Trans Indian Inst Met (October–December 2013) 66(5–6):731–737
DOI 10.1007/s12666-013-0291-5

TECHNICAL PAPER

TP 2731

Megalithic and Continuing Peninsular High-Tin Binary Bronzes: Possible Roots in Harappan Binary Bronze Usage?

Sharada Srinivasan

Received: 12 January 2013 / Accepted: 5 May 2013 / Published online: 3 July 2013

Abstract This paper attempts to trace the development of an unusual and skilled class of alloys, of binary high-tin bronze (i.e. alloys of only copper with a higher percentage of tin), which are found from surprisingly early contexts from Indian antiquity. In particular, the deliberate use was made of binary beta bronze with around 22–24 % tin, specifically exploiting the properties of higher hot-forgability of bronze of this composition due to the formation of the high temperature beta intermetallic compound phase of 22.9 % tin. Quenching resulted in the retention of the beta phase, yielding a musical alloy with golden lustre and improved tensile strength as compared to the as-cast state. Examples of hot forged and quenched high-tin beta bronzes studied by the author from the South Indian Iron Age and megalithic cultures from Tamil Nadu and Maharashtra and Gandharan Grave Culture of Taxila are summarised here ranking amongst the earliest and most finely wrought such finds. There are technological and morphological similarities to surviving high-tin bronze crafts practices documented by the author in Kerala since 1990. Since the 1990's she has also documented the making of high-tin delta bronze mirrors at Aranmula with a composition closer to the pure delta phase of 32.6 % tin, which instead exploited the specular properties this alloy while managing its brittleness. Although it is difficult to speculate about origins, a long standing practice of using binary tin–bronzes (i.e. only copper–tin alloys) can be detected going back to Harappan bronzes which also seem to be predominantly binary bronzes with not much lead added to them. Though most of these seem to be low-tin bronze, the presence of a couple with higher tin of about 20 % is also notable in terms of the above discussion.

Keywords Megalithic · Binary high-tin beta bronze · Vessels · Peninsular · Harappan · Mirrors · High-tin delta bronze · Tin sources · Archaeometallurgy

1 Introduction

It has generally been believed that there was a hiatus in developments of copper–bronze metallurgy between the Indus Valley (3rd millennium BC) and the later cultural contexts in the Indian subcontinent such as the subsequent chalcolithic and megalithic cultures of the second and first millennium BC due to the postulated collapse of the Indus Valley/Harappan civilisation. While not challenging this argument totally, this paper puts together evidence from investigations made by the author on a range of metal artefacts mostly from south India and few from other parts to highlight some threads of continuity linking the Indus Valley finds with artefacts and craft traditions right into the present day. While some tenuous and general connections have previously been commented on, such as in the making of lost wax casting of figurines, these take on greatly added significance when one takes into account new investigations made by the author on high-tin bronzes, i.e. (binary copper–tin alloys with over 20 % tin) from south India; and in particular for the specialised manufacture of high-tin beta bronze vessels (i.e. bronzes made by hot forging and quenching an alloy of 23 % tin–bronze resulting in the predominant retention of the beta phase). Previously it had been thought that the skilled technology of high-tin beta bronze working was developed in Southeast Asia or China and then spread to India, while its use is scarcely reported

S. Srinivasan (✉)
NIAS, Bangalore, India
e-mail: metalart96@gmail.com

outside Asia. Indeed, some of the well dated and studied early high-tin bronzes are from Ban Don Ta Phet, Thailand, *c*. 4th C. BCE [3, 22]. However, subsequent studies have been made by the author of surviving techniques for making wrought and quenched beta bronze bowls and high-tin delta bronze mirrors together with analyses of finds from South Indian megaliths and Iron Age burials from other parts of India dating to the early to late first millennium BC [20, 25, 27, 29, 31, 34]. Given that some of these findings seem to predate the previously earliest known well dated finds, it may be possible to postulate indigenous origins for this technique. As highlighted in this paper, taken together with a few analyses of bronzes of a higher tin content from Mohenjo daro and a pattern in the use of unleaded copper–tin alloys in the Indus Valley it might even be postulated that this technique may have taken roots in Indian prehistory and then perhaps spread to other parts of Asia. Other broad connections with Harappan or late Harappan finds such as of solid lost wax castings and mirrors in southern India, and possible sources of ancient Indian tin are also touched upon.

