# METALS AND CIVILIZATIONS

National Institute of Advanced Studies

Editors:
**Sharada Srinivasan**
**Srinivasa Ranganathan**
**Alessandra Giumlia-Mair**


NIA

# Metals and Civilizations

Proceedings of the Seventh International Conference on the Beginnings of the Use of Metals and Alloys (BUMA VII)

*Editors:*

*Sharada Srinivasan*
*Srinivasa Ranganathan*
*and*
*Alessandra Giumlia-Mair*

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# *Cover Images*

**NIAS EMBLEM**

The NIAS logo is derived from descriptions related to the building of Vedic fire altars in the remarkable Sanskrit work of the Sulva-sutras. Displaying a deep knowledge of geometry, the text is thought to date from pre-Euclidean times, circa 6th c. BCE predating Panini. The NIAS emblem relates to an arrangement of bricks comprising the first layer of an altar called `śyēna-cita'. The altar is shaped like of an eagle or falcon, following descriptions in the eleventh chapter of the Baudayana text. The śyēna-cita was thought to be an apt symbol for National Institute of Advanced Studies, evoking a keen mathematical and engineering sensibility and artistic imagination. It had been designed by the renowned sculptor Sri Balan Nambiar under the initiative of the former Director of NIAS, Prof Roddam Narasimha.

**DELHI IRON PILLAR**

The Iron Pillar in Delhi, one of the best known of Indian historic landmarks, towers at about 7 m. This earliest known massive wrought iron forgingt has resisted corrosion for over 1600 years. The inscription in Gupta Brahmi of about 400 CE suggests that it was a victory monument of the Hindu Gupta king Chandragupta Vikramaditya II. It seems to have been moved to its present location within the spectacular Qutb Minar complex under the Muslim Sultanate king of Delhi, Iltutmish in the 1300's. Robert Hadfield made pioneering scientific observations in 1912 on the iron pillar. Current understanding suggests that the higher traces of phosphorus in the iron contributed to its corrosion resistance, earning it the nickname the 'Rustless Wonder' Seminal contributions to several facets of the history and metallurgy of the pillar have been made by R Balasubramaniam. The pillar is among the 50 moments in materials compiled by TMS, USA. In 2013 ASM recognized it as a Historical Landmark.

**THE CERN NATARAJA**

The bronze image of the dancing Hindu God Siva as Nataraja, often described as 'the Lord of the Cosmic Dance', has been worshipped at the temple of Chidambaram since the medieval Chola times. In 2004, a two metre statue of the Nataraja was gifted to CERN the European Center for Research in Particle Physics in Geneva, by the Indian Government to celebrate the research center's long association with India. This impressive casting was made by master craftsman Rajan from Tamil Nadu supported by IGCAR Kalpakkam then headed by Dr. Baldev Raj, currently Director NIAS. The statue has been installed with plaques with the evocative writings of celebrated art historian Ananda Coomaraswamy and quantum physicist Fritjof Capra. The weaving together of art and science is captured in Fritjof Capra's poetic words that 'the metaphor of the cosmic dance unifies ancient mythology, religious art and modern physics'.

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# Foreword

The National Institute of Advanced Studies (NIAS), Bangalore owes its foundation to the far reaching vision of J. R. D. Tata. It is a multidisciplinary institution with Schools devoted to Humanities, Social Sciences and Natural Sciences & Engineering and came into existence in 1988. It encourages interdisciplinary studies by teams of scholars drawn from the streams of Humanities and Sciences.

Archaeology and History are important themes of research at NIAS. The field of archaeometallurgy has been the subject of increasing interest worldwide in the last few decades and intense research has deepened our knowledge of our own past. In many ways archaeology stands at the intersection of science and history. NIAS had the privilege of bringing the prestigious "The Beginnings of the Use of Metals and Alloys" (BUMA) Conference series to India for the first time. The conference held during September 2009 provided a forum for discussion on all aspects of the field with a special focus on metallurgical interactions across the ancient world, early copper, tin and zinc, precious metals, coinage, iron with emphasis on crucible steel and weapons, ancient bronze, casting technologies, experimental metallurgy and conservation. A large number of papers were devoted to bronze, reflecting current global research trends. More than 100 delegates from 25 nations drawn from the five continents gathered together and presented more than 70 papers covering various aspects of contemporary research shedding new light on ancient use of metals and alloys.

The field of archaeometallurgy is undergoing transformations. The growing application of scientific techniques such as remote sensing, digital 3-D imaging, experimental reconstructions and space archaeology are allowing us to peep into the past with unprecedented precision. In addition, the subject of ethnoarchaeology is growing. The study of craftsmen who produced the objects of vast utility and extraordinary beauty is adding to our scientific and cultural wealth.

It has been said that materials and civilization are synonymous as the latter is defined by the former. It is equally true that cultural imperatives in different civilisations played a role in the ways that materials were used in antiquity. This symbiotic relationship is to be cherished. The hope of BUMA-VII, that new collaborations would result from the interactions in Bangalore, has become a reality.

I also wish to congratulate my two colleagues, Prof. Sharada Srinivasan and Prof. Srinivasa Ranganathan for attracting the conference to Bangalore and for organizing the event with the help of International and National Advisory committees and bringing out the Proceedings.

This volume is now in your hands. Its success will be judged by the promotion of interactions stimulated by it.

Baldev Raj
Director
National Institute of Advanced Studies
Bangalore, India

# A Brief Look at the Past and a Glimpse into the Future

Although the overall attendance at BUMA I in Beijing was satisfactory, there were, however, no more than about a dozen western scholars. Ten of those were participants in a travel grant from the U.S. National Science Foundation. Overall attendance at the next five conferences continued to increase with good participation from European scholars but still lacking many from the U.S.

The attendance at BUMA VI held in Beijing 2006, however, showed a more diverse group (28 from Asia, 13 from Europe, 6 from the U.S. and 1 from Australia). BUMA VI seems to have been a turning point. I am informed that the attendance by scholars in Bangalore (BUMA VII) represents a far wider array of countries (25 countries and five continents). The data should be available in this publication of BUMA VII in your hands.

I am told by participants to the conference in Nara, Japan, 2013 that BUMA VIII showed an even greater attendance and distribution by western scholars.

The proceedings of the BUMA VI conference were published in 2009. ("Metallurgy and Civilization: Eurasia and Beyond", eds. Jianjun Mei and Thilo Rehren, Archetype Publications, 2009).

BUMA VII convened in Bangalore in September 2009. The organizers and chairpersons were Professors Srinivasa Ranganathan and Sharada Srinivasan. The conference provided a forum for many aspects of early metallurgy of copper, zinc, precious metals, special emphasis on crucible steel, weapons and ancient bronze castings. There were more than 100 delegates. Seventy papers were presented. In many ways the choice of Bangalore in Karnataka was an ideal venue since early Deccan metallurgists pioneered for more than two millennia the legendary Wootz steel.

BUMA VIII took place in Nara, Japan in September 2013. Although the data are not yet distributed, there were more than 100 abstracts submitted. Attendance was particularly heavy from adjacent countries along with a good number of Western scientists and scholars.

Looking into my view of the future, I have some concerns for the health of our conferences. One worry is associated with an almost Sino-centric view of our past performance. Professor Rehren writes in his Preface to the BUMA VI volume, "Although the academic nucleus" has been "the organizational drive to establish BUMA as circum-Pacific, the emphasis has always been on Chinese metallurgy." Since BUMA was first held, there have been four in China, two in Japan, one in South Korea and one in India.

BUMA IX is, I am told, scheduled for South Korea in 2017. If the BUMA conferences are to include Pacific Rim countries with an occasional acceptable glitch (for example, Bangalore VII), as I urge, we should bring in scholars from South and Central American countries such as Peru, Chile, Ecuador, Bolivia and Mexico where there are today young scientists engaged in new and interesting studies on early metallurgy (late third millennium BCE). These scholars should be identified and invited to present their studies at future BUMA conferences. Certainly, an academic nucleus must reflect the flow of results of concurrent research and studies. An excellent example is a major underpinning in the origin of the BUMA conference itself. This is a subject I urge the Standing Committee to discuss.

An associated aspect is the membership in the Standing Committee. An effort must be made to appoint members from a variety of academic and other professional organizations to bring in varied views. Any appearance of xenophobia or parochialism may well destroy the integrity and must be avoided.

Finally, I have some angst as to our financial viability. The assignment of future conference venues depends and has always been associated with definite statements from responsible scholars from interested countries. Thus, BUMA VII was assigned after a number of distinguished Indian scientists and scholars expressed their interest in hosting a conference while attending BUMA VI. Costs associated with organizing and conducting an international conference are borne by the host country, but these costs have always been of concern. In the past the host committee has solicited funds from the various sources, professional societies, government and corporations. These funds have in general been used not only for the basic expenses associated with organizing and conducting the conference but in some cases used to fund selected invited speakers. The attendance by Western scholars, although improving, has been at best meager. It is entirely possible that conference organizers, from China, Japan, South Korea and India, do not appreciate the fact that, in their countries, such things are supported by the State. In the UK and the USA, in the world of market-driven capitalist economies, there is no state support. Yes, a professor at a European university can get institutional support to attend a conference, but most often if he/she is on the program and if the conference is held in Europe. The same is true for America, with rare exceptions made for major conferences. No American or European university is going to support travel to China or Japan. Hence, the host country must include funds for travel and subsistence particularly for Western scholars, especially if he/she is a principal speaker. In addition, funds should be set aside to subsidize travel for selected students. In assigning a venue, the Standing Committee should discuss with the interested host country these aspects of acquiring funds.

The BUMA conferences as a unit must define a method for acquiring an endowment. To accomplish this, fiduciary responsibility must be established in order to encourage financial support from public and private sources. The Standing Committee should obtain information of possible associations with established societies, professional or other non-profit organizations.[1] Such an association would provide a fiduciary status and encourage the solicitation of funds. With the accumulation of (primarily endowment) funds, support for publication of proceedings is then possible. I conclude by repeating my remarks for BUMA VI:

*Another serious impression from the past is the absolute necessity of the publication of the proceedings of the conference. They cannot be left to the memory of those who may have attended. The published proceedings constitute a history of what was the state of our understanding of particular subjects at the time. This is a must; the proceedings must be published IN TIME otherwise the conferences proceedings fade away with time.*

I would like to offer my great appreciation and thanks to Professors Srinivasa Ranganathan and Sharada Srinivasan for the gracious hospitality before, during and after my visit to Bangalore. They and their colleagues organized a most successful conference along with a memorable and fascinating side trip to the Mysore region during the impressive Festival of Lights.

Robert Maddin
University Professor Emeritus
University of Pennsylvania

[1] Wootz steel, a discovery by early Indian metallurgists immediately brings to mind wealthy industrialists whose corporations stem from metals as possible contributors (for example, the Indian Steel baron, Lakshmi Mittal).

# BUMA VII – a Personal Perspective

The BUMA conferences have emerged as a unique meeting venue for scientists and archaeologists alike who share an interest in humankind's metallurgical heritage. Founded by two inspirational and visionary leaders of the field, Professor Ko and Professor Maddin, it continues to grow and to attract a lively and highly engaged audience. At the same time, there is something special and unique about each individual conference, something which runs parallel to the scientific programme and captures more the 'spirit' and the ethos of the hosting nation and local institution. In this sense I would like to offer a few comments on the experience of BUMA VII in India, hosted by the National Institute of Advanced Studies in Bangalore. Needless to say, this is a rather personal account and out of necessity only very partial – each participant will have made his or her own experiences, will treasure their own memories and remember special events and situations.

## *The Organisation:*

This was not the first conference I attended, and not the last. However, it stood out in several organisational aspects which remain strong in my memory. There was the pre-event information flow: the organisers ensured that updates in the programme were communicated in a timely and easy-to-follow manner, so that at any one time one felt to be part of it, and not left wondering what to expect or how to proceed. Then, upon arrival, I was impressed by the lushness and greenness of the campus (and that was even before I moved to the campus in Doha, Qatar, the only country with no natural surface water, river, stream or lake), and the beautiful setting of the Institute. This welcome was further enhanced by the very supportive, attentive and friendly local staff – I have never seen so many friendly faces at a conference, even in the heat of the battle with malfunctioning powerpoint files or other perceived emergencies. Thank you to everybody for making us feel so welcome!

## *The programme:*

Compared to most archaeometallurgical conferences, BUMA VII stood out for its well-balanced programme. Twenty papers were on iron and its alloys, and the same number dealt with bronze. Eight papers were on casting technology, and eight on archaeology. This reflects well the relative importance of the two main metals and alloys in ancient societies, and the interest in ancient craft production as a genuine aspect of archaeology. Within the two leading metals there was an emphasis on wootz / crucible steel and high-tin bronze, respectively; both are technologically 'high-end' materials which have fascinated scholars for over a century, and the manufacture of which was particularly highly developed in India and elsewhere in Asia. However, the less common metals were also well represented. Seven papers discussed pure copper; three zinc as a metal; three were on coins; two on gold and two on tin – and even one on lead, the Cinderella of archaeometallurgy.

Despite this diversity in materials, there was a very strong focus geographically. About 80% of all papers were on Asian metallurgy (here defined as covering everything east of the Urals and Mesopotamia). Specifically, there were 59 papers in this category, with a further seven on Near Eastern sites, five on Europe, three on Africa, and none from the Americas. I will come back to this latter aspect later, since it is important. Significantly, this strong regional focus is one of choice by the participants of the conference – a self-selected focus by those who have submitted abstracts for consideration, and not one imposed by the organising committee or any other body. This does not mean, however, that the conference was narrow in its focus (and with Asia as the topic, how could it have been!) – on the contrary, there were a good number of papers that reported work done jointly by colleagues across the continents, demonstrating again that Asian archaeometallurgy is of interest and significance to all of us.

The strong showing of iron-based papers is of particular interest, since it contradicts a sustained and widespread preference for copper and bronze in most international conferences and publications – except of course those that specifically target iron such as the recent meeting on *Early Iron in Europe* and the *World of Iron*. In a recent study of archaeometallurgical publications in the first 50 years of the journal *Archaeometry*, it became apparent that for the first forty years or so, papers on iron and its alloys were very rare indeed. The same trend can be seen in every single *International Symposium on Archaeometry*, which every two years brings together the worldwide community interested in ancient materials. Thus, BUMA VII put the record straight in a rather crucial aspect of archaeometallurgy. Similarly, what was welcome was the relatively strong presence of mostly archaeological papers, i.e. those which were not based primarily on the scientific analysis of artefacts or metallurgical remains. Here, of course, numerous purely archaeological conferences exist that offer a suitable audience for non-analytical papers. However, bringing archaeological enquiry into the heart of BUMA, a conference emerging out of a strong engineering and scientific tradition, is remarkable as well as necessary, and the organisers are again to be congratulated for achieving this.

## *The future:*

This was BUMA VII, the latest event in a conference series quite obviously in good health and with a long pedigree. How do we ensure the long-term future of BUMA? For this, it needs several factors: firstly, a clear academic case and profile; secondly, an engaged and dedicated academic community; and thirdly, supportive leadership.

The original vision of BUMA was for it to be a venue for the study of ancient metallurgy on both sides of the Pacific – in East Asia and in the Americas. This was reflected in the origin of its two founding fathers – Professors Ko from China and Maddin from the US. However, since the early conferences this circum-Pacific ideal has gradually but clearly shifted more and more to an Asia-centric focus. As briefly mentioned above, BUMA VII had no paper offered on ancient metallurgy in America, and I believe that it is time to formally recognise this shift. Of course, we cannot study the archaeology or archaeometallurgy of any one region in isolation, and several papers in BUMA VII made it again clear that there is a constant interaction between people and mutual influences, stimulating technical and social development. However, Asia as a continent has sufficient internal diversity and richness of metallurgical traditions and achievements, within an identifiable specific character of how to do things, that a significant conference such as BUMA can reasonably and realistically sustain itself with an explicit focus on Asia's metallurgical heritage. I doubt that this will ever be to the formal exclusion of non-Asian topics, or lead to a discrimination against papers reporting on the archaeometallurgy of other continents. However, it will help to define BUMA's role and identity in the world-wide concert of conferences. Similarly, it will continue to play a decisive role of communication across disciplinary boundaries. As I have elaborated in some more detail elsewhere, archaeometallurgy is an academic discipline with many mothers. Among the most important ones are (modern) metallurgy; archaeology; geology; and chemistry. The health of archaeometallurgy as a discipline continues to depend on a regular influx of talent, knowledge and expertise from these mother disciplines, through dialogue and cooperation. By far the best place to facilitate this is at stimulating conferences attended by specialists from the various disciplines, providing a forum for exchange and informal discussion. Historically, BUMA has been a major gateway and connecting point between the engineering professions and archaeometallurgy; this BUMA has managed to span this vital bridge even further by extending it into archaeology. Every major speech on the future of academia calls for interdisciplinary research – archaeometallurgy, and BUMA within it, lives this future already now.

And it will continue to do so, simply because it has such a dedicated and engaged academic community. More than 80 scholars actively attended BUMA VII, and many more joined in the audience. Historically, archaeometallurgy was something which people got into in the second half of their academic careers, bringing a wealth of experience as well as the enlightenment and openness of mind that comes with age. The last few decades, however, have seen the rise of archaeometallurgy as a taught programme, alongside the emergence of dedicated journals and conferences, and even established methodologies of enquiry – all the indicators of an academic discipline in the making. The number of young scholars, of students and postdoctoral fellows now active in the field is testament to this development. This trend was also clearly seen in the number of students participating in BUMA, as presenters of research and in the audience. Most likely only some of these will be able to continue their professional careers in archaeometallurgy or historical metallurgy;

there are not that many positions at universities and research institutions to fill. And this is probably a good thing – since this means that a good number of those who were exposed to ancient metallurgy during their studies will eventually follow careers in mainstream engineering and metallurgy. There, they will be able to continue to act as strong bridgeheads ensuring the ongoing flow of expertise and enthusiasm into our field of research, and to support through their activities and future participation the further development of BUMA for generations to come.

Thirdly, BUMA as a conference series can only continue if it continues to be organised by energetic and dedicated colleagues who are able and willing to take on the massive effort it takes to organise such major international events. BUMA exists thanks to the local organising committees that volunteer to give a major chunk of their time to make it happen – over and above their daily workload and commitments. The committee chaired by Professors Srinivasa Ranganathan and Sharada Srinivasan executed the organization in a meticulous fashion and deserve our gratitude. BUMA's Standing Committee can only do so much to facilitate this, by acting as a sounding board for ideas, by offering academic guidance and collective advice, and helping with the publication of the proceedings – the hard work still needs to be done and delivered by the local committee. This is the place to thank again the local team who made BUMA VII a reality, and a success. Without them, representing the best of their professions, it would not have happened. Our thanks at this time go also to the two men who created BUMA – Professors Ko and Maddin. As joint chairmen they gave their vision and support to BUMA, and will forever be associated with it. The advancement of age, however, means that they are no longer able to offer the day-to-day engagement that is needed to steer BUMA into the future, and they very graciously offered to hand over the reins to a younger generation. Maintaining the principle of a joint and balanced leadership, the Standing Committee elected Professor Mei Jianjun and myself as new chairmen of BUMA – a big set of shoes to fill for both of us!

Thilo Rehren
UCL Qatar

# The Significance of BUMA VII

In his foreword above, Professor Thilo Rehren has presented an accurate and well-balanced account of the BUMA VII's organisation and programme as well as his thoughts on the future of BUMA conferences. I wish to add a few words to express my personal appreciation of the BUMA VII and the people who organised it.

First of all, the BUMA VII was a unique and invaluable experience for many of our participants, especially those from China. Without the BUMA VII, many of us would never have had a chance to visit India and to experience her rich, substantial and colourful cultural heritage. The conference itself was a great success, and the impressive programme of visits to museums and ancient sites which was so beautifully organized by our host, contributed to making it a memorable event.

Secondly, as the first BUMA conference held in India, BUMA VII is indeed significant in many aspects. From its very beginning, the BUMA conferences have acted as a bridge, not just to connect scholars in the East and the West, but also to enable the interaction of scholars from different academic backgrounds, such as scientists, archaeologists and museum curators. I remember clearly that we only had one Indian scholar during the BUMA II in Zhengzhou, China in 1986. But in 2009 the BUMA VII was actually held in India due to the great efforts made by Professor Ranganathan and Professor Sharada Srinivasan. What a significant development in the history of the BUMA conferences! I wish to take this opportunity to express my deep appreciation and respect to both of them, as well as to the National Institute of Advanced Studies in Bangalore.

Finally, I am sure that Professor Rehren and other members of the Standing Committee will join me in offering our congratulations and appreciation to Professor Ranganathan, Professor Srinivasan and Dr. Giumlia-Mair, three editors of this book for their excellent and painstaking work, which has resulted in this proceeding. Dr. Giumlia-Mair deserves special thanks for her considerable contribution to the professional editing and reviewing. This volume of proceedings will undoubtedly stand as another milestone in the history of the BUMA conferences.

Jianjun Mei
Needham Research Institute
Cambridge, UK

# Preface

The Seventh International conference on the Beginnings of the Use of Metals and Alloys (BUMA VII) was held on the Indian Institute of Science Campus of the National Institute of Advanced Studies (NIAS), Bangalore, from 13th to 17th of September 2009. The Organizers and Chairpersons of the Conference were Srinivasa Ranganathan and Sharada Srinivasan, both professors at NIAS. Given that the conference has been mainly held in Far Eastern countries, one cannot underestimate the regional significance of bringing the conference to South Asia in terms of integrating this venue more closely not only with the rest of Asia but also with the wider international community of researchers working in these areas.

More than 100 delegates from 25 countries participated and presented over 70 papers on various aspects of research on ancient metallurgy, related to Asia in several ways.

After the conference there were organized trips to Mysore, Somnathpur, Srirangapatna, Belur and Halebidu. The visits offered to the participants the occasion to get to know the copious and very varied historical, archaeological and artistic heritage of southern India.

NIAS in Bangalore also was the perfect venue for a conference dedicated to the fascinating topic of ancient metallurgy, as it has a tradition of multidisciplinary research, and of bringing together sciences and humanities.

The conference was quite a success. The papers were grouped in various sessions such as: Metallurgy and Interaction across the Ancient World, Iron Technology, Early Copper Tin and Zinc, Precious Metals and Coinage, Copper Metallurgy, Ancient Bronze Casting Technology, Crucible Steel and Weapons, Bronze Foundry, Experimental Metallurgy and Methods and Conservation.

Thanks to the collaboration of the many colleagues and friends who took the time to check their texts and to revise, we are now able to present the proceedings of BUMA VII as a fully peer-reviewed volume with the title "**Metals and Civilizations**", containing a large number of valuable papers that cover many aspects of metallurgical researches and widen our knowledge on the metallurgy of the Ancient World in many Asian and non-Asian countries.

This would never have been possible without the generous and gracious support of the Chairmen of BUMA, of members of the BUMA Standing Committee, and of other scholars belonging to the BUMA scientific community who invested their precious time and acted as referees.

We are also grateful to Prof. Robert Maddin, Arlington USA, who at the time of the conference in Bangalore was still Chairman of BUMA, together with Prof. Tsun Ko, USTB Beijing, for the continued interest and support to the conference, even after having resigned from being the Chairman, and for writing a thoughtful foreword to this volume.

We would like to express here our gratitude to them all.

In this volume we have rearranged the sections of the original program, and subdivided the papers into the following topics: Metallurgy and Interactions across the Ancient World, Iron Technology, Copper Technology, Tin and Zinc, Crucible Steel and Weapons and Ethnoarchaeology and Metals.

While at the BUMA VI Conference in Beijing there was a noticeable prevalence of papers on bronze casting and related topics, both at BUMA VII and BUMA VIII there was a clear emphasis on iron technology, however there was no lack of interesting papers that deepened our knowledge on archaeometallurgical researches on various other themes.

In our volume there is an entire section dedicated to ethnoarchaeology and metals, with stimulating papers that open our views on the kind of local peculiarities, beliefs and tradition that can have an impact on processes and technologies in a way that we might never be able reconstruct just by looking at the related finds. They can perhaps shed some light on the data that we have collected by means of analyses of ancient materials and in general from scientific examinations of finds and remains of metallurgical sites or, at least, help us to understand the complexity of human approaches to metal production, and to look with different eyes at our finds and data.

As this conference was organised in India, we are very pleased to have a section dedicated to what we can consider a rather typical “local” and very special product that spread to other countries and acquired a well deserved fame in antiquity: wootz steel.

Finally we have a section that has characterised the last three BUMA conferences and that seems to have become by now the real hallmark of BUMA. These are the researches that study and illustrate the transfer of technologies and products between far away places in the ancient world. We have gathered them in the section Metallurgy and Interactions across the Ancient World.

They give us some glimpse into the thriving trades between far away countries and let us perceive that in antiquity, even if the traveling time to reach distant countries took much longer than now, there were steady threads and contacts, and civilizations were somehow closer, and shared much more in terms of metallurgical products and knowledge than we have ever thought possible in the past.

At the same time these researches also help to appreciate the cultural diversity of the various countries that have been highlighted by the various papers.

Since 1981 the BUMA conference has travelled from Beijing to Zhengzhou, Sanmenxia, Matsue, Gyeonggju, Beijing, Bangalore and Nara. Our colleagues are by now organizing the next conference, BUMA IX, in Busan, Korea.

It has to be underlined that in all these years of studies and researches an active and interwoven scientific community has developed and clustered around the BUMA conference.

Collaborations, friendships, common researches and projects, and scholarly debates have been the results of our meetings, and this demonstrates that the conference founded over 30 years ago by Robert Maddin and Tsun Ko is alive, thriving and has been seminal and unusually valuable to all of us, as well as being a well known framework in which to present and discuss our work.

We hope that this volume will be found to reflect the spirit of previous BUMA conferences as a forum for scholars with similar interests and passion for researches on ancient Asian metals.

We also hope that it will be considered a useful volume and that in the future it will be perused and consulted by scholars working on archaeometallurgical researches not only concerning Asia, but also worldwide topics.

Finally, it must be mentioned that through the holding of the BUMA conference in India much benefit has accrued not only to the host institution NIAS but also to the wider field of archaeometallurgy in India. Generally in the past, studies on inter-disciplinary subjects, such as archaeological sciences and archaeometallurgy, have only had a rather marginal presence in terms of the mainstream Indian academic milieu and have not been a very well supported discipline. There is a still a crying need for the study of various aspects of materials heritage and the documentation of crafts and metallurgical traditions which are steadily declining.  However, the BUMA conference held in Bangalore gave a significant opportunity to draw wider attention and raise the profile of these disciplines and it is hoped that the publication of the BUMA VII Proceedings will also contribute to that. The success of BUMA VII in stimulating further interest in these subjects also indicates that there is relevance in expanding the regional sphere of BUMA to other countries in which there is need for development of such disciplines through international exposure and co-operation.

Sharada Srinivasan
Srinivasa Ranganathan
Alessandra Giumlia-Mair
Editors

# Acknowledgements

Thanks to the collaboration of the many colleagues and friends who took the time to check their texts, to re-write them, and even to write their papers completely afresh, we are now able to present the proceedings of BUMA VII as a fully peer-reviewed volume with the title "**Metals and Civilizations**", containing 28 valuable papers that cover many aspects of metallurgical researches and widen our knowledge on the metallurgy of the Ancient World in many Asian and non-Asian countries.

We are also grateful to Prof. Robert Maddin, Arlington USA, who at the time of the conference in Bangalore was still Chairman of BUMA, together with Prof. Tsun Ko, USTB Beijing, for the continued interest and support to the conference.

A major international event of this magnitude would not have been possible without financial support. These are listed and we express our sincere gratitude to all of them.

We owe an immense debt of gratitude to Dr. Alessandra Giumlia-Mair for joining us as editor. Her rich and extensive experience in editing proceedings, her standards of refereeing and meticulous attention to detail are in the main responsible for the high quality of the volume.

We thank Dr. R. V. Krishnan for support in various facets of the conference organization. We also record our gratitude to Ms. Gayathri Lokhande for her secretarial support during the organization of the conference and her subsequent help in processing the papers through various stages.

Sharada Srinivasan
Srinivasa Ranganathan
Chairpersons
The 7th International Conference on the Beginnings of the Use of Metals and Alloys

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# Section I – Metallurgy and Interactions across the Ancient World

Heavy buckles and plates decorated with almandines and beaded wire imitation, are considered typical Hunnic and are made of almost pure gold. They might have been made by melting down Roman coins of similar purity received as *tributus* by Ruga and Uptar

*Alessandra Giumlia-Mair and Béla Kürti*

# The Bronze Age to Iron Age transition in Southeast Asia – a comparative perspective

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*ABSTRACT* Recent archaeological evidence shows that the adoption of iron for making tools and weapons was quite a long drawn out process lasting several centuries in the Middle East and Western Europe whereas in Southeast Asia, and especially in Thailand, central and southern Vietnam and Peninsula India it appears to have been quite rapid. These regions lacked a developed Bronze Age such as experienced further west and in northern and central China where the control of mining, trade in metals and forging and casting bronzes played a significant role in maintaining elite social groups of complex civilizations. In southern India and in much of Southeast Asia the technical transition was basically from stone to iron.

## Introduction

Discussion of the transition from the use of bronze to iron as the dominant material for making weapons and edged tools has a long history in the archaeological literature which is far too extensive to be detailed here; the early Greek poet Hesiod speculated on a mythical five stage transition from a gold to a silver to a bronze to a heroic to an iron age; more a social that purely technological process developed further by Ovid and other Roman poets[1]. More recently the change has generally been thought of in terms technological improvements and of the wider availability of iron sources and the benefits of iron once the techniques of carburization were realised and mastered and spread, north, east south and west, through a broad diffusionary process from a centre in eastern Turkey and northern Syria[2].

## The spread of iron in the Near East and Western Europe – a slow process

This topic was considered in several presentations in 2009 at the World of Iron Conference (Humphris and Rehren 2013) in, London where both Roberts (pers. comm. 2009)[3] and Renzi et al (2013) pointed out that the adoption of iron in Western Europe was a slow, long drawn-out process spanning several hundreds of years from the first appearance of iron in archaeological sites to its dominance for the manufacture of tools and weapons. The present author found the discussion of this particularly interesting in so far as the European experience seemed to contrast to the situation in Southeast Asia, and especially in Thailand, as he understands it.

Iron smelting seems to have first appeared in a restricted area of the Near East before the end of the 3rd

1 In *Works and Days* Hesiod (8th century BC) divided time into five ages: the Golden age, ruled by Cronos, the Silver age, ruled by Zeus; the Bronze age, an epoch of war; the Heroic age, the time of the Trojan war; and lastly the Iron age. Vedic culture saw history as cyclical composed of *yugas* with alternating Dark and Golden Ages. The *Kali yuga* (Iron Age), *Dwapara yuga* (Bronze Age), *Treta yuga* (Silver Age) and *Satya yuga* (Golden Age) correspond to the four Greek ages (Source, Wikipedia). For a more recent version, see the Introduction in Evans (1881).

2 In the late 20th century archaeologists have generally reacted against the 'Three Age System' recognising the variability in the patterns of change from bronze to iron use and considerable overlap in many regions.

3 Dr B. W. Roberts presented a paper at the 2009 WOI Conference, 'Competition, Collapse or Choice? Analysing the appearance of Iron in Western Europe' which I discussed with him at the British Museum but it was not included in the publication.

millennium BC, was limited to that area through most of the 2nd millennium and progressively spread into Greece, the Balkans and southern Europe towards the end of the 2nd millennium (Collard et al 2006: 406–8). At Hartshill Copse, in the Kennet Valley, UK some evidence for smithing in the form of iron scale fragments appears around 1000 BC (Collard 2005; Collard et al 2006: 405-6) but it is "only with the expansion of iron production after 800 BC did the repertoire expand to include significant numbers of weapons, especially swords and daggers" (Collard et al 2006: 415). Thus the pattern of the spread of iron appear to conform to a conventional diffusionary pattern – a rather slow process marked by clear stages in the size and quantity of objects. (Collard et al 2006:406) "note that "traditionally Northern and Western Europe joined the iron using world … in the second quarter of the 1st millennium BC …" although iron objects were circulating several centuries earlier than this, and many iron objects had been found from the beginning of the Late Bronze Age.

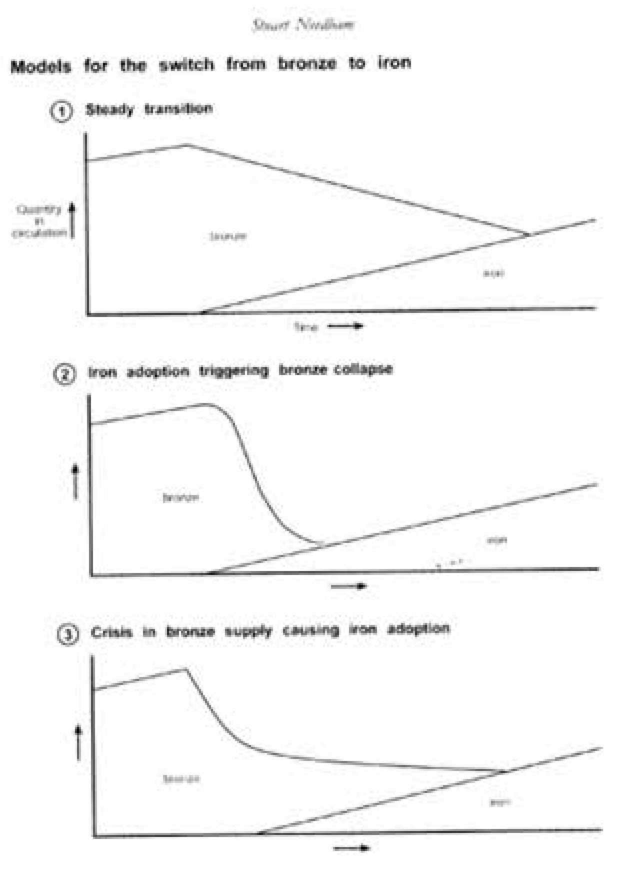



**Figure 1** Contrasting models for the transition from bronze to iron for the principal metal for tools and weapons (Needham 2007: fig.3) Courtesy of Oxbow Books.

As indicated above, Renzi et al (2013) commented out that the adoption of iron in Western Europe was a slow, long drawn-out process spanning several hundreds of years from the first appearance of iron in archaeological sites to its dominance for the manufacture of tools and weapons and it was not a simple matter of iron replacing bronze, but that the nature and structure of the societies in question must be considered. Taking these matters into consideration Needham (2007: 50) set out three contrasting models for the rate by which iron replaced bronze in late prehistoric Europe (Figure 1) but the process in Thailand, at least, does not fit readily into any of the three patterns as is discussed later.

## Dating bronze and iron in Southeast Asia

The date and the sources of the earliest bronze in Southeast Asia have been hotly debated over the past thirty years. Following the early excavations at Ban Chiang in Northeast Thailand claims were made, on the basis of some poorly related thermo-luminescence and radiocarbon dates, that bronze was in use there before 3000 BC and iron by1400 BC – earlier than most locations elsewhere in the world. Subsequent work Ban Chiang and elsewhere in Thailand, relying dates from more reliable contexts, brought the date for the introduction of bronze down to the late 3rd or early 2nd millennium BC according to Joyce White (2008) whereas Higham and Higham (2009) argue from the excavations at Ban Non Wat that bronze only appears in a long, well dated sequence in the late 2nd millennium BC.

**Table 1** shows chronology and cultural sequence for the Upper Mun Valley, Northeast Thailand based on excavations at Ban Non Wat and other sites, (Higham 2002: 168 with permission of the present author and Antiquity Publications).

| Cultural period | Date in calibrated radiocarbon years (BC) |
|---|---|
| Flexed burials | 1750-1050 |
| Neolithic 1 | 1650-1250 |
| Neolithic 2 | 1250-1050 |
| Bronze Age 1 | 1050-1000 |
| Bronze Age 2 | 1000-900 |
| Bronze Age 3 | 900-800 |
| Bronze Age 4 | 800-700 |
| Bronze Age 5 | 700-420 |
| Iron Age 1 | 420-100 |
| Iron Age 2 | 200-AD 200 |
| Iron Age 3 | AD 200-400 |
| Iron Age 4 | AD 300-500 |
| Early Historic | 500- |

Despite the lack of agreement on the chronology it seems now to generally accepted that copper mining and copper-alloy and bronze working was introduced as a 'package' from Southern China in the late third or second millennium BCE (Pigott and Carla 2007) or from Central Asia through southwestern China (White and Hamilton 2008). Pigott and Ciarla (ibid.) argued that the close similarities between smelting furnaces, casting crucibles, mould types and bronze axes and other tools and weapons in Southeast China and Thailand strongly support the argument that early bronze working techniques were imported from the north, perhaps by itinerant craftsmen since many of the artefacts and mould types and even mould markings are similar across a broad region.

On the other hand White and Hamilton (ibid.) argue for introduction across Central Asia and through southwest China rather than from northern into south China – but either way it seems to be clear that bronze casting technologies were introduced into Southeast Asia via China.

## Iron in Thailand and elsewhere in Southeast Asia

The late prehistoric archaeology of Southeast Asia is far less well understood than that of the Near East and Western Europe, and behind even that of India. Nevertheless we can see some patterns in the data that the present author will briefly summarise. About 500–400 BC iron appears in many sites in Thailand[4], perhaps Burma also and in southern Vietnam and rather quickly replaces bronze for the manufacture of tools and weapons[5] although bronze retains it value for making ornaments and religious and secular images, drums, bells and urns and many special alloys such as high-tin bronze (22-28% Sn) were developed for some containers and speculum (+33% Sn) for mirrors. These have only been found in burials or from looters' pits made by villagers so it is difficult to know whether they were intended only for ritual deposition or inclusion in elite group burials like so many Iron Age bronzes in China and Denmark (see below).

Present evidence, according to the present author, suggests that iron working was introduced to Burma, Thailand and southern Vietnam from India and into the Dong Son Culture of Northern Vietnam from Han China; and in Thailand at least the uptake of iron was rapid and thorough[6].


**Figure 2** Iron Age sites in mainland Southeast Asia (Higham 2002: 168, Courtesy of River Books)

Higham (2002: 168) lists over 40 Iron Age sites in Thailand, more than 20 in Vietnam and a handful in Laos and Cambodia (Figure 2). Of the many excavated ones in Thailand, the most significant ones from the viewpoints of dating, sample size, publication and reliable contexts are Noen U-Loke, Ban Non Wat, Ban Na Di, Ban Chiang Hai, Ban Don Phlong Noen, Ma Kok, Ban Wang Hai, Chansen, U–Thong, Ban Tha Kae, Ban Don Ta Phet and Khao Sam Kaeo. Amongst these the sites Ban Don Ta Phet in Kanchanaburi Province towards the west and Khao Sam Kaeo in Chumphon Province on the east coat of the Thai-Malay Peninsula are among the earliest, if not the earliest dated sites in Thailand with both iron and other materials showing strong contacts with South Asia.

4 In a summary of the prehistoric chronology of the upper Mun Valley in Northeastern Thailand, based on many dates from Ban Non Wat, Ban Lum Khao and Noen U-Loke (Higham and Higham 2009: Table 2) place the beginning of the Iron Age between 420–100 BC but assuming that iron reached Thailand from the west it is reasonable that it appears later in the rather remote inland region than on the western coasts and moved north along the easily navigable rivers.

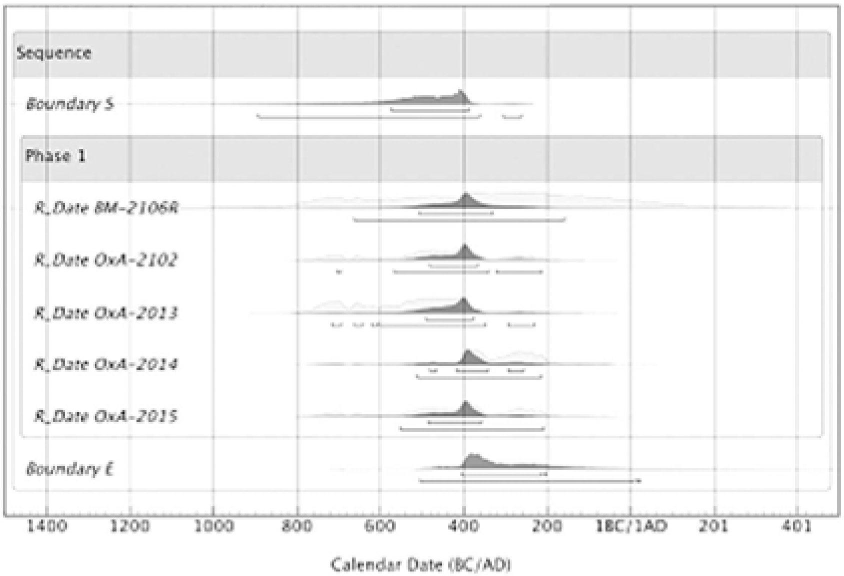
5 Despite the speed of adoption of iron at the site there is no evidence of carburization to improve the hardness and effectiveness of the tools and weapons and to give it an advantage over bronze.

6 Bronson's (1992) discussion is an original and still relevant contribution to our understanding of the patterns of the early trade in metals in southern and eastern Asia but does not deal directly with the chronology and speed of the bronze – iron transition.

