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TWO MILLENNIA OF THE SEA-BOURNE METALS TRADE WITH INDIA

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India has always been both a major producer of metals and an active participant in the international metals trade. However, the long term continuity of this trade has not previously been addressed systematically. This is attempted here utilizing historical and archaeological evidences, reinforced by the growing number of the metal ingots themselves, recovered from dated wrecks. Although India produced a wide variety of metals, from Roman times onwards India was a major market for both precious and non-ferrous base metals and this has continued more or less without a break into the 21st century. Zinc, the metal always so closely associated with India, is an especially interesting case. In the medieval period there is some evidence for foreign trade in either zinc or zinc oxide from India, but it is clear that from the late 16th century AD there was a demand for zinc within India itself that home production could not meet and zinc was imported in considerable quantities first from China and latterly from Europe. It is ironic that India, the home of zinc production, should have become a net importer from the post medieval period on. In contrast iron and steel formed the main metal exports from India through the centuries, either as bulk wrought iron or in a variety of specialist iron and steels. The production was at all stages reliant on copious quantities of charcoal, and thus perhaps the ferrous metals should be regarded as another of the forest products along with the exotic spices and timbers that are the more familiar materials of India's trade with the outside world.

Key words: China, Copper, East India Company, Economics, Europe, Gold, Iron, Lead, Maritime, Middle East, Zinc, Silver, Steel, Tin, Trade.

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Introduction

This paper is dedicated to the memory of Professor Balasubramaniam. In his all too brief career as an archaeometallurgist, he developed keen interests in a wide range of topics relating to the history of Indian metallurgy[1]. These included both non-ferrous and ferrous metallurgy as exemplified by his work on Indian ordnance and on a variety of issues concerning crucible steel[2]. An aspect of the latter was the evidences for Indian iron and steel in international trade. This concurred with the present author's interests and resulted in many hours of happy and productive discussion with Bala at the Indian Institute of Technology in Kanpur.

The vast landmass of India contains many and varied metalliferous ore bodies, often with evidence of having been worked from the distant past (Ball 1881; Coggin Brown and Deye 1955). This present paper attempts to summarise a selection of the evidences for the international trade in metals with India through the past two millennia.

The Trade in Non-ferrous Metals

Trade in Antiquity

India has been trading across the Arabian Sea since at least the Bronze Age. The Harappans were trading with the Middle East (Ratnagar 2006) and the role played by metals in this exchange has been endlessly debated. This debate includes which metals were likely to have been involved and even which way the putative copper trade is likely to have flowed. However, it has to be admitted that in reality there is presently no certain evidence for a metals trade at all.

Following the collapse of the Harappan civilisation there is little evidence for Indian participation in international trade in metals until the latter part of the first millennium BC. Then a combination of contemporary descriptions and archaeological discoveries together provide evidence for the production and trade in metals. Following Alexander the Great's expedition across Asia to the Indus, several Greek travellers and geographers wrote about India, although only fragments of these reports have survived, often preserved in much later Roman works (Giumlia-Mair et al 2009). Around 300 BC the Greek traveller, Megasthenes produced a description of India in which he is reported to have stated that: ‘India has underground numerous veins of all sorts of metals, for it contains much gold and silver and copper and iron in no small quantities, and even tin and other metals which are employed in making articles of use and ornament as well as implements and accoutrements of war’ (McCrindle 1877, p. 31). Megasthenes was travelling in the Mauryan Empire and at about this time the famous Mauryan manual on state administration, the *Arthaśāstra*, was produced. This is traditionally ascribed to Kauṭilīya, the chief minister of the Emperor Chandragupta in the 4th century BC, but there has long been debate over authorship and early date of the work (Trautmann 1971; Mital 2000, for example). However it does contain long sections on the establishment and operation of mines and smelters to produce both base and precious metals (Kangle 1965, I, pp.105-112 etc) that seem to fit in very well with the huge mines for copper, lead, silver (Craddock et al 1989; Willies 1992) and zinc oxide (Craddock and Eckstein 2003; Willies 1987) developed during the Mauryan period that have been excavated in the Aravalli Hills of north west India[3]. Other sources describe gold mining in the Himalayas as well as in south India (Anon. 1963; Willies 1992), and clearly India was a major producer of both precious and base metals at this time.

The next accounts that have survived, compiled some centuries later in Roman times, are very different in several respects, with India being seen as a market for non-ferrous metals rather than as a major producer. The *Periplus of the Erythraean Sea* (Huntingford 1980; Casson 1989) is a short anonymous work compiled for sailors and merchants, detailing the various routes and trade from the Red Sea, particularly from ports such as Mouza and Kane, formerly in Aden (Fig. 1), to the west coast of India.

Major ports are described together with lists of the commodities for which there was a market and those that were offered for purchase. From this it does seem that India required both precious and base non-ferrous metals. Thus, for example, the major port of Barugaza, now known as Bharuch or Broach, in the Bharuch District at the mouth of the Narbada River on the Gujarat coast is described in some detail (Casson 1989, p.27; Huntingford 1980, pp.44-8). It is stated that tin, copper and lead were imported but there is no mention of any metals or minerals amongst the exports. Conversely, copper and tin from Egypt were listed as being amongst the imports at Kane

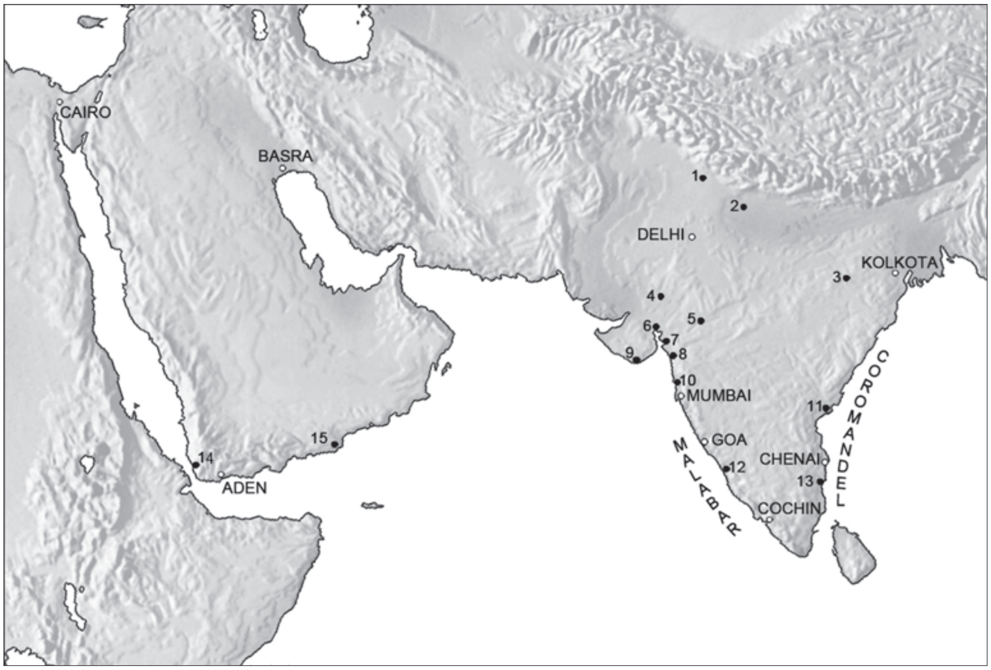

Fig. 1. Some of the principal ports etc. engaged in trade between India and the Middle East mentioned in the text. (A. Simpson)
1. Tons Valley, 2. Kumaon Ironworks, 3. Jamshedpur, 4. Zawar, 5. Barwai Ironworks, 6. Cambay, 7. Barugaza, 8. Seurat, 9. Diu, 10. Thana, 11. Mottupalli, 12. Dahbattan, 13. Porto Novo, 14. Mouza and 15. Kane