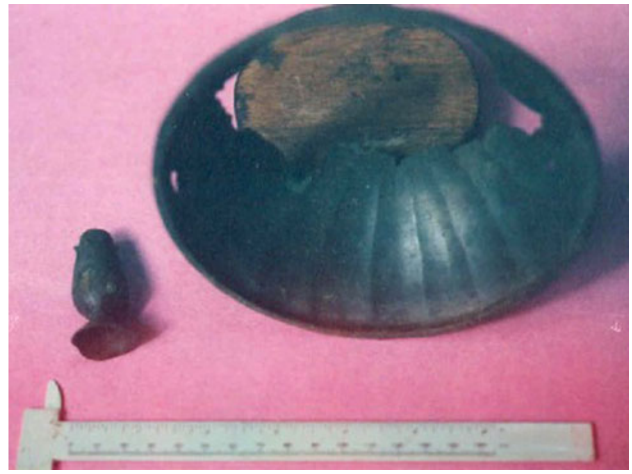

Fig. 1 Wrought and quenched high-tin bronze bowl from Nilgiris, Tamil Nadu of the early to mid first 1st millennium BCE in Government Museum, Madras. (Photograph: Sharada Srinivasan)

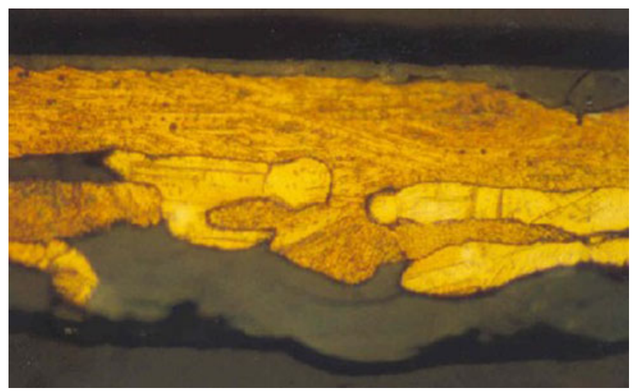

Fig. 2 Micro-structure of a wrought and quenched high-tin beta bronze bowl with 24 % tin from Nilgiri megaliths, early to mid 1st millennium BCE, showing extensively elongated acicular needles of quenched martensitic beta phase indicated heavy working before quenching at ×1,150. (undertaken at Institute of Archaeology, London) (Photograph: Sharada Srinivasan)

2 High-Tin Beta Bronzes from Indian Prehistory

Binary bronze refers to an alloy of only copper and tin. Generally, as-cast binary copper–tin alloys with over 15 % were not much in vogue in antiquity as they become brittle due to the presence of the delta phase component from cooling to ambient or room temperatures. However investigations by the author from pre-historic, medieval to modern south India indicate the continued use of specialised binary high-tin beta bronzes with 22–5 % tin to make artefacts such as vessels, coins and musical instruments right into the present day [25, 29]. In these, the embrittling effect of delta phase was overcome by quenching them at the high temperatures of formation of the beta martensitic phase which is an intermetallic compound of equilibrium composition of 22.9 % tin (Cu_5Sn). Since this phase has the property of high plasticity at higher temperatures, such bronzes can be hot forged to a considerable extent and much more so than lower tin bronzes. Retention of the martensitic beta phase also results in improved properties of tonality and lustre in the bronze.

Metallurgical investigations by the author on very thin vessels of a thickness of 0.2–1 mm from South Indian burials and megaliths of Adichanallur (Fig. 1) and Nilgiris (Fig. 1) of the early to mid first millennium BC and medieval Chola platters (10th–12th centuries) [25, 31] indicated that these were wrought and quenched high-tin beta bronzes, i.e. copper–tin alloys with 23–25 % tin (Fig. 2).

