentator Sankaracarya referred to *'nidhim*, the subject of mineralogy as found in books like Mahākāla etc'. We do not know the author or the approximate date of compilation of the book. Our surmise is that *Chāndogya Upaniṣad* was compiled as early as 8th century BC. Its tradition in mineralogy was sustained later as testified in the 5th century BC. *Aṣṭādhyāyī* of Panini and 4th century BC. *Kautilīya Arthaśāstra*. Theophrastus of Greece wrote his text on mineralogy much later (300 BC). The positive sciences of the Hindus were thwarted to some extent by the retrograde institution of caste. Originally, there was the division of labour but no hereditary caste (Ṛgveda 9.112.3). Gradually, seggregation was introduced in the society by the dominating Priestcraft, and this caused degeneration and the rise of *varnāśrama* or hereditary caste (Ṛgveda 10.90.12). The caste-system created a communication gap between the upper caste scholars and lower caste artisans. The damage perpetrated by the caste system on Indian science and technology cannot be over-estimated.

THE IRON AGE IN INDIA

Iron came later in human civilization compared to low-melting tin, lead and copper which could be easily reduced from their oxides and melted. Thermodynamically, iron oxide can be reduced to iron at any temperature above 800°C, but since the melting point of the metal is 1540°C, the ancient furnaces having a temperature in the range 1100-1200°C could result only in solid state reduction of iron oxide. Caught up in the reduced spongy solid mass used to be molten slag which had to be squeezed out by hammering and forging. The ancient smith took a long time to understand the intricacies of solid-state reduction and the fact that the soft mass of iron could be hardened and made useful only through prolonged contact with charcoal (the process of carburization).

The dates of the earliest iron age sites in India show that the discovery and use of iron started around 1200 BC indigenously and independently in at least three nuclear zones- Karnataka area in the south, U.P.- Rajasthan area in the north and West Bengal-Bihar area in the north-east. The evidences of early experimentation justify the theory of indigenous origin. Since iron could not be melted and cast easily, carburization of thin sheets of iron in charcoal fire and subsequent lamination and forge-welding of alternate layers of uncarburized and carburized sheets proved to be a spectacular and useful Indian discovery made much before the era of laminated Egyptian knife dated 900-800 BC[25].

The earliest evidence of hardening through quenching and tempered martensitic structure (characteristic of steel) obtained so far, pertains to a third century BC iron sickle from Pandu Rajar Dhibi in West Bengal. The iron tool types went on evolving with progress of time. Prakash and Tripathi (1986) divided the period of evolution into three long stages: Period I (1200-600 BC), Period II (600 to 100 BC) and Period III (100 BC to 600 AD). The marvellous and rustless Delhi Iron Pillar was built by Candragupta Vikramaditya (375-413 AD). This forge-welded 1600 years old structure is made of wrought iron (0.15 p.c. carbon). Its astounding corrosion-resistance is partly due to its composition ; high slag and phosphorus (0.25 p.c.) content and low manganese (0.05) and sulphur (0.005) content. This is one of the 'wonders' of the world.

MINES, GEMS AND MINERALS

In the Indian sub-continent, the first urbanization took place during the Harappan Era, and the second after a millennium during the Historical Period starting around 800 BC. There is controversy centering the view that the Iron Age initiated the second urbanization in India. This view may not be fully correct, since we know that the second urbanization hastened the progress of the Iron Age which moved on to the age of carburized iron and steel. The present author has suggested[27] that urbanization and technological progress had deeper reasons in augmentation of trade and cultural links with the external world, which was revived in the sub-continent around 800 BC.

A distinct feature of this second urbanization was the profound interest in the society in mining and metallurgy, minerals, gems and metals. Though it is a text on grammar, the *Aṣṭādhyāyī* of Panini contained a very large number of words related to technology of materials. Discovery *(upajñā)* and its application *(upakrama)* were highlighted. Mine *(Khani)* and its product, mineral *(Khanija)* were discussed. A smelting furnace was named as *pūtigandhi* on account of foul-smelling *(gandhi)* sulphur dioxide being one the gaseous products of the purifying *(pūti)* furnace. Slag was named *pūtikiṭṭa,* the refuse *(kiṭṭa)* out of the purification system *(pūti)*. Bahubhastrikā was many-bellowed furnace. Sattva *(essence)* stood for 'metal' since metal is the essence of a metalliferous mineral.

Kautilīya Arthaśāstra, the fourth century BC text, though primarily dealt with political economy, was also a remarkable compendium on mines and metallurgy. It dealt with management of mines, rock veins of minerals and precious gems, gold, silver, copper and their alloys, fabrication of metallic artefacts and so on.

The author of the *Arthaśāstra* classified gems on the basis of colour and lustre: colourless quartz, diamond etc., green *vaidūrya* (mentioned earlier by Panini) or beryl, blue sapphire, red ruby (*padmarāga* or lotus red), *pusyarāga* (turmeric yellow) or topaz, crimson-red *bālasūryaka* etc. The number of gems and minerals listed in *Arthaśāstra* far exceeded 16 given in the 300 BC Greek text *De Lapidibus* of Theophrastus.

Here we may note that Bauer[28] had written that the name of the rose-red Balas-ruby, a spinel $MgAl_2O_4$, was derived from the name of the place of its occurrence: Balascia (now Badakshan) of the Upper Oxus. The present author has however proposed that both these names were derived from the Sanskrit *bālasūryaka,* the crimson-coloured morning sun. It is quite likely that ever since Kautilya's time, the Indians were familiar with the spinel ruby mines of Badakshan.

At this stage we wish to draw attention to India's primacy not only in the fields of mineralogy and metallurgy, but also to the science of linguistics. The names of many minerals and elements that we find in European languages were originally derived from Sanskrit, and what is more, the Sanskrit names have strong etymological roots! The name 'corundum', a mineral was derived from Sanskrit *kuruvinda*[29], that which abrades. The word 'sulphur' was derived from Sanskrit *śulvāri* meaning that which is enemy *(ari)* of, or reacts with, copper *(śulva)*.

Just as the element or metal beryllium is derived from the mineral beryl, the name 'beryl' itself is derived from Sanskrit *vaidūrya* or better the South Indian word *veluriya*[30]. Panini of the fifth century BC mentioned in his *Astādhyāyī* (4.3.84) that the mineral came from the Vidūra (far away) locality in South India and hence may be termed as adjectival *vaidūrya*. Vidura locality has been identified by Buddhabhatta (*Ratnaparīksā,* 199) and Finot (1896) as the modern Salem district[31]. The mines of Coimbatore used to supply beryl for its export to the Romans. In the Pali texts the mineral was known as *veluriya* and this Dravidian word was derived from *vel* (white) *ur* (town) i.e., the locality which supplied white crystals of crystalline and chalcedonic quartz and also beryl (which is also colourless, unless it contains impurities such as Cr and Fe which make it the popular green beryl). In Arabic and Persian, we find this original meaning retained: billaur means white crystal such as quartz.