(Huntingford 1980, Chap. 28, p.34); and these were very likely to have been for re-export to India, as was certainly the case a thousand years later when the trade was in the hands, or ships, of the Jews and Arabs (see Fig. 1). This has suggested to some scholars that the Indians did not have these metals locally, a view reinforced by Pliny (*Natural History* 34.163, Rackham 1952, IX pp.244-5) who stated that the Indians had no tin or copper[4] and consequently imported these metals from the Roman world (Warmington 1928, pp.267-9). This was clearly different from the situation some centuries before and has puzzled other scholars such as Casson who pointed out that there were abundant ore deposits of copper and lead close to the major trading ports (that is in the Aravalli Hills), and that Strabo (Geography 15.1.69, Jones 1930, VII, pp.122-3) had specifically mentioned items made of ‘Indian copper’. This is true, but Strabo based his account on that of

Megasthenes compiled around 300 BC, when the major mines in the Aravallis were flourishing, but the archaeological excavations (Craddock et al 1989 & 1998a) have demonstrated that by the first centuries AD, when the *Periplus* and the *Natural History* were compiled the mines were very largely out of production following the collapse of the Mauryan Empire, thereby creating shortages that could only be met by imports, a situation that was to recur frequently in India's history.

Evidence for maritime trade to the east, from the Coromandel Coast of south eastern India across the Bay of Bengal certainly has a long history as documented by finds of Indian beads in Southeast Asia from the first millennium BC (Francis 2002), and other items including Indian iron artefacts from the early first millennium AD (Cameron 2011). By the end of the first millennium AD trade between southern India and Indonesia was a major item in the economies of the two regions and was dominated by the Pallava and Chola Empires, based in Tamil Nadu (Wheatley 1961; Christie 1998). The role of metals in this trade is uncertain but it is likely that tin was being imported into India and iron and steel exported[5].

Trade in the Medieval World

Trade across the Arabian Sea continued through the first millennium AD into the medieval period. Marco Polo reported that brass, silver and gold were all imported into the ports of Thana, near present day Mumbai, and Cambay in Gujarat with, in addition, *tutty* (see below) at Cambay (Latham 1958, pp. 266 & 267) (Fig. 1)[6]. Payment for Indian goods, notably spices, textiles and iron (including steel), were very largely made in gold and silver, as India was short of silver sources through most of the medieval period (Deyell 1999; Prasad and Ahmad 1998). The *Āīn-I Akbarī*, written in Persian by Abū'L-Faẓl Allami, who was the Mughal chief minister in the reign of Akbar in the later 16th century, that is just before the arrival of the Dutch and English trading companies, recorded that silver and jewellery were imported from Iraq and Turkey into Gujarat (Phillott 1927, II, p.247).

The maritime trade was often conducted by Arab or Jewish merchants. From their sometimes quite detailed accounts that have survived, such as those between the Jewish merchants in Aden (Fig. 2) and their counterparts on the Malabar coast of south west India (Goitein and Friedman 2008,

Fig. 2. Copper 'melon' ingots, wt. range 4-10 kg, bound for India, from an unknown Portuguese vessel wrecked off Namibia in the 1530s. (S. Chirikure et al., 2010, Oranjemund Shipwreck Database)

Margariti 2007) it is clear that non-ferrous metals were exported to India on a regular basis[7]. As previously stated, precious metals were required to pay for the Indian produce and base metals such as tin, lead, copper and its alloys were required for sale. In particular 'yellow copper' was sent to India in quantity. Goitein and Friedman (2008, p.555, FN 11) believed this to be a high tin bronze but given the overwhelming prevalence of brass, the alloy of copper and zinc, in the Islamic world (Craddock et al 1998a) it is very likely that it was brass that was being exported to India[8].

This reference to the import of copper alloys is especially interesting as the major copper mines both at Ambaji and at Singhana-Khetri at either ends of the Aravallis were in production during the medieval period (Willies 1992). It has also now been established that zinc oxide was being produced at Zawar in Rajasthan from Mauryan times (Craddock et al 1998b; Craddock and Eckstein 2003) mainly to mix with copper to make brass[9]. That production, if ever it completely ceased in the post Mauryan period, was certainly back in operation by the 7th century AD as attested by the radiocarbon dates from both the mines and smelting sites at Zawar Mala (Craddock et al 1998a).

A major problem occurs in the recognition of the various words that could be used for both zinc oxide and for zinc metal in the various surviving documents[10]. There are many references to zinc and its production in the early Indian scientific literature (Ray 1902 etc), but the earliest dated reference to Indian zinc oxide or zinc from outside was made by the Iranian writer Abū Dulaf in his *al-risālat al-thāniya*, compiled around 950 AD (Allan 1979, p.44) where he noted many kinds of *tūtīyā* which he stated come from the vapour of copper (very likely from molten brass), except for the Indian *tūtīyā* which came from the vapour of tin. This statement has puzzled many, including Allan, as zinc oxide certainly cannot have come from tin, but the confusion of zinc with tin was common (see below & EN 18). Abū Dulaf's comment is important, showing that by the 10th century AD metallic zinc was known outside India itself, even if only partially understood, and that Indian *tūtīyā* made by burning zinc metal was already an item of international trade. Two other Iranian writers, Ibn al-Faqīh (circa 900 AD) and al-Tha' ālibī (circa 1000 AD), also mention Indian *tūtīyā*, but without giving any details of how it might be different (Allan 1979, p.44). The *Lapidary Pseudo Aristotle* (which is probably an Arabic compilation of the 9th century AD) stated that *tutty* came from mines on the coast of India and Sind (Ruska 1912, paragraph 12), which could be a reference to production at Zawar (Fig. 1). Al-Kāshānī, writing in the 13th century AD (Allan 1979, p.44), believed that Indian *tūtīyā* came from the sea as a sort of surf, which could also be an indirect reference to a sea-borne trade.

In one of the manuscript sources[11] of Marco Polo's *Travels* it is stated that on his sea journey back to Venice in the 1290s, he visited Cambay, Gujarat (Fig. 1) and that *tutty* was one of the imports of that port (Latham 1972, p.267). The only other reference to *tutty* in Marco Polo's account of his travels was at Kerman in central Iran on his way out to China (Latham 1972, p.39) and there he made a description of the production of *tūtīyā*, or *tutty* as he named it. There are detailed Islamic accounts of both the production of zinc oxide and of brass in the Middle East and Iran, and Marco Polo's description of how *tutty* was prepared in Iran shows beyond doubt that *tutty* is to be understood as zinc oxide. It does seem extraordinary that zinc oxide was being imported into Cambay which must have been almost the closest port to Zawar (Fig. 1). If the report is accurate, and it was not *tutty* as an export that was intended, then this could be evidence that Zawar was out of production in the late 13th century AD, even though there was clearly a market for its products. Certainly the mines are historically said to have been 'discovered' by the Maharana Lakha in the early 15th century AD (Hooja 2006, p.33; Tod 1978, 231-2) and the archaeological evidence would support a big expansion of production from the late 14th century.

Overall in the medieval period it does seem that base non-ferrous metals were imported into India. This would comprise copper and lead and possibly some tin coming ultimately from Europe via the Middle East, and copper alloys, predominantly of brass from the Middle East, together with tin from Southeast Asia all to supplement indigenous production. Precious metals in the form of gold and silver were required to pay for purchases of Indian merchandise. This could either be in coin or as ingots. There are some indications of an awareness of Indian zinc oxide and even of zinc around the end of the first millennium AD, but no real evidence of a sustained trade.

Trade in the Post Medieval period

The spread of European shipping over the world's oceans from the end of the 15th century transformed global trade. The survival and / or study of accounts of this trade are haphazard, but from these sometimes very detailed but disparate records a reasonably coherent pattern does emerge for the trade in metals. These reports can now sometimes be reinforced and given reality by the cargoes of ingots found on the wrecks of some of the early trading vessels (Craddock and Hook 1997 & 2012). Relatively few Portuguese records survive from the 16th century (Souza 1991, p.299), which is unfortunate as Portugal initiated and dominated the India and Southeast Asian trade through the 16th century from bases such as Goa, Diu and Seurat on the west coast of India (Fig. 1), Malacca in Southeast Asia and Macao in southern China[12].