**Figure 3** Excavations at Ban Don Ta Phet, 1981 (Photographs Ian Glover)

At Ban Don Ta Phet (360–390 cal. BC)[7] (Table 2 and Figure 3) over 1000 iron tools and weapons (including broken pieces) were recovered during four seasons of excavation (Figure 4) while bronze, though numerous was reserved for containers, ornaments and figurines (Figures 5–6) (Glover 1990: 161–5). Details of the iron from BDTP, the range of forms, manufacturing technology and analyses were presented by Bennett (this volume) and here the present author will only make some comparisons with the situation in South Asia as he knows it.

**Table 2** Radiocarbon dates from Ban Don Ta P`het
(Courtesy of OxCal and christopher.ramsey@archaeology-research.oxford.ac.uk)




7 It is possible to interpret the calibrated dates from BDTP to suggest early 3rd century BC, but consideration of the dates by the Oxford Dating Laboratory in 2008 recommended that the early 4th century is preferred. Bronson (1986: 206 from Bronson 1999: 190) mentions that there were some 15 radiocarbon dates earlier than 500 BC although many of the associations between iron and the dated samples are far from clear. A date of around 700 BC for iron at Nil Kam Haeng in the Wong Prachan Valley, Lopburi Province has been mentioned, but its association is not clear.

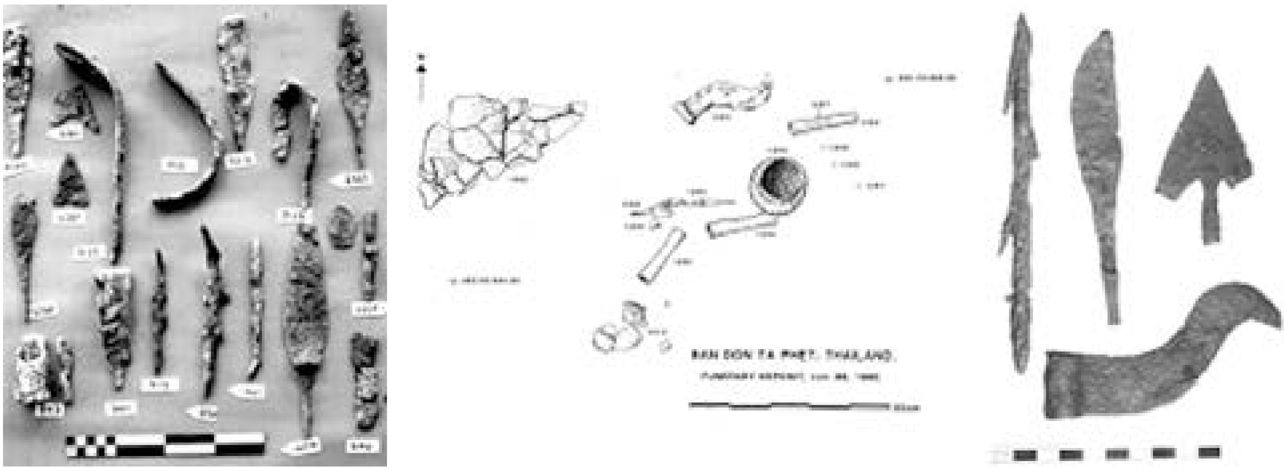



**Figure 4** Ban Don Ta Phet, iron tools and weapons before conservation, in situ and after field conservation (Photographs Ian Glover, drawing L Ryan)

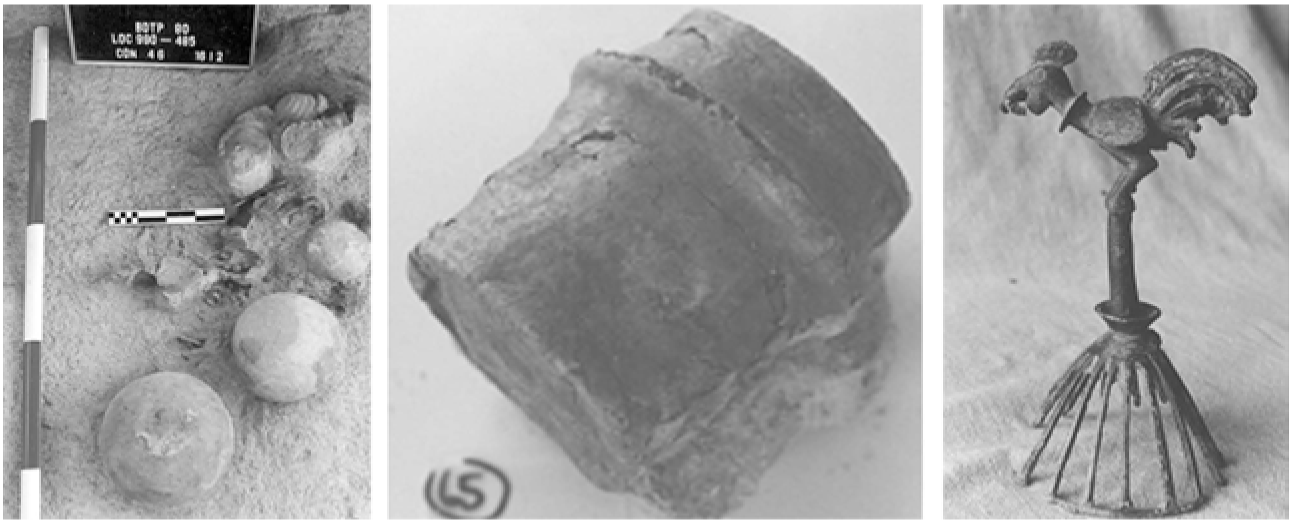


**Figure 5** Bronze containers and a figurine from Ban Don Ta Phet. (Photographs Ian Glover)

## Iron in Vietnam

Iron seems to have reached Vietnam from two directions; in the north it most probably was introduced at the time of the Han invasion in the 2nd century BC, or even earlier during the reign of the First Emperor Qin Shi Huang whose armies are thought to have moved into the Red River Valley a century or so earlier.


**Figure 6** Distribution of Dong Son sites in northern, Vietnam (from Ha Van Tan 1994)

**Figure 7** Dong Son bronze drum – icon of the Vietnamese Bronze-Iron Age (from Ha Van Tan 1994)

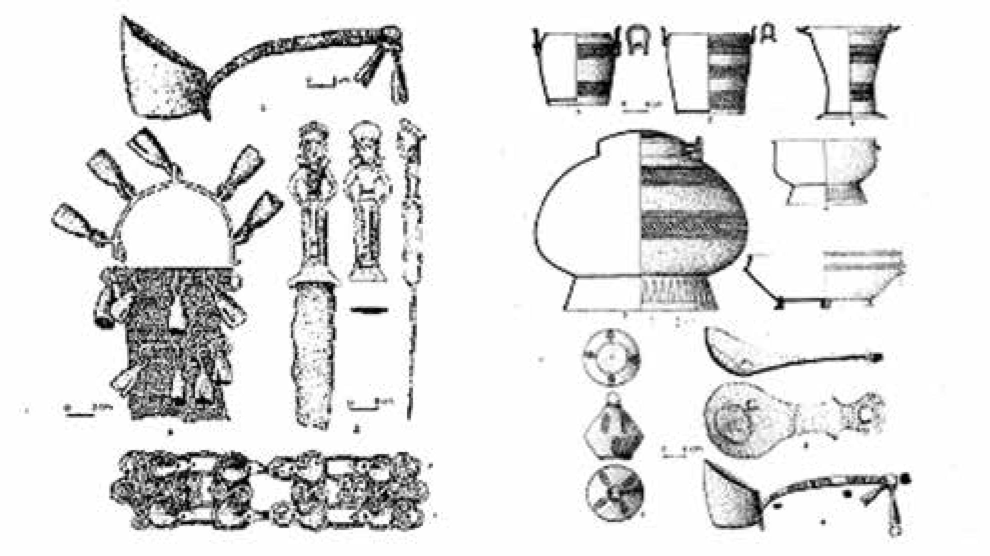


**Figure 8** Dong Son containers, ladles, daggers and ornaments (from Ha Van Tan 1994)

And there it had to find a place in the rich metallurgical tradition of the Dong Son Culture where status seems to have depend on control of the trade of copper-alloys, specialized craftsmen to make the rich array of drums, situla, daggers, axes, figurines and musical instruments (Figures 7–8) which accompanied the community leaders to their burials – but whether the burial pits, less elaborate than those of the Han elite, were dug with iron tools as seems to have been the case in parts of China at this time, or with bronze tools is not known. Or was iron relegated to the use of simple agricultural tools (Figure 9) as the few early examples seem to indicate ?

**Figure 10** Eastern Han bronze vessels, Lai Nghi, Central Vietnam
(Photograph courtesy of Andreas Reinecke)

**Figure 9** Cast (?) iron agricultural tools and casting crucible from a late phase of the Dong Son Culture (Ha Van Tan 1999)


**Figure 11** Western Han bronze mirror from a Sa Huynh site, Central Vietnam
(Photograph courtesy of Mariko Yamagata)

The central coast and southern Vietnam, location of the Sa Huynh Culture (c. 400 BC – AD 200) lacked the rich tradition of ceremonial bronzes found in the north and as, in Thailand, bronze seems to have been produced for a limited range of weapons, ornaments and domestic tools and the drums and more elaborate pieces such as large halberds, sets of containers (Figure 10) and Han mirrors (Figure 11) were probably traded, or given in gift exchange between local rulers further north.

## Iron in Burma (Myanmar)

If archaeological research is underdeveloped in Thailand and Island Southeast Asia, then it has barely started in Burma. Most recent work has been focused on historic sites and the repair and rebuilding of Buddhist stupas and until very recently only Nyaung-gan, a burial site near Monywa north-west of Mandalay containing stone and bronze tools and weapons, but no iron, has been excavated to a reasonable standard (Moore and Pauk Pauk 2002). Since then an energetic French and Burmese team have been researching in the Samon Valley in Central Burma and have excavated a number of bronze and iron age burials at Ywa Htin. But the numbers are low – only about 15 iron pieces from some 30 burials (Pautreau, J.-P. (ed) 2007: 61-2) for which the few radiocarbon dates suggest the iron appears around 400 BC – not very different from Thailand on present evidence (ibid. 87). The iron tools from Ywa Htin and others in the private collection of Win Maung (ibid.177–81) (Figure 12) closely resemble those from Ban Don Ta Phet and other Iron Age sites in Thailand whereas some of the socketed bronze axes probably a little earlier than the iron (eg. ibid. fig. 556) with their roughly parallel sides, look more like bronzes from the Ba Shu culture region of Sichuan and Yunnan than finds from Thailand and Vietnam – suggesting again an origin for the bronze tradition of Myanmar in southern China.

Hudson (2010) has reported on two new excavations in 2009 at Halin in Upper Burma which have recently revealed a series of Neolithic burials (HL 30) below Bronze Age burials (HL 29) and a later Iron Age settlement and burials (HL 28) about 1.2 metres below the present surface. Some of the skeletons are associated with a few iron spearheads and other tools – this level itself overlain by the early historic town. Unfortunately there is still no reliable chronology for the cultural sequence from Neolithic, through Bronze Age, Iron Age to the Historic period at Halin or indeed elsewhere in Burma.


**Figure 12** Iron agricultural tools from Myo Hla, Samon Valley, Burma (Photograph Courtesy, Bob Hudson)

## From bronze to iron

Why is the rate of the uptake of iron in some parts of Southeast Asia so different from in Western Europe or even in the Levant where, so close to the sources of the earliest iron, it was slow to replace bronze for tools and weapons[8]. The present author offers a partial explanation later since on present evidence[9] it appear that iron appears to replace bronze more rapidly in those areas such as western, peninsular, central and northeastern Thailand where bronze technology was relatively undeveloped and craftsmen were making only a limited range of weapons, tools and small ornaments in contrast to the production of large ritual and ceremonial objects such as drums, situla and elaborately decorated axes and halberds found in South China and in the Dong Son region of northern Vietnam.

8 The forging of Israel: archaeometallurgical evidence of early Iron Age metal production in the Land of the Bible, S. Shalev, (presented at BUMA VII, Bangalore, September 2009). See also Finkelstein and Piasetzky (2010) for recent radiocarbon dating of the Iron Age in this area.

9 It must be understood that archaeological research in Southeast Asia is still at an early stage and new finds and dating will alter many of the interpretations offered here.

## Iron in India and Sri Lanka

The present author had long understood that iron first appeared in South Asia, in the northwest about 1200 BC, probably from the Afghan-Iranian Plateau following the earliest production of iron in eastern Turkey and northern Syria near the around the beginning of the 2nd millennium BC. Iron working then spread southwards through the subcontinent between 1000 – 800 BC. Possehl and Gullapalli (1999: 153–54) identified four early iron-using regions; the Gandhara Grave Culture of the Northwest; the Painted Grey Ware Culture (PGW) of the Gangeatic Valley; the Pirak assemblage of Baluchistan where iron appears in Period 3 c. 13th–12th century BC; and the Megalithic Complex of Central India with dates starting around 1000 BC.

There had been of course claims of earlier and independent development of iron smelting in India (Chakrabarti 1976, 1992; Shaffer 1984) but the present author had rather put these assertions aside as being based on poorly dated survey material, theoretical considerations rather than good evidence and, perhaps not a little 'archaeonationalism'. There are also reports of several pieces of iron found in Bronze Age sites, but it seems that the contexts are uncertain none have been analysed (Possehl and Gullapalli (1999: 159–61).

South India seems not to have experienced anything like a regular Bronze Age and by and large moved from a total dependence on polished and flaked stone tools to the use of iron and although a few copper or copper alloy artefacts have been recovered from some late Neolithic sites these are though to have been traded south from copper and bronze using regions.

In a review of the evidence for early iron in South India (Gullapalli 2008) cites that the earliest dates for iron in the area of the Megalithic complex as coming from Hallur on the Tungabadhra River, Karnatika at c. 1100 BC which fits well enough with earlier estimation but significant numbers of iron tools and weapons appear together with copper and gold only in the first millennium BC. However, at the 2009 WOI conference both Tripathi (2009 2007, 2006, 2013) and Singh (2013 and Tewari (2013) confidently asserted that iron can now be dated to the earlier part of the 2nd millennium BC and Singh and Tewari argued that India "was an independent centre for the development of the working of iron about 1800 BC, if not earlier". This would make iron working in India not much later than, but arguably independent of, the usually accepted earliest centre in eastern Turkey and northern Syria. If these dates are well supported[10] then it make it all the more surprising at iron working did not reach Thailand and southern Vietnam until some 1200 years later.

There has been less research on early metals in Sri Lanka which, like much of southern India, seems to have passed rather abruptly from a flaked stone-based 'mesolithic' phase to iron using with the earliest published date in the 10th 9th century BC at the Aligala site, Sigirya and artefacts of roughly the same date from the excavations at the citadel mound at Anurdhapura (Solanggaarachchi 1998).

## Early Iron in Africa

The review article by Killick (2004) presents a good overview of sub-Saharan African iron working to that date; in which he demolished de Maret's assertion that the existence of iron working in Central Africa c.3500 BP was shown by the quantity of flaked stone tools on later open sites where there was no evidence for iron, slag, furnace or and smithing waste. Killick (ibid. 102–4) also casts doubt on the claimed early dates of iron working on the Termit massif since most of the dated materials do not represent metallurgical activity and are also from surface scatters, possibly mixed as a result of deflation of the soil surface. On balance Killick concludes that that there was at the time of writing, no conclusive evidence if iron working in sub-Saharan Africa earlier than the mid first millennium BC. In the same article Killick (op cit 103–5) also considers the evidence for an independent centre of iron working in Africa and finds it wanting; however, at the 2009 WOI conference Darling and Aremu (2009) also postulated that northern Nigeria was an early, an independent and perhaps the earliest centre of iron smelting and forging in the world. Since there will surely be more discussion of this matter in the future the present author will say no more here.

## Iron in China and Korea

At the 2009 WOI conference many papers were presented on iron and iron working in China and some of the old uncertainties, such as the questions about independent invention or diffusion across Central Asia appear to have been resolved. But it is worth pointing out that, as elsewhere, some of the assumptions about early metallurgy have, in the past at least, been based more on faith than solid evidence and in China – which

[10] Discussing these early dates from India with a number of colleagues I have met with a certain degree of scepticism.

is not unique in this regard, (remember the early dates once proposed for Ban Chiang) Thailand – some scholars have been tempted to prefer early dates from reason of local and national pride (Bronson 1999: 179). Furthermore there seems to be much regional variability in the earliest dates for iron before a huge expansion of iron use after the 4th century BC. Bronson (1999:180-81) also makes the important point, surely well known to Chinese scholars, that bronze was often preferred for burial goods at the same time as iron was in regular use for everyday tools; many tombs in China of the 4th–3rd century BC, mainly or exclusively furnished with bronze, were dug with iron tools[11].

## Comparison between iron in Korea and Denmark

Kim (2001) makes an interesting comparison between the spread of early iron in Denmark and in Korea and shows that the process and speed of the transition was quite different in the two areas; a fact which he attributes to differences in the social organisation of the societies and especially the strategies of the ruling elites rather than to the technical advantages of iron.


**Figure 13** Bronzes from the late Danish Bronze Age (from Aberg 1936 fig.10)

In Denmark, although a few iron objects are known as early as 1200 BC its regular use and production started only between 900 – 500 BC and in a context where the power of the ruling groups depended on the import and exclusive control of bronze and elaborate objects made of bronze from parts of present-day Germany and even south-eastern Europe for ritual, even sacrificial deposits in the ground (Figure 12). The uses of iron and bronze differed; before about 500 BC iron being limited to small personal objects and ornaments and inlaying and repairing bronze objects whereas bronze was used for a wide range of spectacular weapons, ornaments, musical instruments and containers. However, as in pre-Han China and northern Vietnam iron seems to have been widely used for everyday tools and agricultural implements and is probably under-represented in the archaeological record. About 500 BC the import and hoarding of bronze from the European mainland declined rapidly and the societies maintained by the strategies of the elite's use of bronze ritual items underwent profound changes in structure and the subsistence economy moved more to stock breeding and more intensive agriculture and bronze had more limited uses.

In Korea there have been no claims for early or independent development of iron technology (North Korea excepted ?) and it is accepted that it was introduced from northern China around the 3rd century BC and rapidly spread throughout the peninsula (Kim 2001: 455). In the late Bronze Age of southern Korea, bronze was mainly for rich grave goods as in Denmark whereas stone was still used for agricultural tools and the earliest iron appears around the end of the 2nd century, imported from Manchuria or the northern region, is also used in both elite and ordinary burials, unlike its treatment in Denmark. Forms included weapons, wood-carving and agricultural tools, axes and shovels. Iron tools are found in middens and ordinary houses although stone tools are more common. By the 1st century AD bronze become rare and iron production was greatly increased. The main differences in the spread and use of iron between Denmark and Korea lie in the rate of the transition and its early use for weapons in Korea – slow in Denmark and rapid in Korea; a development that quickly led to the appearance of several regional states.

## Conclusions

Examining the spread of iron throughout the ancient world I see it as, principally, a rather slow spread from a single broad centre of innovation in the northern part of ancient Western Asia over a period of about 1500

[11] Han Rubin, pers comm..at BUMA VII.

years at the end of which iron was in regular use for most edged weapons and tools from Western Europe to eastern Asia and south through Africa. However the rate and scale of its acceptance as a replacement for stone and bronze for tools and weapons varied greatly according to the differing social and political structures, the availability of both iron, copper and tin sources, the uses to which the metal was put and the contexts into which it was introduced. None of Needham's three models for the transition from bronze to iron in western Europe (2007: fig.3) explain well the process in mainland Southeast Asia. In western and southern Thailand and southern Vietnam, iron seems to have arrived into a region without a well developed "High Bronze Age" as found in parts of northern Europe, China and northern Vietnam but where bronze was scarce, and mostly imported and the transition was primarily from stone to iron – as in Peninsular India. Further the local communities were not organised into powerful states or even chiefdoms, but were locally restricted, small in scale, though active in internal and external trade. This social and political context seems to have been more important as Kim (2001) has argued than the ready availability of the raw materials or the understanding of the process of transforming varieties of iron ore to hard metal and its technical advantage. In western and the southern Thai-Malay Peninsula and southern Vietnam[13], areas which lacked the presence of powerful complex chiefdoms whose ruling elites depended on the status and legitimacy offered by the control, trade in and ritual gift-giving of spectacular and costly bronze objects, then iron once it was known was rapidly accepted in the middle of the first millennium BC following contacts with South Asian traders who also brought the knowledge of glass-making and the skills to work semiprecious hard stone such as agate and carnelian for valuable beads.

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# What's mine is yours: the transmission of metallurgical technology in Eastern Eurasia and East Asia

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*ABSTRACT* Early societies that began to use metals, and especially alloyed metals, have been assumed to exhibit societal complexity. They are thought to appear in places where we can see increased social stratification accompanied by a coalescence of geographically extensive shared artifact inventories including ones of metal. In the case of the beginnings of metallurgy in China, for instance, its study has been particularistic and evolutionary, tied to traditional Chinese historiography and modern Marxist model of social development. This reasoning has lead to, not unsurprisingly, a contest over primacy of one 'culture' over another. Was it an indigenous affair, or was the technology introduced from outside of the Chinese sphere? Below, I argue that it is time to reconsider both the interconnectivity of groups and the transmission of metallurgical knowledge in order to shift emphasis away from ' cultural' interaction to sharing regionally within 'social fields'.

## Introduction

Early societies that began to use metals, and especially alloyed metals, have been assumed to exhibit societal complexity because of the varied demands of the production process. They are thought to appear in places where we can see increased societal stratification accompanied by a coalescence of geographically extensive shared artifact inventories including ones of metal. And although this paradigm has been persistent, it has been challenged most recently with the work of Hanks and Doonan (2009; and Hanks 2009) and more recently by Pittman et. al (2013) at Stepnoye in central, western Siberia. There the analysis of metal production in small scale societies has demonstrated that the production took place at the household level of community and not as a result of more complex societal organization, even though the Sintashta complex had been thought of as a larger production network and interconnected polity. The issue of migration, whether promulgated and made possible with a broader move to pastoralism in Eurasia, and production at local levels has also recently become an active debate among archaeologists, not least because of the publication in 2012 of Michael Frachetti's paper and comments on it in *Current Anthropology*.

In the case of the beginnings of metallurgy in China, for instance, its study has been particularistic and evolutionary, tied to traditional Chinese historiography and a modern Marxist model of social development. This reasoning about China has lead to, not unsurprisingly, a contest over primacy of one 'culture' over another. Was it an indigenous affair, or was the technology introduced from outside of the Chinese sphere? Such discussions have ranged from arguments that suggested that Siberia was the progenitor of the Chinese metallurgical tradition as well as the chariot and horse domestication to ones where China was claimed to have created a unique metallurgical, especially piece-mould cast bronze manufacturing tradition. Although it is much easier to show the transmission of such items as the chariot from outside of China than it is a technology such as the domestication of the horse or metallurgy, most of these arguments until very recently have been caught in a tangle of debates over diffusionist vs. spontaneous developmental models as well as the political circumstances and nationalistic sentiments in all of the candidate locations where the technology traveled or was thought to be invented.

Before returning to the particulars of the eastern Eurasian area and technological transmission and invention *per se*, I think it useful to revisit the arguments about how the problem was dealt with in the past since those discussions still affect thinking today. The prehistorian V. Gordon Childe unapologetically proposed that across many areas, including Eurasia, there was "essentially a pooling of ideas, building up from many sides the cultural capital of humanity" (Childe 1937, p. 4). In the extreme and often dependant on an evolutionary model, diffusionist proponents argued that entire civilizations owed their origins to the external stimulus of an advanced society (Potts 2007, p. 3). Others were preoccupied with cultural contacts that affected the spread of superficially obvious style traits, such as patterns on painted or engraved pottery. This fixation on epiphenomena as opposed to focus on core technologies and infrastructure was and is still observed by some. In its most detailed use, typologies are developed and employed to create or confirm chronological sequences, and if developed in concert with stratigraphic evidence, such sequences have been the backbone of dating in much archaeological investigation in the field.

Kroeber suggested that 'stimulus diffusion,' or selective or partial transmission of ideas and/or objects could explain the adoption of technology beyond its locus of inception (1940). In 1977 Cyril Smith suggested that even adoption of small ideas could provoke connections and cause adjustments of ideas and consequently technologies in the host society (p. 84-85). The concept of 'interaction sphere' suggested equally weighted interactions, or articulation, or as Binford put it, observation of "comparative structural and functional analyses of interaction spheres…allows us to define, quantify and explain the observation that rates of cultural change may be directly related to rates of social interaction" (Binford 1965, p. 208). In such a view, there was no directionality or hierarchy implied in interactions charted and study of closed systems was intended. K. C. Chang adopted this model to explain the rise of the Chinese dynastic state and considered metallurgy as a by-product of increased social complexity (1986). And even more recently, Roberts, Thornton and Piggott have argued for a single invention locus for metallurgy in Southwest Asia arguing that conditions needed to locate and refine ores as well as produce metals required specialists. They downplayed the close analysis of regional settings and the benefit of independent interconnectivity of parts of the process outside the production sites in favor of reasserting an overarching diffusionist model (2009).

And, although meant to explain economic interconnectedness, scholars interested in Bronze-Age cultures flirted with Wallerstein's 1974 influential thesis on the modern world-system applied to ancient Eurasia from Mesopotamia to China. And even though the 'core-periphery' model has now been largely repudiated most especially for its view of macro-scale and treatment of peripheries as passive recipients of stimuli from cores and centers (Kohl 1989), there has been little attempt to deal with these views in relation to the concept of technology transfer and innovation within systems of regional or local interaction, whether the exchange appears to be symmetrical or asymmetrical (Potts 2007, p. 4).

## Homegrown ingenuity?

But, if we invert these models and look at places where technologies spread, as Potts suggests (2007, p. 6), enabling the production of distinctive, culturally local products and or mixed assemblages of artifacts that would otherwise escape notice and not arouse any suspicion of inter-cultural contact and focus on the distinctiveness of ways of doing things, as opposed to end-products, we may find another picture. This would lead the discussion to identifying the difference between 'cultural patterning' at the level of local praxis and 'technological style' as an external or formal extrinsic manifestation, or language and word, as the linguist would say. This circumstance would certainly describe the ultimate response to the transmission of metallurgical knowledge in the center of dynastic China in the late second millennium BCE. It is to that shift of thinking and its application to the period of the beginnings of the use of metals in Eastern Asia that I will now turn.

One of the most persistent as well as unexamined assumptions in this earlier literature is that 'cultures' interacted, that somehow the Chinese interacted with cultures, or peoples, of Siberia, for instance. I will argue here, however, that, dependent on the time and place of origin and use, the introduction and production of metal artifacts were probably products of 'shared social fields' (Wolf 1982, p. 76) or 'technoscapes', as Appadurai suggests for the modern world (1996, p. 33). In this sense, 'social fields,' as opposed to 'whole cultures,' would be inextricably involved with other groups in weblike connections in which technologies such as metallurgy were shared and modified by others caught up in the same process (Kohl 2008, p. 496). This model shifts emphasis away from 'cultural' interaction or meta-theorizing to sharing within 'social fields' or 'technoscapes' that, of course, require close examination of local contexts.

## The Eastern Eurasian Case (Fig. 1)

In the case of metallurgical technology and eastern Eurasia, the debate has been greatly enhanced by the availability of both excavated material and of scientific testing of remains. When connections between the regions of present-day China and Eurasia are argued,


**Figure 1.** Map of Mongolia and Northwestern China: Transmission of Metallurgical Technology through Xinjiang, Gansu/Southern and Western Mongolia (Adapted from: Mei 2004, p. 217)

most scholars have concentrated on the region of Xinjiang, in part because there is now adequate material excavated there to test, and because there is a logical geographic connection between the western regions of Xinjiang and eastern Kazakhstan where analogous materials have been excavated and studied (Mei 2000, 2003a, 2003b; Chen and Hiebert 1995; Linduff 1995, Linduff et al. 2000; Linduff and Mei 2009). This transmission has been thought to have passed through eastern Kazakhstan, especially as it is manifest in Semireiche, with Yamnaya, Afanasievo (copper) and Andronovo (tin bronze) *peoples.* From Xinjiang this knowledge has been thought to travel through the Gansu Corridor and then into territories controlled by dynastic China.

No one doubts that Xinjiang was a plausible point of transmission, but for the sake of discussion, I suggest that we broaden the geographic area of attention and think again about from where and how the transfer might have taken place. Evidence from the region to the north and west periphery of the Chinese Yangshao and Longshan and subsequent dynastic settlements of the Central Plain during the third and second millennia BCE, more particularly, the area north of the eastern Altai Mountains during the Bronze Age is now beginning to be available. Although contiguous to the Chinese sphere, developments there have not yet been entered centrally into the debate about the advent of eastern Eurasian or Chinese metallurgy. Recently though, metal artifacts of steppic, local and/or hybrid models and aesthetics have been found in mortuary settings there and much attention has been paid by Russian and Mongolian archaeologists to categorizing their variants (Kovalev 2005; Kovalev and Erdenebaatar 2009; Grushin et al. 2009). But regardless of what 'types' of artifacts have been located, metallurgical technology was known and used there, at early dates, suggesting that the transfer of technological ideas, people with technological knowledge and/or metal artifacts in the region was possible and perhaps common across a broader region than Xinjiang.

In addition, to the south evidence of production sites has been documented under the Great Bend of the Yellow River dating from the Miaodigou (c. 2500-2300 BCE) and Longshan Phases (c. 2300-1900 BCE) (Linduff et al. 2000). In Shanxi at the site of Taosi three copper items were found in dated contexts; at Zhoujiazhuang copper residue was found; and at Yujialing copper residue from the smelting process has been located—all dating from about 2300-1900 BCE or earlier. And, more recently, refined copper ores have been excavated in Shanxi in the Yuncheng Basin (from the slopes of Zhongtiao Mountain) that are dated from about 1900 – 1600 BCE (Dai Xianming, personal communication 2/17/14), or dates comparable to those from Xinjiang and Gansu. In this region, the team members have found mining pits/wells and mining tools dating to the same period. Copper residue (slag?) was found at Yujialing with pottery sherds dated to between 2300-1800 BCE (Longshan period), and others coexisted with Erligang sherds (1900 – 1600 BCE). Recent carbon dates from the precise context in which the Yujialing slag belong to period from 1900-1600 BCE, but not confirming if there was copper production earlier at Yujialing, although they believe it is possible or even probable since copper slag has been discovered in an ash pit at Zhoujiazhuang (Xi'an) where dates are confirmed at between 2300-1900 BCE.

Moreover, at Shishulin, (c. 1800-1600 BCE) and at Xiwubi (c. 1500-1350 BCE) in the same Yuncheng

Basin experimentation with metal production continued and has been documented throughout the period from c. 1800 to c. 1350 BCE. All of the finds were from ash pits, and in the preliminary sample testing, these remains appear to be residue from smelting and refining copper ore, although copper ore was not found. Smelting and refining copper ore were possibly local activities, but so far this is still a hypothesis and more direct evidence, such as kilns or ovens, special containers, tools, a large amount of ore residue after smelting, workshop areas, and so on are needed to confirm conclusively the existence of a local practice. The excavators remain open to the possibility that refining occurred at these sites, or nearby (Dai Xiangming, personal communication 2/17/14).

This evidence provides early dates for local processing of ores and may even challenge the earliest dates from Xinjiang through where most have thought the technology was transmitted. Even more surprising, brass (copper and zinc) items have been located in dated contexts in Jiangzhai near Xi'an to no later than the fourth millennium BCE (Fan Xuanqing, personal communication 7/13). Both the location and early dates for production, moreover, suggest that in Shanxi and Shaanxi experimentation was perhaps earlier than in Xinjiang and importantly, also suggests that we look at a broader area for contact and exchange.

## North to Mongolia in the Third and Second Millennia BCE: Afanasievo and Chemurchek

Between 1998 and 2008 Alexy Kovalev and Diimaajav Erdenebaatar excavated Bronze Age burial sites north of the Altai in south-central and western Mongolia (Fig. 2). Their expeditions established a chronology for this region and identified sites that yielded finished metal products associated with the Afanasievo, Chemurchek and other traditions analogous in date to metal using sites in western and northern China from the third and second millennia BCE (Kovalev 2005; Kovalev and Erdenebaatar 2009). These Mongolian sites belong to a larger archaeological context in the Altai that has been identified and is currently being investigated by Russian archaeologists (Grushin et al. 2009). Grushin and his colleagues have identified Eneolithic (Afanasievo) and early Bronze Age (Elinuno) sites that precede in date Andronovo metalworking traditions in that region (Grushin et al. 2009, pp. 7-57).

The Afanasievo as it is identified in Mongolia is also an Eneolithic culture with start dates as early as c. 2890/2620 BCE (Kovalev and Erdenebaatar 2009, p. 152) and claimed to be analogous to that of southern Siberia in the Upper Yenissei Valley where is characterized by copper tools and an economy reliant on horse, sheep, goat and cattle breeding as


**Figure 2** Early Metal-bearing sites in Mongolia (Kovalev 2008):1.Ul'gii; 2. Khovd; 3/5. Gobi-Altai; 4. Ulaangom; 6. Bayankhongor; 7. Omnogobi (Map courtesy of Alexy Kovalev)

well as hunting (Figs. 3, 4). In traditional central Asia chronologies the Andronovo culture was thought to follow the Afanasievo, although this is not clearly the case in the Mongolian Altai. The Afanasievo is best known through study of its burials that typically include groups of round barrows (kurgans), each up to 12 m in diameter with a stone kerb and covering a central pit grave containing multiple inhumations. In their Siberian context, burial pottery types and styles have suggested contacts with the slightly earlier Keltaninar Culture of the Aral and Caspian Sea area. The Afanasievo culture monuments, located in the north Altai and in the Minusinsk Basin (the western Sayan), have been used as analogous evidence of exchange. These complexes contain poor collections of metal, but the majority were made of brass, although gold, silver and iron ornaments were also identified. A mere one-fourth of these objects were tools and ornaments, while the rest consisted of unshaped remains and semi-manufactured objects. Its metallurgical tradition has been dated by Chernykh to as early as 3100 to 2700 BCE (2004) and has been documented in Xinjiang as well (Mei 2000; 2003b). Kovalev and Erdenebaatar have excavated barrows in Bayan-Ul'gii, Mongolia, that have been carbon dated to the first half of the 3rd millennium BCE and associated by ceramic types and styles and burial patterns with the Afanasievo (Kovalev and Erdenebaatar 2007, pp. 80-85). These mounded kurgans were covered with stone and housed rectangular, wooden faced tombs that included Afanasievo type bronze awls and knives (Fig. 5).

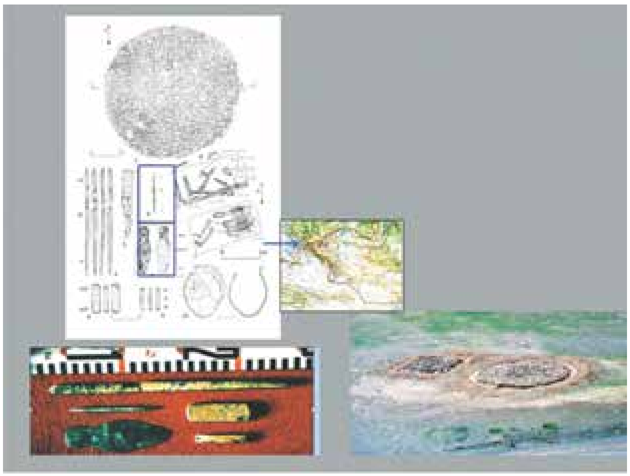

**Figure 4** Afanaseivo culture remains (2890-2620 BCE) Barrow 1 Kurgak govi (Khuurai gov'), Ulaanhus sum, Bayan-Ul'gii aimag, Mongolia; 1. plan of barrow; 2. bottom of wooden vehicle body with burial good inside pit; 3. burial plan; 4. bone arrowhead; 5. wooden object; 6. bronze awl; 7. bronze knife; 8. bone tool; 9. bone pendant; 10. Ceramic vessel (Adapted from Kovalev 2009, p. 151, fig. 1; Photos courtesy of Alexy Kovalev)

But they also excavated sites belonging to the more recently identified Chemurchek archaeological culture located in the foothills of the Mongolian Altai which they associate with the early Bronze Age 'Elinuno' sites to the west reported by Grushin (2009). These sites are carbon dated from the same period as the Afanasievo burials from between c. 2800-2580 BCE (six barrows in Khovd aimag and four in Bayan-Ul'gii aimag) (Fig. 6). In the rectangular stone kerbed Chemurchek slab burials (Ulaankhus sum, Bayan-Ul'gii aimag and *analogies*) bronze items included awls (Kovalev and Erdenebaatar

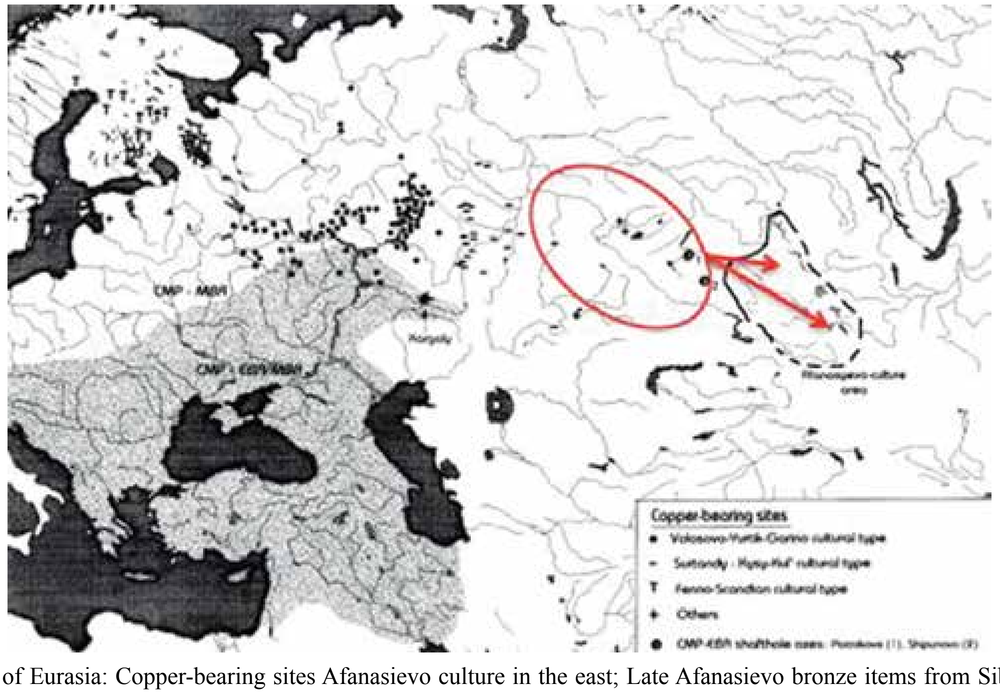


**Figure 3** Map of Eurasia: Copper-bearing sites Afanasievo culture in the east; Late Afanasievo bronze items from Siberia (Adapted from Chernykh, 2004)

2009, p. 153); and somewhat later c. 2600/1850 BCE at Khovd aimag, Bulgan sum, in addition to the stone sculptures, three lead and one bronze ring (Fig. 6) (Kobalev and Erdenebaatar 2009, p. 153). Although we do not know if they were produced locally until much further investigation is undertaken, these discoveries do document knowledge of various metals as well as uses and types of metal objects in various locations in western and southern Mongolia. The types of metal items thus far recovered are simple tools (awls) and rings (ornamental?) that are not unlike those that are associated with Andronovo archaeological cultures as well.

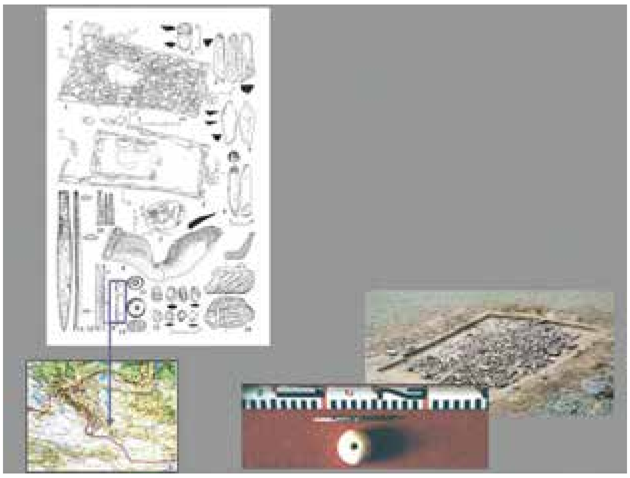

**Figure 5** Chemurchek culture remains (c. 2800-2580 BCE), Southern Altai, Ulaanhus sum, Bayan-Ul'gii aimag, Mongolia Kara tumsik barrow: 1. plan; 2. plan, stone kerb; 3. ochre-covered stele on eastern side of tomb; 4. Kulala ula barrow 1, stele; 5. Eastern Kazakhstan, Kurchum district, barrow Kopa 2, stele; 6. Khovd aimag Munkhairkhan sum, stele; 7. Kumdi govi barrow secondary burial; 8. bone scutcher; 9. bronze awl; 10. bone arrowhead; 11. bone dagger; 13. limestone ball; 12. bone arrowhead; 13. limestone ball; 14. marble ball; 15. stone tools; 16. Kara tumsik barrow, ceramic vessel(Adapted from Kovalev 2009, p. 156, fig. 2; Photos courtesy of Alexy Kovalev)

The absence of known habitation sites as well as animal bones in excavation in the mortuary sites makes it hard to argue for movement of people from either Andronovo or Afanasievo settings. In other areas, for instance, cattle domestication appears clearly only in the Iron Age as evidenced in burials in the northwest (Miller 2009) and central Mongolia (Houle 2009, ch. 6) and in the Minusinsk Basin in the late second millennium BCE (Legrand 2006). This and other evidence has suggested to Houle that some societal complexity and diversity can be found especially in the second half of the first millennium BCE, although interestingly, his data is almost entirely absent of metal objects (Houle 2009, ch. 6).