Outside India, green *veluriya* was known as *beryllos* (Greek) and *beryllus* (Latin). The middle high German *brille* stands for green eye glasses which Emperor Nero used to wear. The Benedictine monks considered the green mineral as a symbol of purity. Finally, we have the English 'beryl' and 'beryllium'. The largest hoard of the Roman coins has been found in the Coimbatore District and this proves the vigorous Indo-Roman trade on quartz and beryl gems.

TAXILA AND THE PRIMACY OF INDIA IN BRASS AND ZINC METALLURGY

The 5^{th} to 2^{nd} century BC era of the Nandas and Mauryas was a golden period for mineralogy and metallurgy in India. This is attested not only in the writings of Panini and Kautilya but also in the archaeological treasures excavated at Taxila[32]. Situated 22 miles north of Rawalpindi in Pakistan, Taxila displayed long and sustained civilization from 500 BC to 400 AD from the eras of the Nandas and Mauryas to the era of the Guptas.

Excavated in Taxila were many gold and silver jewelleries, gems, inlays, intaglios, metal coins and beads. For making the beads, the principal minerals used were carnelian, agate, quartz, malachite, lapis lazuli, garnet, jasper etc. arranged in decreasing order of abundance. Evidently, lapis lazuli continued to be imported, carnelian produced indigenously, and beryl exported. Shell and faience beads were also very common. Glass beads were of seventeen colours, the most popular ones being green and blue. Presumably, these were imitations of beryl and lapis.

Taxila displayed huge number of artefacts made of iron and copper, both pure as well as alloyed. The principal alloying elements were tin, lead, antimony, nickel and zinc, while traces of iron and arsenic had got into copper as impurities. Taxila produced soldering alloy containing 50 p.c. lead, 46 p.c. tin and 3 p.c. copper. Around 1 p.c. antimony in several copper samples seems too low to suggest deliberate alloying. Probably, the antimony-rich copper ore from Badakshan, Balkh and Kabul might have been tapped; this type of ore also resulted in the Taxilian white opaque glass (5.08 p.c. Sb_2O_3) and turquoise blue powder (2.42 Sb_2O_3 and 3.6 CuO). During the medieval period, antimony sulphide of this region was indeed used to make high-antimony *Khārsini alloy*. In Taxila, 'white copper' alloy (known as *pai-tung* in China and *packtong* in Europe) used to be made containing nickel, 9 p.c in the early third century BC samples, and later a fairly regular proportion of 19-21 p.c. This ductile alloy was valued for its silvery lustre and employed for jewellery, coinage etc. Appearances of antimony and nickel in the copper artefacts of Taxila were indicative of trade contacts with Afghanistan and China.

Taxila provides us with a link in the continuity of our narrative on brass and zinc in India. We have referred to the earliest brass in Lothal and Dwarka and then Atranjikhera. India continued to make brass through the cementation route, namely reduction of copper ore and zinc ore in the same furnace simultaneously. While zinc oxide is easily reducible at the usual temperature of the smelting furnace, the metal zinc is produced in the vapour state, since it has a low boiling point 917°C. Zinc vapour gets absorbed in copper to produce cementation brass.

It has been proved through replication experiements[33] that the cementation process cannot give brass containing more than 28 percent zinc. Therefore, we cannot fail to note the overriding importance of the vase (BM 215-284) excavated from the Bhir Mound at Taxila and dated fourth century BC which was before the Greeks arrived in India. This brass sample contains 34.34 percent (much more than the critical Figure of 28) zinc, apart from some tin and lead. The sample must have been made through mixing of pure zinc and pure copper, and provides very strong evidence for the availability of metallic zinc in the fourth century BC[34]. Now it is accepted that India was the first to make this metal zinc *(rasaka)* by the distillation process as practised for the other metal mercury *(rasa)*. The ancient Persians tried in vain to reduce zinc oxide in an open furnace when the reduced zinc vapour quickly reacted with air to give back white dust of zinc oxide! The Indians empirically discovered the art of closed retort reduction and condensation of zinc vapour in a reducing atmosphere.

The ancient zinc ore mine at Zawar, 30 km. south-west from Udaipur, has revealed C-14 dates of timber such as 430 ± 100 and 380 ± 50 BC etc., Willies[35] has provided vivid description of the ancient zinc mines of Rajasthan, particularly the Zawar Mala mine, where Hegde[17,19] identified several five liter capacity pear-shaped pots as Ahicchatra 10A type pottery datable to the last quarter of the first millennium BC. The second century AD text *Rasaratnākara* of Nāgārjuna referred (1.31-32) to the reduction-distillation of calamine yielding zinc: "an essence of the appearance of tin". It seems that the Greeks closely followed the Indian developments in the fields of brass and zinc technology. Their term for brass was 'oreichalcos' which was adapted in Sanskrit during kautilya's time as *ārakūta* (just as Greek 'cassiteros' for tin was converted to *kastira* in Sanskrit). Eventually, however, the Sanskrit term for gold-like yellow brass was *pīta-tāla* (yellow alloy) or *pitala*. In view of the Indian quest for substitute gold, the name for zinc was changed from *rasaka* (that which is distilled like *rasa* or mercury) to *yaśada* (that which gives *yaśa* or fame alluding to gold). It is this later Sanskrit word *Yaśada* which was converted to *dastā* in the other Indian languages and 'zinc' in the European languages.

The Greeks appear to have carried back to their country a sample of Indian zinc as souvenir. In the course of the excavation of the Agora in Athens, a roll of sheet zinc was found in a sealed deposit and this has been dated to belong to the third/second century BC[36]. Analysis showed it to be nearly pure zinc with 1.3

p.c. lead, 0.06 Cd, 0.016 Fe, 0.005 Cu with traces of Mn, Mg, Sn, Ag and Sb. It is well-accepted that the Greeks never made any such thing themselves during 3rd/2nd century BC[34]. Most possibly they carried this material from India and this can be confirmed through trace analysis and lead isotope ratio matching between the cited sample and Zawar ore. Ever since 4th century BC India has been the only country in the world to make pure zinc and high-zinc brass. The technology of reduction-distillation of zinc was developed through centuries, and we would describe it (as it stood during the medieval era) later.