From the beginning of the 17th century the VOC (*Verenigde Oostindische Compagnie*, the Dutch East India Company) and the EIC (the

English East India Company), joined in the later 17th century by the *Compagnie Français pour le commerce des Indes Orientales*, were steadily supplanting the Portuguese trading with the Mughal Empire and its dependencies (Habib 1982). To this end they established their own bases in India at ports such as Seurat on the northwest coast of India (Fig. 1), and their records are much more complete and make regular references to *tutenague*[13] (Coolhaas ed. 1960 & Meilink-Roelofsz et al 1992 for the VOC, Foster ed. 1906-1927 & Morse 1926 for the EIC and Ray 2004 for the French). The Dutch at Seurat, for example, in the first part of the 17th century AD regularly reported that they needed zinc, copper, mercury, lead and tin (Prakash 1984, ps. 84, 93 & 146. & 2007, ps. 116, 147 & 304). The contemporary records of the European merchants based in China and South East Asia show that through the 17th and into the mid 18th centuries India was a major market for all non-ferrous metals (Souza 1986). The VOC and the Portuguese, and subsequently just the VOC, were sending metals such as copper from Japan (Fig. 3) and China, silver from Japan (and also indirectly from the Americas), mercury, zinc (Fig. 4) and gold from China and tin (Fig. 5) from Southeast Asia (Cortesāo 1944, I, p.99: Valentyn 1726, 5, ps.34, 138) to India.

Fig. 3. Typical Japanese copper ingots, typical wts. ~ 100 gm, from the VOC *Waddingsveen*, wrecked off the Cape of Good Hope in 1697 on its journey to Europe. Similar ingots were traded to India. (BM PE Reg. 1995, 12-1, 1-6)

Fig. 4. Typical Chinese zinc ingot, wt. 2.5 kg, from the VOC *Witte Leeuw* wrecked off St. Helena in 1613. (BM PE Reg. 1990, 12-4, 1)

Fig. 5. Typical Malaysian tin 'hat' ingot, wt. 0.8 kg, from the EIC *Vanisttart*, wrecked off Banca Island, Indonesia in 1789, enroute to India. (BM PE Reg. 1997, 2-3, 1)

The first vessels from Europe brought copper, lead and tin as exemplified by the cargo of the Namibia wreck (EN 12). From the late 16th century copper was in short supply in Europe until the early 18th century such that large quantities of copper came to Europe from the Far East (Fig. 3) (Craddock and Hook 1997) and the main base metal export from Europe was lead (Fig. 6).

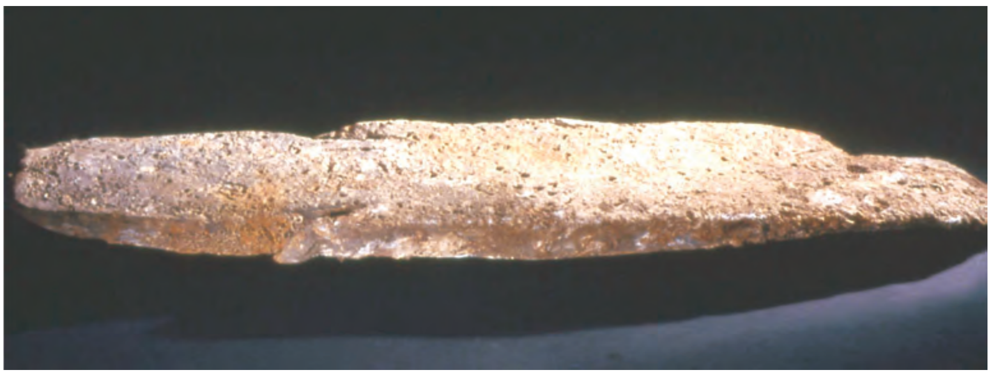

Fig. 6. Typical lead ingot, wt. 72 kg, probably from Derbyshire, England, From the VOC *Campen*, wrecked off the Isle of Wight in1627 en route to the Batavia. (BM PE Reg. 1987, 6-8, 1)

The rise of the British copper industry through the 18th century (Day 1991) led to the revival of European copper exports (Fig. 7) together with tin (Fig. 8) and lead (Fig. 9) to India and China (Craddock et al 2002).

It must be emphasised that metals did not feature prominently in the international trade. Once the European trade was firmly established, a Dutch or English ship of the 17th century setting out from Europe to India would purchase textiles in India to sell in South East Asia and purchase spices. Calling back to India on the return voyage more textiles (and cotton) and spices (especially pepper) together with indigo and saltpetre would be loaded for Europe. Metals were relatively unimportant, except for silver (Fig. 10) to pay for purchases[14] and lead as a necessary ballast cargo. Although lead deposits occur widely all over the world, and has always been a relatively cheap metal, European lead usually found a ready market in both India and China, presumably it was competitive in price as its carriage was effectively free[15].

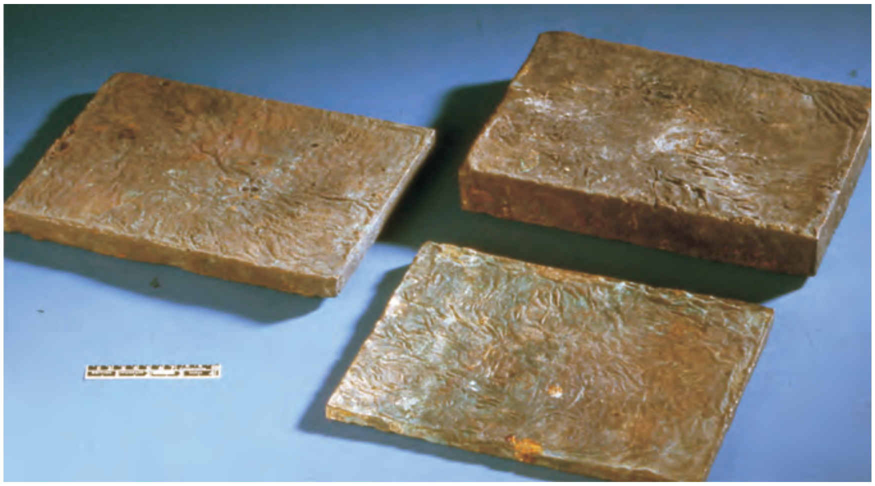

Fig. 7. Typical European copper ingots; battery plates, wts. 14, 28 & 56 lb, 6.5, 12.3 & 25.5 kg. These were made from ore mined in the south west of England and smelted in Swansea. From the EIC *Carnbrae Castle*, wrecked off the Isle of Wight in 1829, enroute to India (BM PE Reg.1994, 4-5, 1-3)