Despite early analyses reported in [5] of a few vessels from the Nilgiri cairns of 20–25 % tin–bronze and by [13] of such a vessel from Adichanallur, the possibilities of a local continuing tradition had not been articulated or explored by previous scholars, while [12] opined that such vessels were imported. The author was the first to have both identified such a continuing tradition of high-tin beta bronze vessel making from any part of the world, in the village of Payangadi in Kerala (Figs. 3, 4) in 1991 (first reported in 1991: [29]; although this activity has now sadly ceased to take place at this village) and to have also metallurgically correlated these with micro-structures in vessels from the South Indian megaliths of Adichanallur and Nilgiris as seen in Fig. 2 [25, 31]. All of these were made by extensively hammering out, in cycles of annealing and hot forging, an alloy close to a composition of 23 % tin between 586–798 °C when a plastic beta intermetallic compound (Cu_5Sn) of equilibrium composition (22.9 % tin) forms, followed by quenching resulting

Fig. 3 Hot-forging of high-tin beta bronze vessel (around 23 % tin) in Palghat district, Kerala observed in 1998 by Sharada Srinivasan and Ian Glover (Photograph: Sharada Srinivasan)

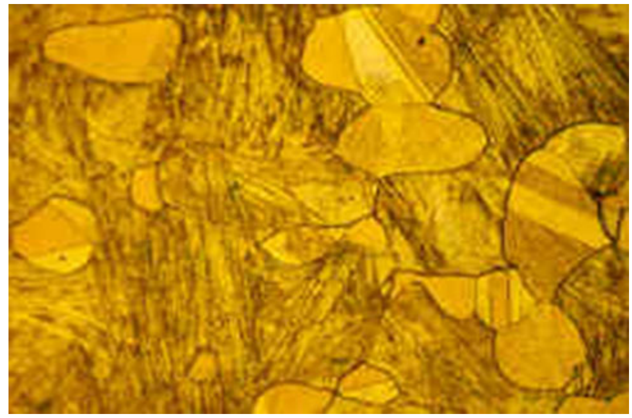

Fig. 5 Micro-structure of above wrought and quenched high-tin beta bronze bowl with 23 % tin made in Payangadi, showing alpha plus beta structure with the formation of martensitic beta phase from quenching, ×450 (undertaken at Institute of Archaeology, London) (Photograph: Sharada Srinivasan)

in the retention of needle-like beta phase (Figs. 2, 5). This prevents the formation of brittle delta phase and the resultant alloy has musical properties and takes a golden polish (Fig. 4) as seen in the photograph of a modern high-tin bronze vessel. In contrast, low-tin bronzes have limited workability. Although prior to these studies non-Indian sources had been suggested for the bowls from the Nilgiri megaliths in West Asia [12] or East Asia [22] it now seems likeliest that they were made in ancient Kerala since they closely resemble the wrought and quenched high-tin beta bronze bowls from Payanagadi, not just metallurgically but also stylistically in the use of concentric rings in the centre of the bowls made in 1991 at the workshop using a hand-turned

Fig. 4 Wrought and quenched high-tin beta bronze bowl with 23 % tin made in Payangadi (as documented and procured during a visit by Sharada Srinivasan and Digvijay Mallah in 1991 in Kerala), showing inner golden polish, exterior darkened quenched skin while inner diameter indicates original size of ingot (Photograph: Sharada Srinivasan)

lathe. This is consistent with local lore where the Todas, the original inhabitants of the Nilgiris, claimed that such vessels came from Kerala [25]. Allchin and Allchin [1] also postulate indigenous developments for the south Indian megaliths.

The fieldwork to the workshops in Kerala to Aranmula and Payangadi was undertaken in 1991 with the support of Digvijay Mallah, the author's husband, hailing from the Badaga community of the Nilgiris; and the use of such high-tin bronze vessels by his community members has also been noted and on auspicious occasions such as weddings. Such bronze vessels were also in the collection of late anthropologist Evam Piljian, a dynamic member of the indigenous Toda community of the Nilgiris whose collection the author examined in 1996 with Digvijay Mallah. It was the author's late maternal grandmother Janaki Subban in 1990 who had given the clue to look for the making of such vessels in Kerala as she mentioned that such vessels which broke easily were made in Trichur in Kerala. This was reminiscent of the account reported in the seminal paper by [22] of the Greek Nearchus that Indians made vessels which shattered like pottery which they concluded referred to high-tin bronze vessels. This led the author to the identification of the high-tin bronze bowl workshops in Kerala as reported here.