THE RATNAŚĀSTRA TEXTS AND THE INDO-ROMAN TRADE ON GEMS

The science of gemmology in India started with the 4th century BC *Kautilīya Arthaśāstra.* We do not know the dates of the early authorities such as Mahākāla or Vyādi. The Indo-Roman trade picked up during the turn of the millennium and prospered during the post-Christian centuries[37-40]. Following this Graeco-Roman trade on gems, the Ratnaśāstra (gemmology) texts were compiled by successive authors in India. The Tamil text *Śilappadikaram*[41] was compiled during 2nd century AD. The 5th century AD texts *Brhat Samhitā* of Varahamihira and *Ratnaparīkṣa* of Buddhabhatta were outstanding. Many more texts were written upto 13th century AD. Many of the original texts have been published with translations[31,42].

The ancient Indians were attracted by the lustre and colour of gems which they tried to categorise in terms of colour. This led to some confusion since two entirely different gem minerals could show the same colour. Hence, relative hardness was introduced as an important criterion in distinguishing one from another. Density or specific gravity was also recognised as an important property of the gem minerals. Dichroism, the property of some transparent gems of exhibiting two different colours, when viewed through perpendicular directions, was known. Birefringence *(dvichhāyā)* of calcite-like minerals was also observed. The Indians processed a wide variety of gems starting from the hardest diamond (Moh's scale of hardness ten), corundum (nine) down to talc (one), pearl etc.

The sources of diamond (mines) in India were keenly investigated in the *Ratnasastra* texts as well as by the Roman authors. Early literature refers to *akara* (mine of diamond) and *ākarāvanti,* Avanti the mining town. The crystalline properties of diamond were noted: eight symmetric facets *(samaphalaka),* twelve sharp edges *(dhārā),* six prominent solid angles (koṇa) etc., (in the text *Rayanaparikkhā,* 23-24). Diamonds were classified in terms of transparency, colour and 'castes'. The price of a crystal increased with approximately the cubic power of the mass or size. With a tenfold increase in mass (from 2 to 20 *taṇḍula* or 4 carats), price increased approximately 1000 times. A text (Agastimata 50) suggested that diamond is approximately four times heavier than water. Its specific gravity is now taken as 3.52. The traders knew that relatively heavier pieces were impure; the usual impurity zircon has a higher specific gravity 4.68.

Both diamond and corundum powder were widely used as abrasives. Corundum was used to polish Asokan sandstone pillars and exported to Rome for marblesawing and polishing gems. Pure Al_2O_3 lattice corresponds to colourless *Kuruvinda* (corundum) and some substitution in the lattice by chromium makes it red *padmarāga* (ruby) and iron or titanium in the lattice makes it blue *indranīla* (sapphire). The substitution lowers the surface free energy and hardness to some extent. Although the theory was not known, Buddhabhatta correctly observed *(Ratnaparīksā,* 137) that corundum is slightly harder than ruby and sapphire. Asterias or star sapphire is a chatoyant star, reflecting light from the surface of microscopically small tubular cavities. *Kautilīya Arthaśāstra* (2.11.31) described this as *śravanmadhya* or 'streaming interior showing rays shooting like flowing water'.

We have earlier mentioned beryl, a very important gem of India. The present author has presented elaborate discussion on the etymology and trade of beryl *(vaidūrya)* and emerald or *marakata*[45]. Emerald was well-known to Indians as an Egyptian *(masara)* gem *(galu),* masāragalu or māsaraka and also as marakata, the gem which is obtained from a mine (in Egypt) which is reached after one crosses the desert *(maru)* and the coast *(kata).* The etymological links between (a) veluriya-beryl and (b) masāraka-smaragdos-esmeralda-emerald indicate the power of the Sanskrit language and the primacy of India in gemmology.

We may cite another glorious example of the twin primacies of India in the fields of gemmology and linguistics. The *Periplus* has documented that India exported ivory to the Graeco-Roman world through Barugaza in Gujarat, which had a sizeable population of elephants. Schoff recorded[38] how the Sanskrit word *ibha* (elephant) and *ibha-danta* (elephant's teeth) were converted to abu in Egyptian, Semitic article *el* prefixing *ibha-danta* to give *elephas* in Greek, and the English words 'elephant' and 'ivory'!

The Romans were fascinated with the Indian merchandise of beryl, quartz, chalcedony group of gems such as carnelian, agate and above all the gem of gems: the Indian oyster-pearl. There were elaborate testing procedures for checking the right qualities of pearl; this involved heating the samples in specific liquids, washing and rubbing with cloth which remove the lustre of only the sub-standard pearls. Small pearls were priced in terms of weight of a large number of collection.

Bigger pearls were priced individually as in the case of diamonds. The price varied directly as weight raised to the power n where n was anywhere between 2 to 3. Indian pearl-necklaces, given names according to the large variety of designs, were adored all over the world. It was testified by Kautilya and Megasthenes that Indians exported pearl and imported coral. Pliny observed (*Naturalis Historia,* 32.11) with some surprise that red coral, which was not so much in demand in the Roman empire, was as highly prized in India as the white pearl at Rome. He was effusive while describing how the Indian pearls were adored by the Roman ladies[38]. The Indian trade-centres were conduits for gems from the neighbouring countries also, such as ruby, sapphire, zircon, tourmaline from Sri Lanka, callaina or turquoise from 'back of India' (Pliny probably did not know that it was from Khorasan of Persia).

Most of the authors of the *Ratnasastra* texts speculated on the origin of the gems, and tended to support the mythological theory that these were derived from the body of the slain demon Bala. In his *Brhat Samhita* (80.3), Varahamihira hinted at a more scientific explanation that the gems were caused by 'the characteristic qualities of the earth'. The idea was however not seriously pursued, and the Indian gemmologists spent more energy in linking gemmology with astrology and prognostication.

THE RAŚĀSASTRA TEXTS ON OTHERS MINERALS AND METALS

The 4th century BC text *Kautilīya Arthaśāstra* dealt with both gems as well as non-gems, other minerals and also metals and alloys. In the post-Christian era, the *Ratnaśāstra* texts dealt exclusively with gems *(ratna)*, and the rest of the topics was left for *Rasaśāstra*. *Arthaśāstra* used the word *rasapāka* meaning smelting of ores involving liquid *(rasa)* through heat and melting. This subject had been initiated earlier by the specialists in medicine like Caraka who were in search for the ideal rasa or elixir which could prolong life indefinitely. They believed in therapeutic values of organic as well as inorganic materials such as metals and metallic compounds; they also aspired to convert base metals into gold. This alchemical dream was boosted when Nagarjuna of 2nd century AD claimed (*Rasaratnākara* 1.3) that zinc ore roasted thrice with copper converts the latter into 'gold'. It was gold-like, brilliant yellow brass!