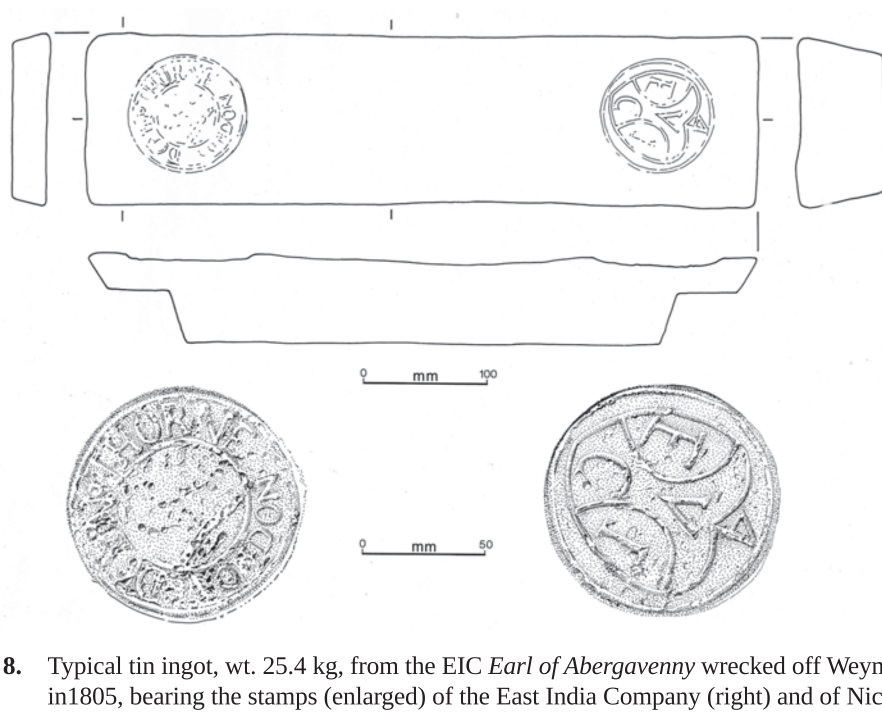

Fig. 8. Typical tin ingot, wt. 25.4 kg, from the EIC *Earl of Abergavenny* wrecked off Weymouth in1805, bearing the stamps (enlarged) of the East India Company (right) and of Nicholas Donnithorne (left) who negotiated the supply of Cornish tin to the EIC (Craddock et al 2002). (B.R. Craddock)

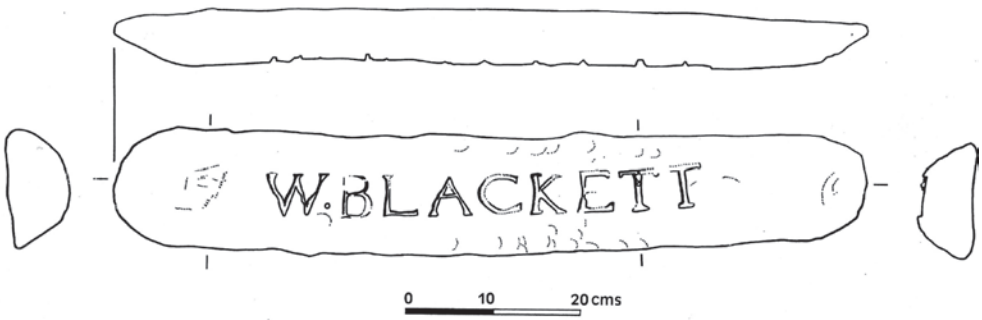

Fig. 9. Typical lead ingot, wt. 70 kg, from the EIC *Henry Addington* wrecked off Weymouth in 1798. The ingot bears the moulded name Blackett, showing it was from the north Pennine mines of the well-known and long established firm of Wm. Blackett (BM PE Reg. 1993, 6-7, 1), very similar to the ingots found off the shore at Poompuhar, Tamil Nadu, being part of the ballast cargo of an unknown wreck (Tripati et al 2003) (see EN xv). (B.R. Craddock)

Fig. 10. Silver ingots from the VOC *Bredenhof*, wrecked off Madagascar in 1753. The bars, which probably originated in the Americas, weigh approximately 2 kg each, and would have been used to pay for merchandise in India and the East

Evidences for the Post Medieval trade in zinc

By the end of the first millennium AD zinc metal is likely to have been produced on an industrial scale in India[16], and major zinc smelting was in operation in the 15th and 16th centuries AD at Zawar (Craddock et al 1998a). This raises the question as to how much the new metal was known outside of India and to what extent it was traded.

Once again there is the problem of terminology. In the late medieval – early post medieval world of the 16th century in the Indian Ocean at least four base white metals are likely to have been traded, lead, tin, pewter and zinc but there are often considerable problems identifying which specific metal is being referred to in individual documents and it is quite likely that the compilers of these documents were themselves also confused, inconsistent or careless. The medieval Arab word *raṣāṣ qal'ī* could, for example, be either lead or tin (Goitein and Friedman 2008, p. 558, FN 27). The related word, *kalaem, kaleem* or *calaem*, mainly found in Portuguese documents, could refer to either tin or to zinc[17]. More specifically, in the early documentation zinc metal could be confused or associated with tin and to a lesser extent with lead and even with silver, to those unfamiliar with the metal[18].

What could be the first reference to European trade in Indian zinc occurs in 1519 with a record of a Portuguese vessel loaded with 21 *quintals* (960 kg) of *kalaem* at Cambay, in Gujarat (Fig. 1) setting sail to Sofala, the main Portuguese port in southern Africa, now in Mozambique, presumably en route to Europe (Godhino 1991, I, p.204). The *kalaem* in this instance could have been tin, but a major cargo of that metal from Cambay, thousands of km from the sources of tin or its usual trade routes seems unlikely, whereas, as already noted, Cambay was the nearest port to the Zawar mines which were in full production at this time.

Another reference is contained a letter from an Italian diplomat, Antonio Bavarin, writing from London on October 12th 1513[19]. There he states that he had received letters from Lisbon advising of the arrival of three spice vessels, which '….besides the first, and much merchandise: an annual cargo being also sent of some 400 pieces of tin which if good will be very detrimental to the English, for they (the Portuguese) say they can have as much as they please.' This could be real tin metal from Southeast

Asia, which the Portuguese had reached in 1512. If so then this cargo would have been on the first return voyage and there is no record of the ships being laden with tin or zinc. It is more likely that the ships referred to here had returned from India, where the Portuguese were already well established, laden with 'Indian tin' that is, with zinc[20].

Whatever the reality or otherwise of a trade in Indian zinc in the early 16th century, the Portuguese were already sending zinc to India around 1600 AD from China (Souza 1991, p.301). From about 1600 AD with the arrival of the much more comprehensively-documented Dutch and English trading companies, it is clear that there was already a major trade in Chinese zinc, much of this bound for India, and this large, if somewhat irregular trade in Chinese zinc continued through the 17th and 18th and into the early 19th centuries (Souza 1991)[21]. European vessels setting out from China would also have gold and silver to pay for purchases in India and in addition very often with zinc as the ballast cargo at least from the end of the 16th century (Morse 1926, p.185; Souza 1991). Detailed Dutch and English records make it clear that a typical cargo could include many tons of zinc and that its purchase price in China was only slightly higher than lead and much cheaper than tin (Morse 1926; Souza 1991). The export of Chinese zinc to Europe was still of the order of approximately 40 tons per annum in EIC vessels to England through the 1760s and 1770s and several hundred tons per annum to Holland in Dutch vessels as late as the 1780s (Bonnin 1924, pp.11-13), but this trade fell off sharply at the end of the 18th century with the cessation of the VOC in the 1790s, and as European production gathered pace (Almond 1998). However the trade in Chinese zinc to India was much more considerable and lasted well into the 19th century (see below and EN 21).

It must be stressed that many of the European vessels were engaged in the so-called country trade between South Asia, Southeast Asia and the Far East, and it does seem that a preponderance of the Chinese export zinc was loaded onto vessels bound for India where there was a long established market for it (Prakash 1984 & 2007), rather than for Europe at this period (Fig. 4). As Lord Macartney noted on his trade mission to China in the 1790s, although zinc was no longer then being sent to Europe, there was still a considerable country trade to India (Cranmer-Byng ed. 1963). This trade to India continued well into the 19th century, as exemplified by the EIC *Diana* which sank on her way to Calcutta laden with Chinese zinc in 1812

(Fig. 11) (Ball 1995). Sir T. Dick Lauder stated in the *Edinburgh Philosophical Review* IV for 1826 (quoted in Bonnin 1924) that 'Tutanag is an article of very extensive commerce between China and India …. It is employed by the natives of India as an alloy for copper to make brass for their domestic utensils' (Holland 1834). However, only a short time later John Holland (1834) claimed that in 1826 the importation of Chinese *tutanag* into Calcutta had ceased, replaced by imports of German *spelter*.