In addition, Kovalev and Erdenebaatar identified a new Middle Bronze Age archaeological culture called 'Munh-Khairkhan and 13 barrows were excavated in Khovd, Zavkhan and Hovsgol aimags that can be dated to c. 1800-1500 BCE (Kovalev and Erdenebaatar 2009, p. 154). In these tombs objects including bronze awls, knives with their wooden attachments were excavated. (Fig. 7).

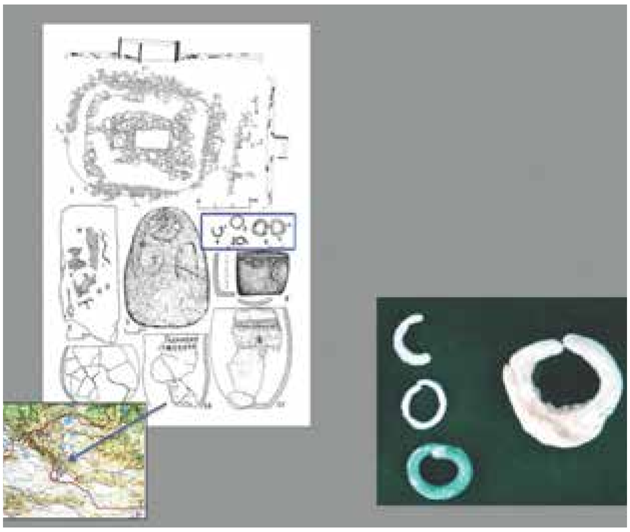

**Figure 6** Chemurchek culture remains (c. 2600-1850 BCE), Khovd aimag, Bulgan sum, Mongolia 1. Kheviin am barrow 1, plan and sections; 2. Yagshiin khodoo barrow 3, stone slab and sections; 4. barrow 1, lead ring; 5. barrow, lead ring; 6. barrow 3 lead ring; 7. barrow 1 bronze ring; 8. Burial kharyn ar barrow, stone vessel; 9. ceramic vessel; 10. ceramic vessel; 11. barrow 3, ceramic vessel (Adapted from Kovalev 2009, p. 157, fig. 3; Photos courtesy of Alexy Kovalev)

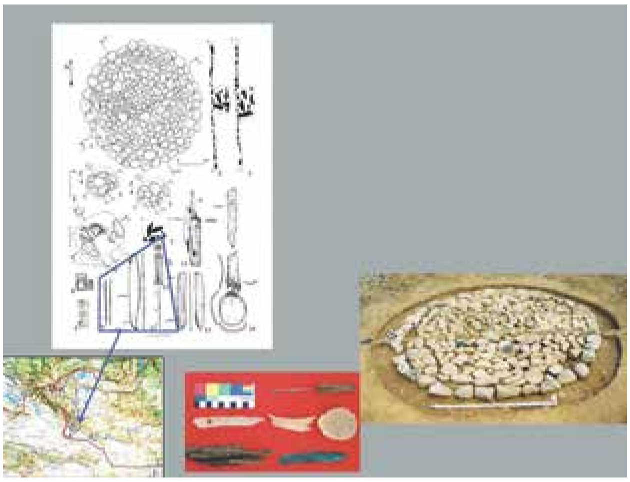

**Figure 7** Munh-Khairhan culture remains, (c. 1800-1500 BCE), Khovd, Zavhan and Hovgsol aimags, Mongolia 1. Ulaan goviin uzuur barrow 1, plan B-B'; 2. section; 3. section C-C'; 4. grave plan of stone vault; 5. stone vault 2; 6. plan; 7. section D-D'; 8. Burial ground Khuh-Khushony-Bom barrow 1, bone head from torque; 9. Tsagan uushig barrow 3, disc-shaped strips; 10. bronze awl; 11. Galbagiin uzuur barrow 2, bronze knife; 12. barrow 1 wood handle from bronze awl; 13. Ulaan goviin uzuur barrow 1 bronze awl; `14 wooden handle from bronze awl; 15. bone scoop (Adapted from Kovalev 2009, p. 162, fig. 4; Photos courtesy of Alexy Kovalev)

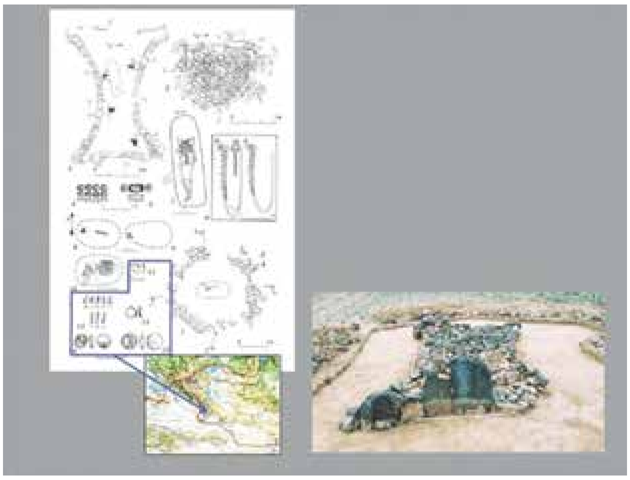

**Figure 8** Tevsh-Baitag culture remains, (c. 1400-900 BCE) 1. Baruun gyalat barrow 2, plan; 2. barrow 2, plan; 3. Samyn buts barrow, plan; 4. Baruun gylat barrow 2, cornelian beads; 6. Tevsh uul gold head ornaments (exc. Volkov); 7. burial ground Uliastain gol III, barrow 7 plan; 8. plan of pit; 9. plan of pit; 10. Kheviin am 1, secondary burial, plan; 11. tip of bronze knife; 12. Uliastain gol III, bronze beads from barrows 7 (above), barrow 3 (below); bronze ring; 14. Bronze button; 15. Bronze button (Adapted from Kovalev 2009, p. 164, fig. 5; Photos courtesy of Alexy Kovalev)

**Table I:** Metal Object Types (listed chronologically by earliest date and archaeological culture name):

| | |
|---|---|
| Knives | Afanasievo, Barrow I, Kurgak govi c. 3000-2500 BCE; Munh-Khairkhan, Galbagiin uzuur (similar to Qijia knife from Linjia, and Seima-Turbino (c. 2000-1600 BCE); Kheviin am I, Bulgan sum, Khovd aimag (bronze knife tip) (c. 1400-1100 BCE) |
| Spiral Rings (lead and bronze) | Chemurchek Khovd aimag, Yagshiin khodoo (c. 2500); Munh-Kairkhan (c. 1800-1600 BCE); Ulaistain gol III—Tevsh-Baitag (c.1400-1100 BCE) (re. Karasuk, Qinghai Zongri M122, Siba) |
| Awls | Chemurchek (c. 2nd half 3rd millennium BCE); Munh-Khairkhan, Galbagiin uzuur (c. 2000-1600 BCE) |
| Earrings (gold 'head ornaments') | Tevsh uul, Bogd sum (c. 1400—1200 BCE) (also gold ring in necklace) sheep head ornaments (called Chaodaogou by Kovalev) |
| Buttons | Ulaistain gol III—Tevsh-Baitag (c.1300-1100 BCE) (one km from Chinese border) |

## Discussion

What is clear, if even in a preliminary way in this cursory review is that metals were being used across the area continuously from the early third through the first millennium BCE (Fig. 9). These finds do not represent a continuous cultural evolution from one culture to another, but rather they document simultaneous use in several places. The diversity of archaeological cultures and the local character of the bronze objects represented in the region does not necessarily argue for a single group as the more technologically sophisticated and as the transmitter of the technology or objects, but only for the adoption of the technology rather than importation of finished goods. It looks like an area in which technologies spread, enabling the production of distinctive, culturally local products that might otherwise escape notice. This distinctiveness of local ways of doing things implies patterning perhaps at the level of practice of rather primitive metallurgical technology, which according to Potts implies a formal extrinsic manifestation of contact (2007, p. 6). This would seem to be a good case, therefore, where 'social fields,' as opposed to 'cultures,' were inextricably connected through some sort of web-like relations in which metallurgical technology was shared and modified by others caught up in the process, as Kohl proposes for western Asia (2008, p. 496).

Moreover, knowledge of the metal-using sites in Mongolia creates a distribution in Eastern Asia and Eastern Eurasia that is wider than previously documented, and thereby implies that there were multiple routes of transmission of metallurgical knowledge throughout eastern Asia, including into present-day China. Both Mei (2009, p. 219-23) and I (Linduff 1995; 2000) have proposed that the range of technology known in sites in western China suggests that experimentation commonly took place at the local level in the third and second millennia. Alternatively, such metal artifacts could have been both produced locally and imported. In Mongolia, although the materials have not been tested, the same pattern of variety appears to hold, at least with regard to type. Moreover, in the far northeast of present-day China, there may have been yet another point of transmission and that has been suggested by Shelach (2009).

And finally, so far these metal objects are found in ritualized settings, in burials, and even in the case of the awls and knives their obvious utilitarian function in the lives of the living was transformed into a ritualized role in death. Moreover, the burials show that there were multiple craft specializations in ceramics, lithics, bone and woodcarving, and metals. In the Mongolian case, metallurgical knowledge would appear to have been adopted as desired across the region and time and the lines of intersection and transmission would seem to have been plural and fluid (Barfield 2009, p. 240). Thus, a much enlarged shared social field or technoscape including eastern Eurasia and northern and western China is more plausible in the third and second millennia BCE than previously thought.


**Figure 9** Map of Mongolia and Northwestern China: Transmission of Metallurgical Technology through Xinjiang, Gansu/Southern and Western Mongolia (Adapted from Mei 2004, p. 217)

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# Hunnic gold in Hungary and the Hunnic-Asian connections[1]

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*ABSTRACT* The Hunnic treasure of Nagyszéksós was found in 1926 in a vineyard just outside Szeged, in the Hungarian County of Csongrád, but it has been only partly seen by the public on the occasion of two exhibitions. In total there are 157 objects, many decorated with precious stone inlays. The hoard is the largest and most important Hunnic treasure in Europe. This paper presents the results of XRF analyses carried out on the different components of the gold objects from Nagyszéksós. The composition of the gold and the manufacturing technique of the pieces allow us to distinguish different traditions and reflect the many populations of the "Hunnic Kingdom".

## Introduction

Around 370 CE, nomadic tribes from Central Asia, known in Europe as the Huns, crossed the River Volga, and defeated and subjugated the Alans and the Goths. In 425 CE the Huns founded a Kingdom in the Pannonian Plain (Hungary), and settled down in the area between Tibiscus/Tisza–Cris/Körös and Maros. From here they attacked the Eastern Roman Empire in Thrace, Cappadocia, Armenia and Syria. After a treaty they became mercenaries of both the Western and the Eastern Roman Empire, and of the Goths, and greatly increased their number by incorporating more ethnic groups such as Gepids, Sarmatians, Scirii and Rugians. During their invasion of Europe they left traces of destruction, but very few remains, because they lived in tent camps. Hunnic objects are found scattered all around Europe, mainly as single finds. The Nagyszéksós treasure represents an exception and is - with its 157 objects of precious metals, and inlaid with precious stones - the largest and richest Hunnic hoard found in Europe. Aim of this paper is the study of the hoard and the distinction of the different metallurgical traditions belonging to the Hunnic Kingdom.

## Xiongnu and Huns, historical background

The earliest mention of the Huns in European classical texts is in the *Periegesis* of Dionysius (*Geographi Graeci Minores*, 730), dated to the 2nd century CE, in which they are listed together with Skythi, Caspii and Alani as tribes living around the Caspian (Müller 1861, 149). His contemporary Claudius Ptolemy (III, 5, 25) mentions them in his *Geographia*, as a Sarmatian population. The previously generally accepted identification between Xiongnu and Huns has been challenged by several scholars, because the Xiongnu spoke a proto-Siberian language never identified in Europe (Vovin 2000), but the names Xiongnu and Huns were used to indicate the same nomadic tribes. For example, in an

[1] This paper was presented at the conference in Bangalore, and intended for publication in the BUMA 7 proceedings, as a foretaste of a more detailed publication to come. As things turned out, the publication of BUMA7 was delayed, and the paper has appeared in the Journal The Silk Road in Dec. 2013. The present paper must serve as an introduction and summation leading to the more detailed paper in which all data, analysis results and histograms are given (Giumlia-Mair 2013), however here more detailed information on Huns and Xiongnu, new bibliography and different photos are presented.

Indian text of 280 CE, only surviving in Chinese and Tibetan translations, the name of the same ethnic group is translated as Xiongnu in Chinese and as Huna in Tibetan (Daffinà 1994, 9-11; Blason Scarel 1996, 16). A further piece of evidence is found in North-West China in the form of a letter sent by a Sogdian merchant to a merchant-prince in Samarkand: Nanai-Vandak informs the noble lord Varzakk, that 2 years earlier (311 CE), Luoyang had been destroyed and Changan had been conquered by the Huns (Daffinà 1994, 11-12). Some Chinese sources also seem to identify the Xiongnu with Huns. The Wei Shu, states that in the 4th c. BCE the Xiongnu defeated the Alanliao (Di Cosmo 2002). In the Han Shu (1938-1955, 19) the Alans are called the Alanliao, a collective name comprising the Aorsi tribes, defeated by the Alans (Zadneprovskiy 1994). Alans and Aorsi are mentioned in classical texts as warlike nomadic tribes in the Aral- and Black Sea regions. In the same area the Huns also defeated and incorporated the Germanic Gepids, Goths and Skires.

The Xiongnu appear in China around the 4th century BCE and are described as nomadic warriors with a complex social structure, who founded an empire in the steppe region of the northern Ordos and in the area to the northwest of the bend of the Yellow River (Fig.1). Xiongnu and Huns have in common the bow, cauldrons, used for funerary rituals and found buried in river banks from the Great Wall to the Black Sea and the Pannonian Plain, diadems worn by women, and so-called nomadic mirrors of a type which originated in China, but was adopted also by Alans, Gepids and Goths (Tomka 1994, 29-34). Even more complex are the links between Huns, Chionites, Hepthalites (White Huns, who attacked the Sasanians), Kidarites (Red Huns, who defeated the Kushans in India), Uar or Avars, Yuehban (Weak Huns, who founded a kingdom in Central Asia, while the "Strong Huns" came to the West), Yanda, Yuezhi, Rouran or Juan-Juan and other ethnic groups mentioned by ancient Greek, Armenian and Chinese sources as separate tribes. They all seem to be connected by customs, religion, habits and material culture, and are difficult to keep apart (Grignaschi 1980; Kradin 2005).

There is also archaeological evidence, in particular numismatic, for the early use of a trade route through the territories of these tribes from the northern Pontic area to Central Asia, China and India, dating back to at least the 2nd century BCE (Mielczarek 1997). The trade route from the Caspian coast to the Sea of Azov, Armenia, Media, "Babylonia" and to India was important and well known in antiquity (Josephus Flavius VII, 7, 4; Jordanes XXXIV, 178; Strabo 23, XI, 8).

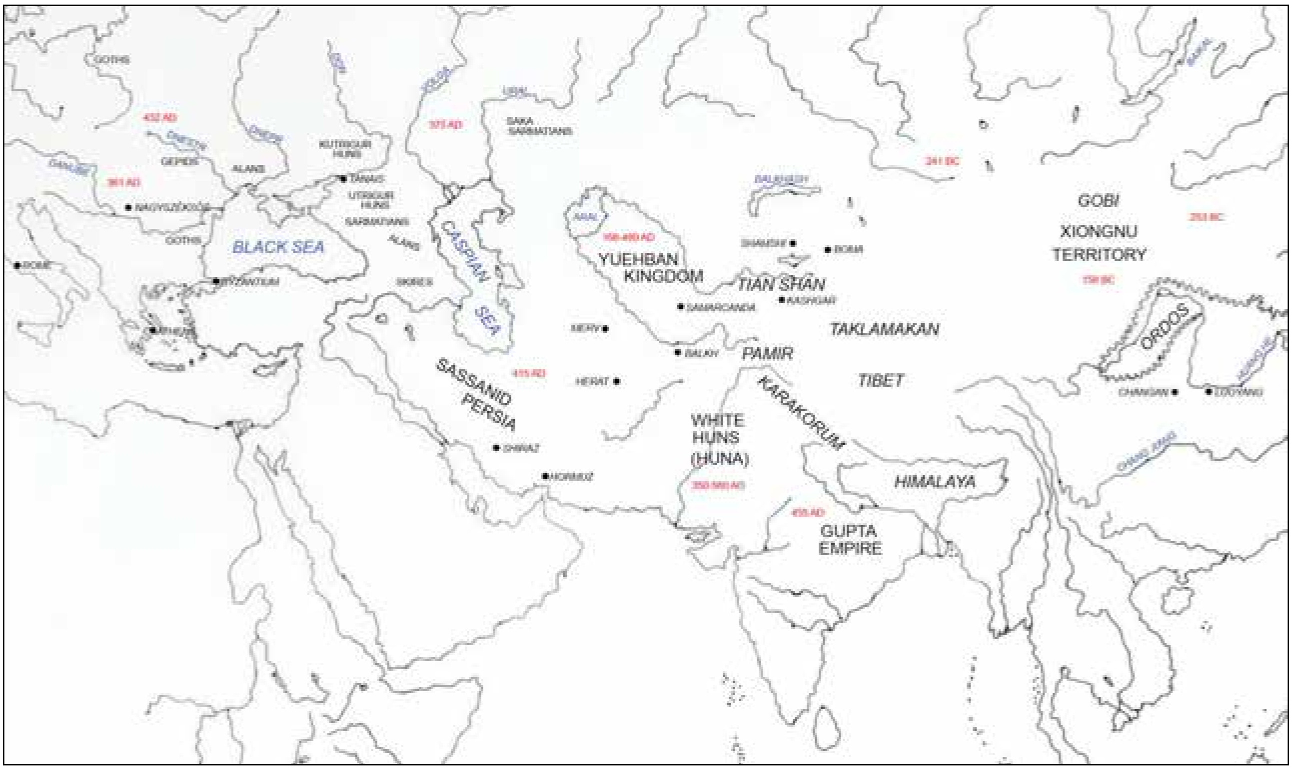


**Figure 1** Map of Eurasia showing the most important areas and places mentioned in the text. The dates indicate when Xiongnu and/or Huns are mentioned in the records in different regions.
(drawing A. Giumlia-Mair)

## The hoard

**Figure 2** Large gold buckle decorated with almandines, dated 400-450 CE, gift of J. Pierpont (17.190.697) in the Metropolitan Museum New York. L.: ca. 6 cm. It looks remarkably similar to the buckle inv.no.05 from Nagyszéksós (see fig.3). (Photo A. Giumlia-Mair)

**Figure 3** Large gold buckle decorated with almandines inv.no.05 from the Nagyszéksós treasure, now in the collections of the Ferenc Móra Museum in Szeged (Hungary) L. ca.8 cm. (Photo B. Kürti)

The complex of Nagyszéksós consists of 157 golden objects and fragments, many of which decorated with precious stones. Among the finds there are also lumps of molten silver. No human remains were identified, but there was a large number of precious gifts which represent the remains of offerings on a funerary pyre, erected for the death of a king (tentatively identified with Oktar/ Uptar) or of a leading member of his family. Uptar and Rua/Ruga were predecessors of Attila, i.e. the finds are dated to around 430 CE (Bóna 1991, 46-60). Funerary pyres and ritual banquets were the prerogative of males of the royal family (Bóna 1991, 149). The objects are most probably only a small part of a much larger hoard. During his emergency excavation, the archaeologist F. Móra discovered that the children of the village had been bartering shiny metal pieces for apples and slices of pumpkin pie for quite a while, and long before the Museum was alerted. Many objects found their way to the international market and are now presumably on display in museums around the world (Bóna 1991, 162, fig.63; 261, n.63). For example in the Metropolitan Museum New York there is a buckle (fig.2), dated 400-450 CE, gift of J. Pierpont (17.190.697) which looks remarkably similar to the buckles from Nagyszéksós. Even if it does not belong to the Nagyszéksós hoard, it cannot have been made very far from the workshop which produced the buckle with the inv.no.05 (fig.3).

## The analysis

As no invasive sampling was allowed, over 300 non-destructive XRF analyses and 290 microscope examinations were carried out on the different parts of the 157 objects of the hoard. The surface is not representative of the whole object, and the most common problem with gold alloys is that silver and copper can be underestimated, because of corrosion and oxidation. The only way to avoid misleading results is the abrasion of the surface, but here this was obviously not possible. However the Nagyszéksós hoard found several decades ago, has been repeatedly and thoroughly cleaned, and it has been mostly possible to identify spots suitable for analysis. Contamination with molten silver from objects destroyed on the funerary pyre could also be avoided by examining the surface with the microscope. In a few cases only, with burnt objects, the results were unsatisfactory even after repeating the measurements several times on different areas, and have been omitted.

## Discussion of analysis results

The aim of this research was the identification of the alloys and the determination of the manufacturing techniques. The results made it possible to group the objects into different clusters, according to composition and technique, and in several cases, to distinguish the various metallurgical traditions to which they belong. Among the gold pieces, there were also silver objects which, having a lower melting point, were destroyed by the fire of the pyre. The molten silver dripped on to the gold and the silver layer was often so thin that it could be distinguished only by microscopy. During the second analytical campaign, carried out in March 2010 to complete the study, a large number of measurements were repeated after a detailed microscopic examination, so as to obtain more precise results. The complete study has been published in the journal The Silk Road (Giumlia-Mair 2013) while here only an overview of the results is given.

Silver remains are abundant both as droplets on the gold objects and as shapeless silver lumps. Some of it comes from molten rivets. In other cases larger lumps are intermingled with gold sheets. On the pyre there were clearly gold decorated silver objects, but

**Figure 5** Heavy buckles and plates decorated with almandines and beaded wire imitation, are considered typical Hunnic and are made of almost pure gold. They might have been made by melting down the Roman coins of similar purity received as *tributus* by Ruga and Uptar. (Photo A. Giumlia-Mair)

**Figure 6** Gold alloys with 3-6% Ag 0.5-2% Cu have been used for objects with a very distinctive cloisonné decoration, considered typical for Germanic tribes, allies of the Huns: Visigoths, Heruls, Gepides, Langobards, Burgundians, Franks, Suebians, Vandals and Alamans. (Photo A. Giumlia-Mair)

regrettably none can be recognized. It is difficult to determine the silver composition as most of the remains have a high gold content which comes from the gilding. However the largest lump of silver (inv.no.75) and the silver remains in the bowl (inv.no.162, Nemzeti Mus. Budapest) have a low gold content and give an idea of the original composition as in both cases the silver contains 15-20 % of copper. In antiquity this kind of silver alloy was commonly used for objects with practical functions, such as vessels, boxes and mirrors (Pike et al. 1997; Lang et al. 1984; Lang and Hughes 1985; Bachmann 1993; Giumlia-Mair 1998; 2000) We can hypothesize that small luxury objects - vessels or perhaps large fibulae - were present in the hoard.

**Figure 4** The heavy gold buckle inv.no.02 from Nagyszéksós is one of the objects with the lowest Ag and Cu contents in the hoard (less than 1%). It belonged most probably to the royal horse fittings. W. 7 cm, L. of pin 8.3 cm. (Photo A. Giumlia-Mair)

The lowest silver and copper contents (less than 1%) in the gold objects were found in the torques (inv. no.01), the heavy gold buckle (inv.no.02; fig.4) and in the many fragments of decorated sheets (inv. nos. 76-144). The gold sheets show a thickness of around 0.05 mm, therefore the high purity would not have been necessary, but of course the high purity allowed it to be more easily hammered. The soft gold makes the heavy buckles and torques prone to scratches and is not functional. The only reason for the alloy choice seems to be the wish of having a beautiful golden colour. The sheets were used to cover the handles of daggers and for the visible parts of ceremonial saddles, while the heavy gold buckles probably belong to the royal horse fittings. These ceremonial objects (Fig.5), belonging to the king, are considered typical Hunnic and are made of almost pure gold. It is well known that the Romans paid every year a *tributus* of 160 kg of gold coins to Ruga. Later, at the time of Attila, the *tributus* became as large as 300 kg of gold *solidi,* the coins introduced by Constantine in 310 CE to replace the *aurei*. In 368 the fineness of the *solidi* was increased from 95% (the fineness of the earlier *aurei*) to 99% (Johns 2010). The almost pure gold of the torques, the large buckles and most of the gold sheet, might indeed have come from melting down the Roman coins received by Ruga and Uptar.

A different class of gold alloys, with a silver content between 3 and 6% and a copper content from under 1 to around 2 %, was utilized for a group of objects with a very distinctive cloisonné decoration: buckles, fittings with gold rivets, mostly without beaded wire on the stone mounts (for example 07; 08; 11; 2-14; 30-33; Fig.6 and 7) and the roundel of a bowl (inv.no.69). The colour is similar to that of pure gold, as the low silver content is counterbalanced by the low copper percentage, but the alloy is more wear-resistant. In some cases patterned gold sheets were used as backing for the flat cut garnets, for example in the cicada-shaped fitting (inv.no.30; Fig.7). This kind of cloisonné is typical of Germanic tribes, several of which - Visigoths, Heruls, Gepides, Langobards, Burgundians, Franks, Suebians, Vandals and Alamans - were first subjects and then allies of the Huns (Bóna 1988, 119-121; 1991; Zasetskaya 2007; Menghin 2007). Some of these tribes fled from the Huns and, between 378 and 406, invaded the Western Roman Empire, eventually provoking its fall.

**Figure 7** The "Germanic" cloisonné objects are decorated with almandines and finely worked beaded wire. Patterned gold sheets were used as backing for the flat cut stones. The rivets are made of gold. (Photo A. Giumlia-Mair)

Among the cloisonné items there is also a group of objects made of different gold alloys, with higher contents of alloying elements and different manufacturing techniques. In one set the silver is as much as 8% with copper additions of around 6%. The alloys for the rivets contain more copper (around 10%). In a second set - consisting of horse fittings with round garnets (Fig.8) and cloisonné studs with crescent-shaped garnets - the silver content goes up to 20 %, and the copper up to 14%. For one set of larger trefoil-shaped ornaments and flat garnets, some brass was added to the gold instead of copper. These alloys are harder and it is possible that these fittings were not just used for ceremonies. The

**Figure 8** In horse fittings with round garnets the Ag content goes up to 20 %, and the Cu up to 14%. The rivets with flat heads are made of silver with about 20% Cu and also had the function of backing for the garnets. The irregular composition with a wide range (4 - 30% Ag; 0,5 – 5% Cu) is similar to that of gold objects from Crimea. The large fitting with 4 round garnets is ca.6 cm wide. (Photo A. Giumlia-Mair)

**Figure 9** The plates with protruding stones (inv.nos. 21-24) are of Au with 3% Ag and 2% Cu. The sheets are framed by beaded wire imitation. Different stones have been used, e.g. the cut central plate (inv.no.22) shows a garnet, a red stone with inclusions or red glass, and a purple stone, i.e. a garnet or an amethyst. These plates belong to the Hunnic tradition and their technique is similar to that of the diadems worn by women. The largest plate is ca. 8 cm long. (Photo A. Giumlia-Mair)

rivets are not made of gold, but of silver with about 20% copper. The flattened rivet head also had the function of backing for the garnets. The ornaments are carefully worked and show excellent workmanship, and their technology suggests that they belong to a different metallurgical tradition. No Germanic or Gothic gold objects dated to this period or from this area have been analysed, and in general very little analytical work has been done on any kind of materials dated to the first half of the 5th century CE, so that no comparison is available. However the silver and copper content of some gold objects from Crimea (La Niece and Cowell 2008, 154-155, tab.1 and 2), seem to be more similar to that of this group of finds, with irregular percentages of alloying elements and a wide range (4 - 30% Ag; 0,5 – 5% Cu).

The decorative plates (fig. 9) with elongated stones (inv.nos. 21-24) are made of a rather pure gold alloy with around 3 % silver and 2 % copper. They are framed by an imitation of beaded wire. Differently coloured stones have been used. For example one plate (inv.no.22) shows a dark garnet, a red stone with inclusions or bubbles (garnet or red glass) and a violet stone (garnet or possibly amethyst). Decorative plates with protruding stones are considered typical for the Hunnic tradition and are similar to those of the diadems of Hunnic women (Bóna 1991, 147-149). Such plates can be applied as decoration on saddles, horse fittings, weapons or representative belts, and it is impossible to attribute them to a particular object. The gold ornaments of Hunnic wooden bowls (inv. nos.71-73 and 157) have similar compositions with around 7 % silver and 2% copper. The fragmentary bowl from Nagyszéksós inv. no.81.1.2, Nemzeti Museum Budapest, is also made of an alloy with 10 % silver and only traces of copper, like the typical Hunnic objects described above, with their very low percentages of copper and varying silver content.

Plates (fig.10) with round or oval cabochon stones (inv.nos.41-42; 54-68), used as ornaments for a saddle and for horse fittings, are considered typical Alanic ornaments. Alans were, like Sarmatians, a population of Iranian language (Alemany 2000), perhaps originating from the Aral region. When defeated by the Huns, they moved to the Caucasus or joined the nomadic Hunnic warriors and fought at their side, as valued archers and riders. The gold alloys employed for these pieces contain 6-7% of silver and only very little copper, mostly under 1%. The stones have been damaged on the pyre, but the less altered seem to be chalcedonies with a bluish or white colour. The only one in good condition is a rock crystal. A few of the stones are framed by an imitation of beaded wire. The very low copper content suggests that it was in the gold as an impurity and that only silver was added or perhaps that the gold was diluted with a silver alloy with a relatively high copper content. The 23 pyramidal sequins (inv.nos.21.29 a-z; fig.11) are also considered typical Alanic decorations [Bóna 1991, 162-166; Anke et al. 2008, 19-20]. They were originally sewn on thin fabric. Nine pieces have been analysed and are made of the same gold alloy with 9% silver and 3 % copper. They must have been obtained from the same metal sheet, struck with a die to produce the pyramidal shape and the decorated rims. The sequins and horse fittings, show a relatively high silver content but are very low in copper. This composition might be distinctive and indicative for Alanic gold items, but this hypothesis would have to be confirmed by more analyses of Alanic objects.

**Figure 10** Ornaments with round or oval chalcedony cabochons, sometimes with beaded wire imitation, are considered Alanic and were probably applied on saddles and horse fittings. The gold contains 6-7% Ag. Cu is mostly under 1% and seems to be typical for Alanic objects. (Photo A. Giumlia-Mair)

The gold cup (inv.no.81.1.1; fig.12) in the Nemzeti Museum Budapest, contains around 11% silver and only around 3% copper. The bowl of the cup was cast by the lost wax technique, with the internal part of the sockets for the stones showing the marks left by a warm tool on the wax. Bóna interpreted the cup from Nagyszéksós as an object of Iranian origin and compared it with almost identical contemporary Iranian glass cups. One is in the Museo Nazionale d'Arte Orientale in Rome (inv.no. 2705, Bóna 1991, 168, fig. 64; 261, n.64). A second was found in a grave dated to the Northern Zhou Dynasty in China, at Li Xian, Hopei (An 1986/2, 173-181, fig.1, tab.1-2), and a third, dated to the 4th century CE was published by von Saldern in Washington (1963, 12).

An analogous mount and technique are found on the "pectoral" hanging from a gold torques from a Hunnic grave at Wiesbaden which looks like the lid of a small box or an element of a bracelet adapted as a pendant (Bernhard 2007, 124). On the back it shows the name Artachshatar, (or Ardashir I, Lat. Artaxerses), founder of the Sasanian Dynasty who, at the time of Alexander Severus (222-235 CE) attacked Mesopotamia, Syria and Cappadocia (*Hist. Aug., Alexander Severus*, LV). Apparently this piece had been looted and re-used as pectoral, most probably by a socially prominent Hunnic warrior. The Iranian name on an object with a construction similar to that of the cup of Nagyszéksós seems to confirm the Iranian origin of both the vessel and its decorative technique.

**Figure 11** The 23 pyramidal sequins belong to the Alanic tradition and were originally sewn on thin fabric. They are all of the same Au alloy with 9% Ag and 3 % Cu. The gold sheet was struck with a die to produce the pyramidal shape and the decorated rims. H.: ca. 1,5 cm. (Photo A. Giumlia-Mair)

**Figure 12** Gold cup from Nagyszéksós, inv.no.81.1., Nemzeti Museum Budapest. H.: ca. 9 cm. The Au alloy contains 11% Ag and 3% Cu. The cup is a lost wax casting. The interior of the stone sockets shows the marks left on the wax by a warm tool. (Photo A. Giumlia-Mair)

## The Huns and their Asian connections

The two garnet decorated gold vessels and a gold mask with garnet inlays (Koch 2007) excavated at Boma in Xinjiang, are reminiscent of some of the Nagyszéksós finds. The cells on the vessels from Boma are similar to that of the central rosette of the Nagyszéksós bowl and the shape and the stone settings are similar to that of the cup, while the cells of the moustache and eyebrows on the mask look like the cells of the cicada-shaped finials (inv.nos.17-20) from Nagyszéksós. The crescent-shaped garnets depicting the beard of the mask are similar to those of the studs inv.no.52-53, however the mount of the Boma garnets is of much better quality, with the cells of the crescent stones surrounded by granulation. Lin Ying (2008) discussed in detail the "Western" characteristics of the finds from Boma, and interpreted them as objects produced in the Turkic Empire of Central Asia. She stated that these populations "transmitted material and cultural achievements between East and West, but also combined in their own distinct culture the elements of different civilizations" such as the Byzantine, Iranian, Indian and Chinese (Lin 2008, 25). The researches by Périn et al. (2006) have shown that the vast majority of archaeological garnets in the 5$^{th}$-7$^{th}$ centuries CE, comes from the metamorphic belts in Rajasthan and from the East coast of India. Only a few come from Ceylon as do most of the garnets in Roman times. Pyropes from Eastern Europe have only been employed after the 7$^{th}$ century CE. The large amount of garnets on Hunnic gold, but also on the jewellery of the populations from the Sarmatic Plain, the Aral region and the Caucasus, such as Alans, Goths, Merovingians, etc. makes one wonder, if these stones did not arrive to Europe through land trade, i.e. over the ancient mountain routes through Xinjiang, Ferghana, Bactria or Parthia (Giumlia-Mair et al. 2009, 40-41).

Gold coins of the Indian king Kumaragupta (414-455 CE), of the Sasanian Shah Varakhran V (420-438) and of the Kushan Shah Kidara (425-430) have been found near the *ordu*, i.e. the king's camp in the Pannonian Plain. Many languages were spoken in the Hunnic Kingdom and the names of the warriors are Hunnic, Germanic, Latin, Iranian etc. (Mänchen-Helfen 1973, 382) All these elements seem to confirm the wide connections and the links between the "Huns" from Central Europe, to Central Asia and to their various Asian kingdoms. The different metallurgical traditions shown by the finds from Nagyszéksós in Hungary reflect the multiple ethnicities of the "Hunnic Kingdom".

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# Khao Sam Kaeo - an archaeometallurgical crossroads for Trans-Asiatic technological traditions

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*ABSTRACT* Recent archaeological investigations at Khao Sam Kaeo, on the Upper Thai-Malay Peninsula, have furnished evidence for a mid/late 1st millennium BC cultural exchange network stretching from the Indian subcontinent to Taiwan. Typological, compositional and technological study of Khao Sam Kaeo's copper-base artefacts has identified three distinct copper-alloy metallurgical traditions, with reasonable analogies in South Asian, Vietnamese, and Western Han material culture. Furthermore, analyses of technical ceramic and slag suggest that Khao Sam Kaeo metalworkers may have been using a cassiterite cementation process to produce high-tin bronze ingots for export or onsite casting/forging. Not only would this industry constitute the earliest evidence for the exploitation of Peninsula tin resources, but we also offer a speculative argument for the source of Khao Sam Kaeo's copper-base production technology.

## Introduction

Whilst cultural transmissions across the Bay of Bengal from the mid-1st millennium AD are undisputed 'facts' of Southeast Asia's past, the prehistory of these interactions is an ascendant field of enquiry (e.g. Bellina 2007, Bellina and Glover 2004, Bellina and Silapanth 2008, Glover 1990, Rispoli 2005). Some scholars (e.g. De Casparis 1983) had posited that the trans-Asiatic encounters responsible for the florescence of Southeast Asia's historical polities must have had antecedents for which we lack textual evidence, but it was Ian Glover (1983, 1990a, 1990b) who first attempted an account of prehistoric regional relations with the subcontinent; largely derived from his excavations in west-central Thailand at Ban Don Ta Phet. Finds of what were thought to be characteristically South Asian agate, carnelian, and glass ornaments (Glover 1996), as well as high-tin bronze bowls (Bellina 1999, Bennett and Glover 1992, Rajpitak and Seeley 1979) supported the argument that the 'indianisation' phenomenon could have been underway by the mid-1st millennium BC (e.g. Bellina 2001, 2007, Bellina and Glover 2004, Bellina and Silapanth 2008, Glover 1990b, Srinivasan 1998).

It was formerly assumed that prehistoric material culture with South Asian attributes were simply sporadic imports from South Asia, and that Southeast Asian social groups unquestioningly adopted their 'Indian' materiality (Martinón-Torres and Rehren 2009, Miller 2005, Taylor 2008), but subsequent research has enriched our appreciation of the social significance and multilateralism of so-called 'indianisation' processes (e.g. Bellina 2007, Bellina and Glover 2004). Technological analysis of carnelian and agate ornaments from across South and Southeast Asia (founded upon an ethnoarchaeological study of a hard-stone bead industry with reasonable historical continuity in Khambhat, Gujarat, India: see Roux 2000, Roux *et al.* 1995) resulted in the identification of artefacts from mid/late 1st millennium BC contexts in Thailand, Vietnam, and as far as the Tabon Caves in the Philippines, all bearing stigmata of highly skilled South Asian production techniques (Bellina 2001, 2003, 2007). Critically, the realisation that ornaments with distinctly Southeast Asian typologies had been formed by complex 'Indian' techniques suggested that trans-Asiatic flows of cultural information had been multi-directional, and that South Asian, or South Asian-trained, artisans adapted their production to fulfill Southeast Asian demand - within the latter's aesthetic/ideological repertoire (Bellina 2001, 2003, 2007). The traditional unilateralist perspective of 'indianisation' was further upset by the recognition of production debris at Khao Sam Kaeo (hereafter 'KSK') on the Upper Thai-Malay Peninsula. The ethnoarchaeological data (Roux 2000, Roux *et al.* 1995) strongly suggest that such highly specialized hard-stone knapping and polishing skills would require lengthy apprenticeships to master. This leaves two scenarios: either Southeast Asians were trained on the subcontinent for extended periods or, as Bellina (2001) proposed, small numbers of South Asian artisans may have settled at KSK, arguably to better respond to Southeast Asian desire for high quality ornaments conveying or emphasising elevated social status.