The texts compiled between 7th to 13th century AD or the 'Tantric Period' pursued the alchemical dream. For another three centuries, Hindu chemistry progressed through the 'Iatro-chemical Period', abandoning alchemical dream, and concentrating more on medicines derived from minerals and metals.

Rasārnava (RNV), a 12th century AD text, described a large number of equipment or apparatus, crucibles, furnaces etc., for processing of minerals and metals[44]. The flames were stated to be specifically coloured due to specific salts of copper, tin, lead etc. (RNV 49). Procedures were described for making metal from *mākśika* (RNV 7.12-13) *vimala* (7.20-21), *sasyaka* (7.41-44) etc., the first two being pyrites bearing copper, and the third copper sulphate, and the wonderful observation was made that all the three red products seemed to be identical: *tāmra* or copper! This observation made centuries before the discovery of elements and Daltonian chemistry, cannot be belittled. In the 5th century AD. Prasastapada had speculated in his *Padārtha-dharma-saṁgraha* that atoms *(anu)* form, through dyads *(dvyānuka)* and triads, *(tryānuka)*, gross bodies ('molecules' in modern terminology) and 'this gives rise to different qualities in a substance'. The Indian alchemists were groping in the dark, but were very close to modern chemistry.

Rasārnava arranged six metals: gold, silver, copper, iron, tin and lead in the order of increasing rate of corrosion (RNV 7.89-90) and poetically described high reactivity of sulphur with most of the metals: There is no such elephant of a metal which cannot be killed by the lion of a sulphur" (RNV 7.142). We have indicated earlier the evolution of the word 'sulphur' itself. In the previous incarnation it was *śulva* (copper) *ari* (enemy) or *śulvāri*; the evolution clearly bears the imprints of the Sanskrit language and the imaginative Indian alchemist.

The 13th/14th century text *Rasaratnasamuccaya* (RRS) showed further progress in the Indian *Rasaśāstra* tradition; Joshi[45,46] has translated and annotated this very useful text. In RRS we find many details regarding gems, non-gem minerals, metals, alloys, reduction-oxidation in mineral-metal-metal oxide systems, conversion to sulphides etc. For the conversion of minerals to a pharmaceutical recipe, acceptable to the body, many unit operations were described: purification of the mineral, metallic extraction *(satvapātana)*, liquefaction, distillation, incineration etc. RRS contains description of several kinds of crucibles made of fireclay *(vahnimrttika)*, funaces, implements and equipment to be used in the alchemical laboratory. The concepts of alloy or mixed metal *(miśra loha* or *yukta)* and heat-treatment by quenching *(śastrapāna)* were elaborated. Alloys of five metals *(pañcaloha)* and eight metals *(aṣṭadhātu)* were developed mostly for making auspicious icons.

Among the non-gem minerals and natural products we find listed: cinnabar, calomel, stibnite, orpiment, realgar (many of these used to be imported on account of their medicinal values). Locally produced were mica, pyrites, chalcopyrite, zinc ores of different varieties, mordants like alum, green and blue vitriols (ferrous and copper sulphate), borax (a flux), salts like *culikā lavana* (potassium chloride), *sorā* (potassium nitrate), *srotāñjana* or *sohtā* (carrollite, which is copper-cobalt sulphide), red ochre etc. All of these had well-defined Sanskrit names. For some of the gems, the Arabic and Persian names gained usage in medieval India.

RRS provided valuable descriptions with regard to zinc technology in medieval India as well as to the different varieties of Indian iron and steel. We would mention these in our following sections.

ZINC TECHNOLOGY IN MEDIEVAL INDIA

Even though Hindu science and technology suffered stagnation and decay after the collapse of the Gupta dynasty in the fifth century AD, it survived beyond 1200 AD, a date which marks the onset of the medieval period in India and when the Muslims established their stranglehold on a sizeable part of the sub-continent. Of course the Muslims could not dominate over several other regions in the country such as the Hindu Kingdom in Udaipur, southern Rajasthan, where zinc technology reached a developed stage in the 13th century AD. This technological outfit has been recently discovered archaeologically in 1983-1984 and described in detail by Hegde[47,48] and the present author[1].

The excavation in Zawar revealed an extensive arrangement of furnaces with retorts 30-35 cm long and 10-15 cm diameter. There were 36 retorts in a 6X6 arrangement contained within the truncated pyramid of each furnace. The retorts were supported vertically on perforated bricks through which the condenser tubes passed into the cooler zinc collectors beneath. This arrangement of downward distillation retort with the condensing unit underneath is precisely what had been described[46] in *Rasaratnasamuccaya* (RRS 2.157-166; 9.48-50). The brinjal-like retorts in Zawar are also similar to the *vṛntākamūsā* described in RRS (10.22-23).

Sphalerite with impure dolomite and quartz was mined, crushed, ground and mixed with a small quantity of common salt and a large quantity of carbonaceous matter. The charge (about 1.5 Kg. per retort) was loaded into the retorts, fitted with the funnel-like condenser tubes, and heated externally, possibly at 1250°C for six hours. The reduced zinc vapour was condensed and collected. It is likely that 200-500 gms of zinc were extracted per retort, or 7-18 kg per smelt of 36 retorts. A part of the zinc oxide was converted[49] to well-identified silicate phases and thus could not be recovered as reduced metal. At present there are 8 lakh tons of debris at Zawar containing 6 lakh tons of spent retorts. Each retort weighs about 3 kg. and might have produced 500 g. of zinc. On this basis it is estimated that about 0.1 million tonnes of zinc might have been produced at Zawar during the 13th-18th century AD period.

The technology became extinct by the end of the 18th century on account of the repeated invasions of the Marhattas. However, during 1720-1743 there was a technology-transfer from Zawar in India to Bristol in England. Craddock et. al.,[50] have conceded that some Englishmen had visited Zawar, and William Champion's 1743 process 'was notoriously close with details to the Indian process at Zawar'. They have also noted[50] with satisfaction (1985, p. 52) that this technology-transfer is 'a striking example of continuity and the reciprocal nature of scientific and technological development throughout the world'.