Fig. 11. Typical Chinese zinc ingots from the EIC *Diana*, wts. 0.7 & 0.8 kg, wrecked off Malacca, Malaysia in 1816, enroute to Calcutta. Dick Lauder (1820) recorded that Chinese zinc was sent to India in plates approximately 8 or 9 inches long by 5½ inches wide and 5/8 thick (20-23 cm × 14 cm × 2 cm, almost identical to those in the plate illustrated here) (BM PE Reg. 1997, 2-2, 1 & 2).

The zinc was used by the Indians to make brass as noted above and by Souza (1986, pp.120-3), but there also other more specific uses. It is likely that most of the zinc-alloy *bidri* wares made in the Deccan used Chinese zinc (Ball 1886; Craddock 2005)[22]. There were also low denomination coinages, both indigenous local issues (see EN 16), often mislabelled as lead, and coins produced by the foreign trading communities, such as the *bazaruco*, first issued by the Portuguese before 1608 (Souza 1991, p.301) and then also by the Dutch and much used amongst the trading communities of the west coast of India at centres such as Cochin, Goa, Seurat and Diu (Souza 1986, p.179). These coins were of brass or latterly of zinc as confirmed by the analyses of Yih and de Kreek (1993).

The importation of Chinese zinc to make coinage used by the merchant communities in the 17th and 18th centuries AD on the west coast of India graphically demonstrates that nearby Zawar no longer featured in world trade, just as the Hindi word for zinc, *jasada*, seems never to have been used by the foreign merchant community. Even so it is likely that Indian zinc production was known to the European trading community situated on the north west coast of India as the first European zinc smelting process, that of William Champion of Bristol in the 1730s (Day 1973), is certainly based on the Indian rather than the Chinese technology (Craddock 2009b)[23].

An explanation for the failure of Indian zinc, specifically from Zawar, can be found in the historical and archaeological evidence. Production of zinc metal (from which a superior zinc oxide could be made by combustion) was in operation in India around a thousand years ago. However, there is no mention of anything that could be interpreted as zinc oxide or zinc in the detailed Jewish records of trade items made in the 11th century AD, referred to above; and Marco Polo apparently listed zinc oxide, *tutty*, as a material required at Cambay in the late 13th century. At Zawar and there is little physical evidence of activity at this time, but Maharana Lahka's 'discovery', of zinc and silver at Zawar, referred to above, coincides with field evidence for renewed activity at the mine at the beginning of the 15th century AD. Production of zinc metal probably peaked at Zawar during the 15th and 16th centuries as evidenced by the extent of the production debris there, often amidst Jain temples with dedicatory inscriptions of this period.

Few early European (that is Portuguese) trade records survive, but they do provide some evidence for a trade in Indian zinc metal to Europe early in the 16th century and it is quite likely that some of Zawar's production went south to be purchased by the Portuguese as *kalaem* or 'Indian tin'. However, by the end of the 16th century zinc was already being imported into India, especially to the ports on the north-west coast where there was obviously an existing demand. The most likely explanation for this reversal was the attack on the independent Rajput kingdoms of Rajputana by the Mughal Empire in the late 16th century (Tod 1978 I, pp.258-92; Hooja 2006).

The kingdom of Mewar, in which Zawar lay, was decisively defeated in battle in 1576 and occupied, but resistance continued with almost continual fighting, guerrilla raids, insurrection and reprisals under Maharana Pratap Singh and his successors, with Zawar itself sometimes being directly involved in the fighting (Tod 1978 I, p.272; Hooja 2006, p.472). Mewar finally submitted 1615, but in the preceding 40 years trade and industry were severely interrupted and is likely that zinc production ceased or at least was heavily curtailed during this period. The demand for zinc had to be met by imports and when peace was finally restored in Mewar the market was firmly in the hands of the foreign merchants, and thereafter zinc is always listed as a material required at the trading ports of north-west India, never again as a commodity for sale[24].

The archaeological evidence from Zawar itself suggests there was only limited zinc production in the 17th and 18th centuries AD until 1812 when production by the traditional process ceased forever. Zinc smelting may have declined in the 17th century, but for the first time in the mine's history there is archaeological evidence for silver / lead smelting. This is supported by the surviving Mewar revenue documents of the 18th century in Udaipur, which specifically mention silver production at Zawar[25].

THE TRADE IN IRON AND STEEL

India has a long tradition of iron making stretching back to the mid 2nd millennium BC (Tewari 2003), and already by the latter part of the first millennium BC crucible steel was in use in northern India as evidenced by the steel items excavated at Taxila (Hadfield 1951).

Ancient and Medieval Trade

Trade between India and the Roman world flourished (Tomber 2008) and there is evidence that Indian iron and steel were important items in this trade. Pliny, in the *Natural History* (34.145, Rackham 1952, p.233) praised the iron sent to Rome by the *Seres*. The *Seres* are usually identified with the Chinese, although Warmington (1928, pp.257-8) suggested many years ago that the Cheras of south India as more likely candidates. This view has been supported by Juleff (1998; Wayman and Juleff 1999), who derived *Seres* from the Sinhalese *Seri*, the Tamil kingdom of Cheras. Irrespective of the identification of *Seres*, it is likely that South Asia was a major supplier of iron to the Middle East and Roman Empire. The *Periplus* (Huntingford 1980, pp.21-2) stated that both iron and steel were exported from India to Africa and thence up the Red Sea to the Roman Empire[26]. Further evidence for the reality of the trade in iron comes from the lists of duties payable on items imported into in the Roman Empire. The laws of Marcus Aurelius and Commodus, originally compiled in the second century AD make specific reference to *ferrum indicum* (Pleiner 1971).

The very distance of this trade has led some to assume that the iron must have been of very special quality, even to the point of speculating that it must all have been crucible steel[27]. However, other more mundane interpretations are possible. The production of wrought iron consumes enormous quantities of charcoal, and thus of timber[28], and this trade could well have been the export of good quality wrought iron from well-wooded South Asia to the desert lands of the Middle East where good quality charcoal must have been at a premium. Much of the trade from the Malabar and Coromandel Coasts of southern India was in the so-called forest products, spices being the most familiar, but it is possible to see iron as a forest product at one remove, by virtue of the charcoal requirements. There are well documented later examples of such a long distance trade in the export of charcoal-smelted wrought iron from Russia and Sweden to Britain in the post medieval period (Barraclough 1984, pp.56-8, and see below).

As well as a likely trade in wrought iron it is evident that crucible steel was also produced and exported from India and Sri Lanka in Roman times (although this was questioned by Bronson [1986]). The clearest and most detailed record of the knowledge that the classical world had of Indian crucible steel and its products is included in the work of the alchemist, Zosimos of Alexandria, compiled in the second century AD (Giumlia Mair et al 2009 and Giumlia Mair pers. com.)[29]. Under the heading ‘Tempering of Indian iron’ Zosimos stated that soft (that is wrought) iron was to be broken up and sealed in a crucible together with various ingredients including the skins of dates and of *terminalia*. The crucible was to be strongly heated until the iron melted. The iron so produced was to be used for the manufacture of marvellous swords, and furthermore the process had begun in India but was presently in the hands of the Persians. This must refer to the manufacture of crucible steel, and as such would have been a broadly accurate outline of affairs for the following 1700 years.

