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Preliminary Insights into the Provenance of South Indian Copper Alloys and Images Using a Holistic Approach of Comparisons of their Lead Isotopes and Chemical Composition with Slags and Ores

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An attempt is made to gain greater insights into probable sources of copper alloy images and artefacts from south India by comparing lead isotope ratios and elemental analyses of artefacts with those of ores and slags. About 130 south Indian copper alloys were investigated using lead isotope and ICP-OES analysis. The vast majority of these are historically and artistically important south Indian images from the collections of the Government Museum, Madras; the Victoria and Albert Museum and the British Museum, London. To determine possible ore sources, trace element comparisons, investigated by EPMA-WDS, are discussed alongside those of slags from five sites with evidence of mining and metal extraction in antiquity from southern India. The following classification of images, as ratified by their As, Bi, Ni, Co and Sb element distributions, is: Pre-Pallava (c. 200-600 AD), Pallava (c. 600-850 AD), Vijayalaya Chola (c. 850-1070 AD), Early Chalukya-Chola (c. 1070-1125 AD), Later Chalukya-Chola (c. 1125-1279 AD), Later Pandya (c. 1279-1336 AD), Vijayanagara and Early Nayaka (c. 1336-1565 AD) and Later Nayaka and Maratha (c. 1565-1800 AD) periods. From trace element comparisons it is probable that Kalyadi was a source of smelted bronze for the Vijayalaya Chola group of images and Tintini of copper for Vijayanagara images. Lead isotope studies indicate discrete lead sources for Vijayalaya Chola images (which may have been Ambadongar), Vijayanagara and Early Nayaka images and for most Chalukya-Chola images, while in the Pallava period the use of lead from two sources is indicated. Lead isotope studies indicate that Ambaji was clearly a source of lead, and probably also of metallic zinc, for western India and a minor one for south India by the 12th-13th centuries; that Dariba in northwestern India was a source of lead for south India in the late medieval period; and that for Andhra Satavahana coins (c. 1st-2nd century) both local lead from Andhra and imported Mediterranean lead were used. A source of metallic zinc for south India as early as the 4th century AD is also indicated from a zinc ingot representing some of the earliest known evidence for metallic zinc. Trace element trends of four 'Indo-Roman' copper coins (4th century AD) suggest local manufacture.

Keywords: Provenance; South India; Copper Alloys; Pallava; Chola; Vijayanagara; Early Historic Period; Lead Isotopes; Trace Elements; Slags.

Introduction

Copper alloy images from southern India form one of the most important Indian artistic expressions, as represented by the well known iconography Nataraja, depicting the cosmic dance of Siva, which has been acclaimed by artists like Romain Rolland and Rodin (Coomaraswamy 1924). As with other Indian metal artefacts, there are many problems in making provenance, chronological and stylistic attributions for south Indian copper alloys and images, due to their poor contexts. Many images were recovered from hoards buried to protect them from iconoclasm (at various periods during Islamic raids and also from Portuguese vandalism) (Nagaswamy 1988) or come from temple vaults. While Hindu, Buddhist and Jaina religious images have been made, the majority are Hindu which were seldom inscribed, unlike the others, so making it difficult to give attributions. South Indian image casting also represents one of the longest continuous traditions and is still being practised in the Tanjavur district of Tamil Nadu. This has also compounded problems in the dating of images through imitations of earlier styles and repetitive iconography.

Indeed, some of the above issues are also part of a wider problem in the study and typological classification of all Indian metal artefacts. The fact that a significant proportion are found in hoards rather than in stratigraphical contexts, for example, the copper hoard artefacts of the Indo-Gangetic Valley of about the second millennium BC; the lack of marked burial traditions from at least the early historic period (i.e., Christian era), and the preference for ritual cremations according to Hindu or Brahmanical practice, are probably significant contributing factors. In addition quite a number of artefacts from South India have been uncovered from river beds, as in the case of some 'Indo-Roman' coins discussed in this paper. Hence there is relevance in exploring the usefulness of a scientific approach for gaining greater insights into the archaeology or art history of these artefacts and in building up analytical data on these artefacts against which comparisons can be made.

Methodology

A holistic (integrated) analytical and archaeometallurgical study has explored the implications of analysis and studies in ancient metallurgy for art history, chronology, style and provenancing of south Indian images and related copper alloys (Srinivasan 1996). Images were sampled from the important collections of the Government Museum, Madras, India, the Victoria and Albert Museum, London and the British Museum, London. Compositional and trace element analyses were performed on 106 sets of images (each set comprises one accession number, but can consist of more than one image or include accessories which also may have been analyzed) and ten miscellaneous artefacts (such as coins, charters and bowls) for eighteen elements, using inductively coupled atomic emission spectroscopy (ICP-AES) at Royal Holloway and Bedford New College, UK (TABLE 1a, b (at end)). Lead isotope analysis was done on

60 objects using Thermal Ionization Mass Spectrometry (TIMS) at the Isotrace Laboratories, Oxford (Srinivasan 1996, in press a). Both lead isotope and elemental analysis were performed on 39 objects. Comparisons were also made between traditional image casting practices observed by the author in Tanjavur district in mid 1990, and casting features observed from technical examination of the ancient images. This is reported in Srinivasan (1996).

This is the first comprehensive study using a range of analytical techniques on a significant number of bronze images from south India. The study includes a fairly representative sequence of bronzes of artistic and historical importance from various dynastic periods and their associated styles.