The Zawar technology had been kept a well-guarded secret; Abul Fazl[51,52] in Akbar's Court knew nothing about the details. As late as 1751 AD, *Postlewayt's Dictionary of Trade and Commerce* admitted ignorance about zinc technology. While the rest of the world manufactured brass by the cementation route only, and none of this assayed more than 28 p.c. zinc, India alone produced high-zinc brass. The artisans of Bidar (83 km from Hyderabad in South India) produced during the 15th century AD 'Bidri' alloy, containing as high as 76-98 p.c. zinc, 2-10 p.c. copper, at times 1-8 p.c.lead, 1-5 p.c. tin and trace of iron. Vessels made of Bidri alloy were darkened by applying a paste of ammonium chloride, potassium nitrate, sodium chloride and copper sulphate. The precise composition of the amorphous black patina is not known; scanning electron microscopy reveals that the 10μm thick surface assay 30 p.c. copper as a contrast to 3 p.c. in the bulk[53]. Before the blackening procedure, appropriate design used to be engraved on the vessel, and on this, silver, brass or gold wire was inlaid or encrusted. After blackening, washing and polishing, the Bidriware-a *huqqa,* ewer, bowl or *pan* box-appeared as a lustrous dense black body contrasting with the brilliant lining or inlay- white (silver) or yellow (brass or gold)[54].

MINERALS IN PRE-MODERN INDIA

While surveying the topics of gems, non-gem minerals, iron and steel in pre-modern India[55-57], it has been noted that the information on science and technology in general during the Muslim period in India is very scanty[58]. Much of the valuable information is gleaned from the 18th-19th century writings of the British observers of what we would call 'pre-modern' rather than 'medieval' India. The monograph of Valentine Ball[59] on mineral reserves and mineral-based industries in pre-modern India is of excellent standard.

We have some idea about the wealth of precious gems in medieval India from the account of Allauddin Khilji's loot of South India (1310-1312 AD) and his collection of gems provided by Hazrat Amir Khusrau in his *Khazainul Futuh* or *Treasures of Victory* and by Thakkara Pheru (born 1270 AD) in his *Rayanaparikkhā*. Odarodo Barbosa reported in 1519 'the gem market at Vijayanagara' and Jean Baptiste Tavernier wrote on precious gem mining in India (1665-1669) and the gem treasures of the Mughals. We have the description of six varieties of corundum at Pipra and the description of the Ratanpur mine, processing agate and carnelian.

There were five distinct groups of diamond mines in India: Cuddapah group on the Pennar river, Nandial, Ellore or Golconda group on the Krishna, Sambalpur on the Mahanadi and the famous Panna group in Bundelkhand. Dutt[60] surveyed various reasons for the decline of Indian diamond industry: exhaustion of the diamond-bearing rocks, water trouble in the excavations, oppressive nature of the mining and political administration, absence of systematic prospecting operations, superstitions amongst the workers and the discovery of diamond fields in other parts of the world (such as in Brazil, 1728).

Tabling action or flowing-film concentration along the bend of Indian rivers had concentrated heavy minerals like diamond and gold for ages, and toiling masses have further purified the same through painstaking efforts. Major J.R. Ouseley[61] published his note on the process of washing for the gold dust and diamonds at Hirakund (which literally means diamond mine) on the river of Mahanadi near Sambalpur. Ouseley described the manual process and suggested mechanisation featuring the principles of sieving, gravity settling and tabling–which had never been done in the medieval India.

Salt reserves in Punjab were quarried or mined for centuries. The principal quarries were at Bhadur Khel, Malgin, Jatta etc. The Salt Range mines such as those near Pind-Dadan-Khan, about 100 miles north-west of Lahore, were also exploited from time immemorial. Burnes[62] left an interesting account of the mines[62].

Reh is the Indian term applied to efflorescent salts which had accumulated in the soil and sub-soil water of large tracts in India. The principal constituents in the Reh samples from Moradabad, Meerut, Kanpur etc and in the Sambhar lake bittern and Lonar lake incrustation were Na_2CO_3, $NaHCO_3$, NaCl and Na_2SO_4. The Lonar sample contained 4-10 p.c. K_2O in addition. The crude mixtures ware lixiviated and concentrated. The final products sustained many industries in medieval India such as NBPW pottery, glass, soap, bleaching and dyeing, curing hides, medical formulations etc.

Saltpetre was a bio-geological deposit containing not only KNO_3, an important constituent of gunpowder, but also nitrates of sodium and calcium and several chlorides. After lixiviation, filtration and evaporation the solute was used for cooling water. The major use however was in refining of saltpetre. Fractional crystallisation of potassium nitrate (which 'unlike other constituents is non-hygroscopic') enabled its use in gunpowder. This technology was practised by the Dutch and the British in India[63]. The manufactures of blue vitriol (copper sulphate), alum and green vitriol or copperas (iron sulphate) from bacteriological end-products and residues were widely practised in India and carefully summarised by Valentine Ball[59].

We have earlier mentioned zinc ore mining in ancient and medieval India. Ball has recorded many reports on lead, copper and iron ore mines. There were many ancient lead mines[59] in Southern India, Afghanistan, Baluchistan and Rajasthan. Whereas the shafts and galleries at Feringal mine in Afghanistan 'showed a most surprising degree of mining knowledge', the lead ore mines at Ajmer were in bad shape. 'The tortuous course of the vein precluded the practicability of removing mine water'[64].

There were many copper mines of great antiquity which have not been C14-dated. Pheru and Abul Fazl recorded copper smelting at Babbai and Singhana respectively. Related to pre-modern copper technology in India two beautiful reports are available: on Singhana[65] and on Kolihan[66]. It is estimated that around 6 million tonnes of copper ore were mined in the Khetri area during 1590-1895 and more than one lakh ton of copper metal must have been produced during this time[67].

IRON AND CRUCIBLE STEEL IN PRE-MODERN INDIA

Valentine Ball[59] recorded the diversity of iron ores mined, purified and processed by the iron smelters of pre-modern India, citing the reports of the earlier workers. In medieval India, three types of furnaces were used for smelting: small blast furnaces (4-5' feet high), tall blast furnaces (typically 10' feet high) and bowl-shaped open hearths. India produced three kinds of products: crude wrought iron, pure wrought iron and high-carbon wootz steel made in crucibles. The 13^{th}/14^{th} century AD text *Rasaratnasamuccaya* (RRS 5.70-99) cited three kinds of iron: *muṇḍam* (wrought iron) which could be *kuṇṭham* or *kaḍāram,* less ductile containing some carbon, second variety *kāntam* (magnetic or made from magnetite), and third *tīksnam* (cast or carburised iron or steel) which again was known in six varieties to be described later.