A vessel from Mahurjhari from the Vidarbha megaliths excavated by Deccan College, Poona, and analysed for micro-structure by the author also was a quenched high-tin beta bronze with about 21 % tin [34]. A bowl excavated from the Gandharan Grave Culture of Taxila in Pakistan (*c.* 1000 BC) investigated by the author (courtesy I. Glover and Pakistan Archaeological Survey) was also a high-tin beta bronze with 24 % tin. Taxila was settled since Early Harappan times while the Gandharan Grave Culture of the second to first millennium BC is typified by finds of iron and gray ware. As discussed further, two samples excavated from the Indus Valley site of Mohenjo daro (*c*. 2500 BC) were also of 22 % tin–bronze [14], which suggests local continuity in the use of bronzes of a high-tin content. Kenoyer (pers. comm) observed that similar vessels still seem to be forged in parts of Pakistan. It may now even be considered a possibility that the technique of making high-tin beta bronze bowls may have had roots in Indian prehistory as these finds seem to predate others, and then spread to other parts of Asia where finds are known from the mid to late first millennium BC from Thailand [22] and from Iran attributed from the Sassanian period of the mid first millennium BCE to Islamic periods [8]. While it is more widely known that the Indian subcontinent and the southern Indian region was a world leader in the production of high-carbon wootz crucible steel, the skills in working higher tin bronzes has not been as widely known and is also noteworthy [37]. The above account may suggest a departure from well entrenched ideas (e.g. [7]: 23) that the Indian subcontinent would have more likely received diffusionist bronze technologies or traded bronze from tin-rich Asia, especially Southeast Asia.

Fig. 6 Mirror made by late Janardhan Achari in Aranmula, Kerala showing the craftsman, documented by Sharada Srinivasan and Ian Glover in 1998 (Photograph: Sharada Srinivasan)

3 High-Tin Bronze Mirrors and Links with Indus Finds

Another surviving high-tin bronze craft in Kerala is the making of 'delta' bronze mirrors in Aranmula. The author's first fieldtrip was in 1991 with Digvijay Mallah and the process was also studied by her with Ian Glover who acquired some equipment from JanardhanAchari in early 1992 and whom they then visited in 1998 [31, 33]. Figure 6 shows the late JanardhanAchari, mirror maker from Aranmula with his reflection photographed in 1998. The author's technical investigations [31, 35] were the first to establish that the properties were due its specific composition correlating to high-tin delta bronze, i.e. of 33 % tin–bronze, so-called because of the match with the composition of pure delta phase, an intermetallic compound ($Cu_{31}Sn_8$) of 32.6 % tin (Fig 7). These studies also identified that the mirror-effect was obtained by optimizing its presence since it is a very hard, stable and silvery compound of hardness close to 500 VPN which can hence be polished with the best possible reflectance and mirror effect. The studies made by [21] on the Aranmula showed it to have a micro-structure of a bronze with around 30 %, however the more accurate analyses reported since by the author using SEM, EPMA and AAS techniques confirmed the alloy to be closer to 32–34 % tin bronze nearer to the delta phase composition. The structure of the delta phase prevalent in the Aranmula mirrors seems similar to gamma brass with icosahedral clusters [36]. Although the high-tin delta bronze alloy is highly brittle and shatters almost in the manner of glass, this is offset by casting a very thin (no more than 3 mm thick) flat oval blank in a two-piece closed crucible-cum-mould as reported in fuller detail in [31, 32, 33].

While mirrors were widely made in China [24] from the Warring States period and in the Roman world, these do not provide the likeliest precedents for the Kerala mirrors, which seem to derive more from developments within the Indian milieu and from the local unleaded high-tin bronze traditions of the region discussed earlier. While the Chinese and Roman mirrors are more decorated and thicker, these are nevertheless mostly made of 25 % tin with 7–8 % lead [18]; which need not have resulted in as good mirror properties since the addition of lead would have made the alloy more opaque. An early historic period sample from Sonepur in eastern India (*c*. 500 BC–500 AD) from period II reportedly had 32.4 % tin [4] which closes matches the composition of high-tin delta bronze, suggesting that the specialised alloy for the Kerala mirror was used anciently in the Indian subcontinent. A mirror from Taxila (*c*. 4th C. BC) is reported to be of 25 % binary tin–bronze [17] and is thin and flat recalling to the shape of the Kerala mirror blanks. The use of the wooden polishing board itself as the mirror after polishing the blank is postulated in [31] from iconographic comparisons of medieval sculpture. Morphological parallels can particularly be detected in mirrors are reported from Quetta and Harappa from Indus Valley contexts (*c*. 1900 BC) which are of uniquely flat, thin and circular shapes that differ from other West Asian prototypes such as Egyptian mirrors [2]: Figs. 159, 160, 161): broadly speaking these could have been cast in a manner similar to the Kerala mirrors, in narrowly spaced two-piece moulds within closed crucibles which are photographed in [31].