Analyses of less than a dozen early medieval south Indian bronzes (8th-13th centuries AD) have been reported by Werner (1972), and Johnson (1972). Previous provenance studies of religious icons from the Indian subcontinent include about 150 copper alloy images from the Indo-Tibetan region (Reedy 1986). Statistics were employed to discriminate between images from different regions, based on compositional analyses, stylistic criteria, and clay core analyses. For south Indian bronzes, these being solid cast without clay cores, the present study is based solely on metal.

The potential of the lead isotopes in helping to solve archaeological problems is well established and is discussed by Gale (this volume). Lead isotope analysis, which is a more powerful tool for provenancing leaded metal artefacts than elemental analysis, has been used in this study alongside trace element analysis, to determine if analytical signatures of groups of bronzes can be identified as a help in their typological classification.

Lack of information on ore sources, needed before attempting any provenance studies, need not be a deterrent in the use of lead isotopes. These remain a powerful diagnostic device for exploring internal consistencies within groups of artefacts and so may be used to characterize them. For example their use in elucidating the art history of West African figurines (Joel *et al.* 1995) where, although many of the sources could not be identified, discrete lead isotopic groupings were observed between Benin, Udo and Ife castings. Similarly, lead isotopes in conjunction with elemental analysis have been used in the study of Chinese Buddhist religious images now in the Freer Gallery of Art (Sayre *et al.* 1992).

Complete lead isotope data on the analyzed south Indian images as well as data on Indian ore sources are given in Srinivasan (in press a). Lead isotope measurements were made using a fully automated multicollector thermal ionization mass spectrometer (VG 38-54-30) calibrated with NBS SRM 981 standards.

The implications of such studies for stylistic re-analysis of south Indian images are discussed elsewhere (Srinivasan, in press a), while a revised catalogue for the sampled collection is to be published in a forthcoming monograph (Srinivasan, in press b).

This paper discusses some of the inferences that can be made from empirically observed chemical similarities within artefacts in trace elemental and/or lead isotope ratio data about shared sources or histories of processing of metal which may help their typological classification or characterization.

The lead contents of the 60 artefacts selected for lead isotope analysis were semi-quantitatively determined, all but a few had more than 1% lead. It is recognized that even a 1% alloying of lead would swamp the lead isotope ratios from trace amounts of lead in the copper or zinc components of the alloys (Stos Gale pers. comm.). Hence, essentially it is the source of lead in the alloys that is being provenanced.

Trace element patterns on the other hand are more likely to reflect the source of copper, with those like nickel and cobalt being chalcophilic. Indeed, different ore deposits can have characteristic trace element distributions based on ore geochemistry; for instance Mookherjee & Phillips (1979) found that nickel and cobalt values in copper ores from Ingaldhal in south India are linearly correlated. However, the final levels of trace elements in any processed metal would be affected by contributions from fluxes, by the partitioning of trace elements from ore to smelted metal (Merkel 1983) and refining, so that it is difficult to attempt correlations between artefacts and copper ores. This is a topic that requires concerted study. Comparisons with metal remnants in slags should reflect the processed metal more accurately. But in any case consistencies in trace elements could indicate the use of similar sources or at least the use of similar batches of processed metal leading to such uniformity.

To explore these aspects further, a preliminary study was made of ores and slags from old mine workings and slag heaps in south India. These were subjected to trace element analysis using electron probe micro-analysis with wavelength dispersive X-ray spectrometry (EPMA-WDS), at the Wolfson Laboratories of the Institute of Archaeology, University College London. Lead isotope ratios on a few specimens of galena taken from these ore sources were also measured. Firstly, the nature of the base metal smelting that seemed to have taken place was determined from the slags. Secondly, quantitative analyses of the metallic remnants or prills in the slags was performed to see whether characteristic elemental patterns could be observed which then could be compared with finished artefacts. The main reason for attempting chemical comparisons between finished artefacts and metallic prills in slags rather than ores was because a limited number of microanalyses on hand specimens by EPMA showed the ores to be heterogeneous on a fine scale and extensive bulk analyses of a statistically significant number of ore specimens were outside the scope of this study. Furthermore ores undergo great chemical changes during smelting. However, the relationship between the composition of metallic prills and finished artefacts is less tenuous since the prills represent trapped solidified droplets of metal dispersed through slag and so their composition should be representative of the molten ingot produced in the furnace.

Bearing in mind these limitations any foray into exploring sources of metal must be preliminary. The more conclusive body of evidence showing analytical signatures relating to groups of artefacts is discussed here briefly, but given in full in Srinivasan (in press a, b).

Lead isotope ratio and trace element data for a typological classification according to dynastic chronology and implications for provenance

The sampled images and artefacts are categorized under the following groups according to dynasties as listed in Table 1a, these are based on re-assessments made on the published art history literature, plus insights provided by scientific analysis (Srinivasan in press a, b). The lead isotope and trace element trends for different stylistic groups are set out in Srinivasan (in press a). It should be noted that the chronological boundaries of these groups are broadly fixed by what is known of dynastic chronology and are, in that sense, approximate and not absolute. The groups are:

-Andhra & Pre-Pallava	(*c.* 200-600 AD)
-Pallava	(*c.* 600-875)
-Vijayalaya Chola	(*c.* 850-1070)
-Early Chalukya-Chola	(*c.* 1070-1125)
-Later Chalukya-Chola	(*c.* 1125-1279)
-Later Pandya	(*c.* 1279-1336)
-Vijayanagara & Early Nayaka	(*c.* 1336-1565)
-Later Nayaka & Maratha	(*c.* 1565-1800)

Scatter plots are shown of Pb 208/206 against Pb 207/206 and Pb 206/204 against Pb 207/206 for south Indian images and copper alloys. FIGURE 1 is a scatter plot of Pb 208/206 against Pb 207/206 with symbols for dynastic style/chronology. FIGURE 2 is a scatter plot of Pb 208/206 against Pb 207/206 with symbols showing different metal types. The ellipses marked on both figures indicate groups of artefacts within which there is internal stylistic coherence. Inter-element scatter plots from ICP analysis for cobalt against nickel, bismuth against arsenic and antimony against cobalt are shown in FIGURE 3 a, b and c.