Not only did this study extend the sphere of prehistoric subcontinental cultural influence from the Thai-Malay Peninsula far into the South China Sea, it both overlapped and supported previous proposals (e.g. Bellwood 1984-5, 1985, 1991, Bellwood *et al.* 1995, Solheim 1961a,b, 1966, 1984, 1988, 2000, 2006) for 'Austronesian groups' circulation and/or exchange networks (Fig. 1). Recent compositional studies suggesting that Fengtian (Taiwan) nephrite roughouts and finished artefacts were also circulating from east to west, as far as peninsular Thailand at least,

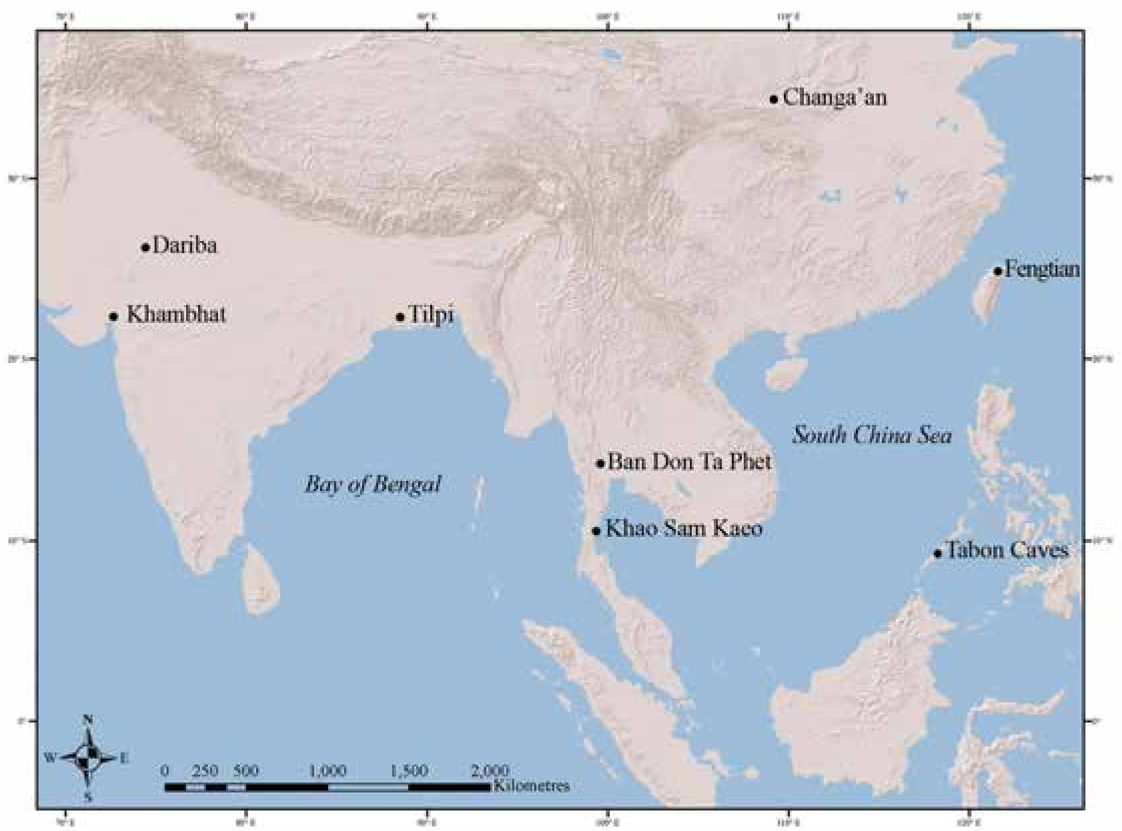


**Figure 1** Relief map of the Bay of Bengal and South China Sea theatre of prehistoric maritime exchange, with major sites mentioned in the text – 'Khambhat' is the location of Roux's (1995) ethnoarchaeological hard-stone bead study and 'Chang'an' (now Xi'an) was the capital of the Western Han empire; these locales are shown to show the potential extent of trans-Asiatic interactions. Courtesy of ESRI, elevation data derived from SRTM.

further highlights the reciprocity of material and social exchanges around the South China Sea (Bellina and Silapanth 2008, Hung *et al.* 2007); and the latest data (expanded upon below) would now incorporate Western Han Chinese interactions over the same geographical range at the turn of the 1st millennium BC/AD (Bellina & Silapanth 2008, Pryce *et al.* 2008: 304-305 ). Thus, the combined data indicate a segmented but interlocking trans-Asiatic sphere of prehistoric maritime interaction spanning in excess of 5000km.

Located at the narrowest point of the northern Thai-Malay Peninsula, the Kra Isthmus, the settlement and industrial centre of KSK constituted a physical and cultural crossroads between the Andaman Sea and the Gulf of Thailand from the 4th century BC to the 1st century AD (Fig. 2). An overland route via broadly contemporary west coast sites like Phu Khao Thong and Ban Kluai Nok with South Asian-related material culture potentially saving over a thousand kilometres of maritime passage via the Strait of Melaka (cf. Bellina and Silapanth 2008: 262-263, Jacq-Hergoualc'h 2002: 83). The site covers c. 50 hectares over four hills on the eastern bank of the Tha Thapao River, c. 8km upstream from the present shoreline of the Gulf of Siam (Fig. 3). The heavy erosion of a dynamic monsoon environment and the ravages of modern looting ensure that KSK's stratigraphy is a frequent source of headaches, but survey and excavation

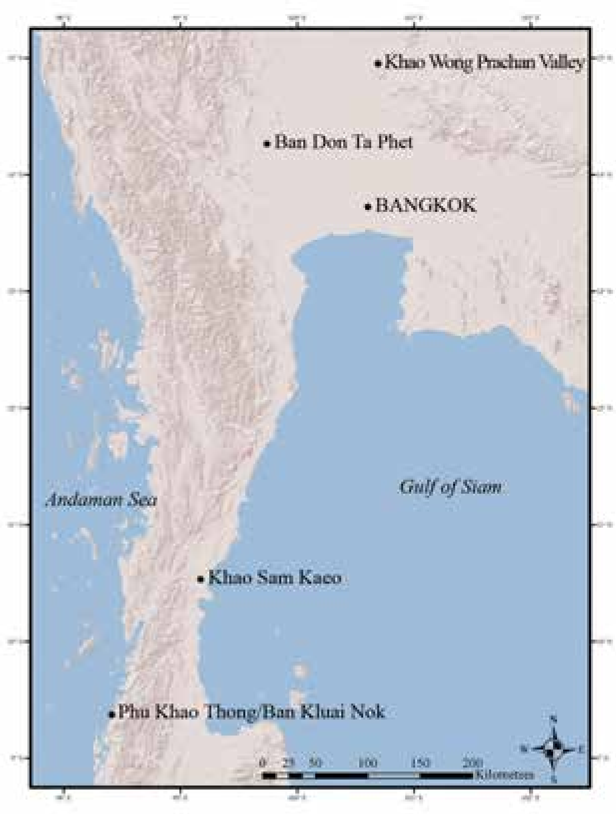


**Figure 2** Relief map of the Upper Thai-Malay Peninsula and central Thailand, with major sites mentioned in the text. Courtesy of ESRI, elevation data derived from SRTM

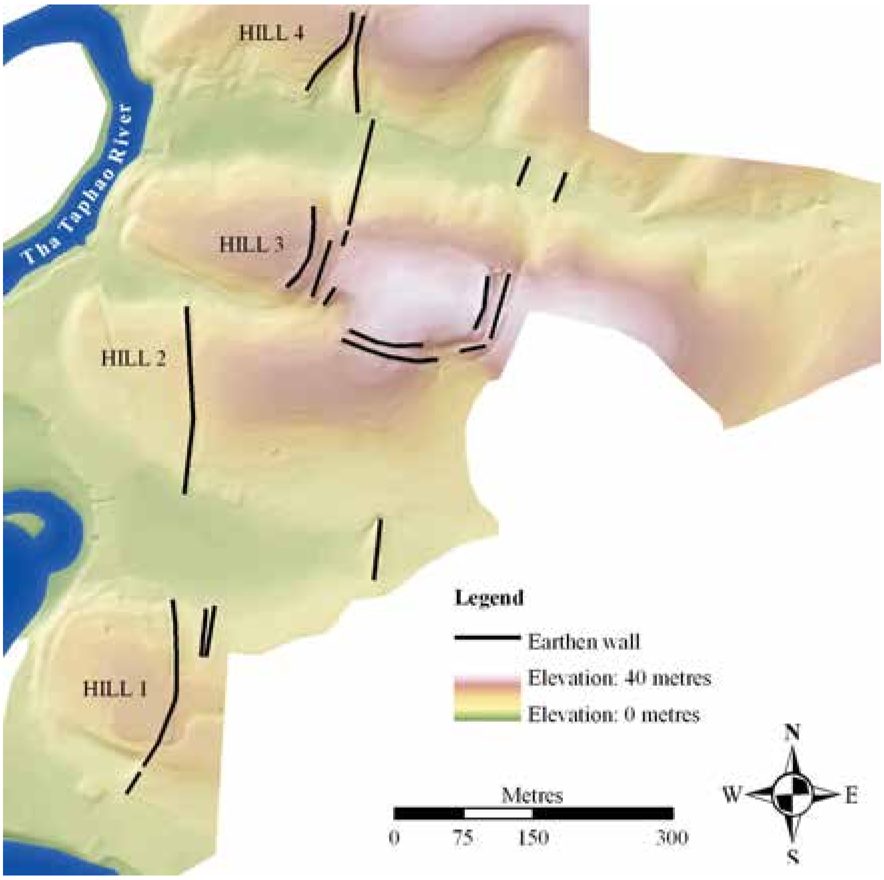


**Figure 3** 3D relief map of Khao Sam Kaeo, with defensive and hydraulic earthworks marked. Courtesy of Julie Malakie, elevation data produced by Vincent Bernard (both of Khao Sam Kaeo Archaeological Mission)

since 2002 have discerned coherent evidence for earthworks, occupation, and industrial activities; with archaeobotanical and palaeoenvironmental studies ongoing. The distribution of hard-stone, glass, and metal working debris at KSK appears to indicate the presence of craft production quarters, with metallurgical ceramics and slags concentrated on and around Hill 3 (Fig. 3). These quarters could relate to ethnic as well as artisanal identities (Bellina 2008: 265); a hypothesis supported by a recent GIS analysis demonstrating artefact patterning to be statistically significant (Malakie 2008). Over the decade since the idea of 'limited South Asian artisan migration' was first aired, KSK's multiple strands of technological and anthropogenic landscape evidence have contributed to the ongoing rebuttal of 'indianisation' as a foreign imposition by emphasising the selective adoption and adaptation of exogenous material culture and materialities by Southeast Asian social groups actively involved in local, regional, and inter-regional economic and/or political relations (Bellina 2008).

Where does metallurgy fit within the developing KSK narrative? Concentrating on KSK's copper-alloy consumption evidence, typological and macro-technological study have identified reasonable analogies in South Asia, Vietnam and Han China; seemingly indicative of the site's metallurgical cosmopolitanism (Pryce *et al.* 2008: 300-306), and complementary to the long available Ban Don Ta Phet evidence (e.g. Rajpitak and Seeley 1979). The bulk of the present paper relates to the supplementation of these preliminary KSK data with compositional and microstructural analyses, and the correlation of these results with the archaeometallurgical literature available from South and East Asia, and other areas of Southeast Asia. We argue that the KSK data constitute a robust, though partially contingent, classificatory triangulation, demonstrating the presence of three distinct copper-alloy metallurgical traditions onsite, and thus reinforcing the Peninsula's role as a cultural crossroads. But what of the production evidence? Mirroring the stone ornament industries, were the metallurgical products also aimed at feeding trans-Asiatic exchange networks?

Of course, for the Thai-Malay Peninsula, a long-term interest has been the history of the region's formerly vast tin reserves (Bellwood 2007: 277, Bronson 1977, 1992, Jacq-Hergoualc'h 2002: 43, 45, 66, 195, Pryce *et al.* 2008: 306). Unfortunately, the destructive nature of 19$^{th}$/20$^{th}$ centuries mining and smelting techniques, the sluicing of ores and the meticulous crushing and re-smelting of slags, including ancient ones, dictates that the Peninsula's metallurgical past will remain hazy. Nevertheless, we present tentative evidence suggesting that KSK metalworkers were producing high-tin bronze ingots for export and/or onsite casting/forging. We also contend that this copper-base technology has its closest analogies in South Asia, with potential ramifications for the ethnic and political structure of the settlement.

The present study had two main objectives: 1. To identify and document intersections between KSK metal artefacts' stylistic, compositional, and manufacturing characteristics. 2. To investigate what kind of metallurgical production activities were being carried out at KSK. To achieve the first objective we studied metallic artefacts with three different stylistic influences: Southeast, South, and East Asian; and for the second objective we examined samples of slag and technical ceramic.

## Methodology

A stratigraphic sampling strategy of KSK's metallurgical assemblage (metal, slag, and technical ceramic) provided material for analytical study, which was carried out at the UCL Institute of Archaeology's Wolfson Archaeological Science Laboratories. The bulk chemical composition of the technical ceramics was analysed by polarising energy dispersive X-ray fluorescence ([P]ED-XRF) using a Spectro X-Lab Pro-2000 (Tq-0261a algorithm). The results are qualitative due to the scanning of unprepared surfaces without a vacuum, but permitted the sub-sampling of technical ceramics with high metal contents, then mounted in resin and polished to 0.25µm.

Optical microscopy under both plane polarised light (PPL) and cross polarised light (XPL) was used to identify areas of interest for further analyses by scanning electron microscopy with energy dispersive spectrometry (SEM-EDS), performed with a Philips XL30. The SEM-EDS system used an accelerating voltage of 20kV, a working distance of 10mm, a spot size of 5.3, and a process time 5, corresponding to a deadtime of c. 30%. The data was processed by INCA Oxford spectrometer software, outputting data as elements for metal samples, and adding oxygen by stoichiometry in ceramics and slag. Ceramic chemical compositions are quantified from 8-10 analyses of an approximate area of 600x400 µm incorporating the smallest inclusions and trying to avoid larger ones.

As the detection limit of the SEM-EDS unit was c. 0.5wt%, wavelength dispersive electron probe micro analysis (EPMA) was carried out to measure minor and trace elements. A JEOL JXA-8100 electron probe microanalyser was used, with an accelerating voltage of 20kV and a 1000 magnification corresponding to an area of 151x88µm. Chemical compositions given are the average of 10 area analyses per sample. The standard Bronze IPT 10A, Certified Reference Material Nº 0683 from MBH® Analytical Ltd., was used to monitor the reliability of the analyses. Metallographic examinations were carried out on metal artefacts after the chemical analyses, using an alcoholic ferric chloride etchant solution and an etching time of 3 seconds, following Scott (1991: 72).

## Metal Artefacts

All 36 copper-base artefacts recovered at KSK were ornamental rather than utilitarian and had distinct stylistic influences (Pryce *et al.*). From this group we selected 10 trying to have a representative sample of typological variation (Fig. 4):

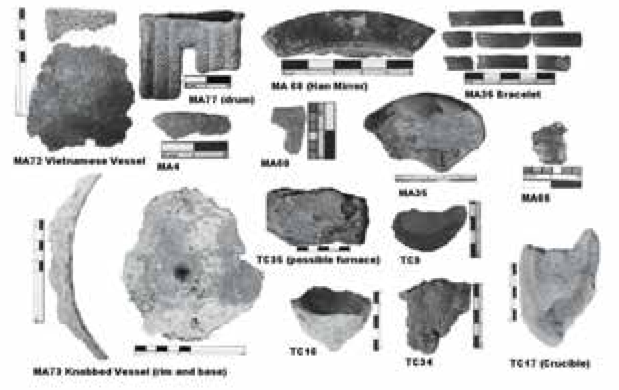


**Figure 4** Assemblage studied

-MA73, is a knobbed vessel with concentric circles around the central cone. These kind of vessels have been documented in metal, ceramic, and stone from the 3rd/2nd centuries BC on the Indian Subcontinent (Bellina and Glover 2004, Singh and Chattopadhyay 2003) and have parallels with those found at Ban Don Ta Phet (Bennett and Glover 1992, Rajpitak 1983), Khao Kwark in Ratchaburi Province, several sites in Lopburi Province (Pigott *et al*. 1992), as well as the Dong Son region of northern Vietnam (Bellina and Glover 2004).

-MA72 is a decorated vessel whose cast geometrical motifs echo those found on North Vietnamese Dong Son artefacts (Pryce *et al.* 2008). Similar decorated bowls have been recovered at Ban Don Ta Phet (Bennett & Glover 1992, Rajpitak 1983, Rajpitak and Seeley 1979). From now on, we may call MA72 "Dong Son related vessel" to denote its stylistic influence, but not necessarily its provenance.

- MA77 appears to be the handle of a Dong Son drum. Supposed to have a north Vietnamese or South Chinese origin those drums have been widely discovered across insular and mainland Southeast Asia and Southern China (e.g. Bellwood 2007, Bennett 2008, Bernet Kempers 1988, Calò 2009, Cooler 1996, Imamura 1993, Pirazzoli-T'serstevens 1979, Sørensen 1976, 1979, 1988, 1990, 1997, Srisuchat 1993). Three drums were discovered at KSK in 1970 and two are now exhibited in the Chumphon National Museum.

-MA68, a fragment of a Western Han mirror provides the East Asian connection. Typically dated 206 BC - 9 AD, other Western Han mirrors have been found in central and southern Vietnam, but this is the first reported from peninsular Thailand (Pryce *et al.* 2008). The typical alloy for casting these mirrors is the ternary Sn-Cu-Pb alloy with around 22-23 wt% Sn (Guiver *et al.* 1996-1997, Mei 2000, Wang 2002).

-MA35 is a thin fragment of either a vessel or, due to its morphology and composition (a ternary Sn-Cu-Pb alloy), a bell similar to those exhibited in the Sirindhorn Anthropology Center in Bangkok.

-MA36 is a fragmentary bracelet decorated with 5 deep parallel grooves. Under the naked eye, some polishing marks or what could be engraving or drawing lines were observed.

Three other indeterminate objects were analysed, MA4, MA 60 and MA66, which were thin fragments with incised decoration based on lines and small circles. Finally, we also selected MA78, a possible copper-base ingot that fits snugly within the 'nippled' technical ceramic vessels (see Fig. 5).

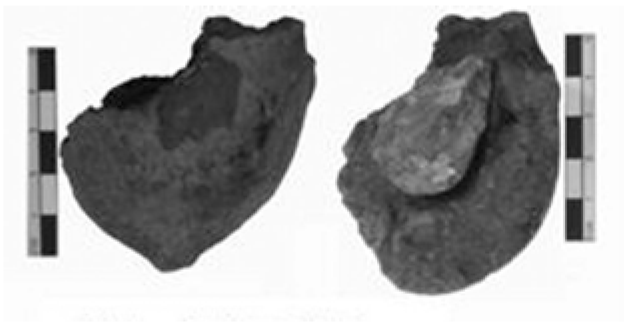

**Figure 5** Ingot mould from KSK with a high-tin bronze ingot inside

We analysed both working techniques and chemical composition to assess the homogeneity of the assemblage, potential correlations between alloys and types or influences, and possible different provenances on the basis of their trace elements.

The first attribute of the chemical dataset that draws attention is the relatively high tin content, which varies between 7.5 and 24.9 wt%, typically staying above 10 wt%.Lead contents vary widely from undetected to 12 wt%. Possibly as a result of the heavily alloyed nature of the artefacts, we cannot discriminate chemical groups on the basis of their impurities, as their relative proportions may be too distorted through dilution and mixing of signatures of different metals. Two groups could be distinguished. The similarity between them was higher than 80%, the differences deriving from alloying constituents more than from impurities. Only one artefact (MA 35), containing 2 wt% of antimony, clearly stands out, whereas all the other samples show virtually no impurities at levels above 0.5 wt% . However, two groups might be differentiated on the basis of As, Ni and Ag traces: one group with silver impurities (MA 78, 68, 72 and 36) and another one with As and Ni impurities, which always appear together (MA 60, 73 and 78). Nevertheless, definitive correlations between compositional, stylistic, and technological data cannot yet be made, but forthcoming lead isotope analyses may help to resolve provenance issues[1]. Two groups were defined on the basis of working techniques and correlated with the alloys chosen to produce them: objects with lower tin contents were typically left as cast, whereas high-tin bronzes were invariably hot-worked and quenched (with the exception of the ingot). These and other aspects are detailed below.

*'Standard' tin bronzes*

There is only one unleaded 'standard' bronze (~15 wt% Sn), MA72 (the decorated vessel with possible Vietnamese influence). This artefact exhibits a cored dendritic structure, indicative of casting followed by fast cooling and an eutectoid inter-metallic solution composed by α and δ layers (Fig. 6). Grey segregates of copper sulphide can be seen at higher magnification (Fig. 7).

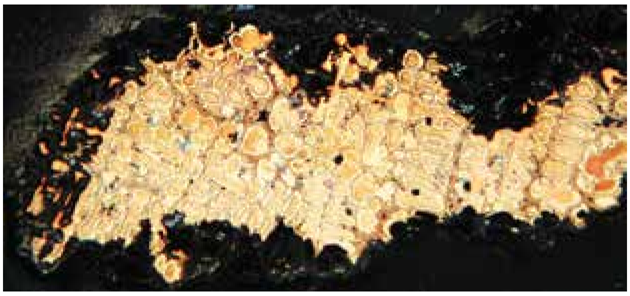

**Figure 6** Microstructure of the Vietnamese vessel. Width of field c. 2mm. Plane polarised. Note the core dendrites

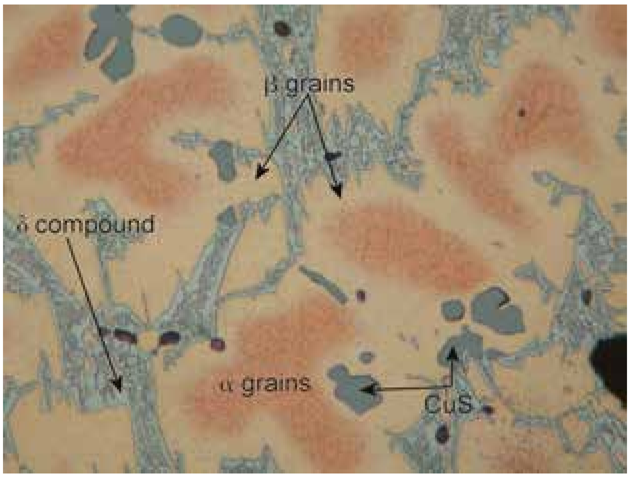


**Figure 7** Detail of the Vietnamese vessel. Etched. Width of field c. 0.2mm. Plane polarised. Note core dendrites, chalcocite and the eutectoid δ compound

*High-tin bronzes*

With the exception of the ingot (MA78), all the high tin bronzes were cast, hot worked, and quenched. The fast cooling treatment prevents the development of the brittle δ-phase and retains the β-phase that forms the characteristic martensitic structure of high tin alloys (Rajpitak 1983, Goodway and Conklin, 1987, Scott 1991). The knobbed vessel (MA73) and other two possible vessels (MA4 and MA66) show clear evidence of casting before hot working, with the dendritic structure still discernible in spite of the subsequent hot working and quenching. In MA73, the solid orange phase is the remnant of α-phase with the 'bluish' areas corresponding to the eutectoid compound of the dendritic microstructure. Hot working can be inferred in this sample because equi-axed and twinned grains can be seen inside the orange islands and the copper sulphide segregates developed a linear morphology (Fig. 8). The vessel was then quenched to produce a very hard β-phase, but one much less brittle than β-bronzes slowly cooled to the α-eutectoid room temperature form (Scott 1991).

**Figure 8** Knobbed vessel. Etched. Width of field c. 0.5mm. Plane polarised. Note the linear disposition of chalcocite.

Remnant casting structures are less clear in MA60 (one of the indeterminate decorated pieces) and MA36, the bracelet fragments. In the latter artefact, the linear tendency of copper sulphide segregates was seen under the microscope. This morphology does not surround the surface decoration but is arranged on parallel lines, so chasing or *repoussé* does not seem to have been used as a decorative technique, but engraving may be

[1] This paper was originally written in 2009/2010 and since then a substantial body of Southeast Asian lead isotope data has been published - Pryce, T. O., et al. 2014. More questions than answers: the Southeast Asian Lead Isotope Project 2009-2012. Journal of Archaeological Science, 42, 273-294.

considered likely, as supported by the lines on surface. Finally, the 'ingot' MA78 shows a columnar dendritic structure, indicative of a fast cooling from the melt, as well as copper sulphide segregates.

High-tin bronze is notoriously difficult to work at heat and impossible when cold, owing to its hardness and brittleness, characteristics described in Strabo's *Geography* when he records that "the Indians used vessels which were cast instead of beaten and which broke like pottery when dropped on the ground" (quoted in Rajpitak & Seeley 1979: 28). These qualities make high tin bronze unsuitable for tools or weapons, but the alloy's reflectivity and sonority made it desirable for bells and mirrors, just as their silver-white colour may have added appeal.

*Leaded bronzes*

The addition of lead can improve a copper alloy's casting characteristics by reducing the melting point and viscosity, and increasing the workable casting range and rendering greater detail in the mould. However, the miscibility of lead in copper is low, resulting in globular segregates of lead in copper alloy microstructures that increase brittleness and reduce strength. Leaded bronze was used to cast three KSK artefacts: MA35 (a possible bell), MA68 (a Western Han mirror), and MA77 (the 'Dong Son' drum handle), with their lead contents ranging between 5.0 wt% and 9.4 wt%. All leaded bronzes were cast, as can be inferred from their dendritic structure, and their metallographies mainly differ on the basis of their tin contents.

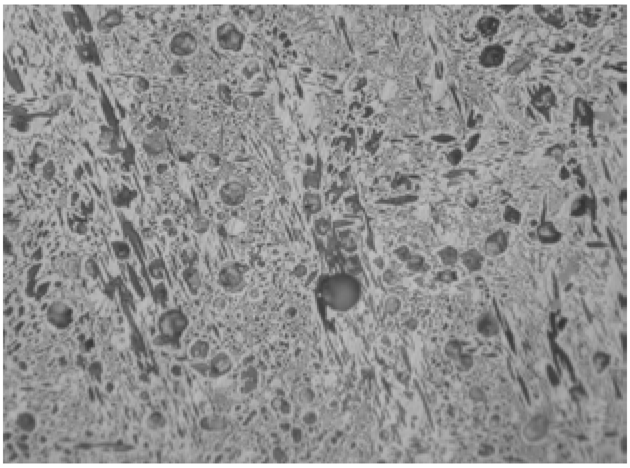

**Figure 9** Microstructure of the Han mirror. Etched. Width of field c. 0.2mm. Plane polarised

The Western Han mirror metallography (MA68), with high tin levels (~25 wt%), shows clearly the hard and brittle laminar δ-phase compound. Fig. 9 shows a general view of the mirror, where α grains can be distinguished in a matrix of an eutectoid δ-phase compound, laminar and lighter. Lead appears as globular segregates. The mechanical properties of this heavy ternary alloy are even poorer than those of unleaded high tin bronzes (discussed below). Nevertheless, once polished, these alloys are highly reflective (Bowman 1991, Rovira and Gómez 2003), which is probably why they were chosen for both Chinese and Roman mirrors (Rovira and Gómez 2003: 24, Scott 1991: 108). Cast ternary alloy mirrors with 22-23 wt% tin have been documented from sites in the Central Plains and Xinjiang regions of China during the latter half of the 1st millennium BC (Mei 2000: 47). Guiver *et al*.'s (1996-1997) study of Chinese bronzes suggested that 'low-tin' bronze was the preferred alloy for weapons, tools, and vessels and leaded bronzes for coins, whilst high-tin leaded bronzes were chosen almost exclusively for mirrors. Guiver *et al*. (1996-1997: 100) also noted that pre-Han mirrors contained c. 20 wt% tin, and Han mirrors c. 25 wt% tin, after which the tin content seems to have reduced, which they proposed may have been due to economic reasons.

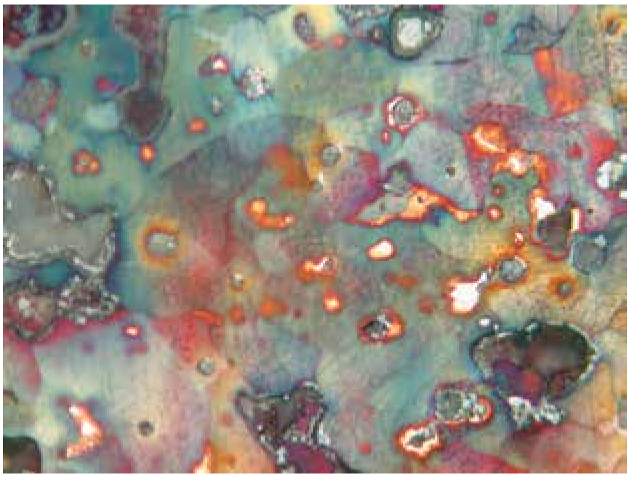

**Figure 10** Microstructure of the Drum. Etched. Width of field c. 0.2mm. Plane polarised

The drum handle (MA77), also a leaded bronze, presents a different microstructure due to its different concentrations of tin (~10 wt%) and lead (~12 wt%). In particular, segregates of δ-phase appear as bright white phases (Fig. 10). This observation is in agreement with Rajpitak (1983), who states that, in practise, the brittle δ-phase appears from c. 5-7 wt% tin. Cuprite is also present, and clearly distinguished by its red internal reflections in XPL, and the cored aspect of the dendrites is indicative of a fast cooling rate. The metallography of this artefact also allowed us to determine that the handle was not soldered to the vessel but cast, as was the decoration, due to the absence of high structural stresses that are caused by chasing or engraving.

Finally, it can be noticed how the possible bell (MA35), which displayed a different chemistry, namely in its high content in antimony, has also different working techniques, being the only object which was annealed after casting to get a higher homogenisation through re-crystallization (Fig. 11).

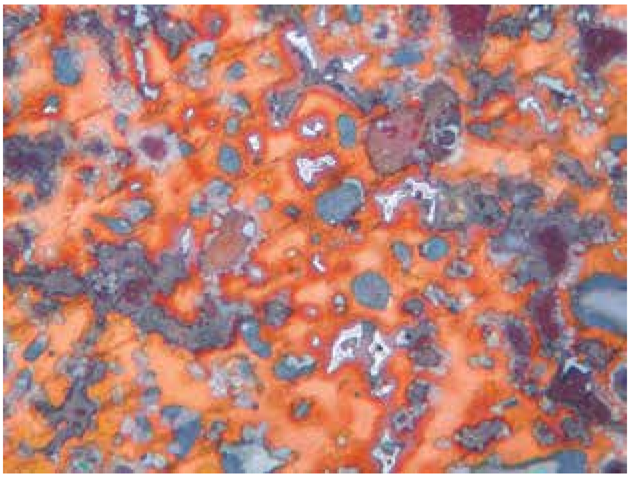

**Figure 11** Microstructure of MA35. Etched. Width of field c. 0.5mm. Plane polarised

## Technical Ceramics and Slag

Four different kinds of technical ceramics have been found in KSK: i. amorphous fragments (TC34), ii. possible pyrotechnological structures (tentatively called 'furnace' ceramics) (TC35), and two types of vessel: iii. smaller ones with a 'nipple' on the base (TC9 and TC16), and iv. a bigger one whose base is missing (TC17), so we do not know if it is a larger version of the 'nippled' type (Fig. 12). The first issue was to determine if these ceramics had been used in metallurgical activities, and secondly, to evaluate the possibility of the smaller vessels being used as ingot moulds, similar to those documented in central Thailand by Pigott and Ciarla (2007: 83) and the bigger one as a crucible.

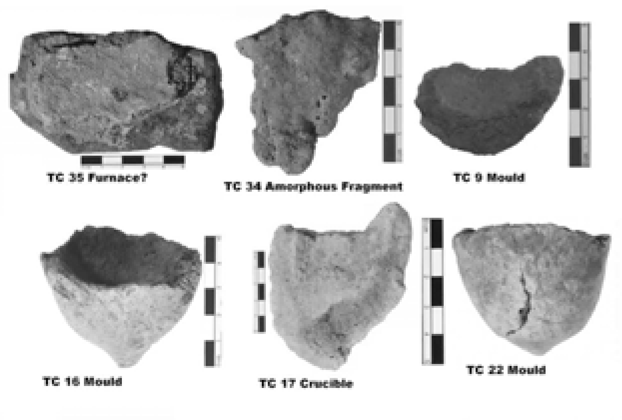


**Figure 12** Technical ceramics from KSK

SEM-EDS compositional analyses of the technical ceramic fabrics allowed the differentiation of two groups, differing principally in their alumina contents. The 'low alumina' group is constituted by the sample of vitrified, amorphous ceramic (TC34), and the 'furnace' fragment (TC35). Their structures show a highly bloated ceramic matrix, with abundant quartz grains and smaller and fewer inclusions of zircon, rutile, monazite, and zinc silicates. The vitrified state of these ceramics leaves little doubt that they were involved in high-temperature technologies, but given the lack of any metal traces we cannot confirm any link to metallurgical activities - they will not be discussed further.

The 'higher alumina' group comprises solely the vessels, all of which can confidently be ascribed to copper-base metallurgical activities. This might be indicative of a preferential selection of alumina-rich clays for metallurgical vessels but it should be noted that 'alumina-rich' is relative; these vessels would still have mediocre refractory properties (Freestone and Tite 1986, Martinón-Torres and Rehren 2009). The ceramic fabrics in this group are similar to each other, characterised by an abundance of elongate voids left by organic temper (although some organic inclusions remain) and less abundant quartz grains, zircon, and silicates of iron and zinc. Another noteworthy feature of this ceramic group is the relatively low vitrification documented in the matrices, particularly for the smaller vessels. Considering the limited refractoriness that we can infer based on the ceramic composition, the lack of vitrification indicates that either they were not exposed to high temperatures or, if they did, this exposure did not last long.

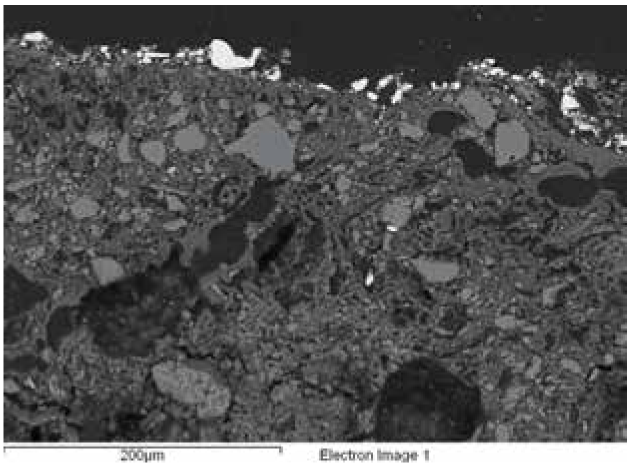


**Figure 13** Metal remains inside TC9. Width of field c. 0.5mm. SEM-BSE image

Focusing now on the smaller nippled vessels, surface XRF analyses of two of them (TC9 and TC16) indicated the presence of both copper and tin, and the microanalytical study of TC9 shows traces of oxidised bronze mechanically adhering to the inner surface, with virtually no chemical interaction (Fig. 13). This, coupled with the low vitrification and their overall shape, lead us to suggest these vessels constitute ingot moulds, where the metal would solidify relatively quickly (cf. Pryce *et al.* 2008: 301, who initially suggested use as crucibles). Somewhat exceptional is the 'mould' TC16, which shows a lump of bronze slag adhering to the outer surface, but this is probably owing to some accidental contact between the two. The interpretation of these vessels as moulds is consistent with the matching high-tin bronze ingot found on site (see previous section) and with the broadly comparable 'cup mould' tradition found in mainland Thailand (Pigott and Ciarla 2007).

The larger vessel (TC17) was clearly engaged in a different process, and we interpret it as a crucible due to the 1-3 mm layer of slag adhering to its inner surface. This slag is mostly composed of fayalite crystals ($Fe_2SiO_4$) immersed in a matrix of K-melilite ($KCaAlSi_2O_7$) containing traces of tin oxide. Small prills of copper sulphide were detected in the crystalline matrix, as well as larger (~100 µm) prills of corroded bronze towards the surface (Fig.14). The oxidation of these prills is probably post-depositional, as indicated by the ghost structures preserved in all of them, together with the presence of covellite and fayalite, which indicate reducing conditions – though these were probably variable due to the coexistence of fayalite and K-melilite.

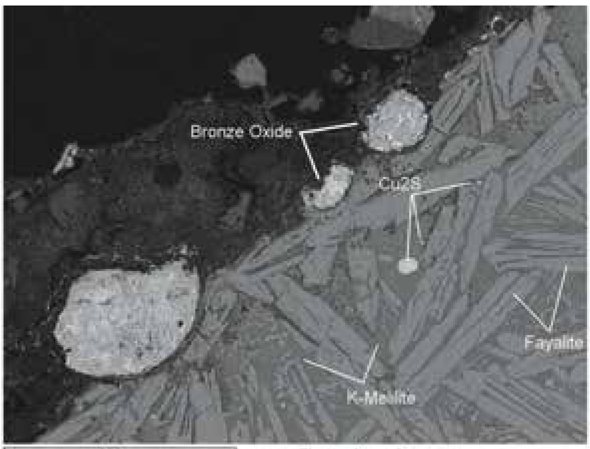


**Figure 14** Slag layer of TC17. Width of field c. 0.75mm. SEM-BSE image

The presence of copper and tin in the crucible slag suggests four potential *scenari*: i. the melting of bronze, ii. the alloying of metallic copper and metallic tin, iii. the co-smelting of copper minerals and tin minerals, and iv. the cementation of tin minerals with metallic copper.

Although some degree of chemical interaction between the slag and the ceramic fabric is noticeable at the interface, the high iron content in this slag residue, as evident in the formation of fayalite, is far in excess of the iron oxide in the ceramic (c. 3 wt%). This indicates that the charge was rich in iron and suggests that at least one of the components entered the charge in a mineral form, possibly bringing iron oxide as gangue as might occur when panning placer cassiterite associated with ferrous 'black sands'. Although the refining of iron-rich bronze might also be a possibility, the relatively low iron content of the metal artefacts from KSK and elsewhere in Thailand argue against this supposition. Hence we favour the 'crucible smelting' *scenari* iii and iv, instead of 'crucible melting' possibilities i and ii.

It is difficult, however, to decide between options iii and iv, mostly owing to a scarcity of comparanda (but see similar examples of bronze slags interpreted as byproducts of co-smelting cassiterite and metallic copper recently found in Portugal: Figueiredo *et al*., 2010; Valério *et al*., 2013). According to Rovira (2007), slags deriving from co-smelting copper and tin minerals typically contain malayaite ($CuSnSiO_5$) or other copper neosilicates, as well as prills with compositions varying from pure copper to high-tin bronzes. Such features are absent in crucible TC17. Also following Rovira (*ibid*.), a conspicuous characteristic of crucible slags related to cassiterite cementation with metallic copper is the presence of clusters of nodular cassiterite, which are not found here either. However, as a preliminary interpretation, we are inclined to interpret this as a crucible where bronze was made by cementation of iron-rich cassiterite with copper metal. Under reducing conditions, the bulk of the cassiterite could be reduced to the metallic state and absorbed by the copper, either by cementation or with both metals in a liquid state, depending on the temperature; whereas the same atmosphere would allow for an iron ion equilibrium towards $Fe^{2+}$, which can form fayalite. This tentative reconstruction is not only consistent with the analytical data, but also with the geological environment (notably, the ready availability of cassiterite and the lack of copper ores) as well as with the archaeological reconstruction (see below).

Even more difficult to interpret is an amorphous c.150 g lump, 74x70x40 mm in size, originally categorised as 'bronze slag', which has both similarities and differences when compared to the preceding sample. The microstructure of this piece is extremely complex and heterogeneous, alternating areas of metallic copper, oxidic slag phases and lumps of vitrified ceramic - the latter, indicating that the piece may originate from a highly distorted crucible. Besides the alkali oxides that may be attributed to molten ceramic and/or fuel ash, the main compounds present in the slag matrix are oxides of copper, tin and lead. Copper is present in the form of metallic globules but also as cuprite prills, indicating a relatively oxidising system. Indeed, metallic prills are sometimes surrounded by a halo of oxidation. In other areas of the sample, copper appears bound with lead oxide and silica, forming globular phases that appear interspersed with acicular cassiterite. This phase is also very abundant, and it often appears concentrated in discrete clusters (Fig. 15).

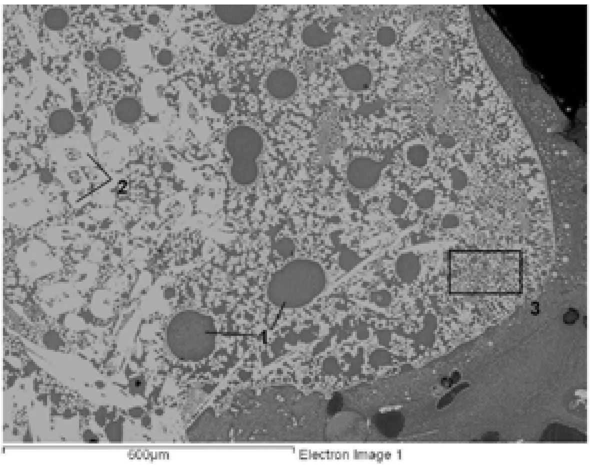


**Figure 15** Slag lump. Width of field c. 1.2mm. SEM-BSE image

Like the TC17, this sample appears to be related to bronze production. The clustering of cassiterite is a strong indication that it entered the system in a mineral form, rather than resulting from the oxidation of a bronze during melting. However, in this case, the reducing conditions necessary for the production of bronze by cementation seem not to have been achieved or maintained for long enough. A further peculiarity is the presence of lead, which could have entered the system with the metallic copper or as a separate component. In the relatively oxidising environment, lead could have reacted preferentially with oxygen and silica from the ceramic, to form the phases described above. The reasons why the making of bronze was not completed in this case can only by hypothesised, although the failure of the crucible and subsequent abandonment of the operation seem plausible. The (unexpected) presence of lead, oxidised during the process, could have been the reason for the failure of the vessel in this case, as lead oxide is highly aggressive towards siliceous ceramics (Rehren 1996).

## Discussion

In order to understand the nature and importance of metals and metallurgy at KSK, the crucible, mould, slag and metal evidences must be brought together. The first aspect deserving attention is the stylistic variety of the metal artefacts. Their stylistic influences clearly show South Asian, Vietnamese 'Dong Son', and Western Han Chinese characteristics, which indicate the cosmopolitan character of KSK during the late prehistoric period (Bellina 2008). Turning to the rest of the assemblage, we have tentatively established the presence of nippled moulds for high-tin bronze ingots as well as larger crucibles that would have been employed for the production of copper/tin alloys via cementation of cassiterite with metallic copper. Considering the lack of copper ores in the Thai-Malay Peninsula, in contrast with the availability of tin ores (Pryce *et al.* 2008), the emerging picture suggests that KSK metallurgists could have imported copper or bronze from other regions (i.e. the Khao Wong Prachan Valley in central Thailand, see Pryce 2010, or the copper mining complex at Phu Lon, Pigott *et al.*, 1992), and 'added value' by cassiterite cementation. The resulting high-tin bronze could have been employed locally for artefacts such as those analysed here, but the presence of ingot moulds and a high-tin bronze ingot strongly suggests that production was also oriented for exchange.