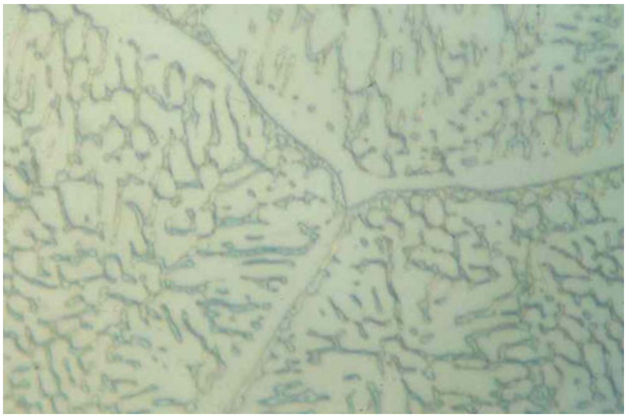

Fig. 7 Micro-structure of delta high-tin bronze mirror made in Aranmula with about 33 % tin (purchased in 1991 from Gopalakrishna Achari of Aranmula during visit by Sharada Srinivasan and DigvijayMallah and studied at Institute of Archaeology, London) (Photograph: Sharada Srinivasan)

4 Indus Valley Finds of High-Tin Bronzes and Copper-Based Metallurgy

When one tries to trace back the antiquity of the Indian high-tin bronzes, the analyses from the Indus Valley site of Mohenjo-daro [14] of a few bronzes of the composition of binary high-tin bronze would surely rank amongst the earliest in the world, although without metallurgical study it cannot be established if these were beta bronzes, i.e. with the quenched beta phase, or merely as-cast bronzes of this composition. These are reported from corroded samples from deep digging in Block 7 of the DK area and Mackay's notes suggests that he did not doubt that these were from an Indus valley context (*c*. 2000 BC). Sample DK 9722 at 30 feet below datum had 22.2 % tin, with scarcely any lead at 0.86 %, typically matching the composition of high-tin beta bronze; sample DK 9567 had 26.9 % tin with no lead found at 26.8 feet below datum, while two more samples had 19 % tin with no lead.

In fact if we look at a compilation of some 140 analyses of objects from Indus Valley contexts in [14, 16] and in [6] a noticeable trend is that although about 30 objects from Mohenjo daro have tin contents over 5 % and contain no lead, and about 24 have more than 8 % tin and no lead while only 4–5 objects have more than 2 % lead. Indeed overall, out of 30 % bronze objects from different Indus sites with over 8 % tin, only one sample from Mohenjo daro had any substantial lead, of 14.9 % and that is in fact a beta bronze with 22.1 % tin. The addition of such high amounts of lead would have improved the castability and reduced brittleness although this would not be a beta bronze but more of a bell metal alloy which has a good tonality. This might suggest that, rather than being accidental, lead could have been deliberately added with the intention of experimenting to overcome the brittleness of the binary beta bronze alloy in the as-cast state. However the use of lead metal is also seen in the form of what is described as a plumb bob, a lead ball of about an inch in diameter [14] so that it appears that the alloying of tin and lead would have been intentional with some knowledge of the properties. As for other examples of bronzes of a high tin content, bangle piece from Kuntasi reported in RajamSeshadri's thesis 'The Metal Technology of the Harappans and the Copper Hoard Culture-A Comparative Study' had a composition of Cu 69.34 %, Pb 6.67 %, Sn 22.57 % [6]: 112.

All of the above suggests that the Mohenjo daro craftsmen may have gone some way towards experimenting with the use of unleaded tin bronze and high-tin bronze. It must also be pointed out that, given the developed system of chert weights and measures from in the Indus Valley it would have been possible to measure out the fairly precise amounts of tin for high-tin bronze. Kenoyer [11] points out that complete sets of smaller weights were found even at rural Indus Valley settlements, apart from major trading centres.