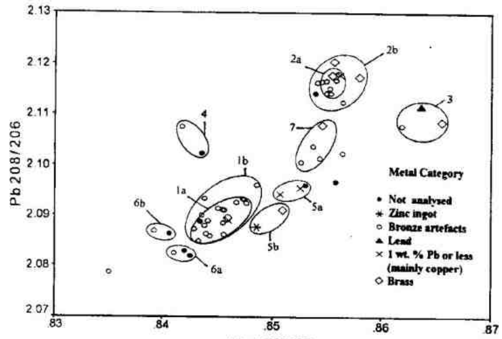

Figure 1: Scatter plot of lead isotope ratios of Pb 208/206 against Pb 207/206 ratios for south Indian base metal images and artefacts (excluding two), with markers indicating dynastic chronology of artefacts. The ellipses and line indicate groups of artefacts within which stylistic coherence was observed. The cross bar indicates that the error in measurement of lead isotope ratios is less than 0.1%, and also indicates the spread in isotopic composition for groups of artefacts.

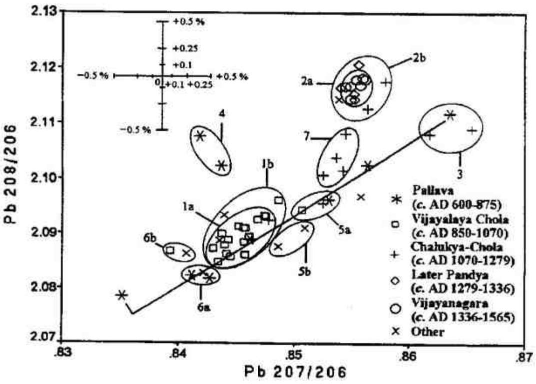

Figure 2: Scatter plot of lead isotope ratios of Pb 208/206 against Pb 207/206 ratios for south Indian base metal images and artefacts (excluding two), with markers indicating metal category of artefacts, whether they are of leaded bronze, lead, copper or zinc or brass. The ellipses indicate groups of artefacts within which stylistic coherence was observed.

FIGURES 1 and 2 show that leaded images of the Vijayalaya Chola (*c.* 850-1070 AD) fall predominantly into Group 1a, and the spread in isotopic composition for this group is narrow enough to suggest that the objects came from a discrete lead source. The Vijayalaya Chola images represent the most artistically significant and prolific group of south Indian bronzes with bronzes attributed to the munificent patrons of the lineage of Vijayalaya Chola such as the remarkable dowager queen Sembiyan Mahadevi, described by Harle (1994) as one of the great patrons of all time, and king Rajaraja Chola (Barrett 1965; Dehejia 1990). Well known images, previously attributed by art historians to this period for which lead isotope and trace element trends fit include a Nataraja, (acc. no. IM-2-1934) (FIGURE 4), from the Victoria and Albert Museum, attributed to Sembiyan Mahadevi's patronage by Dehejia (1990) and Schwindler (1975), and the fine Velankanni Nataraja (acc. no. 234) in the Government Museum, attributed to Rajaraja Chola by Schwindler (1975) and Srinivasan (1963). Indeed Rodin (1921) remarks that this latter Nataraja rivals the Medici Venus in its graceful execution.

Group 2a consists predominantly of Vijayanagara period bronzes (*c.*1336-1565 AD), another powerful dynasty in southern India under which the sprawling capital city of Vijayanagara was built at Hampi in north Karnataka. A published image fitting this group is the Rama (acc. no. IM-71-1927) from the Victoria and Albert Museum attributed to the Vijayanagara period by Michell (1995). This group also seems to represent a discrete lead source from its narrow spread of isotopic ratios, as does group 7. This group consists of images classified as Chalukya-Chola (*c.* 1070-1279 AD) including an image of Kiratarjuna (acc. no. 43-IS-1887) dated by Nagaswamy (n.d.) to the 12th century. The line on FIGURE 2 indicates that images and artefacts (including a lead coin and a copper plate charter) from the Pallava period (*c.* 600-875 AD) have lead isotope ratios plotting roughly along it, suggesting that lead in these artefacts may be the result of the random mixing from two sources leading to a linear combination of their ratios. A published image fitting this trend is the Natesa from Kuram in the Government Museum, Madras (acc. no. 53/38) attributed Nagaswamy (1988)

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Figure 4: Siva Nataraja (acc. No. IM-2-1934), Tanjavur district, Tamil Nadu, of the period of Chola queen Sembiyan Mahadevi (c.950 AD) which fits lead isotope and trace element trends for the Vijayalaya Chola group (c.850-1070 AD) Reproduced by permission of Victoria & Albert Museum.