It is quite likely that there were some foreign interactions with the iron and steel industry in India during the Mughal period. Some of the South Indian iron-making furnaces (10-15' feet high, 3' feet diameter) resembled Stuckofen smelters in Germany; Dutch influence in the design of this kind of furnace cannot be ruled out. The Dutch were consumers and even producers (in the Orissa coast) of Indian iron and steel. The iron industry in Kathiawar had furnaces of unusual shape: 'something of the nature of a reverberatory furnace', the development of which might have been assisted by some European technicians. Some Chinese influence was evident in Upper Assam where the smiths used contrivances quite different from those used in India proper. They used special blowing machines—single-acting or double-acting blowing cylinders-which substantially raised the temperature of the charcoal-fired furnace.

Bennet Bronson[58,68] has wondered how early was wootz or crucible steel made in India, and grudgingly conceded that it could have been as early as second century AD. Excavations have revealed crucibles dated 250 BC in Tamilnadu. *Kautiliya Arthaśāstra* (2.12.23, 2.17.14, 3.17.8, 4.1.35) repeatedly mentioned *vrtta* which is carburised iron or steel. Vrtta means circle and denoted crucible of circular cross-section in which wrought iron was fused with carbon. The word was changed to wootz in South India (*wuz* in Gujarati, *ukku* in Telugu).

There were two distinct processes for making *wootz*. The process practised in Sri Lanka, Tamilnadu and Karnataka merely carburised wrought iron in crucibles. The Persians were interested in the second process practised in Golconda or Konasamudram, Hyderabad, described in detail by H.W. Voysey[69].

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, was converted to *wootz* (various samples of ingot, blade, dagger and sword assay 1.1 to 1.874 p.c. carbon, many in the 1.6-1.7 p.c. carbon range) by melting it with wrought iron. 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 notion that *wootz* was merely carburised iron.

Sherby and Wadsworth[70] have suggested that high-carbon *wootz* cakes were probably forged at not-too-high a temperature: between 'blood-red' 650°C to 'cherry-red' 850°C, and then heat-treated by quenching, to produce damasked sword. They authenticated their suggestion through replication experiments. This is also attested by the vivid description of Tavernier, the French traveller, made in 1679:-

"The steel used by Persians is brought from Golconda (Hyderabad), and is the only sort of steel (anywhere in the world) 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".

The unique thing about Indian *wootz* was that annealing at less than 850°C made it hard as well as ductile. Attempts made by famous scientists such as Faraday[71] to simulate wootz failed, because they were trying higher temperature for annealing.

Three centuries before Tavernier, six varieties of tīksnam or steel were described by Vāgbhat in his *Rasaratnasamuccaya* (RRS 5.75-5.82). *Pogaras* meant hair-like lines which may be surmised as white cementite streaks. The *Khara* variety was brittle with 'mercury-like shining fracture surface' (RRS 5.76). *Hrnnāla* was very hard, and *vajra* was full of hard *bogaras*. The best was *kālāyasa:* 'bluish black, dense, smooth, heavy, bright and its sharpened edge not spoiled by hammering'. This description is close enough to that of the damascened steel swords 'of a dull blue colour and with meandering lines'[70], which have compressed and elongated cementite grains or streaks in pearlite-graphite-martensite matrix. The excellence of Indian *wootz* was attested by the great scientist of the modern era, Michael Faraday.

FACTORS UNDERLYING MEDIEVAL STAGNATION IN INDIA

Having documented India's primacy in mineralogy and metallurgy, from the pre-Harappan era 7000 BC to the Gupta Period 500 AD, and having shown that the tradition survived even in the medieval era beyond 1200 AD, it is now necessary for us to explain the factors underlying medieval stagnation, not only in the two said disciplines but also in Indian science and technology in general.

Up to 5th century AD, India was one of the leading nations in the world, not only in the technological fields related to minerals and metals but also in some of the basic sciences such as linguistics, medicine, astronomy and mathematics. India produced a large number of mathematician-astronomers starting from Aryabhat in the fifth century to Bhaskaracharya of the twelfth century AD. But the caste system ruined Indian science and technology. The upper caste intellectuals hardly helped or interacted with the low caste artisans. There was widespread secrecy and isolationism in the society. The irrational approaches were hardly countered. Scientific logic was often offset by theological obscurantism. The divided Hindu society succumbed as an easy prey to the Muslim onslaught.

During the sixth to tenth century period, the Arabs took over the intellectual leadership and transmitted to the Europeans in Spain not only the Greek thoughts but also the Hindu sciences such as astronomy and algebra of Brahmagupta. However, it was a different story in India of the twelfth century. While the barbaric Muslim invasion of India was having catastrophic effects on the Indian society, Baghdad itself collapsed under the Mongol invasion. Irfan Habib[72] has candidly described the scenario:

"That time (after the death of Ibn Rushd or Averroes in 1198 AD), science received a setback throughout the Islamic world. There was a heavy onslaught on reason. In medieval India, therefore, Islam was received when the scientific tradition in it was in the process of decay".

"The Mughal empire has produced not a single worthwhile text on crafts or agriculture, how many volumes of poetry or histories it might have to its credit. The Indian rulers' refusal to Western science and thought was at par with their indifference to technology".

On account of the rulers' barbarity and indifference, the artisans missed the benefits of the European science and technology. Mining of gem, non-gem and metalliferous minerals was pre-scientific, and the miners had no geological knowledge to pursue through the depleted rocks. The problems related to mines, their drainage, lack of pumps, lack of mechanisation etc. which had earlier been faced and favourably tackled by the Westerners, continued to haunt medieval and pre-modern India, gasping in vain for solutions.

The indigenous iron and steel smelters of medieval India faced acute shortage of charcoal in the country and lacked the technologies related to coal mining, coke production and superior blowers for the blast furnaces. The cost of production of indigenous iron and steel was going up, and at this stage the British traders, with their newly acquired political strength, started flooding the Indian market with cheap iron produced in big British blast furnaces. Large-scale economic breakdown and loss of political independence resulted in the disappearance of the indigenous industries.

Having gained independence, the Indian sub-continent has again regained hope and faith in indigenous technologies and scientific endeavour. The heroic contributions of the artisans (in the fields of gems, minerals and metals) who toiled through the ages, are gratefully recalled. Their vitality was sustained through centuries, and could not be extinguished either by the Hindu obscurantism, Muslim fundamentalism or British colonialism.