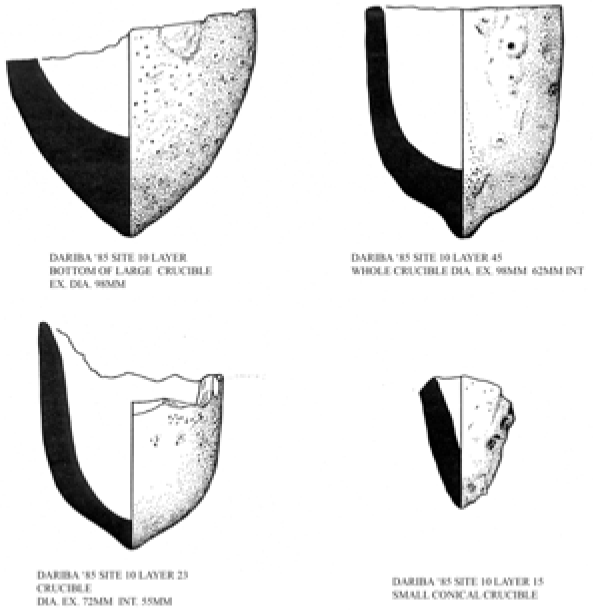


**Figure 16** Examples of 'nippled' technical ceramics from Dariba, Rajasthan; courtesy of Paul & Brenda Craddock

As far as we have been able to discern, KSK's distinctive nippled wares have no convincing analogy with other Southeast Asian technical ceramic assemblages. However, strikingly similar ceramics have recently been reported along with a high-tin bronze ingot from the broadly contemporary site of Tilpi in West Bengal (Datta *et al.* 2007), and even further west from the late 1st millennium BC base metal mines of Dariba in Rajasthan (Fig. 16, Willies *et al.* 1984). It should be noted that at both Indian sites the nippled wares seem to have functioned as crucibles rather than moulds, and that the Dariba examples also appear to be externally heated (Paul Craddock pers. comm.) – contrary to the contemporary Southeast Asian tradition (Fig. 12). These technical ceramic discrepancies suggest that the South Asian metallurgical comparators could be analogous, but given that typologically similar high-tin bronzes are frequent in South Asia and may date the early 1st millennium BC (Srinivasan 1997, 1998, 1999, Srinivasan & Glover 1995), it is conceivable that KSK high-tin bronze production technologies were transmitted by some means across the Bay of Bengal, perhaps being morphed enroute with regard to the employment of nipped ceramics. Such a possibility is in accordance with Bellina's original (2001) model of South Asian artisans settling at KSK and using South Asian techniques to produce 'Southeast Asian' material culture (Bellina 2003, 2007, 2008). However, it must be emphasised that KSK's metallurgical and glass industries lack the rigorously quantitative skill-based ethnoarchaeological studies (Roux 2000, Roux *et al.* 1995) that structure the hardstone ornament artisan 'limited migration' hypothesis.

## Conclusions

Bearing in mind that KSK has now been almost entirely obliterated by looting, the relatively low sample numbers of the present study permit a tentative reconstruction of late 1st millennium BC copper-base metallurgical activities in the Upper Thai-Malay Peninsula. Here are our concluding points.

1. The trace element similarity of the artefacts did not reliably identify potential production signatures, although lead isotope analyses should provide useful insights.
2. Technical ceramics can be classified due to their functionality into ingot moulds and crucibles.
3. Archaeometallurgical by-products also suggest high-tin bronze production by cassiterite cementation at KSK.
4. Both the working techniques employed and the bronze production by cementation shows the advanced skills of KSK metalworkers and their knowledge of alloying effects and working properties.

If our reconstruction even partly coincides with historical reality, not only would KSK have provided the earliest evidence for the exploitation of Peninsula tin in the last centuries BC and confirmed a long suspected material contribution from the Peninsula to the trans-Asiatic exchange network, but it would also support Bellina's (2001) original thesis for highly skilled South Asian artisans having settled in Southeast Asia or trained Southeast Asians – whether at the behest of local social groups or of their own volition. The archaeometallurgical research conducted by the Khao Sam Kaeo Archaeological Mission has now yielded further multi-disciplinary evidence for the prehistoric meeting of South, East, and Southeast Asian social groups, with KSK itself acting as a major cosmopolitan trans-Asiatic industrial and exchange centre participating in the circulation of skilled technologies and hybridised cultural products.

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# Early use of iron in Aksum - trade and technology transfer across the Ethiopian highland

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*ABSTRACT* The beginning of the use of metals in sub-Saharan Africa has been a controversial topic for several decades. The study of the use of iron is central to the issue, because iron is considered as the earliest fashioned metal in that region. Some argue that the introduction of iron into sub-Saharan Africa was a result of the Greco-Roman influence penetrating from the Mediterranean coast through the Nile valley, while others suggest that it came in with waves of trade and migration from the southern Arabian Peninsula.

The areas that might be candidates for the earliest use (and perhaps also production) of iron are the Sudan and the Ethiopian highland in north-eastern Africa. The present study focuses on the latter region that, for some centuries, was the dominion of the Aksumite kingdom, a mighty political formation in Late Antiquity. The goal of the present study is to evaluate questions concerning the introduction of the use of iron and its production in Aksum by revisiting the historical and epigraphic sources in light of recently published archaeological evidence. The present study focuses on plausible interpretative models for the provenance and use of iron in the Axumite territory. It reconsiders previous claims and controversies, including the theory regarding the introduction of iron to Aksum through trade and migration from the southern Arabian Peninsula during the 1st millennium BCE, and an alternative hypothesis which associates Aksumite iron with Nubian (Meroitic) influence in a later period. The goal of the study is to check the consistency of the argumentation supporting the two hypotheses, and to assess the significance of the existing evidence for the various interpretative models in order to assess the veracity of each argument.

## The beginnings of the use of iron in sub-Saharan Africa

The controversy over the introduction of iron production and usage into sub-Saharan Africa has gone on for several decades (s. Shinnie 1971, Oliver and Fagan 1975, Amborn 1976). An initial question was whether iron was introduced into Africa from outside (e.g. from the Mediterranean coast, or *ex oriente*), or whether iron production developed independently. The latter issue assumes African iron production as an indigenous discovery which led to a broad variety of techniques that can be documented with ethno-archaeological evidence. Early iron smelting sites are reported in Meroe/Nubia (400/200 BCE – ca. CE 300), in Nigeria (Nok culture, ca. 500 BCE), as well as in East and South-East Africa (ca. 500 BCE) (Miller and van der Merwe 1994). When discussing the earliest areas of iron production, some authors suggest Ethiopia (e.g. Craddock 1995, 261), often in juxtaposition to southern Arabian practice (van der Merwe 1980). Detailed archaeologically-based accounts, however, most often refer to Nubia (Meroe) as the location of early production.

The question of the advent of African iron production is only one part of the study of the history of metal-working technology in Africa. Methodologically these studies follow two main strands of inquiry (van der Merwe 1980):

"One is concerned with the [local] social, cultural, economic and environmental aspects of the introduction and practice of metallurgy. The other describes the chronology, technology and mechanisms of indigenous metals production itself." (Miller & van der Merwe 1994, p. 3)

In the present study the focus lies mainly on the latter, one that involves the selection of the sources and the archaeological evidence. The aim is to evaluate issues concerning the introduction of iron use and production in the Aksumite territory by revisiting the historical sources in light of recently published archaeological evidence.

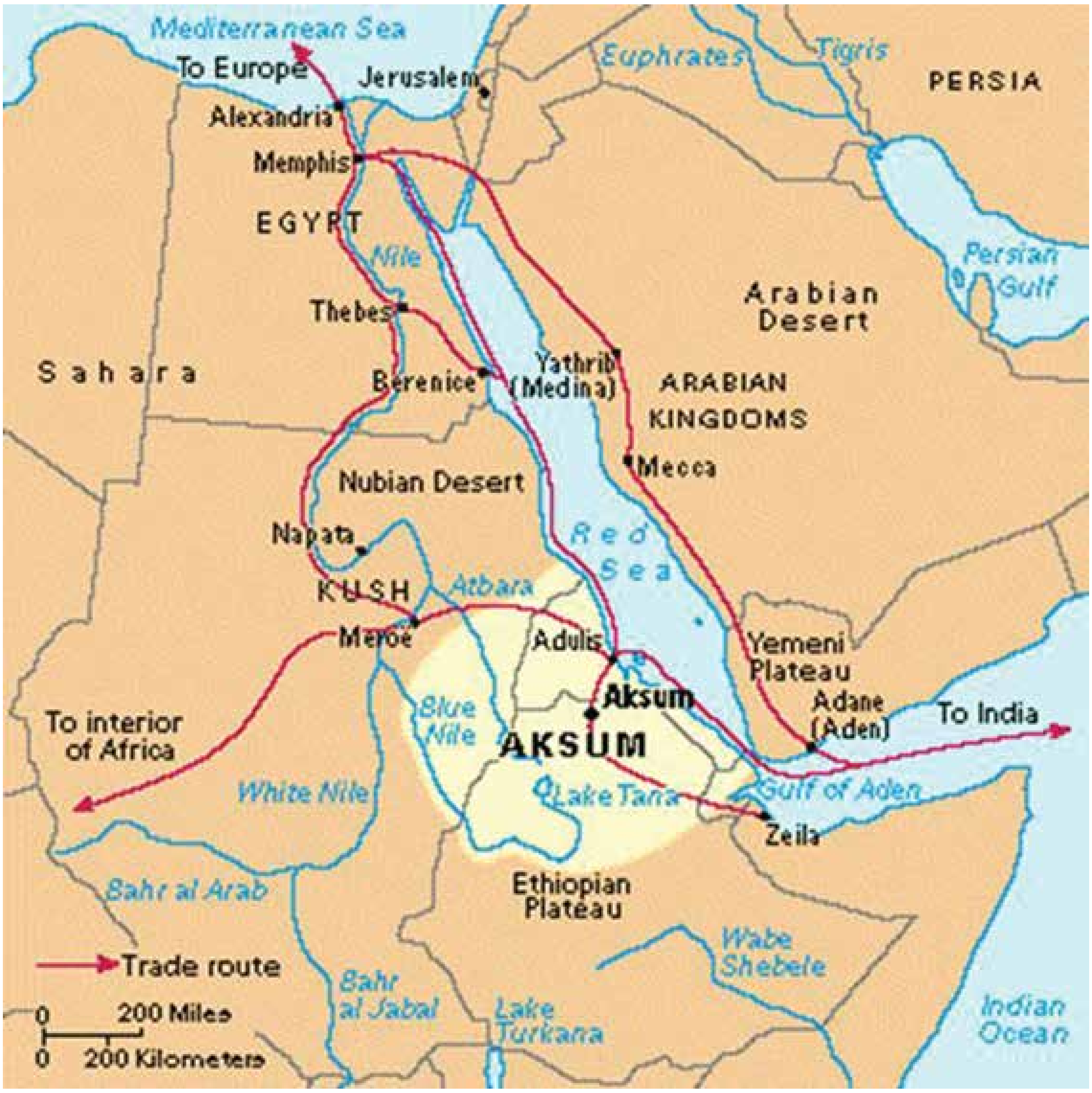


**Figure 1** Map of Aksum

## From the Stone Age to the Iron Age? The kingdom of Aksum in the Ethiopian highland

The African areas with possibly early – if not the earliest – use, and perhaps also production of iron, are in the Sudan and the Ethiopian highland in north-eastern Africa. The present study focuses on the latter region that, for some centuries, was the dominion of the Aksumite kingdom, a mighty political formation of the Late Antiquity (Fig. 1).

For the kingdom of Aksum in Late Antiquity we have only few references from scattered historical sources of other civilisations; this historical evidence has been summarised, analysed and commented on by Kobishchanov (1966/1979). In the major historical source of the 6th century CE, the "*Christian Topography*" of Cosmas Indicopleustes, we find references to several impressive Aksumite constructions made of stone such as the throne and the stela of Adulis (Cosmas 1968, vol. II, 54-55; vol. I, 364-367). Our direct knowledge of the material culture of the Aksumite civilisation, however, began with the first large-scale archaeological expedition in the Aksum region, undertaken in 1906 by the German group under the direction of E. Littmann (Littmann & Krencker 1906). The final report of this expedition (Littmann, Krencker, von Lupke 1913) was the source of nearly all archaeological information about the Aksumite state until the mid 1950s, when several Italian and French groups resumed archaeological investigation by conducting systematic excavations. The present study refers to research conducted by N. Chittick, director of the British East African Archaeological Institute (final report in Munro-Hay 1989), as well as to finds published by D. W. Phillipson (1985/1995; 2000), and Fattovich (2003).

The history of the Aksumite state is generally (e.g. Munro-Hay 1989, p. 17-21) divided into the early (from ca. 100 BCE to 330 CE), the middle (330 – 650 CE), the late (650 – 900/1000 CE) and the post-Aksumite period (1000-1100 CE). The material evidence of the early period comprises epigraphy (200 – 270 CE) and coinage (since 270 – 330 CE). Major historical events during the middle Aksumite period are the conversion of the *negus* (king) Aezana (Ezana) to Christianity in ca. 340 CE, as well as the decline of the Nubian state in the North of Ethiopia (better known under the name of its capital Meroe) possibly besieged by Aksumite forces during the reign of Aezana.

The most impressive among the material remains of the Aksumite civilisation are the tombs and the stelae, monoliths of varying sizes which can be still seen scattered in the Aksum area at an altitude of 2200 m (Phillipson 2004, 83). One of the questions with which the present study is concerned regards the tools supposedly used and the materials needed for constructing and erecting the gigantic stelae in order to interpret the (scarce) iron finds in the Aksumite tombs or elsewhere, and to reread the arguments concerning the hypotheses on the provenance of the iron found in Aksum.

The basic contextual assumption for dating the archaeological finds (including metal objects) is that the megaliths (stelae) were erected *before* the Christian era, i.e. during the first centuries CE, probably in conjunction with funerary practices (Phillipson 2004, 3). The finds mainly comprise stone objects, pottery and coins with which we can build a contextual frame for our question regarding the early use of iron in Aksum.

## Iron in Aksum: Archaeological evidence

The earliest archaeological finds of iron in the Aksumite territory are iron artefacts found in tombs in Yəha, in the South of the urban centre of Aksum. They have been assigned to the pre-Aksumite period, ca. 5th century BCE (Munro-Hay 1989, 221; Munro-Hay 1991, 60). In the royal tombs and in the funerary buildings of the Aksum area several iron weapons, such as iron spear blades (but no swords!), as well as tools, including sickles, tweezers, saws, knives and hammers, were found. Of particular importance is a remarkable object with a bronze blade fitted on an iron shank (Phillipson 2000, vol. I, 88). Some iron rings, presumably for binding prisoners, were found in Matara near Aksum. No furnaces have been discovered yet. However, there exist a controversy over the interpretation of the excavated slag and its use. On the one hand slags have been associated with iron production (T. Rehren, 2009, personal communication), on the other, they are supposed to be the residue of the production of metals other than iron (Munro-Hay 1991, 226). Furthermore, interpretations of trenches suggest that they could have been used for iron working or could just be burnt areas. Finally the absence of swords among the early iron finds underlines the missing of a clear indication that iron weapons were used during the pre-Aksumite period.

In an archaeological introduction and guide of the Aksum area Phillipson mentions that the Gudit Stelae Field was “a place used for the interment of less prominent or wealthy members of Aksumite society”, where “grave goods including pottery, iron tools and […] glass goblets” were found. The combination of study of types of “artefacts and radiocarbon dates show that the Gudit Stelae Field was in use during the second and third centuries AD.” (Phillipson 2003, 62). Phillipson does not comment on the possible provenance of the iron tools. In his study on the Aksumite stelae J. Phillips suggests that initial steps of work on the megaliths in the quarries (e.g., producing wedge-marks) were made with a thin chisel-like tool, probably made of iron (Phillips 1994, 107), although no such tools were found on site and the few iron tools found in Aksumite tombs (Munro-Hay 1989, 221-228) constitute a rather poor evidence for their practical use in the quarries.

Because only few copper or bronze items were found, the most convincing hypothesis suggests that in Aksum a direct transition from the stone to the iron age might have taken place during the early Aksumite period.

## Iron in Aksum: Epigraphic evidence

In an inscription found at Aksum and attributed to the 4th century CE, the Aksumite king (*negus*) Aezana (Ezana) mentions that his soldiers burnt the towns of the Nubian tribes and seized their copper, iron and brass. It is the same inscription that mentions the conversion of the *negus* to Christendom (Littmann, Krencker, von Lupke 1913, vol. IV, pp. 32-42; Pankurst 1961, pp. 29-30). Moreover, it is known that early iron smelting was practiced in the Meroitic (Nubian) kingdom (Miller and van der Merwe 1994), but that Meroe never recovered from its decline during the end of the 3rd / beginning of the 4th century CE. This decline is thought to have been caused by Aksumite aggression or by other factors such as hostility from other Nubian tribes).

The use of panegyric texts on commemorative steles as evidence of specific material culture is not without problems. Pankurst (1961) and Bowersock (2013) quote, contextualise and comment on several Aksumite epigraphic examples. The epigraphic text quoted above is remarkable because it appears on two stelae at Aksum, one discovered and described already in 1805, the other discovered at a different site in Aksum in 1981 (Bowersock 2013, 68). Whatever the acquaintance of the Aksumite state with iron in the 340s CE might have been, it is certain that “copper, iron and brass” are here symbols of military power, and "seizing their copper, iron and brass" means that the Aksumite king extended his own power over the Nubian territories occupied by the Noba, apparently tribes who filled the power vacuum after the decline of the Meroitic state. Beyond this symbolic indication, however, a straightforward implication that knowhow and use of iron existed in the Aksumite state proper in the mid 4th century CE cannot be derived from the inscription quoted above.

## Iron in Aksum: Historical evidence

In the merchant's manual, *Periplus maris Erythraei,* detailed information about routes, harbours in the Red Sea, and products traded during the 1st century CE is provided (Bowersock 2013 ; Casson 1989). Of particular interest in our context is the evidence concerning market commodities transported and traded near the port of Adulis, the main harbour of the Aksumite kingdom on the Red Sea (Fig. 1). In this list iron is mentioned as an imported commodity for making spears for hunting and war. Its provenance should be Egypt. In addition, Indian iron and steel are also mentioned as imported commodities (Casson 1989, 55).

A further source for study of iron use in Aksum is the *Christian Topography* of the Greek merchant Cosmas Indicopleustes, probably written in 549 CE. The treatise mentions iron as an export article of the Aksumite trade. According to this account, the Aksumite king exchanged cattle/meat, salt and iron for gold from Sasu – a place probably situated in the South-West of Aksum (Cosmas 1968, vol. I, 360; Pankurst 1961, 40; Munro-Hay 1991, 174, 182).

In an account written some years later, the historian Procopius (6th century CE) mentions a detail regarding Indian and Ethiopian (Aksumite) shipbuilding, which seems to contradict the acquaintance of the Aksumites with iron: "… The Indians and the Aethiopians possess neither iron nor any other thing suitable for such purposes [fastening the planks together by nails]." According to the same account, they were unable to buy such items from the Romans (Byzantines) as this was explicitly forbidden by Roman law, and anyone caught violating this prohibition would be punished by death (Procopius 1961, I, xix, 23-26; Pankurst 1961, 39-40; Munro-Hay 1991, 220). Indeed, the shipbuilding technology in the Red Sea and the Indian Ocean during the Late Antiquity (and even later) was different from the Mediterranean practice with respect to fastening the planks. It remained different even after the Arab-Muslim expansion, which began in the 7th century CE. The explanation provided by Procopius seems to circulate as commonplace in the narratives and the *mirabilia* of that period in the eastern Mediterranean, but its value as a historical document is relatively poor.

## Interpretive models

On the basis of the historical, epigraphic and archaeological evidence summarised above several models regarding the use of iron in the Aksumite state, with a focus on the 3rd-4th centuries, seem plausible:

a) The iron items found in Aksum (prestige objects, trade articles) were imported – possibly also re-exported. Imported iron bars were traded and re-exported, too. This hypothesis combines the historical narratives of the *Christian Topography* and the *Periplus*, complies with the symbolical value of Aezana's epigraphy, and does not touch the question of iron weapons or tools.
b) Iron was imported in bars and was worked by local blacksmiths into (small) items on site.
c) Know-how of producing iron from local deposits was imported.
d) Combination of the above models, i.e. import of iron objects, as well as local workshops, and (perhaps) small-scale local iron production.

## Critical remarks and provisional conclusions

Any conclusive argument needs reliable historical evidence and archaeological evidence regarding the provenance of the material, possible workshops, and production places, including the existence of slag deposits. The symbolic value of iron and the *genre* of the narratives render the reliability of the extant historical and epigraphic sources regarding provenance and use of iron in Aksum quite questionable.

Finds in tombs were presumably prestigious imported commodities and iron tools were only found there and not in quarries. For the working of the carved stelae, stone tools are more efficient since iron tools are brittle and, therefore, less appropriate for the needs of carving the stelae. These aspects support interpretative model (a).

Iron (like salt) was considered precious and was apparently used as a sort of "currency" in the Aksumite kingdom (e.g. in the 6th century CE). Both iron bars (b) and iron items (a) could fulfil this function.

The small size of the finds could be both related to limited smelting capacities (c) and/or expensive import, i.e. model (a) or (b). However, archaeological evidence on pits and slag is necessary for model (c).

There remain questions regarding the typology of the finds. Without providing rigorous argumentation Amborn claims that “the type of the objects suggests that in this period iron was processed by local smiths” (Amborn 2007, 189). It would be interesting to reconsider from this perspective the material presented by Phillipson (2000) in comparison with iron objects found in neighbouring regions.

Any consideration of model (a) involves knowledge of trade routes in northeast Africa, as well as trade exchange between the Arabian Peninsula and the Ethiopian highlands. Trade historians support the theory that considers commodities such as iron coming by trade and migration waves from the southern Arabian Peninsula during the 1st millennium BCE, whereas archaeologists working in Sudan support the alternative hypothesis which associates Aksumite iron with Nubian (Meroitic) influence. The latter hypothesis considers Meroe as “an obvious place from which the new techniques [of iron-working] could have spread” (Shinnie 1967). This hypothesis is compatible with comparisons which claim that the Meroitic furnaces are similar to those introduced in Egypt by the Romans. Obviously, the spectrum of the iron-related activities in Meroe possesses such a variety of developmental patterns that models for diffusion towards Aksum are difficult to defend against proposed alternative influence lines.

It is remarkable how the heterogeneous, time-stretched and contradictory historical evidence regarding iron production in Aksum is used differently by authors to interpret the scarce archaeological finds. The vague information on mineral resources in Aksum mentioned by Pankurst (1961) has become a certainty in the assessment of G. Connah: “Mineral resources were such that iron must have been mined and smelted in Ethiopia, as perhaps some other metals were.” (Connah 2001, 87). Munro-Hay claims that the iron finds in the Aksumite tombs confirm the account of Cosmas about the Aksumite iron export (although Cosmas does not explicitly mention iron *objects*). Ironworking should have been introduced into Aksum during the pre-Aksumite period either from South Arabia or from Meroe; several iron objects were certainly imported (Munro-Hay 1989, 221). P. Craddock claims that “the earliest areas of iron production south of the Sahara were apparently in the Sudan and Ethiopia”, but in the following he discusses only well-known evidence from Meroe, Sudan (Craddock 1995, 261-264). In “The Aksumite roots of Medieval Ethiopia” D. W. Phillipson notes that “metalwork was likewise mainly local”, and enumerates several techniques employed by the locals (Phillipson 2004, 83). Apart from coinage, “metalwork” can only refer to iron – in his previous accounts of iron objects found in excavations in Aksum, however, he does not present any evidence for such elaborate iron production and processing inside the Aksumite territory (Phillipson 2000). In a recent assessment Amborn compiles the references to the import of iron objects in the *Periplus* with the iron finds in the Aksumite territory, and concludes that “the type of objects suggests that in this period iron was processed by local smiths” (Amborn 2007, 189). In respect with the same objects Munro-Hay claims that “among these Aksumite tools, weapons, and fittings are very few that do not fit into the categories to be expected from a contemporary site in the Roman Empire” (Munro-Hay 1989, 321).

## Outlook – questions for future research

The controversial claims on iron production in the Aksumite territory imply that the issue can only be unambiguously traced through use of archaeological evidence. Typological analysis could yield arguments for localising the provenance of the worked objects, but for the identification of iron smelting traces of slags and relics of furnaces are needed. This kind of evidence is still missing.

Modern data on iron resources in the area of Aksum imply a poor exploitation potential at a couple of places (GSE 2010). Certainly, this fact does not exclude former exploitation, e.g. of (superficial) meteoritic iron, but it is by no means encouraging the hypothesis of old iron mining in the area of Aksum.

Environmental factors could also be considered such that archaeobotanical study of environmental change could elucidate the possibility of intensive use of wood fuel for iron working or smelting in Late Antiquity. In the modern landscape wood is scarce however, pollen analysis has yielded very poor evidence of arboreal pollen in the proto-Aksumite period. Such evidence does not necessarily contradict the hypothesis of local iron production – it simply makes it more complicated to prove.

A final remark concerns the historical framing of the issue. Since the spectrum of the iron weapons found in Aksum is rather limited, we should imagine the army of the Aksumite kingdom mainly armed with stone-weapons. In such a case the military supremacy of Aksum over Meroe – a state known for its iron production – needs more consideration.

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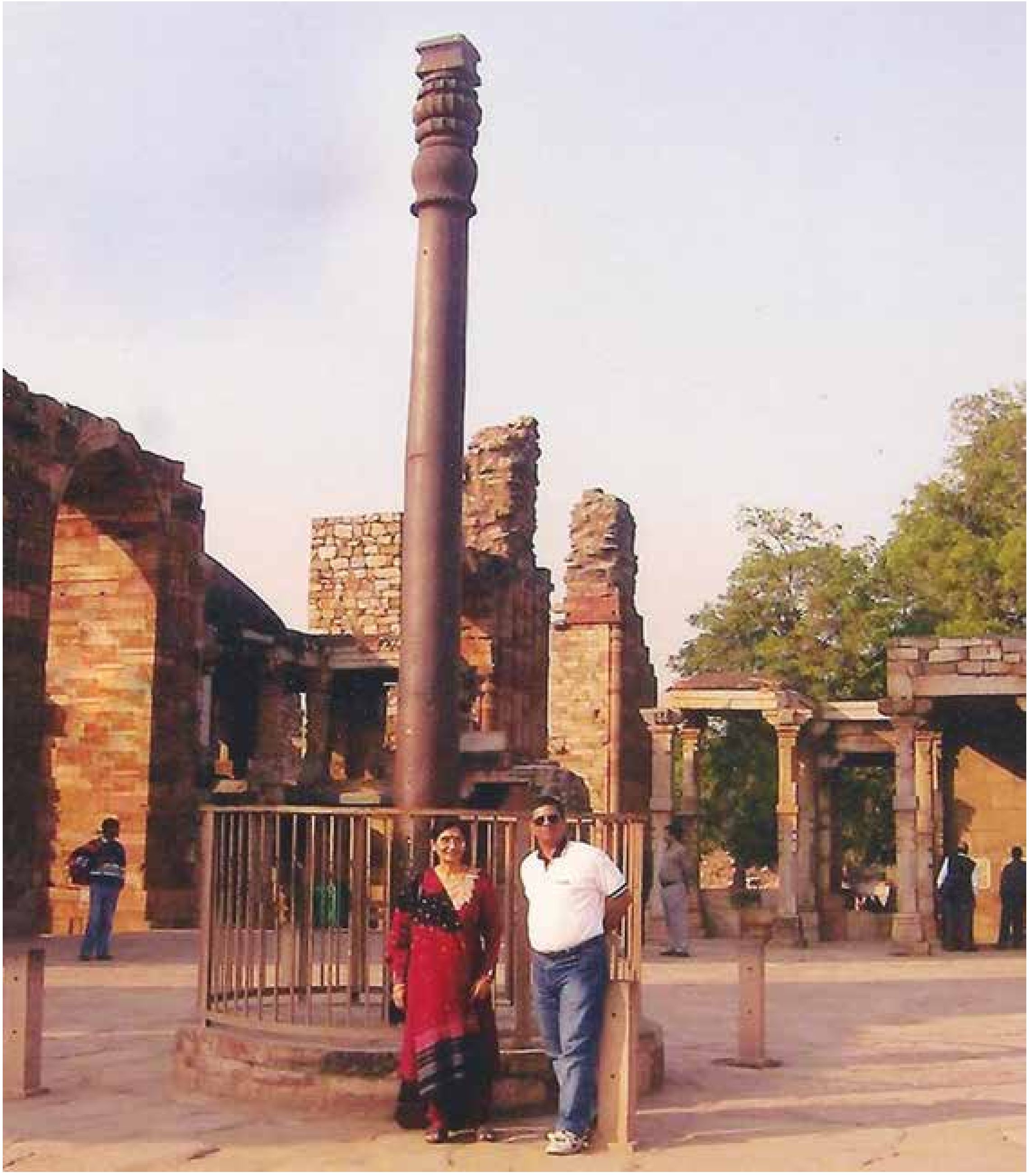
# Section II – Iron Technology



Vibha Tripathi and R Balasubramaniam with Delhi Iron Pillar

*Vibha Tripathi*

# Iron lumps formed from the ancient copper smelting: an example from Naganobori, Japan

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*ABSTRACT* The iron lump formed from copper smelting at the ancient Naganobori mine, Japan, was compared with the iron-copper alloy produced by the replication experiment and also with the iron lumps unearthed from an ancient bronze casting workshop. The compositions of the metals and matte in the iron lumps from three cases are similar in each other. The iron contains 1.4-10 % Cu. The copper contains 0.4-4 % Fe. The bornite solid solution consists of two phases, dark phase (ca. 58 % Cu) and light phase (ca. 66 % Cu). The carbon content of the iron varies from less than 0.01 to over 0.77 % C. The important factor for the formation of iron lumps is the presence of a small amount of sulfur in higher-temperature reducing conditions.

## Introduction

The use of man-made iron gradually increased in the second millennium BC and it became on a large scale in 1200-1000 BC in regions of the eastern Mediterranean (Waldbaum, 1999, p. 32; Tylecote, 1992, p.47). It is, however, still not known when and where iron was intentionally smelted from iron ores in the Bronze Age. Iron was formed frequently as a byproduct of copper smelting (Gale et al., 1990; Hauptmann, 2007, p. 207), and copper-smelting sites might be mistakenly interpreted as iron smelting remains. It is therefore important to know the characteristics of the byproduct iron.


**Figure 1.** Map showing locations of the Naganobori copper mine site and the Kajiyashiki remains, near Nara

This paper describes the iron lump formed from copper smelting at the ancient Naganobori mine, Japan (Fig. 1). The iron lump was compared with iron-copper alloy produced by the replication experiment of ancient smelting and also with iron lumps unearthed from the ancient bronze casting workshop, Kajiyashiki, near Nara, Japan.

## Naganobori

The Naganobori mine site lies in Mito-cho, Yamaguchi-ken, southwest Japan. In the 8th century copper from the mine was used for casting a huge bronze statue of Buddha (AD 749) at the Todaiji temple in Heijokyo (present Nara city). The Naganobori mine site lies in the eastern foot of a limestone plateau, Akiyoshidai. There are several small skarn-type copper deposits. In 1972 the Board of Education of the town started a preliminary survey for the ancient copper mine, and it was followed by detailed excavation from 1989 to 1998. A large amount of slag was unearthed from the Ōgiri (Ohgiri) smelting site in the mine area, with wood strips and earthenware typical for the early 8th century (Mito-cho Board of Education, 1990, 1993, 1998; Ueda, 2002).

Many small copper skarn deposits occur at the eastern edge of the Akiyoshi limestone plateau. The deposits were formed around a granite porphyry stock of the Cretaceous age. The primary ore minerals are mainly chalcopyrite with bornite, tetrahedrite, magnetite, pyrite, pyrrhotite and arsenopyrite. In the weathered profile, oxidized ore is capped by reddish-brown limonite (gossan).

Unearthed materials from the Ōgiri smelting site include ores, slags and fragments of furnace. The result of the observation of more than one hundred unearthed ores revealed that ores were classified into two types; malachite-bearing garnet skarn ore and copper-bearing limonitic ore (Yoshikawa et al., 2005, p.33; Izawa, 2009). Garnet skarn ores are disseminated by malachite and chrysocolla and contain 3 to 10 % Cu and less than 10 ppm to 53 ppm As. Limonitic ores consisting of goethite and hematite contain 1 to 18 % Cu and are often rich in arsenic (0.4 to 11 % As).

Arsenic minerals were identified as olivenite ($Cu_2AsO_4OH$) and cornwallite ($Cu_5(AsO_4)_2(OH)_4$). There is no sulfide ore, though a small amount of partially oxidized chalcopyrite occurs in some samples. Table 1 shows the chemical composition of representative ores, which were unearthed from the Ōgiri site.

**Table 1.** Composition of ores and slags (XRF analyses).

| Sample no. | Naganodori (8th century) | | | Experiment |
|---|---|---|---|---|
| | 030820-6 | 030823-7 | 00820-17a | 061105-1b |
| | Malachite ore | Limonitic ore | Slag* | Slag** |
| $SiO_2$ (%) | 42.11 | <0.01 | 42.25 | 55.20 |
| $TiO_2$ | <0.01 | 0.01 | 0.03 | 0.10 |
| $AL_2O_3$ | 2.43 | <0.01 | 1.25 | 3.96 |
| $Fe_2O_3$ | 19.66 | 60.44 | - | - |
| FeO | - | - | 33.15 | 11.79 |
| MnO | 0.10 | 0.06 | 0.66 | 0.51 |
| MgO | 0.13 | 0.50 | 0.26 | 1.82 |
| CaO | 18.50 | 0.13 | 17.10 | 27.69 |
| $Na_2O$ | 0.04 | 0.15 | 0.18 | 0.17 |
| $K_2O$ | <0.01 | <0.01 | 0.46 | 1.47 |
| $P_2O_5$ | 0.03 | 0.05 | 0.08 | 0.23 |
| S | 0.08 | 0.05 | 0.40 | 0.09 |
| Cu | 9.57 | 17.50 | 1.85 | 0.11 |
| Zn | 0.03 | 1.03 | 0.85 | <0.01 |
| Pb | 0.01 | <0.01 | 0.05 | <0.01 |
| As | 0.01 | 11.30 | 0.03 | <0.01 |
| Sn | 0.20 | <0.01 | 0.06 | - |
| LOI | 3.71 | 12.35 | - | - |
| Total | 96.61 | 103.57 | 98.65 | 103.14 |

Total Fe is expressed as $Fe_2O_3$ or FeO; — = not determined.
*Outside of the iron, **Furnace bottom slag.

Slag excavated from the Ōgiri site is composed mainly of silicates (calcium bearing fayalite and ferrowollastonite) and wūstite with a small amount of copper prill and matte (Cu-Fe-S phases). The copper content in slag ranges from 0.4 to 4 %, and sulfur ranges from 0.2 to 2 % with Cu/S ratio >1 (Table 1). Frequent occurrence of wüstite in slag indicates that the smelting environments were strongly reducing. In addition, one sample of slag, formed at the furnace bottom, contains an iron lump of 2 cm in diameter (Fig. 2).


**Figure 2.** Photograph showing cross section of an iron lump in the slag of copper smelting at ancient (8th century) Naganobori. Sample 030820-17a

The iron lump was microscopically examined and analyzed using EPMA. Coexistence of iron and copper with a small amount of matte is a characteristic of the iron lump (Fig. 3). Osawa (2008, p. 87) examined etched structures of iron and concluded that the central part of the iron was ferrite (α-iron: <0.01 % C) but rimmed by pearlite (0.77 % C). Iron contains 4.0 to 9.9 % Cu and copper contains 1.8 to 4.2 % Fe in solid solution, plus invisible minute inclusions.

The matte phase is bornite solid solution consisting of two phases. The curved irregular shaped dark phase exsolved from the originally

**Table 2.** EPMA analyses of iron, copper and bornite solid solution in the iron lump from the Naganobori (8th century) slag. Sample 030820-17a.

| Phase | Iron | | | Copper | | | bornite-ss | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Dark | | | Light | | |
| Point | P1 | P2 | P3 | P4 | P5 | P6 | P7 | P8 | P9 | P10 | P11 | P12 |
| Cu (%) | 4.03 | 5.98 | 9.94 | 95.52 | 96.77 | 97.20 | 57.58 | 59.07 | 59.24 | 64.63 | 64.92 | 65.86 |
| Fe | 92.80 | 90.53 | 90.21 | 4.19 | 1.75 | 2.64 | 15.75 | 15.21 | 15.21 | 10.93 | 11.25 | 11.08 |
| S | 0.00 | 0.00 | 0.00 | 0.06 | 0.02 | 0.00 | 26.42 | 25.61 | 25.60 | 24.47 | 23.42 | 24.10 |
| Total | 96.83 | 96.51 | 100.15 | 99.77 | 98.54 | 99.87 | 99.75 | 99.89 | 100.05 | 100.03 | 99.59 | 101.04 |

homogeneous bornite solid solution. The dark phase is relatively copper poor and contains 57.6 to 59.2 % Cu. The light matrix phase contains 64.6 to 65.9 % Cu (Table 2).

In other slag samples there are several small prills of metal and matte. Some metals are As-rich copper (17 % As) and others are Sn-rich copper (11 % Sn).

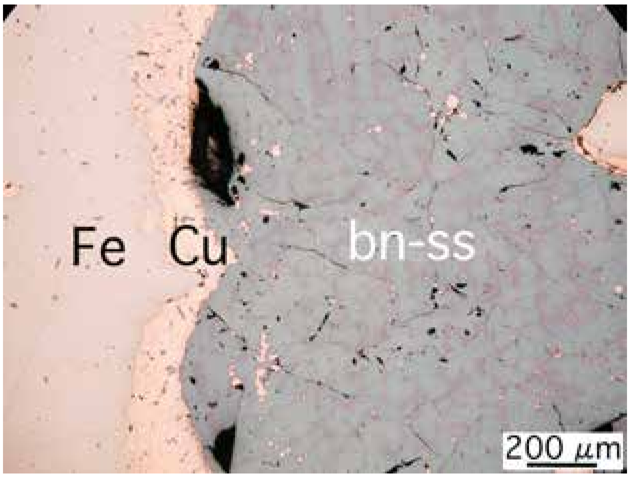


**Figure 3.** Photomicrograph of the iron lump. Iron coexists with copper and bornite solid solution (bn-ss). Sample 030820-17a

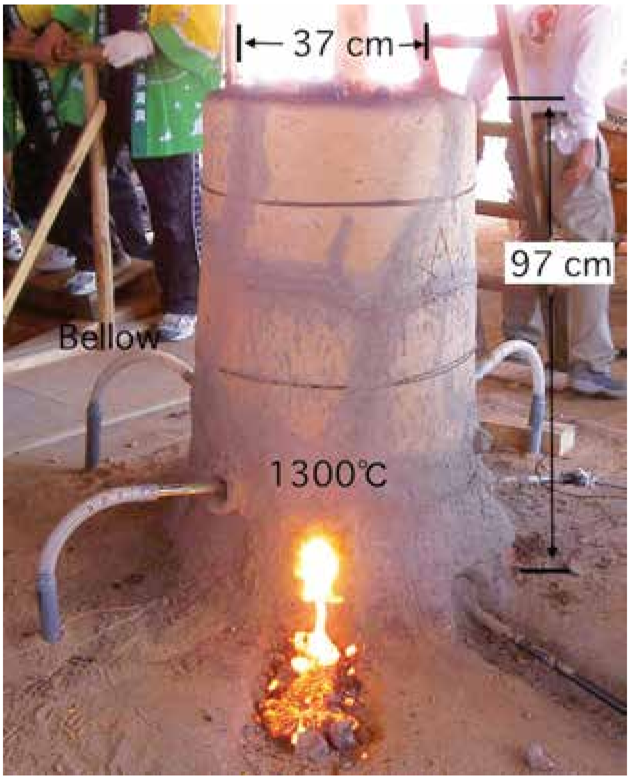


**Figure 4.** The smelting furnace of the replication experiment

**Figure 5.** The half broken smelting furnace after operation showing un-melted ore pellets. An initial reaction of ores was examined using a piece of the pellets

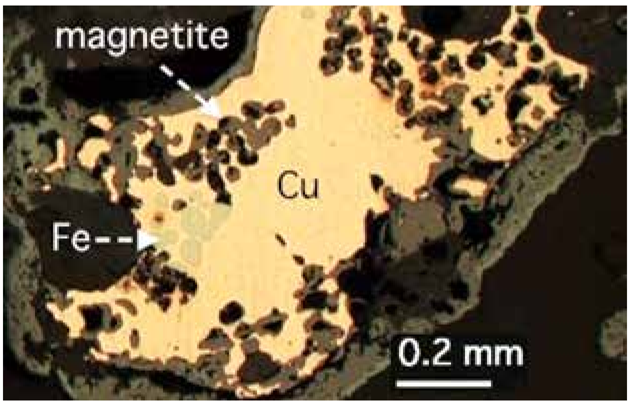


**Figure 6.** Photomicrograph of ore pellet (Osawa, 2008, p.75). Copper, iron and magnetite were formed in a fragment of malachite during the initial reaction. Sample 0611-1

## Replication experiment

A replication experiment of ancient copper smelting was performed at Naganobori in November 2006, using Chilean malachite ore and copper-bearing limonite from Naganobori itself (Izawa et al., 2009). They were pelletized with calcium carbonate and the ore pellets were prepared for smelting. A shaft furnace, 97 cm in height and with an inner diameter of 37 cm, was constructed (Fig. 4). About 60 kg of ore pellets and an equal weight of charcoal were used for smelting and slag was tapped three times during a 4 hours and 30 minutes operation.