As such, the rather tiny lost wax castings of the Harappan era, although skilled (as exemplified by the famous Mohenjo daro dancing girl), and the relatively limited finds militate against the Indus Valley finds representing perhaps a full-blown copper–bronze tradition when compared to West Asia or China where large bronze castings had already come into vogue at a comparable period. However, it must be said that it would not have been easy to make large castings of bronze without the prevalence of liberal amounts of lead, due to shrinkage, porosities and brittleness in the casting of tin bronze which the addition of lead greatly minimise. It's a matter for conjecture whether the restricted use of lead compared to tin detected by the author in the Harappan period was due to its scarcity and whether this contributed to the tinier sizes of Harappan bronzeware. As for the Daimabad bronzes (compiled in [6], it is interesting that they are also consistent with this trend noted in this paper of Harappan bronzes generally having not much lead. Some aspects of the Harappan finds seem distinctive and not entirely derivative when compared to coeval ones from West Asia; for instance, the flat circular mirrors. Indeed [14] as excavator also comments that the Indus Valley mirrors were different from those from Egypt, Sumer or Elam. However their shapes do recall to the flat Kerala mirror blanks discussed in this paper in connection with the making of the Aranmula high-tin bronzes.

5 Sources of Tin in Indian Pre-history and for Indus Region

The sources of tin, a scarce commodity in India today, has been an enigma since tin deposits in the Indian subcontinent are sparse. However it must be remembered that deposits which would be termed as uneconomical in industrial today could have been sufficient for small scale, labor intensive mining, while placer mining of tin leaves no traces. For the finds from the Indus Valley and Taxila, Afghanistan seems a plausible source of tin with some stannite and cassiterite deposits, while Misgaran in Herat is reported to show some evidence of early exploitation [19, 23]. Jarrige [9] points to the influences from late bronze age bactria and Magria in Afghanistan on the later Indus Valley period and indeed it remains a possibility whether the high-tin bronzes reported at Mohenjo daro are linked to developments in these regions, although the author is not so far aware of similar analyses from these areas. Eastern India also has some tin deposits in the Hazaribagh region with some evidence for pre-industrial exploitation [30].

Indeed the author's investigations on south Indian material surprisingly throws up more evidence for local sources of tin than previously suspected. For one, the high-tin bronzes beta bronzes from south Indian megaliths had sufficiently different patterns of trace elements from those from Thailand to suggest different sources of metal for the Indian examples [31]. Interestingly, investigations by the author on slags from the ancient mining region of Kalyadi within Hassan district of Karnataka indicate that these are bronze smelting slags with up to 7 % tin from co-smelting copper and tin ores due to the presence of metallic iron, rather than casting slags from alloying copper and tin [26, 28, 30], which points to exploitation of indigenous sources of tin. Malroney [15] mentions that tin was one of the items sent out of the Karnataka coast in Solomon's times along with peacocks and naves (i.e. the pre-christian era). Indeed some sparse alluvial tin is reported with alluvial gold in the Karnataka region and given the extensive evidence for ancient exploitation of gold in this region it is not impossible that some local tin ores could have also been exploited [28]. It is thus may not be coincidental that the high-tin bronze vessels found in South Indian burials such as Adichanallur and Nilgiris (1st millennium BC) also occur with finds of gold ornaments [1], and in fact it has at least been postulated that gold from the Karnataka region collected by neolithic cultures reached the Indus region.

It is also significant against this background that [11] points out that the goods being traded out of Meluha or the region of the Indus to Dilmun and Magan i.e. modern Bahrain and Oman included tin or lead together with copper, gold, silver, carnelian, pearls, ivory and peacocks, which may re-inforce the idea of the Indus region being at the forefront of ancient experimentation in copper-bronze technologies, suggested by the few finds of high-tin bronzes.