REFERENCES

1. Biswas, Arun Kumar., 1996. 'Minerals and Metals in Ancient India Vol. I. Archaeological Evidences, D.K. Printworld Pvt. Ltd., New Delhi.
2. Dana, E.S., 1965. A Textbook of Mineralogy, Wiley, New York, 1914; 17th edition revised by C.S. Hurlburt.
3. Hemley, Russell J., 1999. Mineralogy at a Crossroads, Science, 13 August, Vol. 285, pp. 1026-1027.
4. Biswas Arun Kumar., 1990. The Aryan Myth in Historical Archaeology of India, edited by Amita Ray and S. Mukherjee, Books and Books, pp. 29-47.
5. Jarrige, J.F., 1982. Excavations at Mehargarh, in Harappan Civilization, edited by G.L. Possehl, New Delhi, pp. 79-84.
6. Asthana, Shashi., 1985. Pre-Harappan Cultures of India and the Borderlands, Books and Books, New Delhi.
7. Agrawal, D.P., 1971. The Copper-Bronze Age in India, Munshiram Manoharlal, New Delhi.
8. Caldwell, J.R., 1967. Investigations at Tal-i-Iblis, Illinois State Museum Preliminary Report No. 9.
9. Agarwala, R.C., 1982. Ganeshwar-Jodhpura Culture, in Harappan Civilization, edited by G.L. Possehl, Oxford & IBH Publishing Co., New Delhi, pp.125-134; Aravalli, the Major Source of Copper for the Indus and Indus-related Cultures, in Frontiers of the Indus Civilization edited by B.B. Lal, S.P. Gupta and Shashi Asthana, Books and Books, New Delhi, 1984. pp. 157-162.
10. Dales, G.F and Kenoyer, J.M., 1977. Shell Working at Ancient Balakot, Pakistan, in Expedition, Vol. 19, Part 2, pp. 12-19.
11. Leemans, W.F., 1960. Foreign Trade in the Old Babylonian Period, E.J. Brill, Leiden.
12. Marshall, J., 1973. Mohenjo-Daro and the Indus Civilizations, Indological Book House, Varanasi.

13. Mackay, E.J.H., 1976. Further Excavations at Mohenjo-Daro, Indological Book Corpn.

14. Vats, Madho Sarup., 1974. Excavation at Harappa, Bharatiya Publishing House, Varanasi.

15. Rao, S.R., 1979 and 1985. Lothal – A Harappan Port Town, Archaeological Survey of India, New Delhi, Vol. I, Vol. II.

16. Possehl, G.L. (edited), 1982. Harappan Civilization, Oxford & IBH, New Delhi.

17. Hegde, K.T.M., Karnath, R.V and Sychanthavong, S.P., 1982. On the Composition and Technology of Harappan Microbeads, in Harappan Civilization, edited by G.L. Possehl, Oxford & IBH, New Delhi, pp. 239-244.

18. Agrawal, D.P., 1984. Metal Technology of the Harappans, in Frontiers of the Indus Civilization, edited by B.B. Lal, S.P. Gupta and Shashi Asthana, Books and Books, New Delhi, pp. 164-171.

19. Hegde, K.T.M., 1969. Technical Studies in Copper Artefacts Excavated from Ahar, in Excavations at Ahar edited by H.D. Sankalia, S.B. Deo and Z.D. Ansari, Deccan College, Pune, pp. 225-228.

20. Biswas, Arun Kumar., 1993. The Primacy of India in Ancient Brass and Zinc Metallurgy, Indian Journal of History of Science, 28(4), pp. 309-330.

21. Biswas, Arun Kumar and Biswas, Sulekha., 1996. Minerals and Metals in Ancient India. Vol. II Literary Evidences, D.K.Printworld Pvt. Ltd., New Delhi.

22. Max, Muller., F., 1859. History of Ancient Sanskrit Literature, pp. 249, 313, 435, 497 and 572.

23. Mehta, R.N and Kantawala, S.G., 1987. Stone Tools in the Rgveda, in Vajpeya: Essays on Evolution of Indian Art and Culture, Agam Kala Prakashan, New Delhi, Vol. 1, pp. 23-26.

24. Chattopadhyaya, Debiprasad., 1991. History of Science and Technology in Ancient India II Formation of the Theoretical Fundamentals of Natural Science, Firma KLM Pvt. Ltd., Calcutta.

25. Agrawal, O.P., Narain, Hari., Prakash, Jai and Bhatia, S.K., 1990. Lamination Technique in Iron Artefacts in Ancient India, Historical Metallurgy, Vol. 24(1), pp. 12-26.

26. Prakash, B and Tripathi, V., 1986. Iron Technology in Ancient India, Historical Metallurgy, September, pp. 568-579.

27. Biswas, Arun Kumar., 1969. Science in India, Firma KLM Pvt. Ltd., Calcutta.

28. Max, Bauer., 1968. Precious Stones, two volumes, Dover Publications.

29. Mitchell, R.S., 1979. Mineral Names – What Do They Mean? Van Nostrand, New York.

30. Biswas, Arun Kumar., Vaidurya, Marakata and other Beryl Family Gem Minerals: Etymology and Traditions in Ancient India, Indian Journal of History of Science, 29(2), 1994, pp. 139-154; Gems and Minerals, in History of Technology in India, Vol. I (Antiquity to 1200 AD) edited by A.K. Bag, Indian National Science Academy, New Delhi, 1997, Chapter 3.6, pp. 225-255; Rasa-Ratna-Samuccaya and Mineral Processing State of Art in the 13th Century AD India, 22(1), 1987, pp. 29-46.

31. Finot, Louis, Les Lapidaires Indiens, Paris, 1896, contains French translations and original texts on gemmology or Ratnasastra such as Buddhabhatta's Ratnapariksa, Varahamihira's Brhatsamhita, Agastimata, Navaratnapariksa, Agastiya Ratnapariksa, Ratnasamgraha, Laghu Ratnapariksa and Manimahatmya.

32. Marshall, John., 1975. Taxila-Archaeological Excavation, three volumes, originally

published in 1945 & 1951. Reprint by Bharatiya Publishing House, Varanasi.