After the furnace cooled, its upper part was broken and layers of un-melted ore pellets were removed (Fig. 5). Osawa (2008, p. 75) examined the reaction process at the beginning of smelting using one of the pellets. The pellet consists of quartz, kirshsteinite ($CaFeSiO_4$), magnetite, copper and iron, with small amounts of cristobalite, and glass. Copper - with a small amount of iron and magnetite - was formed in a fragment of original malachite (Fig 6) and many minute grains of iron with a small amount of copper were formed in a fragment of original limonite.


**Figure 7.** Photograph showing the 1/2 cross section of a mass of metal (copper and iron), slag and charcoal mixture formed on the furnace bottom. Right side is the center of the mass

A mass of a mixture consisting of copper, iron, slag and charcoal was recovered from the furnace bottom (Fig 7). The whole mass is 30 kg in weight, 35 cm wide and 12 cm thick. Iron-rich Cu-Fe alloy occurs in the upper portion and copper-rich alloy occurs near the bottom.

The iron content of slag decreased from early tapped slag (19 % FeO) to the slag that stayed on the furnace bottom (12 % FeO: Table 1) indicating that the iron-copper alloy reacted with the surrounding slag and extracted iron from the slag on the furnace bottom. Fayalite is the major constituent phase in early tapped slag and ferrowollastonite is the major constituent phase in slag that stayed with metals on the furnace bottom.

The constituent phases of the Cu-Fe alloy are copper, iron and matte (bornite solid solition) and the same as those of the ancient alloys (Figs, 8 and 9). The compositions of the metals and matte are also similar to those determined in ancient materials (some representative compositions are shown in Table 3). Iron contains 1.4 to 2.8 % Cu and 3.9 to 8.8 % As. Copper contains 0.4 to 2.8 % Fe and 0.3 to 3.2 % As. The bornite solid solution consists of two phases, dark phase (57.0 to 59.2 % Cu) and light phase (64.2 to 67.2 % Cu).

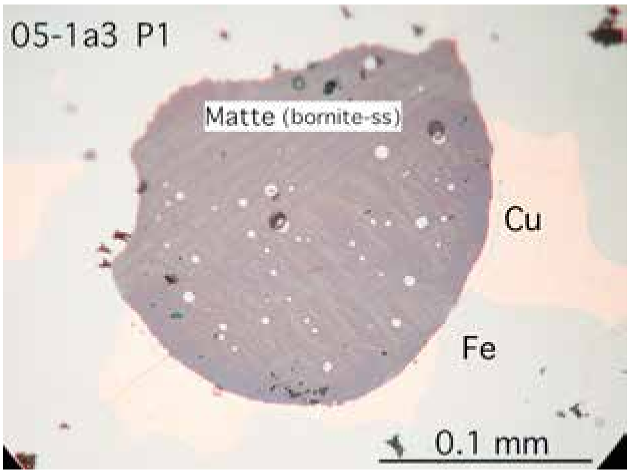


**Figure 8.** Photomicrograph showing the copper-rich metal in the lower part of the mass formed on the furnace bottom. Matte (bornite solid solution) associated with iron and copper. Sample 061105-1a3 (Position 1)

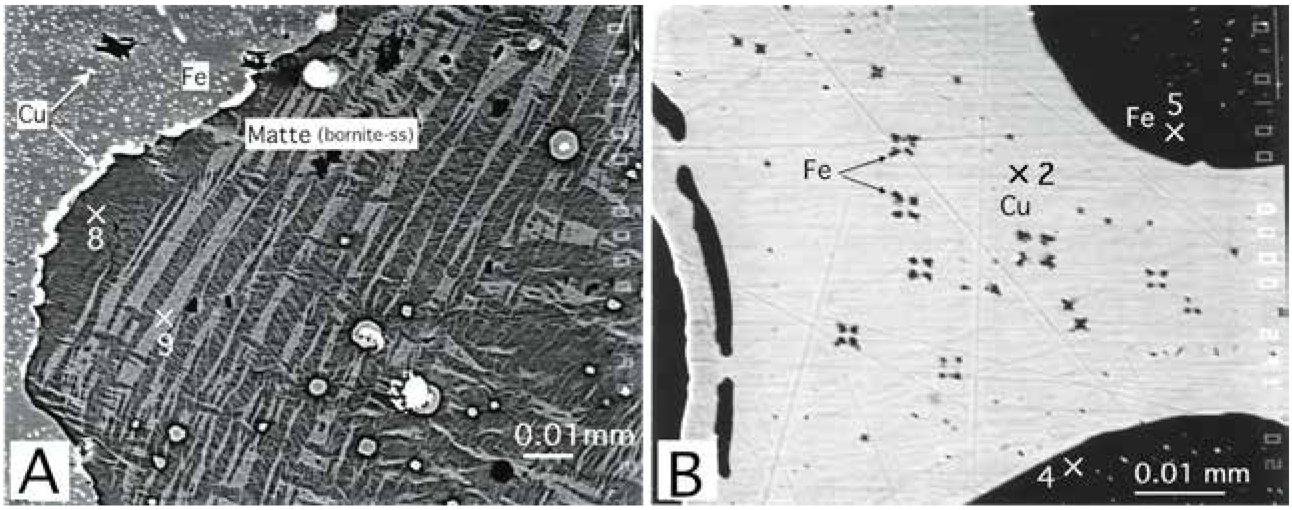


**Figure 9.** Back scattered electron images of sample 061105-1a3 (Position 1). The numbers are points of electron microprobe analyses. (A) Matte (bornite solid solution) shows a complicated exsolution texture. Copper occurs as the rim of the matte and also is scattered as minute blobs in the matrix iron. (B) Iron exsolved as minute stars from the matrix copper

**Table 3.** Electron microprobe analyses of iron, copper and bornite solid solution in the Cu-Fe alloy. Sample 061105-1a3.

| Phase | Iron | | | Copper | | | bornite-ss | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Dark | | Light | |
| Point | P2-15 | P1-4 | P1-5 | P1-2 | P1-3 | P2-17 | P1-8 | P1-11 | P1-9 | P1-12 |
| Cu (%) | 2.77 | 2.31 | 1.98 | 98.86 | 99.09 | 99.71 | 57.49 | 59.22 | 66.23 | 67.25 |
| Fe | 92.66 | 92.67 | 93.36 | 0.87 | 2.05 | 0.94 | 15.74 | 14.50 | 9.71 | 8.08 |
| As | 4.05 | 3.43 | 3.86 | 0.40 | 0.33 | 0.50 | <0.02 | 0.00 | 0.00 | 0.02 |
| Ni | <0.02 | 0.08 | 0.02 | <0.02 | <0.02 | <0.02 | 0.04 | <0.02 | <0.02 | <0.02 |
| Co | 0.12 | 0.16 | 0.12 | <0.02 | <0.02 | <0.02 | <0.02 | 0.03 | <0.02 | <0.02 |
| S | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 26.41 | 26.39 | 24.00 | 23.93 |
| Total | 96.60 | 98.95 | 99.34 | 100.13 | 101.47 | 101.15 | 99.68 | 100.14 | 99.94 | 99.28 |


**Figure 10.** Photographs showing melting of Cu-Fe alloy and waste iron lumps. (A) Melting of Cu-Fe alloy in molten copper in a crucible. (B, C) Residual iron-rich lumps removed from the crucible.

Iron shows a carbon content similar to that of the ancient iron lump (Osawa, 2008, p.64-67) which varied from less than 0.01 % C (ferrite = α-iron) to over 0.77 % C. High carbon steel was formed at the contact place with charcoal and was often associated with $Fe_3P$.

Replication experiments at Naganobori were repeated several times before November of 2006. During the experiment in August of 2006, a miniature (1/30) of the Nara great Buddha was cast at Naganobori using modern copper and tin. At that time a piece of iron-rich copper (180 g in weight), formed in one of the replication experiments, was thrown into molten copper in a crucible as an additional casting metal. The copper dissolved immediately, and three pieces of iron lumps floated on the surface of the molten copper (Fig.10). The iron was removed from the molten copper. The weight of the iron was 120 g, indicating that 60 g of copper were separated from original alloy. The iron was a waste material for the purpose of casting the statue. It is conceivable that iron lumps were similarly thrown away as useless materials in ancient copper casting sites or refining sites.

## Iron lumps from Kajiyashiki

The Kajiyashiki site is an ancient (8th century) workshop for copper casting. The site is located in Kōka-shi, Shiga-ken, near the old capital Heijokyo (Nara). A large number of iron lumps were unearthed from the site, together with copper objects and slag in 2004.

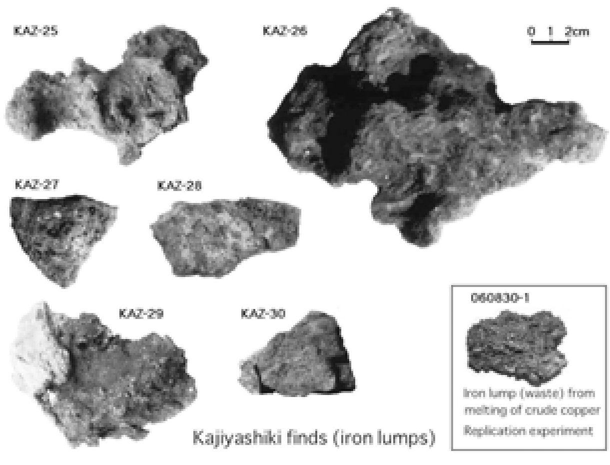


**Figure 11.** Photograph of iron lumps unearthed from Kajiyashiki (Shiga-ken Board of Education, 2006, Plates 121 and 122)

Osawa and Suzuki (2006) reported the results of the metallurgical investigation on seven samples of iron lumps, with sizes ranging from 6 to 18 cm in length and from 75 to 1370 g in weight (Fig. 11). The appearance, size, chemistry and mineralogy of the iron lumps from Kajiyashiki resemble the iron lumps of the replication experiment and from ancient Naganobori. Iron, copper and bornite solid solution were analyzed by electron microprobe (Osawa and Suzuki, 2006, Plates 180 and

181) but the results were expressed as oxides. It was necessary to recalculate the composition as metals and sulfides for comparison with the data of Naganobori slag.

## Discussion

The formation process of the iron lump can be interpreted on the basis of phase relations in the copper-iron-sulfur system by Schlegel und Schüller (1952). In the ancient copper smelting at Naganobori and also in the replication experiment, the ore contained ca. 10 % Cu, 0.1-0.8 % S, and over 20 % of the total Fe with a few % of As. At least three liquid phases coexisted in the furnace at 1200°C, that is, copper-rich liquid, matte liquid and slag liquid. A small amount of sulfur in the copper-rich liquid helped the formation of a Cu-Fe alloy reacting with the iron present in the slag. At around 1300°C, the Cu:Fe ratio in the alloy reached almost 50:50.

During the cooling period the iron (γ-Fe) solidified and separated from the Cu-Fe alloy, leaving copper-rich liquid and a small amount of matte liquid. At around 1077°C the matte solidified as bornite solid solution ($Cu_4FeS_{3.08}$; 62.2 % Cu) (Fig. 12). Below 1000°C this phase was separated into two phases: a Cu-poor phase and a Cu-rich phase.

The coexistence of iron, copper and bornite solid solution is a common feature seen in iron lumps from the ancient Naganobori and the replication experiment (Fig. 12). The iron contains a few % of Cu and the copper contains a few % Fe. The matte phase (bornite solid solution) shows complicated exsolution textures. Although the electron microprobe data of Kajiyashiki do not fit the proper single-phase area on the Cu-Fe-S diagram, the data suggest the existence of two-phase bornite solid solutions (Fig. 12).

The most important factor for the formation of iron lumps is the use of iron rich copper ores and the existence of a small amount of sulfur. Craddock and Meeks (1987, p. 198) emphasized the role of sulfur in significant quantity (>2 %). However, even less than 1 % of S is sufficient for the production of an iron-rich Cu-Fe alloy. In the case of the replication experiment, an iron-rich alloy was produced from the sulfur poor ore (22 % Cu, 77 % Fe and 0.8 % S as calculated ratio). The Cu-Fe-S diagram (Schlegel und Schüller, 1952, p. 424) indicates large compositional range of Cu-Fe alloy (liquid) above 1300°C.

Many skarn deposits have an oxidized outcrop (gossan) which sometimes is rich in copper as at Naganobori. In the higher temperature operation with high fuel ratio, the iron-rich copper ore will be reduced to form a Cu-Fe alloy containing a few % of S. On the furnace bottom the Cu-Fe alloy grows by extracting iron from the surrounding slag (liquid). Products will be iron-containing copper, copper containing iron and a small amount of matte (bornite solid solution). Finally liquid copper and liquid matte with a low melting temperature flow downward leaving a solidified iron lump. This liquation of copper from a Cu-Fe alloy can produce a very iron-rich lump in the upper portion of the mass on the furnace bottom.

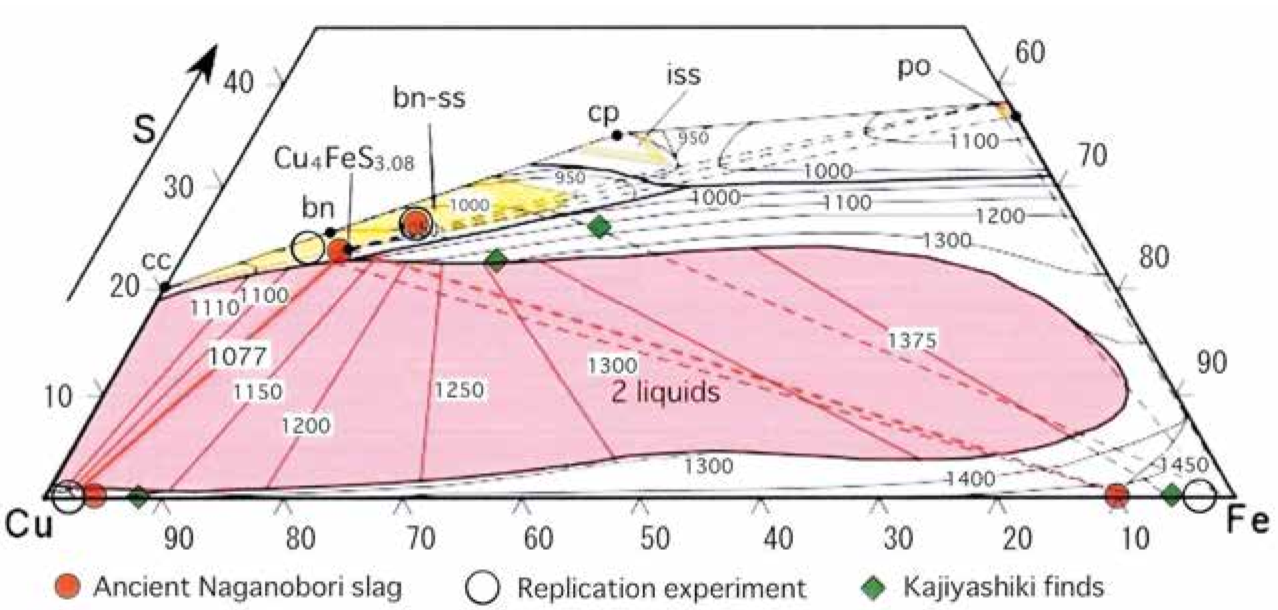


**Figure 12.** Plot of the compositions of iron, copper and bornite solid solution on the Cu-Fe-S diagram of Schlegel und Schüller (1952). Representative compositions of phases were selected for the iron lump in the ancient Naganobori slag (sample 030820-17a) (Table 2), the Fe-Cu alloy formed from the replication experiment (sample 061105-1a3) (Table 3), and iron lumps from Kajiyashiki remains (Osawa and Suzuki, 2006, Plates 180 and 181). The stable phase at 1077˚C, $Cu_4FeS_{3.08}$, is shown by small dot. The lower temperature phases are bornite solid solution (bn-ss), intermediate solid solution (iss), pyrrhotite (po; $Fe_{1-x}S$), chalcocite (cc; $Cu_2S$), bornite (bn; $Cu_5FeS_4$) and chalcopyrite (cp; $CuFeS_2$)

Crude copper produced from iron-rich copper ore contains several % of iron which will be lowered to about 0.5 % by simple remelting (Craddock and Meeks, 1987, p. 192). Refining by simple remelting was probably a necessary process in copper-casting workshops such as Kajiyashiki. If crude copper contained an iron rich Cu-Fe alloy, the iron lumps would float on the molten copper during remelting. The separated lump of iron was a waste material and was rejected around the casting site.

## Conclusions

1. Iron lumps are frequent by-products from smelting iron-rich oxidized copper ores.
2. The important factor for the formation of iron lumps is the presence of a small amount of sulfur in higher-temperature reducing conditions.
3. Sulfur remains as matte (bornite solid solution) coexisting with copper and iron.
4. The bornite solid solution has the average composition of about 62 % of Cu and shows a lamellar texture formed during cooling.
5. The carbon content of the iron lumps varies from less than 0.01 % C (ferrite = α-iron) to over 0.77 % C.

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# Mass and heat balance of pig iron making by Tatara

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*ABSTRACT* Tatara was the Japanese traditional technology for making pig iron and high carbon steel bloom in a row. The furnace is made of clay in box type with 1.2m height, about 3m length and about 1m width. In one campaign of about 70 hours, 1.5 tons of pig iron called "Zuku" and 1.5 tons of high carbon steel bloom called "Kera" were produced from 12 tons of iron sand and 12 tons of charcoal. "Noro" was fayalite slag composed of about 35 mass% silica and about 55 mass% FeO including about 10 mass% $TiO_2$. The silica came about 40% from iron sand and about 60% from clay of furnace. The clay in the lower part of furnace was eroded by "Noro" and the thickness of lower part of wall gradually became thin. After about 70 hr, the furnace was broken. About 50% of iron in iron sand became pig iron and bloom and the other became "Noro". Almost 50% of oxygen in blown air passed through the furnace without burning charcoal. About 50% of heat produced from charcoal burning was wasted in out gas, about 20% was radiated from furnace wall and about 10% was the latent heat of slag and about 10% was that of pig iron and bloom. The fuel ratio was about 4 and the heat efficiency of Tatara was almost same as a charcoal blast furnace in Europe in 18 century.

## The History of Tatara

Tatara is the Japanese traditional technology for making pig iron and high carbon steel bloom in a row. The technology of Tatara was transferred from China to Japan through Korea in the late 6th century AD and was perfectioned in the Middle Edo Period. The commercial production of Tatara ended in 1923, but the old Japanese army continued to produce it until 1945, at the end of World War II, in order to obtain good quality steel, the so called "Tama Hagane", for making Japanese swords. In 1969, 24 years after the end of the Tatara production in 1945, the Iron and Steel Institute of Japan reconstructed the "ISIJ Tatara" furnace in the Sugaya village, Shimane prefecture, and studied the operation technique. In 1977, the Society for Preservation of Japanese Art Swords reconstructed the "Nitoho Tatara" in Yokota, Shimane prefecture. Since then, Tatara furnaces have been in action for 3 campaigns in every winter season.

## The Construction of Tatara furnaces

The Tatara furnace is made of clay, and is of box type, with 1.2m height, about 3m length and about 1m width (fig.1). They have 40 tuyeres installed in the lower part of the two longer walls. Cold air is blown through bamboo pipes, called "Kiro Kan", from a distributor, called "Tsuburi"(fig.2). Two bellows, called "Tenbin Fuigo", actioned by human power are installed on both sides of the Tatara furnace (fig.3). Very fine powder of iron sand and charcoal lumps are loaded every 30 minutes. Until 1945, in one campaign of around 70 hours, 1.5 tons of pig iron called "Zuku" and 1.5 tons of high carbon steel bloom called "Kera" were produced by employing 12 tons of iron sand and 12 tons of charcoal. Since 1977, the "Nitoho Tatara" has produced 2.5 tons of "Kera" and some "Zuku" from 10 tons of iron sand and 10 tons of charcoal.

## Underground construction

In order to obtain a high temperature zone in the furnace and because of the endothermic reaction, humidity should be prevented from vaporizing inside the furnace. The underground construction of the Tatara furnace is called "Tokotsuri" (fig.4) and is divided in upper and lower part by a "Kawara", a dense clay layer in which water does not penetrate. In the upper part, there is a "Hondoko", consisting of a charcoal bed under the Tatara furnace, and two "Kobune" (tunnels) on both

**Figure 1** Nitoho Tatara operation for producing 2.5 tons of high carbon steel, “Kera”, during 3 days and nights, in Shimane pref., Japan

**Figure 2** 20 tuyere in the lower part of furnace wall, 20 pipes and a distributor of blowing air

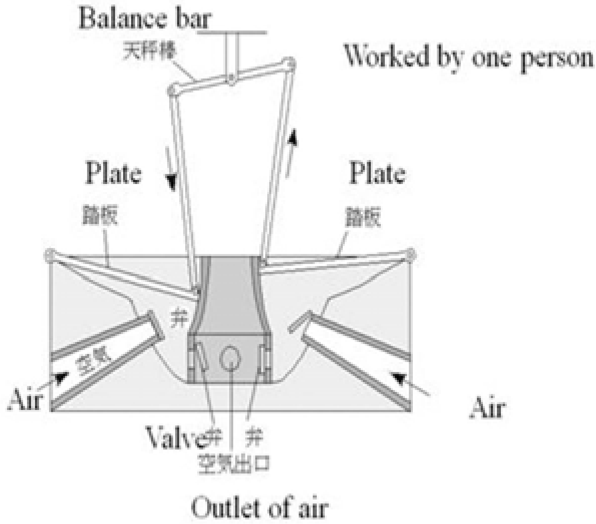


**Figure 3** Tenbin Fuigo blower

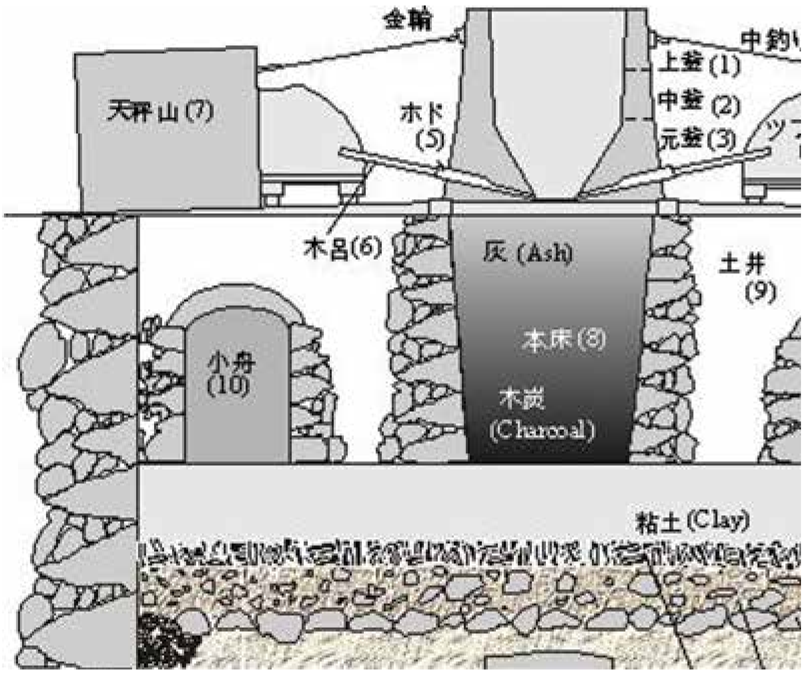


**Figure 4** Construction of underground of Tatara

sides of the furnace. The upper system has the function of drying the furnace during the operation. The charcoal of the “Hondoko” absorbs water from the clay of the furnace and acts as an insulator. As the “Kobune” is always kept at about 40 during the operation, heat and humidity flow from the furnace to the “Kobune” and disperse outside. In the lower part, under the “Kawara”, there are layers of charcoal, a mixture of stones and sand, and a drain in the center of the bottom. The lower system had the function of stopping and draining water from the underground.

## Power of the bellows

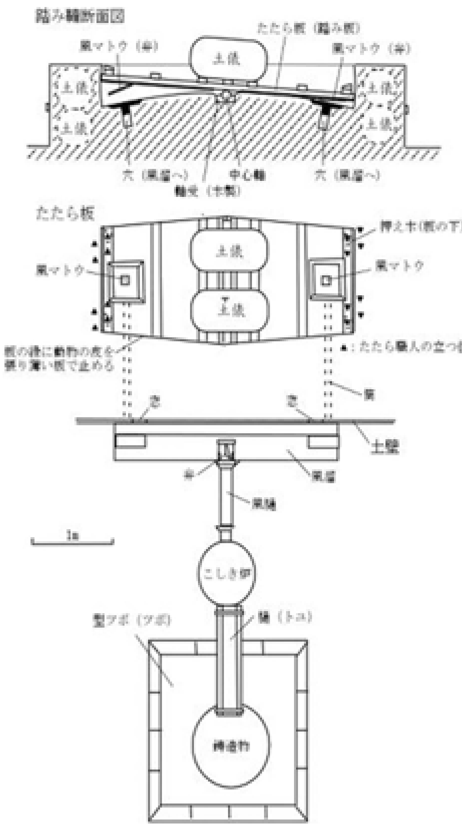

**Figure 5** Fumi Fuigo blower for melting furnace in Meiji period

In ancient times in Japan, the box type bellow with a piston, called “Fukisasi Fuigo”, was used. In the middle ages, a seesaw type bellow called “Fumi Fuigo” (fig.5) was used. In 1719, the “Tenbin Fuigo” bellow (fig.3) was invented and the air blowing improved. One or two workers, called “Banko”, stood in the center of the bellow and pushed two wooden pedals that activated it. The workers on both “Tenbin Fuigo” bellows pedaled according to the frequency of the human breath, and coordinated by the rhythm of the Tatara song. Professor Kuniichi Tawara[1)] investigated the Tatara works and their operations in the late of Meiji period. The size of one wood plate in “Kotoribara Fumi Fuigo” was 1590 mm x 848 mm and the maximum depth of step was 315 mm. Therefore, the volume of air from one step was 0.212 $m^3$. In the case of the “Tonami” Tatara furnace, with 38 tuyeres on both sidewall, the step rate was 28 times per minute in the early stage of operation and 40 times per minute in the final stage. The maximum rate of blowing was 7.44 l/s per each tuyere. The pressure of air was around 3cm water column, i.e. 294 Pa. The force on one plate was 40.4kg-force and corresponded to a human weight. In the case of the “Ataidani Tatara” in Iwami, the maximum rate of blowing was 9.44 l/s per tuyere and the force on one wooden plate was 39.6 kg-force.

## Soft blowing of air preventing iron sand from flying out

In order to prevent the iron sand from flying out, the air had to be blown softly into the furnace. Iron sand and charcoal were also loaded next to the furnace walls so that the high temperature gas passed through the center of the furnace (fig.6). The internal lower part of the furnace had a V shape, and a set of 2 narrow tuyeres faced each other. A strong air blast came into the narrow tuyeres in order to produce a high temperature zone in the burning charcoal. When around 20 parallel sets of tuyeres were installed, the Tatara furnace acquired a box type shape.

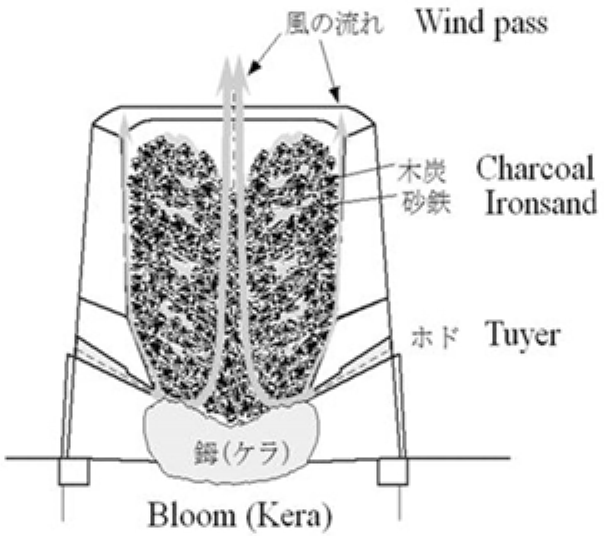


**Figure 6** Load of iron sand and charcoal and flow pass of high temperature gas in the Tatara furnace

## High oxygen potential for the reduction of iron sand

High temperature gasses, such as CO, $CO_2$ and $N_2$, were produced by burning charcoal in air. The oxygen partial pressure in front of a tuyere is about $1x10^{-12}$ atm at around 1350°C [2)]. Under this atmosphere, only iron oxide is reduced to iron and the impurities dissolve as oxides into the molten slag, called "Noro". Thus, "Zuku" and "Kera" have less impurities (see table 1). In spite of the high oxygen potential, reduced iron powder in contact with burning charcoal absorbs carbon very fast. Thus, molten pig iron - the "Zuku" and then a bloom - the "Kera"- are rapidly produced in around 40 minutes (fig. 7).

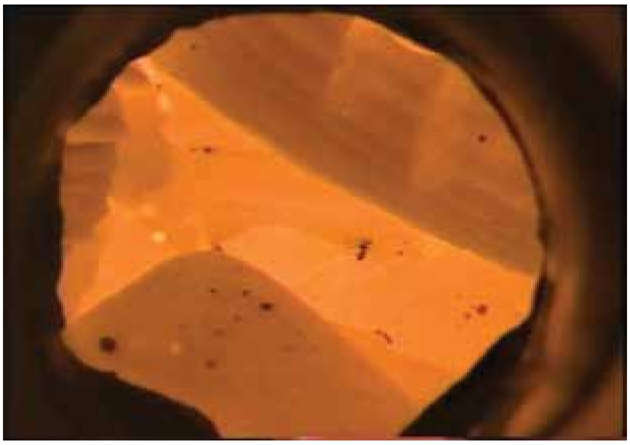

**Figure 7** Production of pig iron on burning charcoal: bright dots are pig iron particles

**Table 1** Compositions of pig iron "Zuku" and bloom "Tamahagane" (mass%)

| Composition | C | Si | Mn | P | S | Ti |
|---|---|---|---|---|---|---|
| Zuku | 3.63 | Trace | Trace | 0.10 | 0.003 | Trace |
| Tamahagane | 1.32 | 0.04 | Trace | 0.014 | 0.006 | Trace |

Note: "Tamahagane" is a good quality steel in the "Kera".

## Tatara flame

Air is cyclically blown into the furnace with the rhythm of human breath, and the flame also cyclically rises at the top of the furnace (fig.8). The condition of the Tatara operation can be judged by the color of the flame, the flowing pattern of "Noro", the round shape of the inside of the tuyeres, and the sound coming from the furnace. Fig. 9 shows the flowing pattern of "Noro" poured from the holes on both sides of the furnace.

**Figure 8** Flame on Tatara furnace

**Figure 9** Pouring slag, called "Noro", and blowing flame from holes at the bottom of furnace

The color of the flame most sensitively changes depending on the furnace condition. There are 4 types of flame color. The best condition produces a golden colored flame, the so-called "Yamabuki Bose" or "Kiwada Bose". "Bose" means flame. An overload of iron sand is the cause of a blackish flame, called "Kuro Bose". On the other hand, an insufficient load of iron sand renders the flame reddish, and it is called "Aka Bose". By these means, the amount of loaded iron sand could be controlled. When a tuyere is clogged and the air cannot pass through, the color of the flame becomes bluish or purplish, and it is then called "Yakan Bose". In this case, the tuyeres are opened with an iron stick, called "Hodo Tuki", and repaired so as to achieve a round shape that looks like the moon.

The yellow color of the flame results from the D line of the spectrum of sodium, when sodium oxide is vaporized in the flame. The sodium oxide ($Na_2O$) is included in charcoal ash as stable sodium silicate slag. In this case, the flame is bluish or purplish. When iron sand is loaded, the iron oxide (FeO) dissolves in the silicate slag that turns to fayalite slag; then the activity of sodium oxide in the slag and the vapor pressure increase. During a campaign, the flame color gradually changes from the color of sunrise in the early operation stages to the sunset color in the last stage. The master of the Tatara operation, the so called "Murage", carefully controls the condition of the Tatara furnace.

## ISIJ Tatara

The Iron and Steel Institute of Japan reconstructed the "ISIJ Tatara" furnace and worked 3 campaigns to produce "Zuku" and "Kera" from October 25 to November 8 in 1969. The committee for the planning of the Tatara reconstruction in ISIJ (1st chairman Prof. Takao Sasabe and 2nd Prof. Yukio Matsushita) was

**Table 2** The sizes of furnace and underconstruction of some Tatara works

| Name of Tatara | Tatara furnace | | | | Underground construction | | |
|---|---|---|---|---|---|---|---|
| | Height (m) (center, end) | Length (m) | Width (m) (center, end) | Number of Tuyeres | Depth (m) | Length (m) | Width (m) |
| ISIJ | 1.10, 1.10 | 2.65 | 0.93, 0.72 | 32 | 3.18 | 6.36 | 6.36 |
| Nittoho | 1.10, 1.20 | 2.70 | 0.87, 0.76 | 40 | 3.20 | 5.50 | 6.45 |
| Tonami | 1.165, 1.120 | 2.967 | 0.860, 0.755 | 38 | | | |
| Ataidani | 1.100, 1.150 | 2.485 | 0.665, 0.515 | 32 | | | |

**Table 3** Weights of ironsand, charcoal and "Zuku", "Kera" and "Noro" for some Tatara works (Unit: kg)

| Tatara | No. | Run Time | ironsand | charcoal | Zuku | Kera | Noro |
|---|---|---|---|---|---|---|---|
| ISIJ | 1 | 76hr04min | 6,656.6 | 7,566.9 | 210 | 1,750 | |
| | 2 | 71hr21min | 7,228.1 | 7,689.4 | 310 | 1,380 | 4,804 |
| | 3 | 68hr45min | 5,722.5 | 5,686.9 | 165 | 700 | |
| Nittoho | | 70hr* | 7,878 | 11,930 | 176 | 1,194 | 5,542 |
| | | 70hr# | 10,233 | 10,545 | 34 | 2,292 | |
| Tonami$ | | 66hr27min | 12,825 | 13,500 | 790 | 2,810 | 15,200 |
| Ataidani$ | | 85hr20min | 18,075 | 18,000 | 4,500 | 337 | |

*: in 1977, #: Average values of 3 campaign in 1999, $: in 1894

nominated in 1967. The masters of Tatara - or "Murage" - were Mr. Yoshiro Horie (83 years old), Mr. Kenjiro Honma (70) and Mr. Daizo Fukuba (83).

Table 2 illustrates the sizes of the furnace and the underground construction of 5 Tatara works. The furnace size of the ISIJ Tatara was 1.1m height, 2.65m length and 0.93m width, and that of the underground construction was 3.18m depth, 6.36m x 3.36m square. These sizes are not so different from those of other Tatara furnaces. The tuyeres were 32 less than in the "Nittoho Tatara". Air was continuously blown through the tuyeres by an electric bellow. This version was very different from other Tatara.

## Mass balance

The weights of iron sand, charcoal and produced "Zuku", "Kera" and "Noro" for some Tatara works are shown in Table 3. The mass balance for the ISIJ Tatara in the 2nd run was calculated. The amount of dissolved wall was estimated. 4,804kg of Noro was composed of 686.5kg in the first half run, called "Komori" in 22 hrs, 46 min; and 4,117.5kg in the late half run, called "Kudari", in 48 hrs 35 min. The compositions of "Noro" of the first and late run were 29.57 mass% and 21.11 mass%, respectively. The amount of $SiO_2$ in the "Noro" was 1,072 kg. 1,900 kg of iron sand, named "Akome kogane", was loaded during the "Komori" period and 5,328 kg of iron sand named "Masa kogane" was loaded during the "Kudari" period. The $SiO_2$ in iron sand was 9.24 mass% in the "Akome kogane", and 4.24 mass% in the "Masa kogane", respectively. The amount of $SiO_2$ in iron sand was 401 kg. The difference of $SiO_2$ in the 671 kg came from the dissolved wall. The composition of $SiO_2$ in the wall clay was 66.03 mass%. Therefore, the amount of dissolved wall was 1,016 kg.

The total iron in the "Akome kogane" and the "Masa kogane" were 54.06 mass% and 61.21.mass%, respectively. The amount of iron in iron sand was 4,288 kg. The composition of $Fe_2O_3$ in the wall clay was 2.50 mass% and the amount of iron from the dissolved wall was 25 kg. Thus, the amount of input iron was 4,313 kg. On the other hand, the iron in "Zuku" was 96.0 mass% and the amount of iron in 310 kg of "Zuku" was 299 kg. The iron in "Kera" was 99.142 mass% and the amount of iron in 1,380 kg of "Kera" was 1,368 kg. The total iron in "Noro" during the "Komori" and "Kudari" periods was 35.29 mass% and 46.50 mass%, respectively. The amount of iron in "Noro" was 2,157 kg. Thus, the total amount of iron in output was 3,824 kg. The difference of iron between input and output was 489 kg. This difference could be the amount of iron sand flying out and corresponds to 11.5 mass% of loaded iron sand. The loss of iron sand is caused from continuous blowing of air because of 1.69 mass% for cyclic blowing by "Tenbin Fuigo".

The amount of emitted gas was also calculated. The consumed charcoal was 7,689 kg. The composition of carbon in charcoal was 92.19 mass% and the amount of consumed carbon was 7,088 kg. The carbon in "Zuku" and "Kera" was 3.50 mass% and 0.80 mass%, respectively, and the amount of carbon dissolved in "Zuku" and "Kera" was 22 kg. Thus, the amount of burned carbon in air was 7,066 kg. The emitted gas was sampled inside at about 20 cm from the furnace wall and at 20 cm from the top of the furnace. The average of CO, $CO_2$, $H_2O$ and $N_2$ in the "Komori" period was 30.7%, 4.4%, 0.9% and 64.0%, respectively, and that in the "Kudari" period was 27.2%, 3.6%, 0.9% and 68.35%, respectively. The emitted gas shows that iron is thermodynamically stable and iron sand is reduced to iron at the temperature between 800℃ and 1,500℃.

Burned carbon of 588.8 kmol (7,066 kg) consumed air of 42,340 $m^3$ at 21.5℃. On the other hand, as the rates of blown air in the "Komori" and "Kudari" periods were 720 $m^3$/hr and 1,548 $m^3$/hr, the total amount of blown air was 91,600$m^3$. Thus, about 50% of air passed through the furnace without burning charcoal. In the case of cyclic blowing, only 10% of air passed without reaction.

## Heat balance

The heat balance for the second run of the ISIJ Tatara operation was reported[3)] as shown in Table 4. 95% of the generated heat was the burning heat of charcoal and about 50% of the dispersed heat was the latent heat of emitted gas. Radiation heat from the furnace wall was about 20%, latent heat of the Noro was about 10% and the heat in the furnace at high temperature was 10%.

**Table 4** Heat balance of 2nd run of ISIJ Tatara

| | Kind of heat | Heat | |
|---|---|---|---|
| | | kJ | % |
| Input heat | Burning heat of charcoal | 4,018,950 | 95.5 |
| | Reduction heat of iron ore | 28,000 | 0.7 |
| | Production heat of "Noro" | 160,740 | 3.8 |
| | Total | 4,207,690 | 100.0 |
| Output heat | Latent heat of "Noro" | 459,250 | 10.9 |
| | Latent heat of "Zuku" | 21,530 | 0.5 |
| | Decomposition heat of $H_2O$ in air | 114,760 | 2.8 |
| | Latent heat of out gas | 2,180,350 | 51.8 |
| | Radiation heat from furnace wall | 240,410 | 5.7 |
| | Heat loss from bottom of furnace | 598,560 | 14.2 |
| | Heat in furnace and "Kera" | 592,830 | 14.1 |
| | Total | 4,207,690 | 100.0 |

## Conclusions

"Noro" is fayalite slag and consists of around 35 mass% of silica and about 55 mass% of FeO, including about 10 mass% of $TiO_2$. About 40% of the silica came from iron sand and about 60% from the clay of the furnace. In the lower part of the furnace the clay was eroded by "Noro" and the thickness of the lower part of the wall was gradually reduced. After about 70 hr, the furnace was broken.

About 50% of iron from the iron sand became pig iron and bloom and the rest became "Noro". Almost 50% of oxygen in the blown air passed through the furnace without burning charcoal. About 50% of the heat produced from charcoal burning was wasted as gas emission, about 20% was radiated from the furnace wall, around 10% was the latent heat of slag and about 10% was that of pig iron and bloom. The fuel ratio was about 4 and the heat efficiency of Tatara was almost the same of a European charcoal blast furnace of the 18th century.

Tatara is the only smelting furnace in the world that produces molten pig iron and a large bloom from fine powder of iron sand by using a soft blow of air. The flame of the Tatara is a very important signal that allows the control of the operative condition, as are also the fluidity of slag, the sound from the furnace and the round shape of the tuyere.