Figure 5: Avalokitesvara (acc.no. IM-300-1914) uncovered from the Krishna delta, Andhra, c. 5th C. AD, which fits trace element trends for the Pre-Pallava and Early Andhra group. Reproduced by permission of Victoria & Albert Museum.

to the Pallavas. An important early image, the damaged Buddhist Avalokitesvara (FIGURE 5) (acc. no. IM-300-1914) dredged from the Krishna delta, Andhra, in the Victoria and Albert Museum, fits the trace element trends for the Pre-Pallava and Andhra group (*c.* 200-600 AD). This group can be distinguished from the Pallava group in having antimony contents of not more than 0.1 wt. %. From its style, it had not been certain whether it was South Indian or Sri Lankan, although its early Deccan affinities had been pointed out by Zwalf (1985), while Sivaramamurti (1963: Fig. 2b) had attributed it to the early Andhra Pallavas around the 5th century; and indeed analysis supports such an attribution.

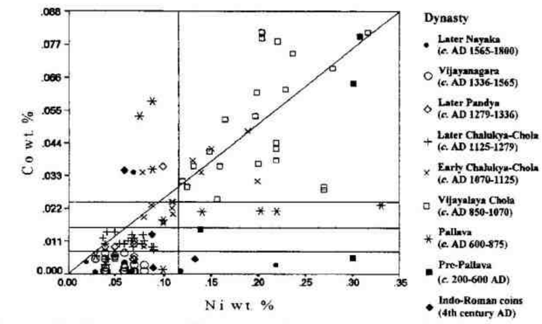

Figure 3a: Scatter plot of Co against Ni contents for south Indian copper alloy images and artefacts analyzed by ICP-OES. The markers relate to dynasty chronology of the artefacts. The diagonal line indicates that a linear trend is noted for bronzes of the Vijayalaya Chola period. The perpendicular lines indicate the boundaries of absolute values for different groups of artefacts. Trends for four 'Indo-Roman' coins analyzed by ICP-MS are also indicated.

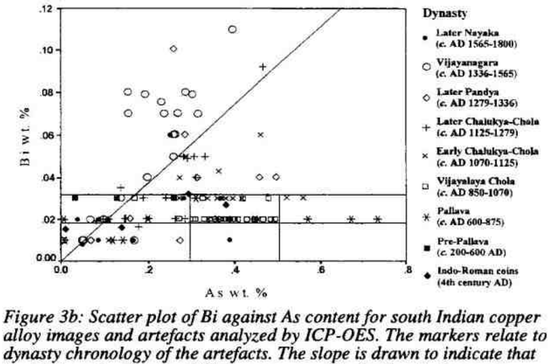

Figure 3b: Scatter plot of Bi against As content for south Indian copper alloy images and artefacts analyzed by ICP-OES. The markers relate to dynasty chronology of the artefacts. The slope is drawn to indicate that the Bi/As ratios for most Vijayanagara and Early Nayaka images is greater than 0.19. The perpendicular lines indicate the boundaries of absolute values for different groups of artefacts. Trends for four 'Indo-Roman' coins analyzed by ICP-MS are also indicated.

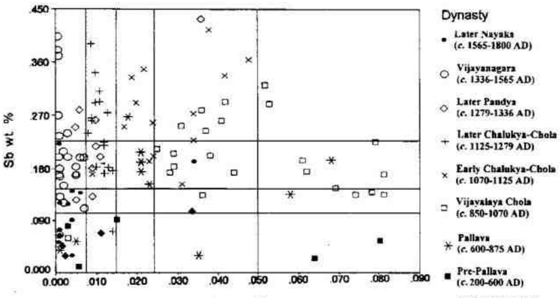

Figure 3c: Scatter plot of Sb against Co content for south Indian copper alloy images and artefacts analyzed by ICP-OES. The perpendicular lines indicate the boundaries of absolute values for different groups of artefacts. Trends for four 'Indo-Roman' coins analyzed by ICP-MS are also indicated.

The discrete trends of the images and alloys for the different stylistic groups as seen in the lead isotope ratio plots, are also generally reflected in the trace element scatter plots (analyzed by ICP-OES, TABLE 1a, b), notably cobalt against nickel, bismuth against arsenic, and antimony against cobalt seen in FIGURE 3a, b and c. Indeed, a linear trend is observed for the Co:Ni ratios of the Vijayalaya Chola group (FIGURE 3a) which may be a characteristic of the copper ore. For the Vijayalaya Chola group, distinct lead and copper sources seem to have been used, which may or may not belong to the same polymetallic deposit. This is also the case for Vijayanagara bronzes. For the Chalukya-Chola bronzes, whilst the lead sources appear to have been similar, the trace element patterns support a separation between Early Chalukya-Chola and Later Chalukya-Chola groups. For most Later Pandya images the source of lead seems to have been the same as the Vijayanagara group. However, for the Early Chalukya-Chola and Later Pandya groups, their trace elements are somewhat intermediary between the trends for the bordering groups: this may be explained if a new copper source was being mixed with earlier metal, which then became more widely exploited in the later periods. However, note that the trace element patterns for different groups need not indicate the use of disparate copper deposits but may indicate the use of metal from different veins/mines within the same mining region.

Examples of images whose compositions suggest re-cycling of metal from their mismatch with earlier groups are discussed in Srinivasan (in press b). However, generally there does not seem to be much evidence for re-cycling, especially between the Vijayalaya Chola and Vijayanagara groups. This may have been because the re-cycling of images was not favoured for religious reasons. This observation is especially true for Hindu images.