33. Werner, O., 1972. Spektralanalytische und Metallurgische Untersuchungen an Indischen Bronzen, Leiden, Brill., Haedecke, K., Gleichgewichtsverhaltnisse bei der Messingherstellung nach dem Galmeiverfahren, Erzmetall, 26, 1973, pp. 229-233.
34. Craddock, P.T., 1981. The Copper Alloys of Tibet and Their Background, in Aspects of Tibetan Metallurgy, Occasional Paper No. 15, British Museum, pp. 1-31.
35. Willies, Lynn., 1989. Ancient Lead-Zinc-Silver Mines in Rajasthan, Mining Magazine, January pp. 31-35.
36. Farnsworth, M., Smith, C.S and Rodda, J.L., 1949. Metallographic Examination of a Sample of Metallic Zinc from Ancient Athens, in Hesperia, Supplement 8, pp. 126-129.
37. Pliny, Naturalis Historia (23-79 A.D.), 37th Chapter.
38. Schoff, Wilfred. H., 1912. The Periplus of the Erythraean Sea (translated and annotated), Longmans, Green and Co., New York and London.
39. Warmington, E.H., 1974. The Commerce Between the Roman Empire and India, Second Edition, Vikas Publishing House, New Delhi.
40. Huntington, G.W.B., 1980. The Periplus of the Erythraean Sea by an unknown author (translated and edited), The Hakluyt Society, The British Library, London.
41. Danielou, Alain., 1967. The Ankle Bracelet, translation of Shilappadikaram by Prince Ilango Adigal, London.
42. Tagore, Sourindro Mohun, Manimala – A Treatise on Gems, two volumes, Calcutta, 1879. This is a compendium on the ancient Indian texts related to gemmology.
43. Biswas, Arun Kumar., 1994. Gem Minerals in Pre-Modern India, Indian Journal of History of Science, 29(3), 1994, pp. 389-420; Non-Gem Minerals in Pre-Modern, 29(3), pp. 421-463.
44. Ray, P.C and Kaviratna, H.C., 1910, 1985. see Rasarnava.
45. Joshi, Damodar. 46, Rasaratnasamuccaya.
46. Rasaratnasamuccaya of Vagbhata, text and translation in English by Damodar Joshi, Indian National Science Academy, New Delhi.
47. Hegde, K.T.M., Craddock, P.T and Sonavane, V.H., 1986. Zinc Distillation in Ancient India, in Proceedings of the 24th International Archaeometry Symposium, Smithsonian Institution Press, Washington, pp. 249-258.
48. Hegde, K.T.M., 1989. Zinc and Brass Production in Ancient India, Interdisciplinary Science Reviews, Vol. 14(1), pp. 86-96.
49. Biswas, A.K., Gangopadhyay, A and Ramachandran, T.R., 1984. Phase Studies on Zinc Residues of Ancient Indian Origin, Transactions of the Indian Institute of Metals, Vol. 37(3), June, pp. 234-241.
50. Craddock, P.T., Freestone, I.C., Gurjar, L.K., Hegde, K.T.M and Sonavane, V.H., 1985. Early Zinc Production in India, Mining Magazine, January pp. 45-52.
51. Abul Fazl, Ain-i-Akbari, see H. Blochmann.
52. Blochmann, H., 1977. The Ain-i-Akbari of Abul Fazl, (edited translation, revised by D.C. Phillott), Oriental Books Reprint Corporation, New Delhi, Vol. I.
53. La Niece, S and Martin, G., 1987. The Technical Examination of Bidri Ware, Studies in Conservation, 32, pp. 97-101.
54. Stronge, S., 1985. Bidri Ware, Inlaid Metalwork from India, Victoria and Albert

Museum, London.

55. Biswas, Arun Kumar., 1994. Iron and Steel in Pre-Modern India: A Critical Review, Indian Journal of History of Science, 29(4), pp. 579-610.

56. Biswas, Arun Kumar., Minerals and Metals in Pre-Modern India, D.K. Printworld Pvt. Ltd., New Delhi, 2000 AD.

57. Biswas, Arun Kumar., Minerals and Metals in Medieval India, in History of Science, Philosophy and Culture in India from 10th to 18th Century, Vol. III, Part I, edited by A. Rahman, 2000 AD, Chapter Ten, pp. 229-264.

58. Raychaudhuri, Tapan and Irfan Habib (edited), 1993. The Cambridge Economic History of India, Vol. 1 (1200-1750 AD), Cambridge University Press and Oriental Longman, New Delhi.

59. Ball, Valentine., 1881. A manual of the Geology of India, Part III Economic Geology, Geological Survey of India, Calcutta.

60. Dutt, N.V.B.S., 1953. Ancient Diamond Mining in Andhra and its Future, Indian Minerals, Geological Survey of India, Vol. 7(1), January, pp. 138-150.

61. Ouseley, J.R., 1839. Process of Washing for the Gold Dust and Diamonds at Hirakund, Journal of Asiatic Society of Bengal, Vol. 8, pp. 1057-1058.

62. Burnes, Journal of Asiatic Scoeiety of Bengal, April 1832, pp. 145-148.

63. Moreland, W.H., 1972. From Akbar to Aurangzeb, Oriental Books Reprint Corporation, New Delhi.

64. Dixon, C.G., 1831. Some Account of the Lead Mines of Ajmer, Gleanings in Science, Vol. 3, April, pp. 111-115.

65. Boilean A.E., 1831. Gleanings in Science, December, pp. 380-384.

66. Brooke J.C., 1864. Journal of Asiatic Society, Vol. 33, pp. 518-529.

67. Raghunandan, K.R., 1988. Ancient Mining in Khetri Copper Belt, Rajasthan, India, in Scientific Heritage of India, edited by B.V. Subbarayappa and S.R.N. Murthy, The Mythic Society, Bangalore, pp. 177-182.

68. Bronson, Bennet., 1986. The Making and Selling of Wootz, A Crucible Steel of India, Archaeomaterials, 1, pp. 13-51; also comments by B.Prakash and reply by B. Bronson, 3, 1989, pp. 95-96.

69. Voysey, H.W., 1832. Description of Native Manufacture of Steel in South India, Journal Asiatic Society of Bengal, Vol. 1, pp. 245-247; Vol. 2, p. 402.

70. Sherby, O.D and Wadsworth, J., 1985. Damascus Steels in Scientific American, February, pp. 112-120.

71. Faraday, Michael., 1819. An Analysis of Wootz or Indian Steel, Quarterly Journal of Science Literature and the Arts, Vol. 7, pp. 319-330; also ibid, 1820, Vol. 9, pp. 319-330.

72. Habib, Irfan., 1986. Capacity of Technological Change in Mughal India, in Technology in Ancient and Medieval India, edited by Aniruddha Roy and S.K. Bagchi, Sundeep Prakashan, Delhi, pp. 1-13.