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# Manufacture, use and trade of late prehistoric iron billhooks from mainland Southeast Asia

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*ABSTRACT* As part of ongoing research, this paper focuses on the billhooks from Ban Don Ta Phet, a protohistoric cemetery in West Central Thailand. The tools are of such a distinctive type, that it was felt that they could provide an opportunity to track their occurrence over a broad area thus helping to place BDTP within a wider context. Their shape suggests a specific function which might help to increase the understanding of the activities practiced by the individuals buried at the cemetery, be they farmers or merchants from a settled community within close proximity or perhaps a travelling community of traders or migrants. Questions were therefore: What were these billhooks used for? Who were they used by? Where were they made?

## Introduction – Archaeological background

Distinctive iron billhooks (Fig.1), dated to the 4th century or early 3rd century BCE were among the 350 identifiable iron tools and weapons excavated in the 1980's at the protohistoric Iron Age cemetery of Ban Don Ta Phet (BDTP) in Kanchanaburi Province in west central Thailand (Glover et al. 1984; Glover 1990a, Natapintu 1976). The site has produced by far the largest corpus of iron objects from any protohistoric site in mainland Southeast Asia and because virtually all of the objects were derived from a controlled archaeological context (Fig.2), which clearly places them firmly at the beginning of the Iron Age, the site has provided ideal material to: -

- Document the technology used in the 4th century BCE or early 3rd century BCE.
- Investigate whether the raw iron material was produced using fairly standardised manufacturing techniques.
- Assess to what degree the manufacture of the objects was consistent within each of the different categories and between them: - socketed digging sticks, bill hooks/ sickles, axes, flat chisels, hollow based arrowheads, socketed arrow heads, tanged arrowheads, harpoons, fish hooks, tanged spearheads, socketed spearheads, tanged knives, tanged rods, ferrules and nails (Bennett 2013a Table 10.1).
- Determine whether the objects which appeared visually similar, were indeed manufactured in the same manner.
- Determine whether the socketed and tanged tools of a particular type, such as the digging sticks, were manufactured in different ways.
- Document whether the more sophisticated and rarer weapons such as the socketed spears were manufactured with a greater degree of skill than the simpler and commoner digging sticks.
- Determine whether there was any evidence of hardening of the working edges or of any heat treatment of the metal.
- Determine whether the objects showed evidence of having been used over prolonged periods of time prior to burial.
- Document the deliberate mutilation which was undertaken of certain objects.
- Assess any evidence as to whether the smelted iron was traded as a raw material, which was then locally forged into the desired tools and weapons.
- Assess the evidence as to whether the smelting and the smithing were both undertaken at central locations with the finished objects being traded to the surrounding areas.

**Figure 1** Photograph showing the different sizes of billhooks from BDTP 72 (3263), 81 (1285) and 46 (614). Photo Seán Goddard

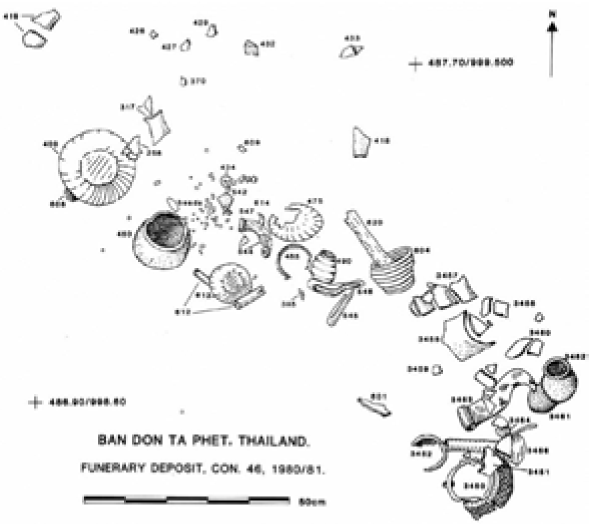


**Figure 2** Drawing of Burial 46, a rich burial with a wide range of artefact types, including 3 iron billhooks, 1 blade, 1 spearhead, 4 digging sticks, 1 possible chalcedony shouldered axe, 12 bronze bracelets, 1 bronze bird figurine, 1 bronze cage, 5 bronze bowls, 1 bronze lid, and numerous agate, carnelian, crystal and glass beads, 1 fragment of human bone (lower arm) and 1 complete pottery vessel. Drawing reproduced courtesy of Ian Glover

## Technology and manufacturing techniques

Because of the long-term preservation problems, the iron objects were carefully documented using photography, illustration and x-radiography. Since it was acknowledged that there were not the resources to allow for long-term preservation of all the material, generous permission was granted by the Thai Fine Arts Department to undertake an extensive sampling program for metallography. Thirty objects were chosen for study either because they were highly representative of a category of object or because they were highly unusual.

Based on this detailed metallographic study, Bennett concluded that the tools and weapons were all forged from good quality bloomery iron. The iron was composed of a piled structure consisting of layers of carbon free ferrite and layers composed of ferrite surrounded by pearlite containing up to 0.7 % carbon (Fig. 3). Regularly aligned slag stringers which ran the length of the samples clearly indicated the direction of working and in some of the more complicated shapes, such as the spearheads, the orientation of the layers and the elongated slag filaments had become contorted during forging (Bennett 2013b Fig. 7).

The manufacture of all of the objects investigated was fairly standardized. The objects which appeared visually similar, were indeed manufactured in the same manner and although the more sophisticated and rarer weapons such as the socketed spears were manufactured with a greater degree of skill than the simpler and commoner digging sticks, the quality of the iron and method of forging remained essentially the same for the whole range of implements.

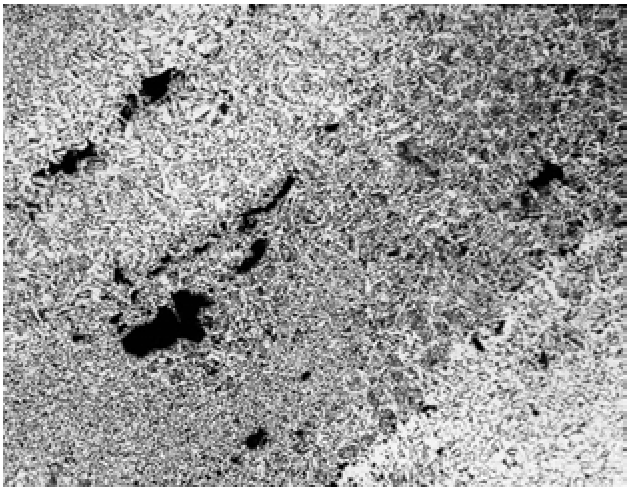

**Figure 3** Photomicrograph showing layers of carbon free ferrite and layers containing up to 0.7 % carbon composed of ferrite surrounded by pearlite

The carbon present in the finished objects was undoubtedly derived from the charcoal fuel used as a reducing agent during the smelting operation and there was no evidence of any attempt to carburise the working edges of the tools or the weapons. Rather, what seems clear from Bennett's metallographic study, is that a certain amount of decarburisation during forging was routinely accepted. During hot working some decarburisation would invariably have occurred at the surface of the objects due to the oxidising conditions in the forge and the location and depth of the decarburised surfaces have provided some information as to the manner in which the objects were manipulated during the smithing. Hammering appears to have been most frequently undertaken from one side, causing the hammered surface to become decarburized (Fig.4). Where both surfaces of the object had become decarburized, one surface was invariably more depleted in carbon than the other. The outer edges of the decarburised surfaces were usually composed of distorted, ragged ferrite grains with spheroidised pearlite at the grain boundaries, a structure typical of material forged in a falling temperature and left to cool very slowly from about 450ºC, - possibly in the hot ashes of the forge or at the edge of the smith's fire. In other samples, Bennett observed austenite grain boundaries and Widmanstätten plates indicating that the objects were forged at a temperature above 850°C and subsequently rapidly air-cooled from this temperature (Fig. 5). Since the working edges of the finished items are invariably thinner than the main body of the objects, these edges would naturally have cooled more rapidly than the matrix. During the final stages of manufacture the thinner edges appear to have been reheated for short periods and worked at a temperature below 723°C with the reheating time being sufficiently short to cause the pearlite in the worked areas to spheroidise, while leaving that in the unworked areas intact.

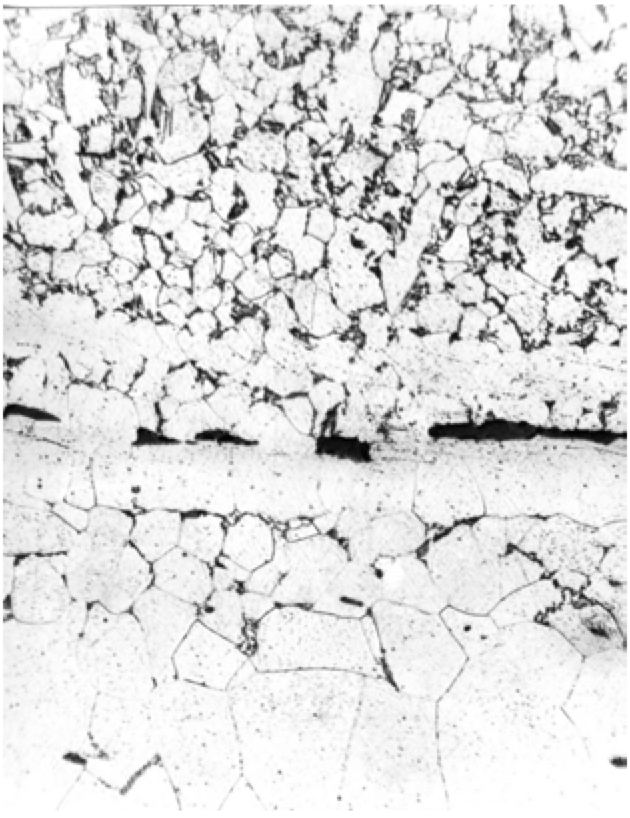

**Figure 4** Photomicrograph showing the outer edges of a decarburised surface composed of distorted, ragged ferrite grains with spheroidised pearlite at the grain boundaries

**Figure 5** Photomicrograph showing austenite grain boundaries and Widmanstätten plates indicating forging at a temperature above 850°C and subsequent air-cooling

## Evidence of use prior to burial

The comparison of the metallographic structures of the samples removed from the working edges of the objects to those removed from the non-working areas, indicate that the soft wrought iron which was invariably present in the non-working areas was notably absent from the samples removed from the working edges. This absence may be the result of an intentional sharpening of the tools. Alternatively the objects may simply have been used over a sufficient period time so as to afford complete removal of the decarburised zone from the working edge, thus exposing the harder more carbon-rich material.

While it has not been possible to confirm that there was no intentional hardening of the working edges of the objects, the hardness values of Hv 165 - Hv 191 in the main portion of the metallographic sections and Hv 102 - Hv 125 in the lower carbon areas suggests that no significant work hardening was undertaken. A certain amount of cold working and a corresponding increase in the hardness of the metal was recorded in some instances where hardness values of 140 in the decarburized areas were higher than the hardness in the body of the sample. This increase reflects a degree of work-hardening, which probably occurred during the normal use of the tool.

## Deliberate mutilation

Evidence of the mutilation of objects from BDTP included 2 out of 23 arrowheads, 15 out of 41 blades, 1 out of 92 digging sticks, 1 out of 8 rods, and 13 out of 23 spearheads (Bennett 2013a Fig.10.8). This mutilation, which involved folding the iron back on itself may have been undertaken as a way of preventing looting by grave robbers or was perhaps associated with religious beliefs. Examination of the metallography of a selection of these items has helped to determine that the objects were used prior to the mutilation rather than, as practiced in the European Viking period, manufactured purely for ritual purposes and never intended for use. Iron blades and spearheads are the two major artefact types that were mutilated, indicating that this was a practice largely reserved for the more prestigious objects rather than the more utilitarian ones. Glover (1990a) and Woods (2002) have identified possible groupings of the BDTP graves into kinship links, which may be seen as the beginnings of social hierarchy and they have documented mortuary differentiation in terms of the variety of materials used within the burials.

The metallographic structures of the samples removed from these deliberately "killed" objects indicated that the bending back process was undertaken in the hot state, rather than in the cold state, suggesting that the people undertaking the mutilation had some knowledge of and access to forging facilities. However because BDTP cemetery is a secondary burial site, where the burials were re-interred with their accompanying objects in a manner to imitate primary burial, the deliberately "killed" objects may have been mutilated before being brought to the area for deposition. Excavations were able to identify a bank and ditch enclosure of the site and C14 dates indicate that all the reburials occurred either as a single event or were undertaken within a short period of time (Glover 1990a, Glover and Bellina 2012).

## Evidence as to whether the finished objects were traded to the surrounding areas

In view of the large numbers of iron artefacts recovered at Ban Don Ta Phet, it is tempting to envisage a local smelting and smithing centre. However, since its discovery in the late 70's and repeated excavations between 1980 and 2000, there is no evidence of any associated settlements or manufacturing sites in the surrounding areas. Since the smelting of iron necessarily generates substantial quantities of waste products in the form of slag, refractory furnace wall and tuyère fragments, any smelting sites within the vicinity should be reasonably easily identifiable. Further, although iron minerals in the form of lateritic stones are found abundantly throughout Thailand, these have a low iron content and Pryce and Natapintu (2009) have argued that such an ore resource would not have proved sufficient for successful smelting. However, based on the analysis of the large amount of smelting slag excavated from seventeen insitu furnaces at the 4th – 2nd centuries BCE moated site of Ban Don Phlong in the Mun valley in Northeast Thailand and at excavations at Non Ban Jak, a late prehistoric cemetery close to Phimai in Northeast Thailand this view is not necessarily accepted (Nitta 1991, 1997, Higham 2014). An alternative potential source might be the rich iron ore deposits of the Wong Prachan valley in the central plains of Thailand, 200 kms Northwest of BDTP which has significant deposits, although there is as yet no evidence of any iron smelting at this date (Bennett 1989; Pigott, Weiss and Natapintu, 1997).

Based on ethnographic parallels our present understanding of the organisation and division of labour in the iron industry is that in many societies, smelting and smithing did not occur in the same production centre. Rather, the customer needing an object acquired the raw iron and supplied it to the smith who contributed his skill in return for part of the raw material as payment (Marschall, 1968, 150). Raw iron may have been imported to the BDTP surrounding area and the objects forged locally according to particular requirements or alternatively, the iron objects themselves may have been imported to the region in the same manner as the sophisticated and rare artefacts such as the high tin bronze bowls, which are thought to be the result of trade with India (Rajpitak and Seeley 1979, Srinivasan and Glover 1995, Glover and Bennett 2012, Glover I.C. and Shahnaj Husne Jahan 2014).

The earliest written evidence of maritime trade between India and Southeast Asia comes from an ancient Chinese text known as 'The History of the former Han dynasty 206 BCE – 25 CE which was written in 32 – 92 CE and which contains a passage describing Han envoys sailing from the modern province of Guangdong to India with the aim of buying luxury goods such as pearls and opaque glass. Another passage in the same text describes the Han court's failed attempt to open the overland trade route leading to Daxia (Bactria) by pacifying the southwestern barbarians. Still another Chinese account written before 91 BCE clearly indicates that the Sichan –Yunnan – Burma – India overland trade route was in use in the 2nd century BCE (Laichen 1997). It therefore seems possible that the techniques of iron working may have been introduced to Southeast Asia via these merchants who were seeking raw materials, such as the plentiful gold ores (Bennett 2010a and 2010b).

The reburial of the individuals at BDTP belongs to a period of transition between the Bronze Age tradition of inhumation burial in Southeast Asia and cremation, which marks the adoption of Indian ritual culture (Glover and Bellina, 2012). A period which coincides with the first appearance of iron in Southeast Asia's archaeological record (Higham and Higham 2009:table 2) and is also about the time that gold, semiprecious stone polishing and glass working first appear. Since no significant numbers of iron artefacts have been found anywhere else in the area in the last 30 years, and given BDTP's geographical location, close to the Myanmar border and the overland trade route through the Three Pagoda Pass and to India beyond it seems quite possible that some of the iron objects found at BDTP could have been imported along this route. Indeed socketed iron spearheads, which are very similar in appearance to those excavated at BDTP, have been found in the Samon Valley in Myanmar (Bennett 2013a: Fig. 10.17, Htin 2007) and indeed Myanmar has very extensive resources of viable iron ores.

## The billhooks and their archaeological context

As part of ongoing research, this paper focuses on the billhooks from BDTP (Figs. 1, 2, 6). In the first instance because they are such a distinctive object type, it was felt they would provide an opportunity to track their occurrence over a broader area and help place the site within a wider context. Further, since their shape suggests a specific function, ethnographic analogies could increase our understanding of the activities practiced by the individuals buried at BDTP, be they farmers or merchants, from a settled community within close proximity of the cemetery or a travelling community of traders or migrants. Questions were therefore: What were these billhooks used for?, who were they used by ? and where were they made ?

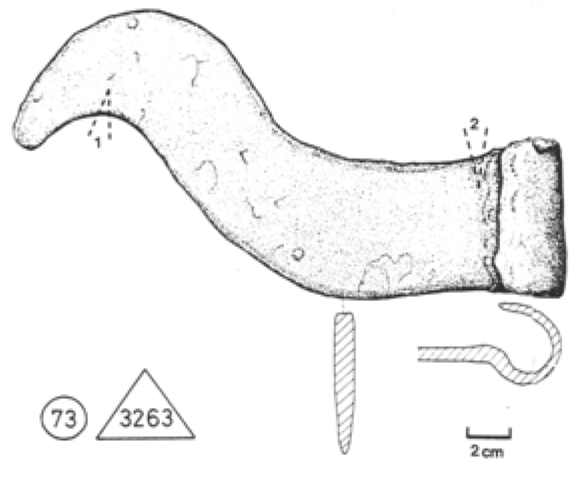


**Figure 6** Drawing of Billhook 73 (3263) sampled in 2 areas. Drawing Anne Farrer reproduced courtesy of Ian Glover

Billhooks occur in abundance at BDTP and were present in 23 out of the 53 excavated graves. Statistical analysis of the grave goods has indicated a relationship in their distribution with that of spindle whorls (Woods, 2002). Whether this distribution is reflected in a correlation between gender and billhooks is unclear since poor preservation of organic material made sex determination of the burial remains impossible, and in any event in this period of Southeast Asian prehistory both men and women appear to have been buried with spindle whorls (O'Reilly 2000). The burials with spindle whorls invariably contained agricultural tools, and were present in eight out of twelve graves with arrowheads, one out of the ten graves with harpoons and two out of four graves with fishhooks (Glover 1990a, 175; Woods 2002). The billhooks in the BDTP burials invariably occurred with agricultural tools, which suggests that perhaps they were used as a form of agricultural sickle. More than thirty years after the initial excavations at BDTP only a few other examples of this tool type have been recorded anywhere in Thailand. There have been a few surface finds from Old Kanchanaburi, from near Chansen and from Lopburi. A few examples can be seen in museum collections in both Kanchanaburi and Ratchaburi provinces (Glover 1990a: 160-165) and there is one in the collection of the National Museum of Chumphon (Fig. 7) (Pryce et.al 2006, Bennett 2013a Fig.10.10) which comes from the contemporary river port site of Kao Sam Khaeo in eastern peninsular Thailand some 800 kms to the south of BDTP (Bellina et al. 2006). Bennett documented a handful of these billhooks, during survey work of the tin mining areas towards the Myanmar border (Fig. 8) (Bennett and Glover 1992). The tools had been recovered by tin miners at Khao Chamook (nose mountain), also known as Huai Suan Plu - west of Chombung and at Khao Kwark in Ratchaburi Province, perhaps suggesting that these tools were mining / digging tools.

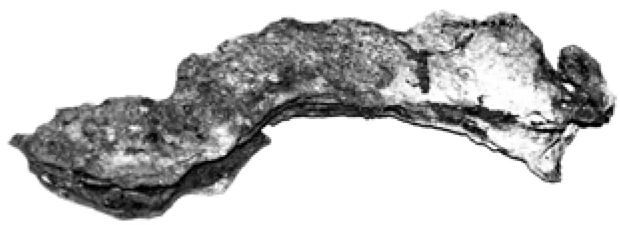

**Figure 7** Billhook from Kao Sam Kao, in eastern Peninsular Thailand which is similar to those from BDTP

The name billhook was initially assigned to this tool type by Ian Glover, director of the BDTP excavations throughout the 1980's, due to its resemblance to a modern billhook/sickle. However, the billhooks from BDTP differ importantly from traditional billhooks in that their handle has a socket at a 90-degree angle to the blade. The BDTP billhooks occur in three basic sizes and are not dissimilar in shape to the *boti* or *boothi* used for cutting in Bengal and Bihar today (Figs.9 and 10). The *boti* comprises a vertically positioned iron blade attached to a wooden board placed on the ground and is used in the kitchen to cut vegetables, fish and meat. The person cutting sits on the floor pressing their feet on the board with their hands on either side of the blade holding the food being cut and moving it against the blade. In an attempt to explore further ethnographic analogies to explain the function of the BDTP billhooks, Kathryn Bonnet undertook field studies in Sri Lanka where a kitchen cutting tool similar to a hand held boti is also still fairly common (Bonnet forthcoming). Other tools encountered in Sri Lanka, which resemble the smallest of the BDTP billhooks, are blades used for bark stripping on cinnamon farms, an important economic activity on the island.

**Figure 8** Billhook and digging sticks similar to those from BDTP found by local tin miners in Ratchburi Province

**Figure 9** Photograph showing the three sizes of *boti* from India. The two on the left are used for meat and vegetables. The small one on the right is for ceremonial use to cut fruit. Photo courtesy of Tathagata Neogi and Kathryn Bonnet

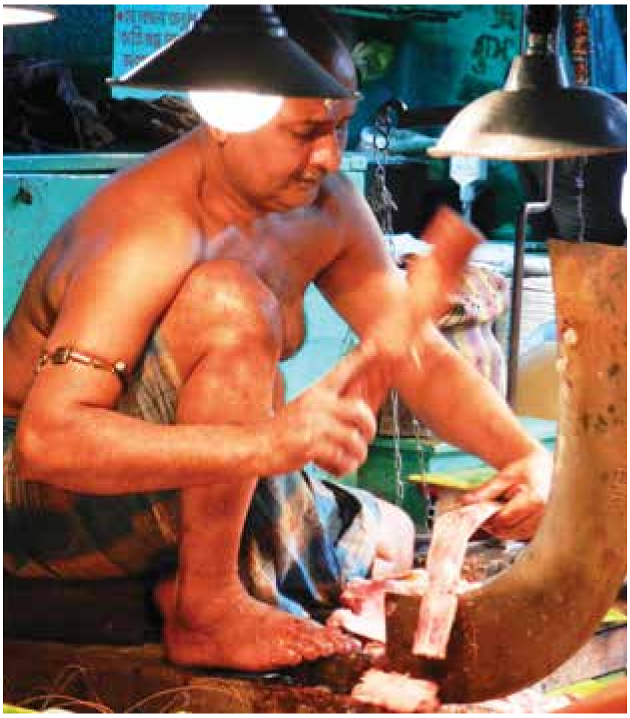

**Figure 10** Photograph showing the use of a large *boti* and a wooden mallet to cut the bone section of a fish. Photo courtesy of Tathagata Neogi and Kathryn Bonnet

## Metallographic examinations of the billhooks.

In an attempt to resolve some of the questions surrounding the manufacture and use of these billhooks, three of examples were sampled in either 2 or 3 areas; 46 (547)(Fig.11) (weight: 169 grams; length: 15 cms), 73 (3263) (Fig.6) (weight: 460 grams; length: 23 cms) and 43 (350) (weight: 350 grams; length: 22 cms).


**Figure 11** Photograph of Billhook 46 (547) extensively sampled in 3 areas

Sample 1, taken as an entire cross section of the blade of 46 (547), through the area of the cutting edge and mounted to expose the lateral direction indicated that the cutting edge was largely composed of acicular ferrite with a high carbon content in the form of spheroidised carbides, a structure indicative of rapid cooling from a high temperature, followed by reheating to, and maintaining at a temperature below 723°C (Fig. 12). A small area of the working edge and the sample removed from the blunt end of the tool were composed of large ragged ferrite grains (ASTM 4) (Figs. 13 & 14) indicating a degree decarburization. The hardness of the cutting edge (Hv 167) was twice that at the blunt end (Hv 86) (Fig.15). Sample 2, a cross section through the area near the socket where the thickness of the metal was at its greatest, indicated that the shaft has been forged by lapping over a tongue of metal and forge welding it onto the blade, although the welding was not complete. The main portion of the sample was composed of equiaxed α grains (ASTM 4-5) surrounded by lamellar pearlite, which showed the beginnings of spheroidisation. The carbon content in this area was 0.2% while the external surfaces and those on either side of the weld have been completely decarburized and the α grains were significantly larger (ASTM 1) (Fig.16). The absence of a decarburized zone along the cutting edge of the blade, may perhaps be best explained by the tool having been repeatedly sharpened during use. The other billhooks examined, 73 (3263) and 43 (350), had similar structures although because of corrosion it was not possible to determine whether the blades had been used and / or sharpened.

In order to verify the interpretations derived from the metallographic examinations and to understand the skills of these ancient smiths, Bonnet (2014) worked with two blacksmiths, one in UK and the other in Sri Lanka. Using the information outlined in Bennett's metallurgical study the procedures to replicate the manufacture of the billhooks were documented using video and written field notes. The aims of the project were to:

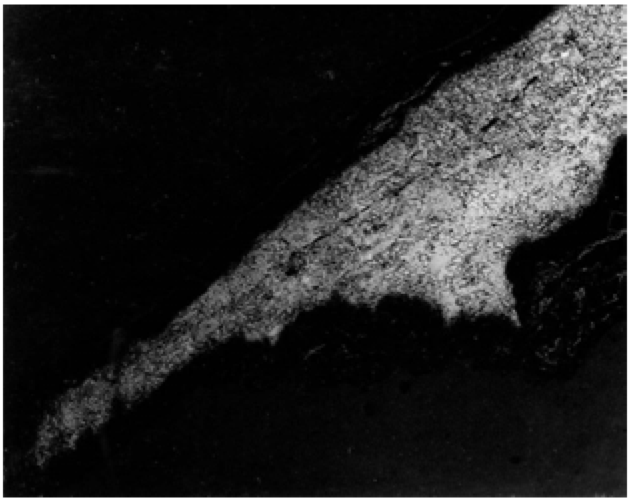

**Figure 12** Photomicrograph of the cutting edge of 46 (547) which was largely composed of acicular ferrite with a high carbon content in the form of spheroidised carbides

**Figure 13** Photomicrograph of the sample removed from the working edge of billhook 46 (547) showing acicular ferrite with a high carbon content in the form of spheroidised carbides. A small area of the working edge was composed of ragged ferrite indicating decarburization

- Verify the interpretation of the technology used to produce the billhooks
- Understand the skills needed to manufacture the tools
- Explore how these tools could have been hafted
- Explore the function and potential uses of the BDTP billhooks

**Figure 14** Photomicrograph of the sample removed from the blunt end of 46 (547) which was composed of large ragged ferrite grains (ASTM 4)

Bennett had assumed that the blade of the BDTP billhooks was forged first and that then the socket was formed. However, both blacksmiths found such a procedure made the forging much more difficult than forging the socket first, which allowed them to hold the socket with tongs while forging the blade. The unusual socket of the billhooks, set at a 90-degree angle to the blade, led Bonnet to instigate a series of trials to investigate how the tools could have been used. The replicated billhooks were hafted using different lengths and types of wood and their effectiveness on different materials evaluated. These will be described by Bonnet in a future publication.

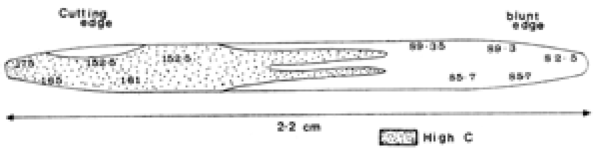


**Figure 15** Drawing of the cross section through the billhook 46 (547) showing the hardness of the cutting edge (Hv 167) which was twice that at the blunt end (Hv 86)

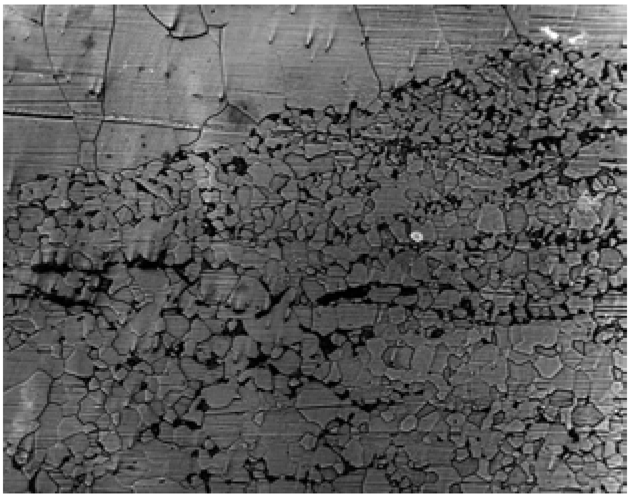

**Figure 16** Photomicrograph of the sample removed from the socket end of billhook 46 (547) showing the decarburized surface and the large α grains (ASTM 1)

## Conclusions

Biggs et al. (2013:327) have recently concluded that that "Although copper based technologies seem to have become reasonably well developed in mainland Southeast Asia by the mid-first millennium BCE, it seems that there was a clear disconnect in the level of skill displayed in this new material, iron ". The iron from BDTP however, clearly shows that by the 4th century BCE, this metal had in some instances completely replaced bronze for the manufacture of tools and weapons. The present study has demonstrated that these protohistoric smiths were able to produce a wide range of very good quality tools and weapons. They appeared to have paid little attention to the amount of decarbursation which occurred during forging since they were able to readily remove the decarburized surfaces from the blade edges during use and or sharpening.

The archaeology of the billhooks indicates that they were a very important element of the material culture assemblage at BDTP and smithing experiments (Bonnet 2014) have clarified the complexity of their manufacture, which had previously been ignored. The high level of skill required to forge the billhook shape might suggest that this tool had a particular use or special role. While it has not yet been possible to identify an obvious use to match this apparent importance, it seems quite possible that these tools were so well adapted as to be suitable for many purposes. The non-standardisation of size of the BDTP billhooks had suggested to Bennett (2013a) that the objects were either forged in a large workshop with many individuals undertaking the smithing, or that they were forged in a variety of smaller independent workshops. Current ethnological observations suggest rather that this variation, which is also apparent in the *botis* from India, may be due to the adaptations of the tools for different functions (Bonnet forthcoming).

All of the objects examined metallurgically showed evidence of use, and the metallographic structures of the samples removed from the bent sections of the "killed" objects, indicated that the people undertaking this mutilation had some knowledge of forging. The question of where this early and rather sophisticated iron was made however remains unresolved. BDTP is not a primary burial site and the objects may therefore have been imported into the area, having already been used and mutilated.

Iron working could well have followed the trade route from India into Myanmar and Thailand - BDTP is not only close to the tin rich belt near the Myanmar border but is strategically close to the overland trade route of the three pagoda pass which in the 4th century BCE would probably have been accessible by river. Current research – both archaeology and technology, points clearly to a strong link to the Indian sub-continent at this time in prehistory (Bellina 2014, Glover 1990b, Glover and Bellina 2012, Glover and Shahnaj Husne Jahan 2014, Higham 2002, 2004, 2014, Manguin 2004, Ray 1994). Noteworthy is that over the last thirty years, the only other examples of these characteristic iron billhooks have been found in the tin mining areas to the west of BDTP and from the ancient port site of KSK on the southern peninsular. Further, both KSK and the area of tin mining at Khao Chamook have also produced rare examples of the characteristic decorated high tin bronze bowls of the type abundantly found at BDTP (Glover and Bellina 2011, Glover and Bennett 2012).

## Acknowledgments

Firstly, I would like to express my thanks to Kathryn Bonnet for her interest in the billhooks. Kathryn undertook experimental smithings and hafting trials as part of her MSc in Experimental Archaeology at the University of Exeter under the supervision of Dr. Gill Juleff and these will be published in detail elsewhere. I extend my grateful thanks to Ian Glover for so many useful discussions and for always being willing to help.

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# Crucible steel at Hattota Amune, Sri Lanka, in the first millennium AD: archaeology and contextualisation

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*ABSTRACT* The discovery of a crucible steel manufacturing site and iron smelting sites of the first millennium AD during the survey of an area bordering the Knuckles range of hills in central Sri Lanka is described. The nature of the evidence for both smelting and crucible steel technologies is discussed and comparisons made with earlier published fieldwork at Samanalawewa. The excavation of the crucible steel site is presented along with a discussion of the interpretations drawn from the field evidence.

KEYWORDS: crucible steel, crucibles, Sri Lanka, iron smelting, Middle Historic,

## Introduction

The gradual increase in archaeometallurgical fieldwork in South and Central Asia is bringing to light more field evidence for crucible steel manufacturing technologies and with each report our understanding of the nature and extent of this significant technology improves, reducing our over-reliance on documentary sources, many of which are secondary re-workings of a limited number of primary sources. This report describes one such site in Sri Lanka and an outline is given here of the main findings of the Hattota Amune survey in advance of

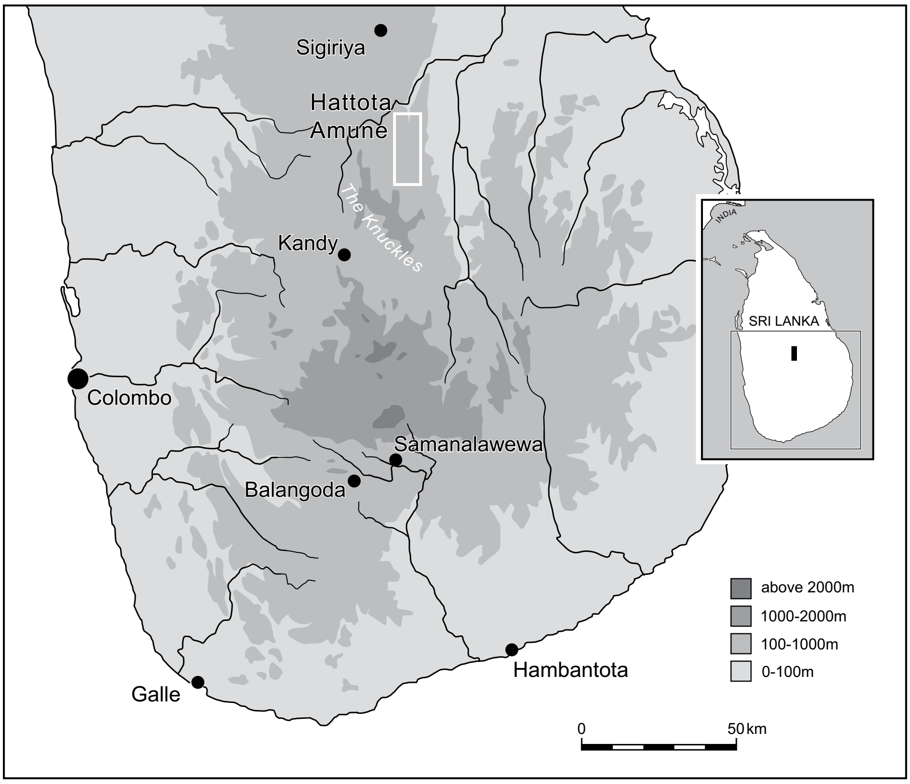


**Figure 1** Map showing location of Hattota Amune survey area relative to the Knuckles and Samanalawewa

more comprehensive treatment of the data and scientific analysis of the crucibles themselves.

The site at Hattota Amune was discovered in 1996 during a reconnaissance survey of the eastern flank of the Knuckles range of hills of central Sri Lanka (Fig. 1). The purpose of the survey was to test the long range continuity of the field evidence for iron production witnessed and recorded at Samanalawewa on the southern edge of the central highlands (Juleff 1996, 1998). The aim was to sample the archaeometallurgical record of a region distant from Samanalawewa and therefore not culturally contiguous but which had similar characteristics and resources in terms of geology and ores, climate and environment. To contextualise the findings of the survey it is necessary to first briefly review the main characteristics of the Samanalawewa record.

Samanalawewa revealed previously unknown evidence of industrial-scale seasonal iron production during the second half of the first millennium AD, based on a low, linear furnace design that was driven by directionally-constant, high-velocity monsoon winds. The many sites of this industry are all located on the leading western edges of hills and ridges with uninterrupted westerly aspects, which is the direction from which the monsoon wind blows, and hence have become known as the west-facing sites and furnaces. Experimental re-enactment of the smelting process established that the furnace was capable of sustaining temperatures in excess of 1400°C and smelting directly to high-carbon steel (Juleff 1996, 1998). The late Middle Historic period of this industry coincides with the Early Islamic period of Western Asia and documentary reference by the contemporary commentator, al-Kindi, to the superior properties of *Sarandibi* steel (*Sarandib* being the Islamic name for Sri Lanka) (Hoyland and Gilmour 2006) and it was postulated that the steel being referred to was that produced in the wind-powered furnaces (Juleff 1998, p. 218). The origins of this unusual technology lie in a smaller, multiple-tuyere, proto-linear-design furnace, also from the Samanalawewa area and dated by radiocarbon to the 4th century BCE (Juleff 1998; 2009).

The wind-powered west-facing technology disappears from the archaeological record at Samanalawewa in the 11th century and is replaced by bloomery smelting in small, bellows-driven shaft furnaces located within valley-bottom settlements. Current evidence suggests there is no dynamic chrono-cultural relationship between the disappearance of one technology and the emergence of another. Village-based smelting continues into living memory (Coomaraswamy 1956) and was last practiced in the mid-twentieth century (Juleff 2009a).

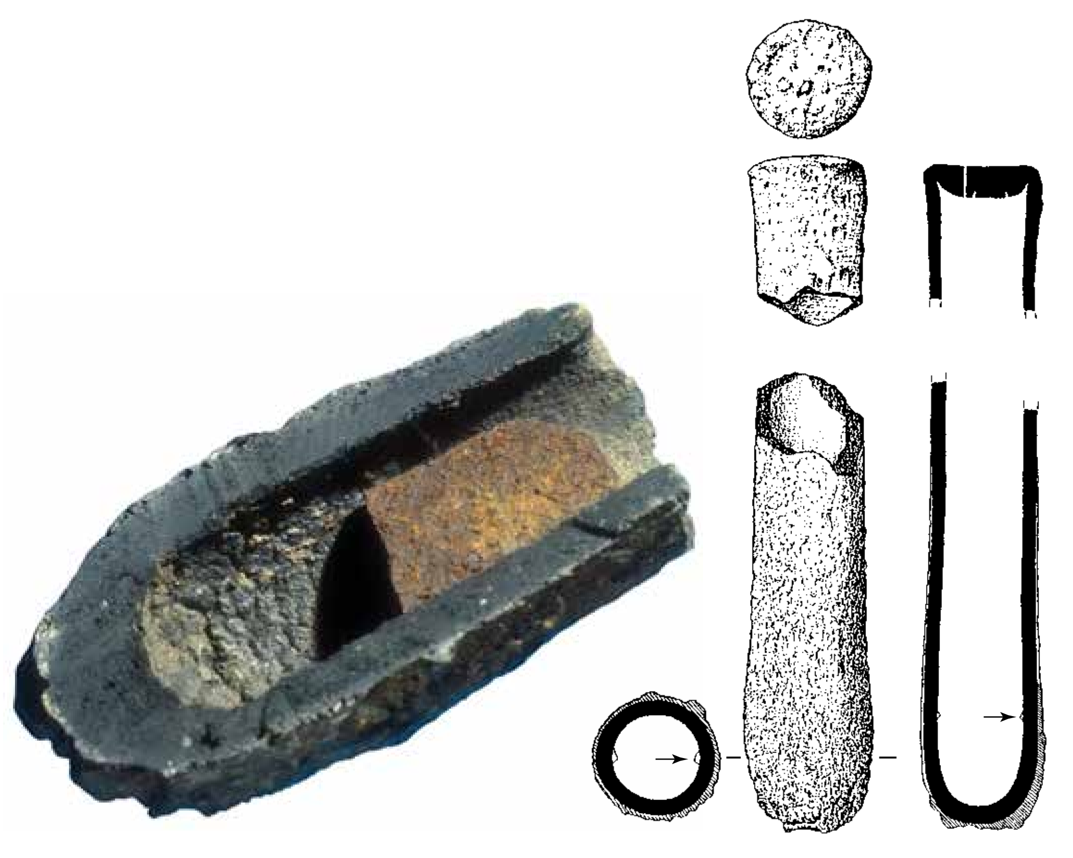


**Figure 2** Early 20th century crucibles from Samanalawewa. Arrows indicate the positions of vertical and horizontal slag 'fins'. Enlarged cross-section through crucible shows a rare fragment of an ingot in its horizontal solidification position (from photo by T. Milton, British Museum Photographic Service).