As with the non-ferrous metals already discussed, there is the problem of recognising and understanding the specific words used for iron and steel. It is immediately clear both from the indigenous Hindu sources as described in the *Rasa Ratna Samucaya* for example (Prakash 1995) as well as the Islamic (Allan 1979) and Jewish sources that there were a variety of easily recognised types of both iron and steel. The Jewish merchants based in Aden for example list five types (Goitein and Friedman 2008, p.315, FN 17), 'eggs' (crucible steel ingots, see also ENs 27 & 30; Goitein and Friedman 2008, pp.369-70), refurbished (scrap iron), regular (fresh wrought iron), shiny (forged crucible steel, suitable for mirrors etc [Craddock and Lang 2004]) and smooth (forged crucible steel). From the various medieval documents there are references to the wrought iron being traded in the form of forged bars, often of some size, and to 'pieces' of steel, or sometimes with more specific names such as 'eggs' or 'pucks', etc.[30]. Crucible steel was made in small crucibles each producing ingots of only a few hundred grams, and the steel was always sold in the as-cast condition (Fig. 12).

Fig. 12. Broken crucible steel mould, 19th century from Mawalgaha, Balangoda, Sri Lanka (BM OA Reg. 2002, 1-31, 3), with a typical contemporary steel piece alongside and another inserted back inside

Islamic authors such, as al Kindi, who produced a very specialised technical treatise on swords (Hoyland and Gilmour 2006), recognised a wide variety of types of iron and steel. It is now apparent that Indian crucible steel was traded into medieval Europe, especially in the Mediterranean (Williams 2007), travelling along the same trade routes that carried European non-ferrous metals to India via the Middle Eastern merchants. The steel could already have been forged into blades or as ingots to be forged in Europe to make items, for example the smiths of Islamic Seville used Indian crucible steel to make scissors.

There are early references to trade in *hinduan* that is, crucible steel, from the Babylonian Talmud, compiled between the third and fifth centuries AD, within the Sasanian Empire (Levene and Rothenberg 2001; Lang et al 1998). In the tractate Avodah Zarah 16/a, Rav Adah, the son of Ahava, stated that it was forbidden to sell iron to other nations, because they would use it to make weapons to use against the Jews. However, this was qualified by Rav Ashi, who died in 427 AD, on the grounds that the Jews now even sold *hinduan* to the Persians, who were their protectors. *Hinduan* was clearly something special and in the succeeding Islamic period it specifically meant crucible steel. Thus this seems to be a record of an early trade in crucible steel in the hands of the Jews, from India to Sasanian Iran, who then apparently, according to Zosimos, notwithstanding the scruples of the Jews, sold it to the Romans. This also recalls the trade of the ancient Jewish communities in the ports such as Cochin on the Malabar Coast of southern India.

This trade survived the Islamic takeover of many of the countries concerned and the establishment of crucible steel making in Central Asia (Rehren and Papachristou 2003). More precise information on the iron trade survives from later in the medieval period (Bronson 1986; Goitein and Friedman 2008). Thus the records of Islamic and Jewish merchants based in Aden in the 12th century show that both iron and steel were traded[31]. Various varieties of iron were involved in this trade, some in quantities of many hundreds of kg at a price that was only about a fifth of the price of copper, clearly this was ordinary wrought iron rather than a sophisticated product such as crucible steel. There are also numerous references to an iron that was traded as large numbers of individual ‘eggs’ or ‘pieces’. These were treated separately and were much more expensive than ordinary iron, thus it seems likely that these were the small ingots of crucible steel.

Rather later, the Dutch conducted a considerable trade in both wrought iron and crucible steel from the Deccan as their contemporary records show (Alam 1988). For example, the Dutch merchant Floris, who was engaged in the iron trade from India in the early 17th century, had a cargo of 78 tons of metal in 1613 valued at a price that was commensurate with wrought iron and far below the cost of steel (Bronson 1986).

Most of the evidence for trade in iron and steel that has been mentioned so far was with the west, but very considerable quantities were being sent to Southeast Asia from the Coromandel Coast of southern India in the 17th century as recorded by both Dutch and English merchants (Bronson 1986). The Dutch in Batavia reported that there was a good market for both Indian iron and steel in Southeast Asia, in competition with iron from China and Japan (Prakash 1984, ps. 199 & 251). The iron was sent in the vessels of Indian and European merchants and comprised bulk wrought iron, often in bars recorded as being from 8 to 10 feet long (2.5 - 3 m) and many thousands of 'pieces' of steel, presumably the equivalent of the 'eggs' or 'pucks' traded on the Malabar coast. In the late 17th -18th century cargoes of 50 – 150 tons of iron from Golconda were regularly sent from ports on the Coromandel Coast, especially Masulipatam. Most of this was wrought iron, but with appreciable quantities of steel, for example the Dutch exported 15 tons in 1681 and 49 tons in 1684 (Prakash 1984).

Post Medieval trade and into the Modern World

In the 17th century the Dutch established a considerable ship building industry in India, which in turn required very considerable quantities of iron[32]. In an interesting example of technical interaction the Dutch bought locally produced wrought iron (which they were still trading to Southeast Asia), made by the traditional processes but established European-style foundries and smithies to fashion the iron on an industrial scale, training up local workers in European methods under European foremen (Lowe 2002; Alam 2002).

However, bar iron began to be exported from Europe in increasing quantities and from the mid 18th century the extraordinary technical development and expansion of the British iron industry (Tylecote 1991) meant that it could undercut the prices of everyone in the world, India included. Thus the Indian export trade in iron was extinguished quite rapidly and the domestic market hugely diminished such that by the end of the 19th century all that survived were the primitive Agaria iron smelters in remote locations (Elwin 1942), with a technology and economy that almost certainly bore little resemblance to the large scale indigenous Indian industry that the imports had replaced (Craddock 2009c).

Conversely, by the mid19th century there were attempts by the British, now masters of India, to either revive the traditional processes but in a European business environment (Campbell 1843, also recorded in Percy 1864, pp.266-7), or to establish European-style blast furnaces, as exemplified by the Porto Novo ironworks, modern Parangipettai, in Tamil Nadu (Fig. 1) (Ball 1881, pp.349-50).

There was some logic in this attempt by the Colonial authorities to encourage Indian production as there was an incipient huge demand for iron from the railway system that was becoming established in India. Also Imperial policy generally had traditionally seen the colonies as markets for finished goods from Britain and producers of raw materials and basic commodities for Britain. In this system good quality charcoal-smelted Indian iron could be regarded as a potential feedstock for the Sheffield steel industry, alongside the existing suppliers from Scandinavia and Russia (Barraclough 1984, pp.56-8: af Geijerstam 2004, p.102), but although export was attempted in the 1850s (Ball 1881, p.350), the trade was unsuccessful (Craddock 2009c)[33].

The most extraordinary attempts to kick-start a modern iron industry in India (albeit still charcoal-fuelled) were the ill-fated Burwai ironworks, in West Nimar, Madyha Pradesh and the Kumaon Ironworks at Dechauri, in Uttaranchal State (Fig. 1) (Ball 1881, pp.406-11; Pande 2002; af Geijerstam 2002 & 2004). These were both to a considerable degree Imperial government initiatives, and to a large measure undertaken to show that India could successfully compete with imported iron and as model enterprises to encourage private investment. However the Burwai ironworks closed after the failure of its first and only smelt in 1864, but the Kumaon works floundered on for 20 years from the late 1850s until its final closure in 1880. Both were victims of bureaucratic bad planning and poor administration, but also of the changing times. Charcoal iron may have been necessary for specialist and crucible steels, but a real modern ironworks producing iron in bulk that hoped to compete with European imports had to be coke-fuelled. Also the ironworks started at just the moment when Bessemer ushered in the age of cheap steel. Even if the Kumaon ironworks had somehow become established it would soon have faced competition from imported steel. As it was the whole exercise was written off as a failure with the Imperial government concluding that 'iron could never be made in India that could compete with English imports'.