That secular scrap was re-mixed is suggested by the trends observed in the lead isotope ratios of the Pallava group (FIGURE 1) where one of the two groups between which mixing occurred (giving rise to the linear trend indicated in the figure) seems to be group 3. This group also contains a Pallava lead coin and two Satavahana lead coins (Srinivasan 1996), suggesting that coins and such utilitarian artefacts were indeed re-cycled. This fits ethnographic observations made in 1990 in Kerala and Tamil Nadu of widespread and organized bartering and re-cycling of utilitarian traditional metalware. By contrast, re-cycling of images was not that common and only to make other images.

In FIGURE 2 the reason for designating groups 1b and 2b as peripheral to the major groups 1a and 2a is to suggest that they consist of artefacts where most of the lead comes from the same sources as the major groups but is mixed with minor amounts of lead from other sources. The same may also be true for other minor peripheral groups including 5 and 6. FIGURE 2 also suggests that some of the smaller clusters comprise artefacts that are also related by metal type. For example group 5b consists of a Deccan zinc ingot, with a Brahmi inscription datable to *c.* 4th century, and a remarkable figurative votive Buddhist brass vessel (acc. no. IM-9-1924) with 14 wt. % Zn from the Andhra region of south India (now in the Victoria and Albert Museum) of about the 5th century. The zinc ingot constitutes some of the earliest evidence for metallic zinc reported anywhere. Group 5a consists of two gilt copper Buddhist images, one from Nagapattinam (acc. no. IPN-2639) in the Tamil region (with trace element trends that match the Later Chalukya-Chola group) and the other dredged off the coast of northern Sri Lanka, namely the famous 1.4 m high gilt Tara (OA-1830-6-12-4) currently in the British Museum (FIGURE 6). Another explanation for the slight shift in lead isotope ratios between 5a and 5b, and their plotting on the periphery of main group 1a (representing a Vijayalaya Chola lead source), could be that it is the result of using different copper, lead or zinc ores from the same mining region. The objects in the above two groups nevertheless share the trace element trends seen in the corresponding chronological groups of south Indian bronzes, increasing the likelihood of their having a south Indian provenance. In fact, out of a dozen images found in Sri Lanka and analyzed by AAS (Von Schroeder 1990), the gilt Tara is the only one which fits with South Indian element analyses, in this case Pallava trends, suggesting, perhaps, re-use of Pallava metal.

Figure 6: Gilt Tara (acc. no. OA-1820-6-12-4) found near Trincomalee off the coast of north Sri Lanka whose analytical signatures suggest a South Indian provenance. (Courtesy of the Trustees of the British Museum, London)

Lead isotope investigations were also undertaken on fewer than ten images found in regions in the southern part of the subcontinent other than the Tamil region (indicated in TABLE 1a) including Karnataka and Andhra Pradesh. Details of these are reported elsewhere (Srinivasan 1996; in press b), but it is worth noting that they either shared trends with, or fell onto, the periphery of lead isotope groups for the corresponding chronological group of Tamil bronzes. This suggests that metals from particular sources were widely distributed over the southern Indian region at particular times.

Ore sources that can be excluded from the analyzed south Indian copper alloys

The identification of exact provenances for leaded artefacts by matching their lead isotope ratios with those of ore sources is complicated by non-availability of all the data for those ore sources. However, it is possible to exclude ore deposits from being the source of an artefact if their lead isotope ratios fall sufficiently outside the field or spread of isotopic ratios for that artefact (Stos-Gale 1993). For the majority of south Indian images and artefacts, precise ore sources could not be pinpointed. There are two exceptions for which ore sources were traced in northwestern India. Other than for some northwestern Indian ores, recent lead isotope data for the Indian subcontinent, as determined from standardized laboratories, are lacking.

Nevertheless, known sources in the old world for which recent and reliable lead isotope data are available, namely Europe, West Asia and parts of Asia such as China, can be eliminated, as the lead isotope ratios of the south Indian images do not fall convincingly within the spread of isotopic compositions for any of the ore deposits from these regions (Stos-Gale pers. comm.) The spread for lead isotope ratios for Indian ore deposits such Zawar and Ambaji in western India is found to be of the order of 1-2% of the mean, as indicated by an inspection of the lead isotope data from the Isotrace data bank. For example, Ambaji has Pb 208/206 ratios ranging from 2.0902-2.14883 for different mines in the same region. This is much higher than that usually observed for ore deposits which is typically not more than about 0.25% of the mean (Stos-Gale 1993). Note that the spread in lead isotope ratios for most of the analyzed south Indian bronzes is around 1% of the mean, so that it is possible that they came from an as yet unidentified mining region in the Indian subcontinent characterized by such a large overall isotopic spread. Another reason for suspecting this might be the case is that there is a chronological shift from groups 1 to 2 with increasing Pb 208/206 and Pb 207/206 ratios.

Lead isotope analyses obtained from galena from two south Indian ore sources were different enough from those of the south Indian images to exclude them. The galenas were from Mamandur in Tamil Nadu (Pb 208/206: 2.39953, Pb 207/206: 1.06335) and the Bandalamottu mine in Andhra Pradesh (mean Pb 208/206: 2.16874, Pb 207/206: 0.94079). Ores from north-western India, some of which are published in Ericson & Shirahata (1985) also do not match. However, there are several other ore deposits in southern India and elsewhere in the Indian subcontinent for which lead isotope data are not available, for example in southern India there are several lead-zinc deposits in Andhra Pradesh including Zangamrajpalle.