6 Summary

From the above studies, one may reiterate the early and unusual exploitation of the properties of intermetallic compounds of beta (23 %) and delta (33 %) high-tin bronze in the Indian subcontinent and megalithic south India of the first millennium to make vessels and mirrors respectively, continuing into the present day. The high-tin beta (23 % tin) bronze processes in Kerala may represent some of the oldest known surviving metallurgical traditions in the Indian subcontinent. The analysis of the vessels from the Iron Age Gandharan Grave Culture finds (*c.* 1000 BCE) of Taxila reported her rank amongst the earliest known such findings anywhere in the world. This is an area that also fell under the late Harappan sphere and is also close to possible sources of tin in Afghanistan. The preponderance of the use of binary bronze in the Harappan period is also significant with the finds of a few bronzes of a higher tin content. The Nilgiri and Adichanallur iron age high-tin beta bronzes from Tamil Nadu represent some of the most finely wrought examples. Although attention has been drawn to their connections with Southeast Asian examples, the megalithic bronzes well may represent a slightly older tradition and their links have been pointed to here with developments in the earlier prehistory of the northwestern part of the subcontinent harking back to the Harappan sphere of influence. This evidence also fits in with opinions of Indus archaeologists such as [9] who also effectively comments that the hiatus between the eclipse of the Indus civilization and later periods is now filled by archaeological finds demonstrating perhaps some threads of continuity in the material culture of the subcontinent.

Acknowledgments The past support in the analyses of Institute of Archaeology, University College London the Freer Gallery of Art, Smithsonian Institution, Washington is acknowledged and currently of National Institute of Advanced Studies, Bangalore and Indian Institute of Science, Department of Metallurgy. The author is grateful to her husband Digvijay Mallah for the assistance in the fieldwork in Kerala to the artisan workshops in the early 1990's which rank amongst the earliest identifications made of these crafts as binary high-tin bronze crafts. The support of late N. Seeley, I. Glover, A. Bennet, J. A. Charles, N. Meeks, London, T. Chase, P. Jett, Smithsonian, S. Ranganathan, NIAS & IISc, Bangalore, V.N. Misra, Deccan College, M. Kenoyer, R. Allchin, R. Krishnamurthy, Dinamalar and K. Rajan, Tamil University, Tanjavur and Kalyadi Copper Unit of Hutti Gold Mines, are acknowledged as well as the past support to the research of Railway Mine and Plantation Equipment, London, British Council, New Delhi, Ancient India and Iran Trust, UK and DST. Some of the preliminary ideas in this paper had been put forth at a conference on 'Indus Archaeology' held at University of Wisconsin Madison in 1998 organised by Mark Kenoyer and the author is grateful for the earlier support of the Homi Bhabha Research Council, Mumbai, and S. M. Chitre and H. D. Pajnigar in this.

References

1. Allchin B, and Allchin R, *Rise of Civilisation in India and Pakistan,* Cambridge University Press, Cambridge (1982).
2. Amiet P, Halim M A, Jansen M, Jarrige C, *Les CitésOubliées de l'Indus*. Musée National des Arts AsiatiquesGuimet and Association Française d'Action Artistiques, Paris (1988).