Some ironworks using coke were set up in the late 19th century but real success did not come until Jamsheji Tata set about establishing a truly indigenous but modern integrated iron and steel works. After long years spent locating suitable supplies of iron ore and coking coal, as well as raising the necessary finance and convincing the Imperial authorities of the viability of the scheme, the Jamshedpur works was built in Bihar (Elwin 1958: Mukherjee 2004). Construction began in 1907, the first iron was smelted in 1911 and the first steel rolled in 1912. Thereafter Indian iron and steel production expanded rapidly through the 20th century, with, after Independence, a combination of private enterprise and large-scale national Government five-year programmes through the 1950s and 60s (Chaudhuri 1975; Lahiri 2002). Now India once again has a major iron and steel industry and Indian companies have become an important force in world steel production.

Conclusion

India contains some of the major mines of the ancient world which were worked for a variety of precious and base non-ferrous metals, and developed sophisticated smelting technologies. Yet paradoxically, India seems only to have participated occasionally in an export trade in non-ferrous metals. Recent archaeological excavations, combined with continuing historical research have gone some way to explaining this, with India's often turbulent and complex history, being partly to blame.

The nature of maritime trade changed much through the centuries, with successively Arab / Jewish traders in ancient and medieval times, being joined and largely supplanted by the various competing European East India companies, followed in turn by the Imperial agencies in the 19th and early 20th centuries before Independence and the modern world of commodity trading. Similarly the sources of the various imported metals changed continually, but the overall pattern of the importation of non-ferrous metals both precious and base, continued through two millennia. Despite determined government efforts towards self-sufficiency since Independence, India remains a net importer of metals.

The situation is most marked with zinc and its oxide. Despite primacy in both production of the oxide and the metal, with the exception of two brief periods in the 9th – 10th centuries AD for zinc oxide and in the 15th – 16th centuries AD for zinc metal, documentary evidence from a variety of sources make it clear that zinc and its oxide were usually imported into India. The Zawar mines were reopened in the mid-20th century, but despite almost continual expansion there and at the other sites of Dariba and Agucha in the Aravalli Hills, India at the end of the 20th century still imported much of the zinc it needs.

Conversely, India was a prime source of good quality but standard wrought iron as well as the highly prized crucible steel from antiquity through until the 18th century. The traditional Indian iron and steel industry was driven almost to extinction in the 19th century, but determined indigenous efforts from the late 19th century led to the establishment of a modern steel industry that now spans the globe.

End Notes

1. See Prof. Balasubramaniam's obituary (Craddock 2010) in the *Indian Journal of History of Science* for a list of his archaeometallurgical publications.

2. See, for example, his work on Indian iron (2007); Indian cannon (2008) and the *Indian Journal of History of Science* **42.** 3 & 4, devoted to Indian iron and steel

3. The perceived lack of Mauryan activity in mining was one of the main arguments by Trautmann etc that the *Arthaśāstra* must have been compiled later.

4. Rackham translates *plumbum* as lead but from the context clearly tin was intended.

5. There is an apparently isolated 13th century (1245 AD) reference to *tagaramu*, which is believed to be a local word for zinc, as a trade item at Mottupalli a port of the Kaktiyas kingdom on the mouth of the Krishna River, Andrah Pradesh on the Coromandel coast (Fig. 1) (Chakravarti 1995), although the Italian traveller Marco

Polo on his return from China by sea in the late 13th century did not refer to any metal that could be identified as zinc on his visit to that port some 50 years later.

6. Jain (1990, p.70), also noted the import of silver, tin and other metals including alloys of uncertain composition, which he understood to be high tin bronzes, but are more likely to be of brass (see the following endnote). He believed that ‘The import of precious and semi precious metals from outside must have supplemented the local supply of silver, copper, lead and zinc from the Jawar Hills in Udaipur.’ (i.e. Zawar), although it would seem more likely that the foreign trade not so much supplemented the local supply, but rather replaced it when that supply was interrupted by war, and ultimately supplanted it.

7. In the mid 12th century AD some members of the Jewish merchant community had established a copper alloy foundry at Dahbattan (modern Valapattanam) in northern Kerala near Mangalore on the Malabar Coast (Goitein and Friedmann 2008, p.58) (Fig. 1). A number of very detailed orders have survived, made by the merchant community at Aden. From these it is clear that scrap copper alloy, yellow copper together with another metal, *qal'ī* (see EN 17), were sent out from Aden to India to be cast into a variety of familiar Islamic vessels, trays and lamps etc and the remainder of the metal sold locally. Extensive analyses of Islamic copper alloy metal work of this period show that the beaten metalwork was of brass (copper and zinc, the yellow copper) but that the cast metalwork was of leaded brass. True bronze, copper and tin, was only used for a very restricted range of items such as mortars and mirrors (Craddock et al 1998b). Thus it is likely that it was scrap brass, fresh brass and lead (*qal'ī*) that were being sent to the Malabar Coast. In the post medieval period lead was exported to India in considerable quantities (see EN 15).

8. At just this time Arab traders were sending cargoes of copper and brass bars south across the Sahara. One such cargo was part of a caravan that came to grief in Ma’den Ijâfen in the deserts of southern Mauritania sometime between the 11th and 13th centuries AD (Monod 1969). The brass was of copper with about 20% of zinc and little else (Werner and Willett 1975).

9. In antiquity brass was made by direct processes, that is, the oxidised zinc ore was added directly to the copper. In the Islamic world this was done by adding the zinc mineral to molten copper (Craddock et al 1998b), but already by the 11th-12th century AD in India the more sophisticated cementation solid state process was used where the zinc oxides were interlayered with copper sheets and heated in a crucible with charcoal as described in the *Rasārnavakalpa* (Roy and Subbarayappa 1976). This process allowed more zinc to be absorbed by the copper.

10. The term for zinc oxide in the Islamic world was *tūtīyā* which certainly comes from Old Persian or Sanskrit, and probably derives from the word for smoke. This is entirely appropriate as it was made by the oxidation of zinc vapour which produced dense white clouds of zinc oxide sublimate.

Tutty was a term also used in medieval Europe by Albert Magnus, for example, in the 12th century AD (Wychoff 1967, pp.249-50). Calamine, the traditional English word for zinc carbonate, the mineral used to make brass by the cementation process, is derived from the medieval Latin word *calamina*, which itself is of uncertain origin. Beal (1884) speculated that calamina derived from a port named Calamina at mouth of the Indus where St. Thomas was reputed to have been martyred. However it now seems that the name is a later medieval confusion and no place of that name ever existed in India. Ball (1886) suggested Calliana, the ancient port near Mumbai, as an alternative although this seems very unlikely even though Cosmas Indicopleustes (literally Cosmas the Indian traveller) stated in his *Christianike Topographia*, written in the 550's AD that copper or brass was exported from there (McKindle 1897).

11. The import of *Tutty* is only mentioned in source Z, a fifteenth century manuscript of the *Travels* that carries more detail than the others, but is regarded as reliable.

12. This trade has been dramatically illuminated by the recent discovery of the remains of a Portuguese vessel off Namibia (Chirikure et al 2010). The vessel went aground enroute to India at some time in the 1530s with a cargo that included 18 tons of copper (Fig. 2) and lead bars as well as about 200 kg of thin tin bars. There were also many thousands of gold and silver coins to pay for cargoes in India.

13. (See also EN18) *Tutty*, originally the word for zinc oxide, seems to have been adopted by some European traders in the Indian Ocean as the word for zinc itself and *tutty*, or variants such as *tutanag, tutenage etc*, became the usual term for the metal from China throughout the post medieval period used by all the European trading companies (Bonnin 1924).

14. The import of silver into India was much increased during the late 16th and 17th centuries as a result of the expansion of European activities. It would seem that the ultimate source of most of this silver was the Americas as demonstrated by Hasan (1969), leading to a substantial price inflation, such as was also experienced in Europe. Similarly in China, Guotu (1997) estimated that between the 16th and early 19th centuries some 500 million *taels* (approximately 18,000,000 kg) of silver, mainly from the Americas, entered the country as payment for merchandise, thereby having a profound effect on the Chinese economy, not least the coinage.