Probable sources for Chola and early medieval south Indian images (9th-14th century)

Although an old analysis, lead isotope ratios of galena from an ore deposit in peninsular India, namely Ambadongar, (Venkatasubramanian *et al.* 1982) with Pb 208/206 ratios of 2.07 and Pb 207/206 of 0.84 fall within a spread of ±1% of the mean of group 1a consisting of High Chola or Vijayalaya Chola bronzes and so it is a possible source. TABLE 2 (at end) indicates preliminary results for Ni:Co and As:Bi ratios from analyses of base metal prills in slags from various sites in southern India by EPMA-WDS analysis alongside those of the analyses of trace elements in the south Indian images of the Vijayalaya Chola and the Vijayanagara groups. This indicates that the slags from Kalyadi in Karnataka may have been a source of metal for the Vijayalaya Chola bronzes since the Ni/Co ratios are comparable.

It is notable that the slags from Kalyadi are bronze slags consisting of an average 7% tin (normalized to a 100%, or 5% un-normalized). Based on the presence of metallic iron in the slag, preliminary indications are that the slags are from direct smelting of bronze using copper and tin ores, rather than from casting and alloying copper and tin metals (Srinivasan 1997). In addition, the average tin content of the Vijayalaya Chola bronzes is 6.8% which does not rule out the possibility of Kalyadi being a source of metal for these bronzes. Although the Vijayalaya Chola rulers ruled from their capital of Tanjavur in the Coromandel region of southern India, their influence extended to south Karnataka in the 11th century where Kalyadi is located. Indeed, there is a literary reference of the Imperial Cholas of Karnataka collecting fees on the export of tin (Kuppuram 1986), providing more evidence for the production of bronze from this region at this time.

Figure 7: Brass Buddha (acc. no. IS-44-1966) from Kanchipuram, Tamil Nadu, c. 1280 AD whose lead isotope ratios indicate that the source of lead, and probably zinc, was Ambaji in western India. Reproduced by permission of Victoria & Albert Museum.

A south Indian Buddhist brass image with 24% zinc and 2.8% lead of the 13th century from Kanchipuram (acc. no. IS-44-1966), Tamil Nadu (FIGURE 7), matched lead isotope data for a mine in the west Indian zinc-lead deposit of Ambaji. A spectacular 1 m high Jaina image of a seated Santinatha (acc. no. 930-IS) from western India in the Victoria and Albert Museum, inscribed to 1168 AD, made of brass (25% zinc, 3.6% lead) also has lead isotope ratios matching the same mine in Ambaji. Since lead and zinc are usually associated with each other, a few percent of lead is often found in smelted zinc. This suggests that Ambaji was a minor source of zinc and lead for south India. However, for the south Indian Nagapattinam-style Buddhist brass image, unlike the western Indian Santinatha image, the trace element patterns, such as their nickel and cobalt values (FIGURE 3) and arsenic, bismuth and antimony values, generally fit trends of south Indian bronzes of the Later Pandyan period (*c.* 1280-1336 AD). This difference can be explained since trace elements are more closely related to the provenance of copper, while lead isotope ratios pertain to sources of lead-zinc. There are reasons to believe that the above evidence points more strongly to the use of alloyed smelted zinc metal, rather than to cementation brass. Craddock (1981) suggests that several per cent of lead would be normally retained in smelted zinc. Brass made from cementation of copper with zinc ore need not contain lead. Moreover, for the two artefacts the sources of lead are the same while the sources of copper are different. Given the rather negligible amounts of lead, it seems less likely to have been deliberately alloyed to cementation brass from two different copper sources, so that it is more probable that smelted zinc from the same lead-zinc source retaining a bit of lead was alloyed to copper from different sources. Furthermore, the great size of the western Indian Santinatha image of 1 m, and about 200 Kg in weight and solid cast, also suggests the use of metallic zinc, since cementation brass would usually be produced in small crucibles so that the production of 200 Kg of cementation brass would have required about a dozen crucibles. Hence the casting of metallic zinc and copper seems more likely. It should be noted that Ambaji is less than 200 km south of Zawar, the site of the earliest known convincing evidence for metallic zinc in antiquity (Craddock 1981). Indeed zinc ores could have been brought over from neighbouring regions to be smelted at Zawar (Craddock, pers. comm.).

Probable sources of metal for Vijayanagara and late medieval south Indian images (*c.* 14th-18th centuries)

The trace element patterns and lead isotope ratios patterns are distinctive enough for the Vijayanagara group of images (*c.* 1336-1565 AD) to suggest that the lead and copper came from discrete sources compared to the other images, although these may or may not be from the same source. The ratios of Ni:Co and As:Bi for slags from southern India analyzed by EPMA, compared with those analyzed for the images from the Vijayanagara period, indicate that the slags from the site of Tintini could have been a source of copper for the Vijayanagara images. This is quite plausible in terms of the archaeology of the region, since Tintini in north Karnataka is reasonably close to the Vijayanagara capital of Hampi, and is close to a shrine to a 16th century metal smith and saint known as Moneshwara.

An image of Ganesha (FIGURE 8) (acc. no. 291) from Nellore (with lead isotope ratios of Pb 207/206: 0.95594; Pb 208/206: 2.2046; Pb 206/204: 16.301) of the Later Nayaka and Maratha period (*c.* 16th-18th century) is only one of two south Indian images that could be traced to a metal source. It matches the lead isotope ratios of lead slag from the northwestern Indian deposit of Dariba (with lead isotope ratios of Pb 208/206: 2.21438; Pb 207/206: 0.95271; Pb 206/204: 16.307) (Srinivasan in press a). Indeed the Marathas were a northern dynasty who were prominent rulers from the Tanjavur region about this time and could have introduced new sources of metal.