3. Bennett A, and Glover I, in *Southeast Asian Archaeology*, (ed) Glover I, University of Hull, Yorkshire (1990) 187.
4. Biswas A K, *Minerals and Metals in Ancient India,* Vol. I, D K Printworld, New Delhi (1996).
5. Breeks J W, *An Account of the Primitive Tribes and Monuments of the Nilgiris*, India Office, London (1873).
6. Chakrabarti D K, and Lahiri N, *Copper and its Alloys in Ancient India*, Munshiram Manoharlal Publishers Pvt. Ltd., New Delhi (1996).
7. Craddock P T, in (eds) Oddy W A, and Zwalf W, *Aspects of Tibetan Metallurgy*, British Museum occasional paper no. 15, London (1981) 23.
8. Gunter A, and Jett P, *Ancient Iranian Metalwork,* Arthur M Sackler Gallery and the Freer Gallery of Art, Washington (1992).
9. Jarrige J-F, *Arts Asiatiques* **50** (1995) 5.
10. Keay J, *India Discovered. The Achievement of the British Raj*, Windward (1981).
11. Kenoyer J M, *Ancient Cities of the Indus Valley Civilization,* Oxford University Press, Karachi (1998).
12. Leshnik L S, *South Indian 'Megalithic' Burials. The Pandukal Complex*, Franz Steiner, Weisbaden (1974).
13. Paramasivan S, 'Investigations on ancient Indian metallurgy: a pre-historic bronze bowl'. In: Proceedings of the Indian Academy of Sciences, Sex A (1941) 13.
14. Mackay E, *Further Excavations at Mohenjo daro*, Government of India Press, New Delhi (1938).
15. Malroney C, Archaeology of South India- accomplishments and prospects. In: Burton Stein (Ed). *Essays in South India*. The University Press of Hawaii, Hawaii (1975).
16. Marshall J, *Mohenjo daro and the Indus Civilization*, Vol. 3, Arthur Probsthain, London (1931).
17. Marshall J, *Taxila,* University Press, Cambridge (1951).
18. Meeks N, in *Metal Plating and Patination-Cultural, Technical and Historical Developments*, (eds) La Niece S, and Craddock P, Butterworth Heinemann, Oxford (1993) 247.
19. Muhly J D, *Am J Archaeol* **89** (1985) 275.
20. Paramasivan S, Investigations on ancient Indian metallurgy. In: Proceedings of the Indian Academy of Sciences on a pre-historic bronze bowl **13** (1941) 87.
21. Pillai S G K, Pillai R M, and Damodaran A D, *J Met* **44** (1992) 40.
22. Rajpitak W, and Seeley N J, *World Archaeol* **11** (1979) 31.
23. Reedy C, in *The Crossroads of Asia. Transformation of Image and Symbol in the Art of Ancient Afghanistan and Pakistan*, (eds) Errington E, Cribb J, Claringbull M, The Ancient India and Iran Trust, Cambridge (1992) 241.
24. Schulten C, *J Met* **48** (1996) 60.
25. Srinivasan S, in *South Asian Archaeology,* (eds) Parpola A, and Koskikallio P, In: Proceedings of the Twelfth International Conference of the European Association of South Asian Archaeologists held in Helsinki University, 5–9 July 1993 SuomalainenTiedeakatemia, Vol. II, Helsinki (1994) 695.
26. Srinivasan S, *The Enigma of the Dancing 'Pancha-loha' (Five-metalled) Icons: Archaeometallurgical and Art Historical Investigations on South Indian Bronzes,* Unpublished Ph D Thesis, University College, London (1996).
27. Srinivasan S, *South Asian Studies* **13** (1997a) 209.
28. Srinivasan S, in *Archaeological Sciences 1995,* (eds) Sinclair A, Slater A, and Gowlett J, In: Proceedings of a conference on the application of scientific techniques to the study of archaeology, Liverpool, July 1995, Oxbow Monograph 64, Oxford (1997b) 136.
29. Srinivasan S, in *Archaeometallurgy in India,* (ed) Tripathi V, In: Proceedings of the First National Seminar in Indian Archaeometallurgy held in Oct *1991, Varanasi,* Sharda Publishing Ltd., New Delhi (1998a) 241.
30. Srinivasan S, *J Met* (1998b) 50.
31. Srinivasan S, and Glover I, *J Hist Metall* **29** (1995) 69.
32. Srinivasan S, and Glover I, *Current Science* **93** (2007) 35.
33. Srinivasan S, in *Encyclopedia of the History of Science, Technology and Medicine in Non-Western Cultures*, Vol. 2, (ed) Selin H, Springer, Berlin (2008) 1699.
34. Srinivasan S, in *'50 years of Southeast Asian Archaeology: Essays in Honour of Ian Glover,'* (eds) Bellina B, Pryce O, Bacus E, Christie J W, River Books, Bangkok (2010) 239.
35. Srinivasan S, and Glover I, Materials Research Society Symposium Proceedings in Materials Issues in Art and Archaeology V, Vol. 462, (eds) Vandiver P, Druzik J, Merkel J, Stewart J, Warrendale (1997) 81.
36. Srinivasan S, and Ranganathan S, *Trans Indian Inst Met* **59** (2006) 829.
37. Srinivasan S, Ranganathan S, and Suwas 'Ultra high-carbon steels and high-tin bronzes:insights into mechanical properties and processing from Indian traditional knowledge', Poster and published abstract, *ICSMA 16*, International conference on Strength of Materials, Indian Institute of Science, Bengaluru, Aug 19–24, (2012).