15. Some late 18th century English lead ingots marked W Blackett have been found off the shore at Poompuhar, Tamil Nadu, being part of the ballast cargo of an unknown wreck (Tripati et al 2003) (Fig. 9).

16. Although the zinc was not necessarily produced at Zawar at this date. Recent, as yet unpublished work, has established that medieval zinc coins are likely to have been produced in the north west of India, with fieldwork suggesting sources in the Tons Valley on the Hamilchal Pradesh / Uttaranchal border (Fig. 1).

17. (See also EN13) Some, such as Forbes (1971, p.282) believed the word derived from the Arabic *kala'i*, that is 'coming from Kedah' (Qalah) in Malacca, or from the

Malaysian word for tin, *kaleng* or *kaling* (Allan 1979, p.27 and should be interpreted as tin or, sometimes as lead. This may be true, but it seems that it had broadened or changed its meaning to include zinc by the time the Portuguese were using the term in the 16th century. Is it possible that the connection was ultimately with the Medieval Latin calamina (Giumlia Mair pers. com)? *Calaem* or *kaleem* was certainly one of the names used for the zinc shipped to Europe in the 17th century. For example, Watson (1786, pp.1-3) noted the case where *calaem* from a Portuguese ship captured by the Dutch in 1611was identified as being of zinc, not tin.

18. Zinc is a white metal which produced a useful alloy with copper, and thus the association and confusion with tin is understandable. For example, even the early Indian Sanskrit iatro-chemical accounts of the preparation of zinc by distillation described the metal as 'having the essence of tin' (Ray 1902 I, p.39 etc). Centuries later in the early 19th century, James Tod, the great historian of Rajputana, who had visited the mines at Zawar shortly after they had been abandoned, still described them as tin mines (Tod 1978 I, ps.10 & 117). A variant was where zinc was called 'Indian tin'. Another confusion was with lead because zinc deposits are often found together with deposits of lead which may in turn be argentiferous and thus the association with those metals is not surprising. Zinc was sometimes known in European silver mines as *counterfeit* or *counterfrei*, that is, false silver, and *wo ch'ien* in China as 'poor lead' for example. The Dutch managed to confuse zinc with the tin alloy, pewter (Dutch *speuter*) from which spelter, the alternative English name for zinc, is derived. In more recent times in English usage spelter was reserved for the freshly smelted metal and zinc for the refined and rolled metal.

Within medieval Hindu India itself the term for zinc was *jasada* (Ray 1902, p.86) and the zinc ores from which brass was made by cementation were usually termed *rasaka*. These words derive from *rasa*, the word for mercury and clearly this is because zinc metal was prepared by a very similar process of downward distillation to that by which mercury was made (Craddock 2009a). The *Āīn-I Akbarī* makes a specific reference to zinc production at Zawar (Habib 1982, p.20; Phillott1927, I pp.41-2). The metal was called *Jast* which Abū 'L-Faẓl understood 'according to the opinion of some, is *Rūḥ-i- tūtiyā* (that is made or originating from *tūtiyā*), and resembles lead.'. Thus Abū 'L-Faẓl, based in India, clearly knew the true nature of zinc, although he then went on to state that the Hindus believe that another metal called *riṣāṣ* (presumably also derived from the Hindi *rasaka*) was silver in the state of leprosy, seemingly not realising that they were one and the same.

19. Calendar of State papers preserved in the Public Record Office, London: Researches in Foreign Archives: Italy 1509-1519.

20. The presence of the tin bars in the Nambian wreck on its way out from Europe to India, is further evidence that the *Calaem* or 'tin' ingots coming from the east back to Europe in Portuguese vessels at just this time, referred to previously, were likely to have been of something else.

21. Souza (1991) estimated that in the first half of the 17th century approximately 200 – 300 tonnes of Chinese zinc were exported annually, but with most going to Japan. Production and exports expanded dramatically in the 18th century with several thousand tonnes being exported each decade in the late 18th and early 19th centuries. No less than 3,000 tonnes were recorded as being exported in 1817, much of it destined for India.

22. A programme of lead isotope analyses on a selection of 17th and 18th century *bidri* pieces failed to link any with zinc from Zawar (Craddock et al 1998a; Craddock 2005).

23. In the 18th century there were various stories of Europeans going out, usually to China, to learn the secrets of the process. These would seem to be without foundation as the Chinese process was completely different from any process ever developed in Europe (Almond 1998).

24. Possible reasons for the failure of Zawar zinc to compete with Chinese imports could be due to the lower production costs of the Chinese process (Craddock and Zhou 2003; Liu et al 2007; Zhou et al 2012). The Chinese used smithsonite ore, zinc carbonate, $ZnCO_3$, which could be charged directly to the retorts, whereas the Zawar ore was sphalerite, zinc sulphide, ZnS, which had to be carefully roasted before charging. Secondly the Zawar retorts could only be used once, whereas the Chinese retorts could typically be used between 7 and 10 times before being discarded. Thirdly, the Chinese used mineral coal extensively, which would have been much cheaper than charcoal.

25. In particular, Munhot Naisi, who was first minister (*deevan*) of Jaswant Singh, Maharaja of Marwar, the state lying to the north of Mewar, through much of the second half of the 17th century, compiled a history of his own times, the *Khayat*. There it is stated that at Zawar there was a silver mine, the daily income from which was between 400 and 500 rupees, and that both silver and zinc were produced (Ojha 1931, II, p.1123)., but clearly zinc production was very much reduced.

    In complete contrast it is estimated that in China, Guizhou Province alone produced over half a million tonnes of zinc in the century between 1725 and 1828 from many different locations (Ma 2011).

26. Apparently the iron and steel were from Ariakē, the land behind Barugaza, that is from present day Gujarat and southern Rajasthan.

27. Ordinary wrought iron would have been made by the so-called *bloomery* or direct process in which the iron ore was reduced to iron metal without ever having become molten (Elwin 1942; Craddock 1995, pp.241-50). The metal was thus heterogeneous and contained significant amounts of slags which seriously weakened the metal; also the carbon content was low. These faults could rectified by taking wrought iron and heating it to very high temperatures in a sealed crucibles with carburising agents such that the iron absorbed about a percent of carbon and melted, giving a homogenous high carbon steel (Craddock 1998; 2003 & 1995, pp.275-83). The resulting crucible steel was always forged in antiquity, never cast.

28. It has been estimated that to produce 1 kg of iron by the traditional Indian processes required 14.6-16.7 kg of charcoal which in turn required 50 - 60 kg of wood (Tripathi and Tripathi 1994)

29. This was previously ascribed to his namesake, Zosimos of Panopolis, a historian of the 5th century AD, by Berthelot (1888, III, p.332) more recently by Mertens (1995) and Giumlia Mair et al (2009). However further investigation has shown that the true author was indeed Zosimos of Alexandria (Giumlia Mair pers. com.).

30. The crucible steel was always allowed to cool and set within the small crucible in which it had been made, and thus it retained the shape of the crucible. Some of the early crucibles from southern India and from Sri Lanka broaden out to an egg shape at their bottom, whereas the rather later crucibles from the Deccan are broad flat bottomed vessels and the resulting ingot was deemed to be similar to the puck used in the sport of polo.

31. Iron was often carried as a ballast cargo, although there was a problem not encountered with the ballast cargoes of lead or zinc, namely the propensity of iron to rust, especially in contact with sea water. On occasions merchants could request that their 'bright' iron be carefully packed lest it begin to go rusty (Goitein and Friedman 2008, p.612).

32. A late 17th century manual on shipbuilding estimated that a typical merchant ship of the type used by the VOC would contain about 80 tonnes of iron (Lowe 2002).

33. The company supplied much of the wrought iron for the Menai and Britannia Tubular railway bridges in Britain.

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