Figure 8: Ganesha (acc. no. 291) from Nellore, Andhra Pradesh, whose lead isotope ratios indicate that the source of the metal is Dariba in north western India; of a style consistent with the Later Nayaka and Maratha group (c. 1700 AD). (Courtesy of the Government Museum, Madras/Chennai).

Sources for the early historic period (*c.* 2nd-6th centuries AD)

Lead isotope ratios for galena from the Bandalamottu mine, Guntur district, Andhra Pradesh in south India matched ratios of a group of Satavahana coins (1st-2nd centuries AD) reported in Turner (1985) and Srinivasan (in press a). The Satavahanas were a dynasty from Andhra Pradesh with their capital at Amravati in the Guntur district. Under them the remarkable Amravati Buddhist stupa was built, parts of which are now in the British Museum. Another group of Satavahana coins matched Sardinian ore from Fluminese published in Stos-Gale (1993) and Srinivasan (in press a). This suggests that local sources may have been exploited by this period alongside trade in metal with far off regions like the Mediterranean, as discussed by Seeley & Turner (1984).

Four coins (4th century AD) recovered from panning in the Karur river of Tamil Nadu were of uncertain attribution. It was not known whether they were true Late Roman coins or Indo-Roman imitations, made in south India in imitation of Late Roman 'aes' copper coins. Srinivasan (1994) using inductively coupled plasma mass spectrometry (ICP-MS) at the Indira Gandhi Centre for Atomic Research in Kalpakkam found that the trace element plots of these coins, cobalt against nickel, arsenic against bismuth and antimony against cobalt, fitted with those observed for Pre-Pallava south Indian artefacts (ca 200-600 AD). This suggests that these coins may be Indo-Roman imitations made in south India rather than true Late Roman coins. The nickel, cobalt, bismuth and arsenic trends of a Pallava image and two Later Chola images analyzed by ICP-MS (TABLE 1) also fitted those observed for the corresponding groups discussed here from ICP-OES analysis of 116 images and artefacts (Srinivasan 1996).

Summary

From the lead isotope results, the exact provenance of lead in the majority of artefacts cannot be identified, due to insufficient lead isotope data from ore deposits in Asia. However, lead isotope data, together with trace element studies of artefacts, help in the typological classification of south Indian images and copper alloy artefacts within dynastic chronologies. This ultimately suggests the use of different copper and/or lead sources over different periods. During these periods, metals from these sources were apparently not restricted to the Tamil region but were widely distributed/traded over the south Indian region, including the Deccan regions of Karnataka and Andhra. This would makes sense, in the light of the fact that the major base metal deposits in peninsular India are in the Deccan rather than the extreme south. Comparisons between the lead isotope ratios of artefacts and ores are compatible with Ambaji in western India being a source of medieval zinc, and probably zinc metal, for north India and, to a minor extent, south India. Dariba, in northwestern India, was a source of lead for the later medieval period, while a source of Satavahana lead of the early historic period was the Bandalamottu mine in Andhra, together with some imported lead from the Mediterranean. These data also tentatively suggest that Ambadongar in peninsular India was a source of lead for early medieval Chola bronzes. Trace element comparisons of nickel and cobalt from artefacts and metal remnants in slags from old slag heaps tentatively suggest that Kalyadi in south Karnataka was a source for the Vijayalaya Chola bronzes (*c.* 850-1070 AD), the smelted tin-bronze with up to 7% tin. Trace element comparisons of nickel, cobalt, arsenic and bismuth indicate Tintini in north Karnataka may have been a source of copper for Vijayanagara bronzes (*c.* 1336-1565 AD). For some artefacts, for which there was uncertainty as to whether they were south Indian or imported, there is now evidence to suggest they are of south Indian provenance given that their analytical trends (of lead isotope ratios and/or trace element trends) are consistent with south Indian ones. These include Indo-Roman coins (4th century AD) from Karur, a Deccan zinc ingot (4th century AD), and the medieval gilt Buddhist Tara, in the British Museum, found in Batticaloa, Sri Lanka, and the Avalokitesvara image, *c.* 5th century, from Krishna delta, Andhra, in the Victoria and Albert Museum.

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TABLE 1: PART 1a

Pre-Pallava and Andhra images and artefacts (*c.* 200-600 AD)
IS-8-1989**, IM-9-1924**, Zinc ingot with Brahmi inscription (*c.* 4th C. AD)*, Vishnukundin coins (5th C AD), IM-300-1914, four 'Indo-Roman' coins (4th C. AD)

Middle Pallava (*c.* 600-850 AD)
223**, IM-13-1934**, 53/38*, Lead coin*, 13, OA-1957-2-11-1*, *OA-1967-7-27-1**, Copper Plate 6,
Seal 1, Seal 2

Later Pallava period (*c.* 850-875 AD)
752/75*, OA-1969-12-16-1*, 459/61*, IM-127-1927, 14/32, 1527/89
OA-1957-10-12-1(Pedestal inscribed; c. 10th C. AD)*

Early Vijayalaya Chola (*c.* 850-940 AD)
Copper plate 2, 19**, 220**, 240**, IM-137-1927**, IM-158-1929**, IM-149-1927**, 217, IM-75-1935**, IS-2-1951, IM-136-1927, IM-8-1924, 720/73**, *OA-1965-12-14-1**
OA-1905-12-18 (Pedestal inscribed; c. 9th C. AD)*

High Vijayalaya Chola (*c.* 940-1070 AD)
IM-2-1934**, IM-71-1935**, 280** (Pedestal inscribed; *c.* 10th-11th C. AD), 273**, 37**, 234**, 238**, 336**, 450/61*, 233*(Pedestal inscribed; 1511 AD), 286, 337, IM-128-1927, IM-131-1927, 475/36,
Velankanni Kali

Early Chalukya-Chola (*c.* 1070-1125 AD)
46**, 43-IS-1887**, IM-70-1935**, 495/65*, IM-135-1957, 215 (2 images), 477/36, 2 (3 images),
IM-1065-1873

Later Chalukya-Chola (*c.* 1125-1279 AD)
315/55**, IM-14-1938**, 721/74**, 477/62, 18, 31, 1427/87, IM-15-1939, IM-196-1937, 316/55, 318/55, 634/64, 1593/89, Spouted vessel, IPN-2639**, *OA-1830-6-12-4**, *OA-1974-12-9-2**

Later Pandya/Later Pandya-early Vijayanagara transitional (*c.* 1279-1336 AD)
40/36**, 8/27**, *IS-275-1869***, IM-1326-1855**, IM-118-1924*, 260*, 142, 123, 288, IM-731935, IM-138-1927, IM-112-1924, IS-44-1966**, *930-IS* (Image inscribed 1168 AD)*, *OA-1967-10-17-1**

Vijayanagara and Early Nayaka (*c.* 1336-1565 AD)
474/36**, IPN-2657**, IS-204-1959**, IM-6-1924**, IM-72-1935**, IM-71-1927**, IM-1-1934**, 212, IM-2-1948, IM-7-1924, IM-5-1928, IM-361-1924 (Pedestal inscribed; 16th-18th century), IM-356-1924 (Pedestal inscribed; 16th-18th century), 47, 59/39, 224, IM-14-1934, IM-129-1929, 107, Bala-2

Later Nayaka and Maratha (*c.* 1565-1800 AD)
IM-118-1943, IM-120-1924, IM-77-1948, 914-IS, Jertala Devi, Jertala Deva, 730-IS, 188, 338, IM-1062-1873 (Pedestal inscribed; *c.* 19th C. AD), IM-1063-1873 (Pedestal inscribed; *c.* 19th C. AD), 291*

*	Indicates those for which only lead isotope analysis was undertaken (Due to limits on access to equipment both lead isotope and trace element analysis could not be undertaken on all images)
**	Indicates those for which both lead isotope and trace element analysis were undertaken
Italics	Indicates images found in regions other than the Tamil region of the majority bronzes (from Karnataka, Andhra, Kerala or Sri Lanka) for which lead isotope analysis was done and which have been included under the above categories for convenience since they tend to share lead isotope trends of at least one other object in the corresponding group. These images are discussed elsewhere in Srinivasan (1996; in press b)

Table 1a: Catalogue and accession numbers of objects under their respective stylistic groups.

TABLE 1: PART 1b

	Average Ni/Co	Average Bi/As
Tintini slag: copper prills	70	0.3
Kalyadi slag: bronze prills	3	not applicable (i.e. Bi, As below detection limits of 0.001 wt.%)
Ingladhal slag: copper prills	0.23	0.42
Somalaragada slag: copper prills	2	1.2
Malapadu slag: copper prills	1.5	6

(Analysed for 17 elements by quantitative EPMA-WDS analysis with measurements for each prill averaged over 15 measurements and with measurements made on at least 6 prills in slag specimens from particular sites. Quantitative analysis was done using a JOEL Superprobe JXA 8600 with ZAF corrections with the total composition being within 1-2 wt. % of a 100 wt.%)

	Average Ni/Co	Average Bi/As
Vijayangara images (19) (ca 14th-16th c. AD)	57	0.22
Vijayalaya Chola images (ca 9th-11th c. AD)	4	0.06

(Analysed by ICP-OES for 18 elements including Ni, Co, Bi and As using Philips combined simultaneous sequential ICP-OES spectrometer)

Table 1b: Compositional analysis of 120 South Indian images and copper alloys.

	Average Ni/Co	Average Bi/As
Tintini slag: copper prills	70	0.3
Kalyadi slag: bronze prills	3	not applicable (i.e., Bi, As below detection limits of 0.001 wt.%)
Ingladhal slag: copper prills	0.23	0.42
Somalaragada slag: copper prills	2	1.2
Malapadu slag: copper prills	1.5	6

(Analyzed for 17 elements by quantitative EPMA-WDS analysis with measurements for each prill averaged over 15 measurements and with measurements made on at least 6 prills in slag specimens from particular sites. Quantitative analysis was done using a JOEL Superprobe JXA 8600 with ZAF corrections with the total composition being within 1-2 wt. % of a 100 wt.%)

	Average Ni/Co	Average Bi/As
Vijayangara images (*c.* 14th-16th century AD) (averaged for 19 images)	57	0.22
Vijayalaya Chola images (*c.* 9th-11th century. AD) (averaged for 28 images)	4	0.06

(Analyzed by ICP-OES for 18 elements including Ni, Co, Bi and As using Philips combined simultaneous sequential ICP-OES spectrometer)

Table 2: Preliminary comparisons between trace element ratios of some copper slags from southern India with those from stylistic groups of south Indian images indicating probable sources of copper.

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