In a further twist of complexity, a very small number of crucible steel sites were also identified at Samanalawewa. These date not from the period of the west-facing industry and *Sarandibi* steel as might be expected but from the 19th and 20th centuries, and are recorded in contemporary literature (Ondaatje 1854; Coomaraswamy 1956). The five crucible steel making locations recorded fall within two larger extended village settlements and represent separate family-based workshops. By comparison with the industrial-scale crucible steel sites of Karnataka (Anantharamu et al 1999), Andhra Pradesh (Jaikishan 2009) and central Asia (Herrmann et al 1995), these sites are small. The crucibles they used are elongated tubes, c. 187mm length and 34mm diameter, with lids that show perforations and a uniform course brown/black fabric heavily tempered with rice husk (Fig. 2). The 'fins' of slag, left adhering to the internal crucible wall, that mark the position of the upper surface of the steel ingot, in these examples indicates that the crucibles were held vertical when in the furnace and then horizontally during cooling so that the final ingot form was of an elongated bar (Fig. 2) (Wayman and Juleff 1999).

One significant absence in the Samanalawewa record is the occurrence of crucible steel sites in the Middle Historic period (defined by Deraniyagala (1992, p.707) as c. 300-1250AD) when the west-facing industry was at its height. This observation, and the interpretations that could be drawn from it, along with the unequivocal dominance of the record by the west-facing technology provided the motivation for sampling a comparable landscape to help to contextualise Samanalawewa.

## Location and setting

The Knuckles are a range of hills extending as a broad spine northwards from the Central Highlands (Fig. 1). Like Samanalawewa, the Knuckles fall within the Intermediate Zone which means its climate and ecology lies between the extremes of the Wet Zone to the south and west and the Dry Zone of the east and north. Climate and topography suggest that it too would experience high velocity dry winds during the monsoon (June – August) and this was confirmed by local inhabitants. Its vegetation cover is comparable with Samanalawewa and thus likely to support populations of tree species suitable for charcoal fuel. While deposits of iron ore are not geologically recorded for the area, small-scale surface occurrences of good quality mixed oxide ores, formed as a result of tropical weathering, are ubiquitous across much of the island and can be found with relative ease.

The area selected for survey comprised undulating flat land extending north from Pallegama and sandwiched between the eastern flank of the Knuckles and the Kalu Ganga river (Fig. 3). Unlike the Knuckles interior, which is thinly populated with scattered traditional villages akin to those of Samanalawewa, the survey area was uncultivated and devoid of settlements until the mid-20th century when colonisers from all parts of the island were encouraged to the area to reinstate rice cultivation and create new communities. However, the landscape is dotted with archaeological evidence for settlement and monastic sites of the Early and Middle Historic periods and the lack of later villages indicates that this area was one abandoned in the 11th-12th centuries during the demographic shift to the Wet Zone at the end of the Middle Historic (de Silva 1981). One of the first activities that new settlers to the area engage in is gem mining, as the deep alluvial deposits of the flood plain of the Kalu Ganga are regarded as a rich source of precious and semi-precious stones. The process of gem mining is simple with square-sided pits of c. 3-6m dug several meters deep into the alluvium. These are only back-filled when the ground is instated for cultivation and consequently the landscape is dotted with old gem pits that allow a convenient window into underlying deposits.

**Figure 3** Two views of the survey area with distant view the Knuckles range (top) and low forested hills and paddy field terrain, with local guide (bottom)

## Survey

Slags, indicating the presence of smelting sites, had been reported from the area by P.B. Karunaratne, a collaborator on the Samanalawewa project, and in November 1996 the first rapid survey was conducted.

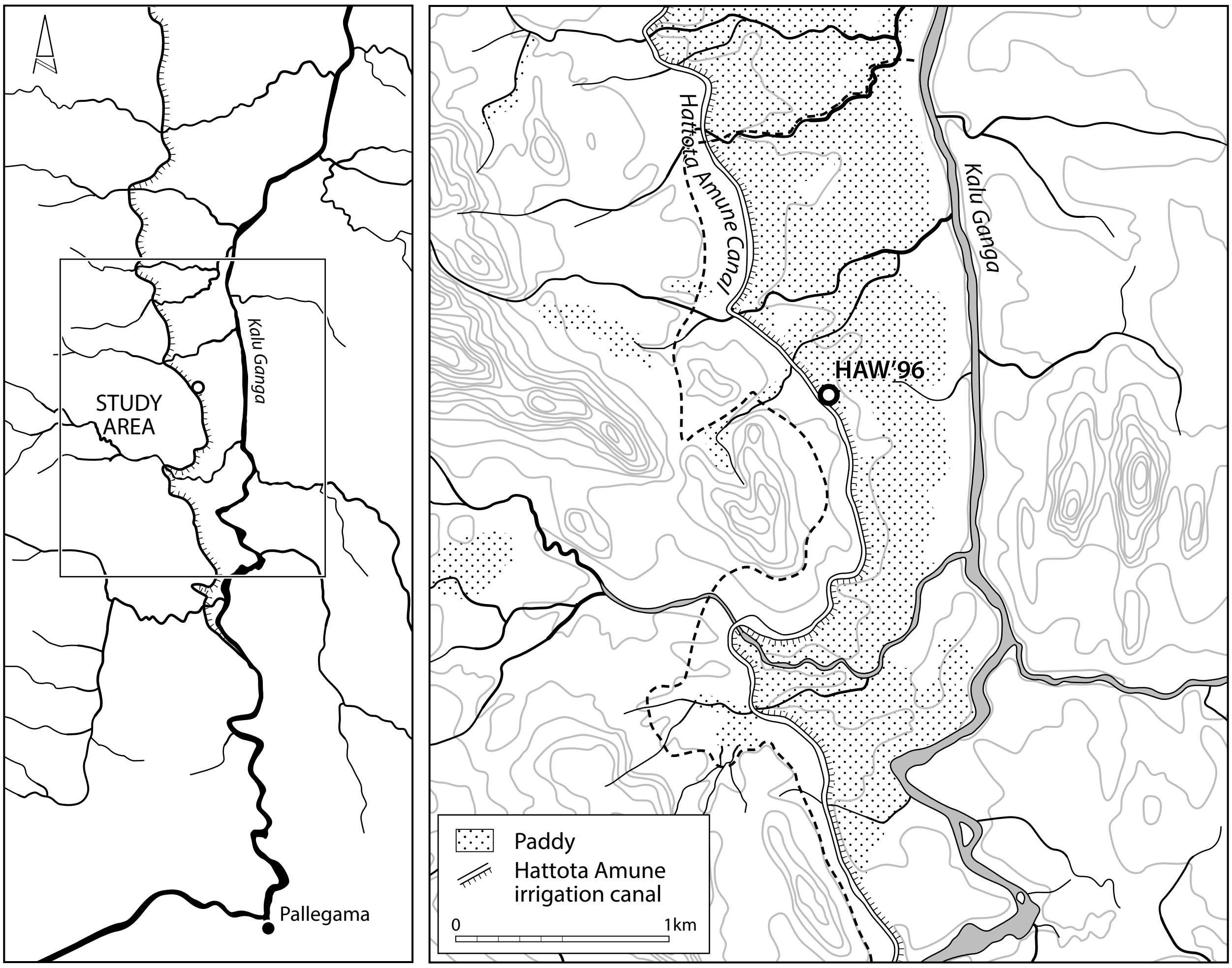


**Figure 4** Map of survey area with crucible steel site marked (other sites described not plotted)

Although only a few days in duration, following as it did in the wake of the Samanalawewa experience, the survey was carefully targeted. Reconnaissance-style survey was used, which meant making enquiries and then being lead to possible sites by local informants (Fig. 3). Extensive narrative field notes were taken, recording landscapes, locations, features and conversations. In all, seven smelting sites, a possible ore deposit and one crucible steel site were located and interviews conducted with two traditional blacksmiths. Further survey in the same area in 1999 and 2000, including that conducted by the Archaeological Survey Department of Sri Lanka, ultimately took the total number of archaeometallurgical sites to 32 in a tract of land extending northwards from Pallegama to Elahera, bordered by the Kalu Ganga to the east and straddling the Hattota Amune irrigation canal to the west (Fig. 4).

Concentrating here on the seven smelting sites located in 1996, five of them fall convincingly within the west-facing technology type on the basis of the macro-morphology of their slags. The unusual design of the west-facing furnaces at Samanalawewa produced a distinctive array of slag morphologies that have been described in detail elsewhere (Juleff 1998, 55-63). Particular amongst these are tuyere-line and tuyere-plug slags. These slag types form inside the furnace when slag builds up against and fills the line of reused tuyeres used to create the foundation of the straight front wall of the furnace. Both forms evidence the use of multiple tuyeres and the tuyere plugs, fragments of cylindrical slag, some tapering, made up of repeated flows, can only form when slag solidifies inside a tuyere. Abundant fragments of tuyeres are also strong indicators of a west-facing-type technology. A further feature of the slags of the west-facing sites at Samanalawewa is the extensive occurrence of pseudomorphed impressions of paddy straw and paddy husk used to line the base of the furnace. At all five Hattota Amune sites assigned as west-facing type tuyere-plug slags were recorded. Distinctive impressions of paddy straw and husk were also recorded at all sites. Tap slags were abundant on all sites and fragments of furnace wall that were flat and without curvature, both also attributes of the west-facing assemblages. On one site a definitive fragment of furnace wall with multiple tuyere slots was observed (Fig. 5). Interestingly, despite being a small sample of sites, there was variation in the degree of taper of the tuyeres, from parallel-sided through slight to noticeable taper. Variation in tuyere taper was present but not a strong feature of the Samanalawewa assemblages which are dominated by tapering tuyeres. The five sites share sufficient traits with the Samanalawewa west-facing material to be classed as part of the same technological tradition.

**Figure 5** Fragment of furnace wall with multiple tuyere slots recorded during survey

In contrast to slag morphology, the locations of the Hattota Amune sites do not follow the Samanalawewa pattern of being on exposed west-facing hills. Here they are on flat or gently undulating ground within or close to the edge of the flood plain of the Kalu Ganga. While most demonstrated thick deposits of slag, occasionally mounding to c. 1m, most did not exceed c. 20m in diameter with one exception comprising at least four loci of activity within an area of over 75m. None are in sheltered positions but equally they are not in particularly exposed positions. Local inhabitants report that the area is subject to very strong dry winds during the monsoon to the extent that roofs need to be weighted with sand bags and tyres. Furnaces could thus be wind-powered but whether they were designed and operated in precisely the same manner as those at Samanalawewa, or also relied on a degree of natural draught induced by increased shaft height, is unclear and requires further investigation. It is possible that they were more akin to the furnaces excavated at Dehigaha-ala-kanda, near Sigiriya, due north of Hattota Amune (Fig. 1). The Dehigaha-ala-kanda furnaces are straight-fronted, use multiple tuyeres, although don't appear to reuse tuyeres in furnace wall construction, and have substantial superstructures, up to 1.6m in height. They were excavated in 1990-91 and described by Forenius and Solangaarachchi (1995), and further discussed in relation to the west-facing furnaces and a postulated wider technological tradition of linear furnaces (Juleff 2009b). They are earlier than the main industrial activity at Samanalawewa, having given seven radiocarbon dates between the 2nd century BC and the 4th century AD.

The five west-facing type smelting sites at Hattota Amune remain undated as they were recorded only from surface survey and thus it is not certain whether they are contemporary with either the earlier Dehigaha-ala-kanda furnaces or the later Samanalawewa furnaces, or possibly intermediate between them. However, pottery collected at several of the sites included types which are generally regarded as typical of the Middle Historic period. Given the pottery evidence combined with the general settlement pattern of the area in terms of the 11-12th century abandonment described above, it is reasonable to suggest that the sites date no later than the Middle Historic period.

The two further smelting sites of the 1996 Hattota Amune survey presented slags that were very different in morphology to those described above. At these two sites the slags were more massive and comprised course-textured furnace slags in block-like forms. Little or no tap slag was observed and tuyeres and other refractory materials were absent. These slags bear no resemblance to either the west-facing or the later village smelting shaft furnaces types of Samanalawewa. The sites are undated but both are located in a more isolated area of hilly terrain were the few sparse settlements are older than those in the flood plain and thus it could be postulated that these smelting sites are contemporary with the settlements and belong to the Later Historic period.

The two remaining sites included a possible small ore deposit comprising a weathered lateritic outcrop with ferruginous gravel and the crucible steel site that will be the focus of the remainder of this paper.

## Hattota Amune Wallewala (HAW'96)

The site at Hattota Amune, Wallewala, (HAW'96) lies at lat. 07°36'16" and long. 80°49'46" and c. 150m msl. It is c. 500m from the nearest west-facing type smelting site and is located in the compound of No. 14 Wallewala, which is situated immediately east of the track that follows the course of the Hattota Amune irrigation canal. The 50m wide compound comprises a traditional house and a semi-wild garden used for fruit and vegetables, and immediately adjoins on its eastern side a wide tract of paddy land that stretches c. 500m to the Kalu Ganga. Slags were clearly visible embedded in the trampled and swept surface of the compound and increased in the vegetable growing area (Fig. 6) where an abandoned gem pit of c. 5x5m and 2m depth exposed a thick deposit of slag and pottery. It was here that the first few fragments of crucible were collected.

**Figure 6** HAW'96,three views of compound including house and swept courtyard (a), scrub area of abandoned gem pit with paddy fields beyond (b) and smithing slag cakes collected from surface (c)

**Figure 7** HAW'96 excavation, cleaning back edge of gem pit

**Figure 8** HAW'96 excavation, after completion of trench I

## Excavation

With the discovery of crucible fragments it was decided that the site would be suitable for an exploratory excavation to determine the nature and possible date of the metal working activity. The excavation took place in December 1996 over 4 days and was lead in the field by Nerina De Silva and Tom Dawson. The objective was to cut back the exposed sections of the gem pit to record and sample the deposit of debris which varied in depth along the sections from 0.50m to 0.70m. In the time between the survey and the excavation rain had flooded the gem pit to half its depth making it impossible to access the sections from inside the pit so it was decided to concentrate on the north section only.

A shelf was cut to create a working platform from which an area 5.5m in length and 0.40m wide, designated trench I, was excavated stratigraphically (Figs 7&8). All excavated material was weighed and sorted. Pottery and crucible fragments were retained and charcoal was sampled following the established procedure of the Archaeology Department. After cutting back and recording the section a further 1x1m test pit, designated trench II, was excavated into the section to increase the amount of charcoal retrieved for dating. A new series of context numbers were given to the excavated layers in trench II.

The stratigraphic sequence in both trenches was the same, with the uppermost topsoil (context 1) overlying a layer (context 2 in trench I and 7 in trench II) containing large amounts of slag (c. 82 kg in total) and some crucible fragments. This layer was up to 0.3m thick and overlay a further layer (context 3 in trench I and 8 in trench II), 0.2m thick, which contained crucible fragments, tapped slag and abundant pottery but far fewer large cakes of slag than context 2/7. The total weight of slag recorded for context 3/8 was 10kg. Below context 3/8 lay context 4, 0.1-0.2m thick, which contained only a few fragments of tap slag and pottery sherds. The final layer excavated, context 5, contained no slag and infrequent pottery. Excavation was halted before the bottom of this layer was reached.

Context 2/7 contained the bulk of the slag and appeared as a dumped layer, visible in all four sections of the gem pit and indicating an active workplace in close proximity. Context 3/8 contained slag but in much reduced quantities. The difference between contexts 2/7 and 3/8 was the absence of large slags in the latter and, as the soil matrix in both is the same, the conclusion drawn was that the smaller size material in 3/8 had worked its way downwards due to the action of roots and insects. The landowner reported removing large trees from the site when he first occupied the site and there was evidence of termite activity. The interface between contexts 2/7 and 3/8 was diffuse with clear evidence of bioturbation. However, it is also possible that the lower layers relate to a phase when metal working was less intense. No evidence for working surfaces or structures was found.

## Dating

The pottery from the excavation was examined by S.U. Deraniyagala and given a tentative Middle Historic date range of 5th-8th centuries. The study of local pottery typologies at the time of the excavation, and still today, is in its infancy and only broad date ranges can be applied to known and recognisable types. The abundance of pottery at a metalworking site indicates sustained domestic activity in proximity with metal working.

The charcoal collected was submitted for dating and the results obtained are presented in table 1. Two observations are immediately apparent. All the dates fall within the Middle Historic period and that they are inverted in terms of the stratigraphic sequence. Possible reasons for the inversion have been considered by the excavation team and mis-labelling of samples has been ruled out, as has inversion of the stratigraphy due to secondary dumping. The remaining explanations are bioturbation, which was noted during excavation, allowing smaller material to migrate through loosely-packed larger slags and the possibility of old heartwood being included in the sample from context 2/7. Setting aside the uppermost early date as possibly anomalous, the dates for contexts 3/8 and 4 could be regarded as most reliable, in particular 3/8 which contained the majority of the crucible fragments. The pottery evidence and the radiocarbon dates combined place crucible steel making at the site in the second half of the first millennium AD, beginning at least in the 7th century.

## Slags and crucibles

The large quantities of slag suggest a well-established and long-lived workplace. Morphologically, the assemblage is not of the west-facing type and is dominated by large and irregular plano-convex cakes and fragments thereof. These are interpreted as smithing slags, probably derived from primary forging of slag-rich iron direct from local smelting. Fragments of tap slag may seem to contradict the smithing interpretation and imply smelting but, although tap slag is in reasonable abundance, it does not occur as large agglomerations of multiple flows. It is likely that it derives from flows of liquid slag produced in a smithing hearth at high temperatures. The observation that the slag cakes are dense and well-consolidated, suggesting they formed from low viscosity slag, reinforces this. No hearth or furnace lining material was observed or collected.

**Figure 9** HAW'96, collection of crucible and glassy slag fragments from excavation

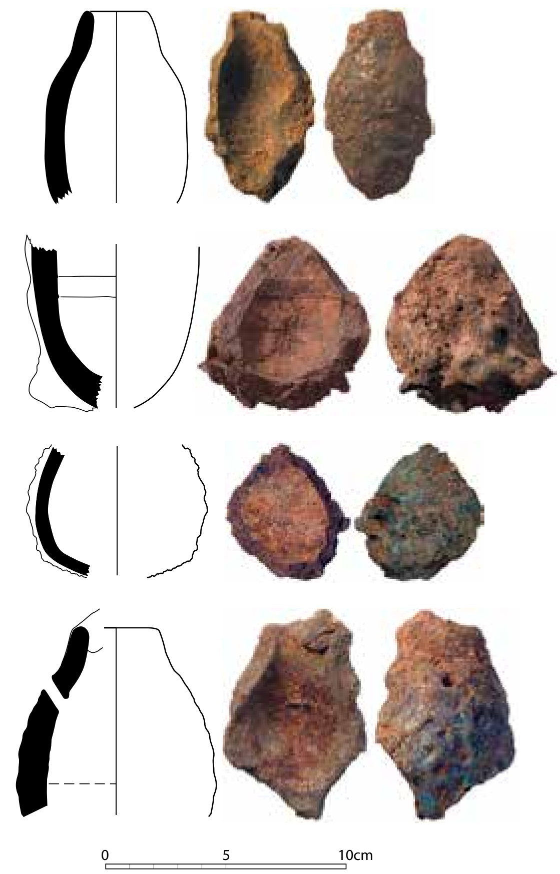


**Figure 10** HAW'96, most complete crucible fragments including example with side wall perforation (bottom)

The crucible fragments form a minor component of the excavated assemblage and, despite a total sampling strategy, only 44 possible crucible fragments were recorded. Examples of the crucibles are illustrated in figures 9 and 10. They are thin-walled (c. 3-5mm) with a dark brown/black, slightly coarse but uniform-textured fabric. Their external surfaces are coated with uneven blue-green glassy vitrification products which accumulate towards the base of the crucible. Internally, the more complete fragments preserve a glassy 'fin' marking the top of the ingot space when the crucible was positioned vertically. The second 'fin' observed at Samanalawewa indicating a horizontal position during cooling is absent here. The most complete profiles indicate that the crucibles are small, narrow-necked rounded flasks. The rim of the crucible is neatly finished and closed with a separate plug of clay, although no full examples of lids remain. The diameter of the neck is c. 15mm while the body expands to 45mm and the internal depth is at least 65mm. It is important to note that, given the small number and size of the crucible fragments, these dimensions are drawn from a very limited sample. From the few fragments of possible crucible lid there was not sufficient survival to determine whether the lids had been pierced as at Samanlawewa and elsewhere in South Asia, however, one example preserved a definite and deliberate perforation of the side wall of the crucible (Fig. 10), a feature which has not been recorded previously. Also within the debris assemblage at HAW'96 are fragments of amorphous glassy slag/vitrification (Fig. 9). This is often blue/green in colour but can also be pale cream. It is clearly the same material as adheres to the exterior of the crucibles.

**Discussion**

The first observation that can be made of the Hattota Amune crucibles is that, while they share fabric traits, they are unlike the tubular forms of those from Samanalawewa. This is hardly surprising in that they are separated in time by over a millennium. From their size, they would produce only small button-like ingots and their neck diameter suggests that charging the crucible would be challenging. The feedstock would have to be in the form of narrow and short bars or small diameter fragments or prills. However, there are some interesting similarities in context between Hattota Amune and Samanalawewa. In both cases crucibles occur alongside plano-convex cakes of smithing slags, although at Samanalawewa the proportion of crucibles to slags is far higher (Juleff 1998, 93). This suggests crucible steel manufacturing was not a sole occupation but one element of a wider repertoire being practiced. On current evidence, crucible steel production at Hattota Amune is minimal, although it is remotely possible that another part of the site could reveal higher concentrations of crucibles.

While it is not the intention of this paper to review the evidence for crucible steel in Asia it is notable, from the growing gallery of crucible forms from across south and central Asia, that although there are similarities in fabric and features such as closed lids, with or without perforations, and co-occurrence of coloured glassy slag across macro-regions, no two areas are alike. Until more forms are recorded and dated it is not possible to compile a typology that allows the development, transmission and adaptation of crucible forms to be traced. What can be interpreted is that all the forms known are effective and that crucible steel is a resilient technology able to tolerate a high degree of variation. This implies a high degree of technological competence and knowhow, which brings the discussion back to the issue of context. All too often crucible steel is studied in isolation as a specialist technology. In contrast, being able to examine crucible steel within wider, regional patterns of ferrous metallurgy, adapted to supplying a wide range of end-users, will afford a better understanding of the techno-cultural role of crucible steel. Like Samanalawewa, using this approach at Hattota Amune a pattern has emerged. Iron was smelted extensively across the area during the mid- to late Middle Historic period, using a technology that is part of the same tradition as the wind-powered furnaces of Samanalawewa. While there are shared traits in terms of furnace design and operation, including use and reuse of multiple tuyeres, there also differences which represent adaptations to local conditions or stages of development. The smelted metal was processed at local smithing sites that also had a minor capacity to refine high carbon steel in crucibles. The level of crucible steel production at HAW'96 would fall short of that for *Sarandibi* steel implied by al-Kindi. At Samanalawewa, the pattern is different. There is no crucible steel manufacturing contemporary with the smelting industry and this is interpreted as implying that the substantial output of the west-facing furnaces was itself *Sarandibi* steel. These Sri Lankan patterns are distinct from those of other areas in southern India in the later second millennium AD when crucible steel became an important economic industry with specialised sites and practitioners focussed exclusively on steel ingot production (Juleff et al 2011).

**Table 1.** Radiocarbon dates for HAW'96

| Sample no. | Site | Context | C14 date b.p. | Calibrated date range (2σ) |
|---|---|---|---|---|
| Beta 101297 | HAW'96 | 2/7 | 1430±60 BP | 530-680 cal AD |
| Beta 101298 | HAW'96 | 3/8 | 1170±60 BP | 680-990 cal AD |
| Beta 101299 | HAW'96 | 4 | 1060±70 BP | 810-1160 cal AD |

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# A new discovery: manganese as a flux agent at the Song Dynasty [960 -1279 A.D.] iron-smelting sites in Xingye County, Guangxi, China.

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*ABSTRACT* This paper offers a recent study on iron-smelting sites and slag of the Song dynasty found in Xingye County, Guangxi Zhuang Autonomous Region, southern China. Archaeological fieldwork was conducted in Xingye County in November 2006 and August 2008. The ancient iron smelting sites are distributed through an area of about 20 $km^2$ in the vicinity of Long'an town. Ten iron smelting and casting sites were investigated. A dozen shaft furnaces and the bottom of one destroyed shaft furnace have been found, as well as a lot of slag heaps, broken *tuyère*, casting moulds and pottery.

Pre-modern texts indicate the presence of such sites in the Southern Song dynasty, though local archaeologists consider that the sites started in the Tang dynasty. The patterns of pottery shards unearthed from the Gaoling site possibly belong to a much earlier period.

Preliminarily analysis using SEM-EDS of 23 smelting slag samples collected from 4 sites are presented. It is noted that all the samples of slag are composed of $MnO-SiO_2$. Analysis of the microstructure of the metallic droplets in the slag by metallographic microscopy shows that all were the product of cast iron smelting. This is the first time that the use of manganese as a flux agent in ancient cast iron smelting has been confirmed in China.

The typology of the remains of straight-round-shaped *tuyère* indicates a shared tradition with earlier copper and iron-smelting finds in the Guangxi area, resembling closely those from South and Southeast Asian ancient iron-smelting ruins.

## Introduction

Iron has been a fundamental material for promoting the progress of human civilization since the second millennium BCE when iron smelting technology was invented (Tylecote 1992, p. 3). Bloomery iron smelting technology was the predominant technique used throughout most of the world in pre-industrial times. However, cast iron smelting technology was developed in central/north China by 800 BCE (Han 2000, p. 1178), and from then on became the main technique within China's cultural area. Guangxi Zhuang Autonomous Region, located in southern China, an important region connecting central China with Southeast Asia, has been a frontier for cultural contact and exchange from ancient times. Archaeological excavations and preliminary studies indicate that iron artefacts began to be used in the Guangxi region at the latest in the Warring States period [475-221 B.C.] (Lan 1989, p. 77; Guangxi Cultural Relics Team, 1978, p. 211). According to extant pre-modern texts, the Guangxi region began iron smelting in the Sui [581-618 A.D.] or early Tang [618-907 A.D.] dynasties, and the earliest records of ancient iron smelting sites situates them at Huaiji (present-day Guangdong province) and Guiling (present-day Hexian County in Guangxi region). (Wu 1935, p.2; Li, Xu 1943, p. 5; Li, Huang 1941, p. 12; Xia, Li, Wang 1986, p.70)

A Song dynasty work *Yudi Jisheng* (*Records of popular places*) by Wang Xiangzhi indicates the presence of iron smelting sites in Xingye County, Guangxi during 1131-1173 A.D (南宋绍兴一乾道年间) (Xia, Li, Wang 1986, p.99, 143, 166), and these were discovered during the National Survey of Cultural Relics in the 1980s.

Studies on their remains offer the possibility for discerning the characteristics of the Song dynasty iron smelting technology in the region, as well as its spread and exchange locally and to neighbouring areas, such as central China, Southeast Asia, and the Indian subcontinent. This paper describes a part of our research achievements in the Guangxi region since late 2006.

## Background of the sites

Xingye County is located in the south-eastern part of Guangxi Province. At the time of the Qin dynasty invasion from the north of the Lingnan area in 214 B.C., the aboriginal nations of the region were known in Chinese literary sources as the Xiou 西呕 and Luoyue 骆越 (Huang, Huang, Zhang 1988, p. 3). At that time, the Qin emperor established three administrative regions or Commanderies (*jun*郡) in the Lingnan area, namely Guilin Commandery, Xiangjun Commandery and Nanhai Commander. The area of present-day Xingye County was under the jurisdiction of the Guilin Commandery. During the early Western Han dynasty the region was controlled by the Nanyue Kingdom [203-111 B.C.], and subsequently became part of the Yulin Commandery or Yuzhou Commandery. From 561 to 665 A.D the region was controlled by the Shinan Commandery, and thereafter became a County, variously named or Shinan, Nanliu and Xingye (Wang, 1992, p. 3500).

## Aims

This paper presents archaeometallurgical studies on the Song dynasty iron smelting sites and slag found in Xingye County. The research had three major goals: to conduct archaeological fieldwork on the ancient metallurgical sites of the region; to appraise its iron smelting technology mainly through the scientific analysis of slag; and to try to reconstruct the history of the indigenous iron-smelting technology, discussing connections with neighbouring areas from the point of view of technological and cultural exchanges.

## Fieldwork

With the instruction and help of Professor Jiang Tingyu of Guangxi Provincial Museum, Professor Wan Fubin of Guangxi University for Nationalities, Liang Chan of Xingye County Museum, local cadres and villagers of Long'an town in Xingye County, archaeological fieldwork was conducted in Xingye County in November 2006 and August 2008. The geographical coordinates of the investigations are between 22°30′N ~ 22°48′N, 109°35′E ~ 110°02′E (GPS measured data).

The ancient iron smelting sites are distributed throughout an area of about 20 km$^2$ in the vicinity of Long'an town. The Yaqiao River, which flows down to Beibu Gulf (Beibuwan), runs through the sites. The fieldwork yielded 10 iron smelting sites at Qiyangling nanpo, Chongtangling, Liuxicun, Shandiling, Shengguoci, Jialing, Niulanchong, Juecaichong, Dapitou, and Gaoling (Fig.1).


**Figure 1** Distribution of iron smelting sites in Xingye County.

**Figure 2** Slag heaps at Juecaichong site in early November 2006.

**Figure 3** Broken fragments of *tuyère* and casting moulds for wok at Shengguoci site.

All of the ancient remains were at the foot of hills of less than 100m in altitude, and located in the upper regions of the Nanliujiang River. A dozen shaft furnaces and the bottom of a destroyed shaft furnace were found, as well as a lot of slag heaps (Fig.2), eroded iron blocks, intact and broken fragments of *tuyère,* and casting moulds (Fig.3). In addition, large quantities of pottery shards, identified by typology and pattern as dating from the Tang [618-907 A.D.], Song [960-1279 A.D.] and Ming [1368-1644 A.D.] dynasties, were found on the surface of the sites. As a result, the local archaeologists consider that the sites started in the Tang, flourished during the Song, then came to an end in the Ming dynasty (Xingyexian Bowuguan, 2006, p.1). Pottery shards possibly belonging to a much earlier period (before 220 A.D.) have also been found at the Gaoling site (Fig.4), but the relation between these pottery shards and the smelting activities requires further study.

**Figure 4** The patterns of pottery shards possibly date to the Han Dynasty (before 220 A.D.) unearthed at Gaoling site.

All the slag found and collected was broken tapped slag of black and brown colour (Fig.5). Slag heaps more than 2m high, much higher than those at any other site, and covering an area of about $1000m^2$ were found at the Juecaichong site (Fig.2).

**Figure 5** Broken tapped slag of black and brown colour remained at the Gaoling site.

Many almost intact *tuyères* were collected at all the sites during our fieldwork. They are of a round-straight shape, about 45cm-50cm in length, with an inner diameter about 4cm-5cm, an outer diameter about 12cm-15cm and made of white mud and sand (Fig.6). We found a little charcoal in the slag heaps at some sites, but we did not find any remains of iron ore.

**Figure 6** An almost intact and broken fragments of Straight-round shaped *tuyère* remained at the Juecaichong site.

**Figure 7** An intact shaft furnace found at Chongtangling site. Its remains are more than 2.5 meters high.

An intact shaft furnace was found at the Chongtangling site. Its remains are more than 2.5 meters high (Fig.7). It has an outer diameter of about 40cm at the upper rim, 110cm at the middle and 120cm at the bottom. The thickness of the shaft furnace wall is about 10cm-15cm, and is made of white mud and sand. There is also an opening for tapping slag of about 20cm width at the bottom of the shaft furnace in its northwest face. The bottom of a destroyed shaft furnace with an inner diameter about 112cm (Fig.8) was also found at the Shengguoci site. Several other almost intact shaft furnaces found underground at other sites during our investigation are also to be excavated to discover their structure (Huang, Li, Wan 2007, p. 23).

**Figure 8** The bottom of a destroyed furnace at the Shengguoci site.

## Scientific examination methods

In order to determine the smelting technologies employed, slag from 4 sites, namely Gaoling, Shengguoci, Juecaichong and Liuxicun, were examined and analyzed using metallographic microscopy, mineralographic microscopy, and scanning electron microscope with energy-dispersive spectrometry (SEM-EDS).

Scanning electron microscopy (SEM) was used to observe the microstructures and compositions of polished sections of the samples. SEM with energy-dispersive spectrometry (EDS) was used to carry out the non-sampling quantitative analysis. This research was undertaken using a Cambridge S-360 SEM-EDS at the School of Materials, University of Science and Technology Beijing. The excitation voltage was 20 Kv. Since light elements, such as carbon and oxygen, with atomic numbers less than 11 could not be detected, only a qualitative analysis of the corroded objects or occluded trace elements could be given. Oxidised components could not be determined. To determine the average components, surface scanning was used with multifaceted scanning on different parts of the samples to discover the precise composition of each sample. Based on previous analyses, the lower confidence limits for this instrument may be established at 0.3 wt%; values below this limit can be taken as indicative only.

Metallographic microscopy was used to observe the microstructures of the iron prills in polished sections of samples of the slag and iron products, and this research was undertaken using a German LEICA DM4000M at the Institute of Historical Metallurgy and Materials, University of Science and Technology Beijing, and at the School of Archaeology and Museology, Peking University.

Mineralographic microscopy was used to observe the microstructures of polished sections of samples of the slag and iron ores, using a German LEICA DM4000M at the Institute of Historical Metallurgy and Materials, University of Science and Technology Beijing.

## Microstructural and chemical analyses

The compositional analysis of the slag, iron products' inclusions and ores is significant for our understanding of the smelting techniques employed and the sources of the ores used. The microstructure of the iron prills in the slag and iron products is also very important for determining the smelting techniques (Tholander.1989, p. 35).

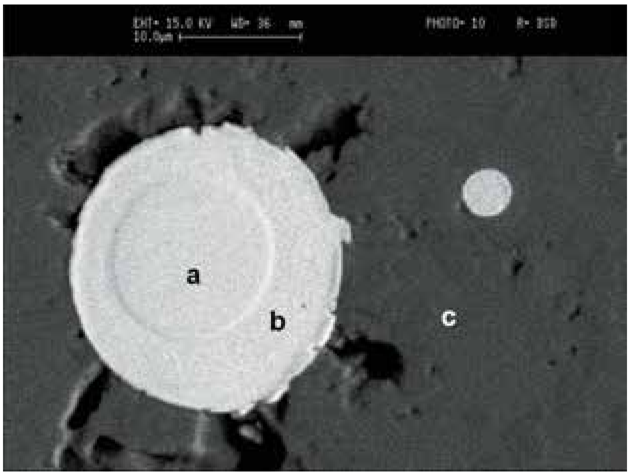


**Figure 9** SEM backscattered electron image of the matrix of the tapped slag No. XS001 from the Shengguoci site (voids are black). The phases present include glassy (c: Mn 59.71% (wt%), Si 22.47% (wt%), Al 11.99% (wt%), Ca 1.65% (wt%), K 2.35% (wt%)), iron prills (a: Fe 89.17% (wt%), P 9.90% (wt%), Mn 0.56% (wt%); b: Fe 97.11% (wt%), P 2.04% (wt%),Mn 0.54% (wt%)). Iron droplet (white phase): point a, the inner bulgy part, higher phosphor; point b, the outside lower part, lower phosphor. Glassy phase (point c), the basic elements of the slag.

The 23 tapped slag samples from the 4 sites were selected at random. The SEM-EDS results show that the microstructure and composition of polished sections of the slag samples can be of one type only. The phases present include glassy, iron prills (Fig.9), and tephroite in some samples (Fig.10). Their composition is almost the same. Their average composition (adding oxide) of FeO was 3.08% (wt%), $SiO_2$ about 32% (wt%), $Al_2O_3$ about 14% (wt%), $K_2O$ about 2.5% (wt%), CaO about 2% (wt%), S about 0.3% (wt%), MgO about 0.09% (wt%), MnO about 46% (wt%) and $P_2O_5$ about 0.01%

(wt%). In addition, we found droplets of iron prills in all of these tapped slag samples.

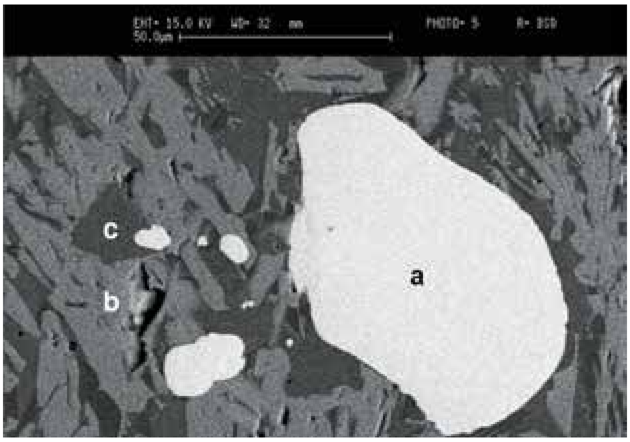


**Figure 10** SEM backscattered electron image of the matrix of the tapped slag No. XL004 from the Liuxicun site. The phases present include glassy, iron prills (white phase: point a), and tephroite (black-grey phase: point b, Mn 79.45% (wt%), Si 16.10% (wt%), Fe 3.42% (wt%)). Point c (grey-black phase) in the tephroite may be spessartite (Mn 57.74% (wt%), Al 37.67% (wt%), Fe 1.87% (wt%)).

The composition of all the iron prills in these samples was fairly high in P (Fig.9), the average composition of P being 3.53% (wt%), while Mn was either not detected or low. Their microstructure also showed white cast iron (Fig.11), as observed by metallographic microscopy.

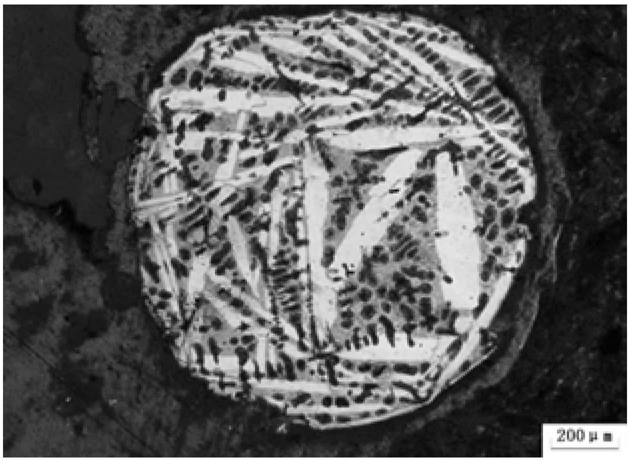


**Figure 11** Optical macrograph of the metallic iron prill of tapped slag No. XL003 at the Liuxicun site. Cast iron, nital etch.

All of the 23 samples were well-melted, as observed under the mineralographic microscopy.

## Discussions

*Smelting techniques*

We did not find Cu, Pb, Zn or Ag and relevant metallic particles among the basic components of the slag samples matrix surface using the SEM-EDS method. Based on current archaeological research about ancient non-ferrous metallurgical slag and iron-smelting slag classification criteria (Li 1995, p. 23; Craddock, Freestone, Gale, Meeks, Rothenbergand Tite 1985, p. 199; Rothenberg, Blanco-Freijero 1981, p.312) we may exclude the possibility that they are copper smelting slag, lead smelting slag, zinc smelting slag or silver smelting slag.

The characteristics of the 23 tapped slag samples, which showed phases of glassy, iron prills and tephroite sometimes, and the microstructure of their iron prills showing white cast iron, is certainly typical of cast iron smelting technology.

*Furnace*

Based on the morphology of the furnaces and slag found at the sites, we can conclude that there was at least one type of shaft furnace for tapped slag. The structure of these shaft furnaces has yet to be determined by further excavation and research.

*Ore*

*Ming Tongyizhi* (*A History of the Ming Dynasty*) records that the local people at Luya Mountain, located in northwest Nanliu County, Yuzhou Commandery, dredged and got green and yellow mud there, smelted them and cast woks (郁林州南流县绿鸦山在州西北三十五里. 州人于此淘取青黄泥炼成铁. 铸成锅) (Zhang 1954, p. 270). We did not find any fragments of iron ores at the sites during our investigation. So we consider that the iron ores (green and yellow mud) used should be sand iron ores, though further evidence is required to confirm this.

*Fuels*

During the National Survey of Cultural Relics in the 1980s, local archaeologists found a lot of charcoal in the furnace hearths at some sites. We also found a little charcoal in the slag heaps at some sites, and based on the potassium content in the slag samples, we consider that the fuel used should be charcoal. However, determining which timber they used to make the charcoal for smelting still needs further research.

*Production*

According to the text mentioned above, *Ming Tongyizhi*, one of the products made at the sites was cast iron works. This was confirmed by the discovery of moulds for casting woks at the sites (Fig.3), leading us to conclude that there were also cast iron foundries at the sites, besides the smelting workshops.

The *Yudi Jisheng*, also mentioned above, indicates that the iron smelting factory at Luya, Nanliu County, yielded iron production of about 64700 (*Jin*斤) (32,350 kg) per year, which was delivered to Censhui factory, Shaozhou (present-day Shaoguan, northern Guangdong province) (绿鸦场在南流县. 岁收铁六万四千七百斤. 往韶州涔水场库交) (Wang, 1992, p. 3505). So, we may conclude that the iron smelting factories at the sites were important for China, during the Southern Song dynasty at least.

### *Flux agent*

Based on the slag samples analyzed, we can conclude that the local people used manganese as a flux agent during cast iron smelting.

Usually, the slag from traditional cast iron smelting will be mainly composed of $Al_2O_3$-CaO-$SiO_2$, according to existing data of ancient cast iron smelting slag in central/north China. In other words, they used limestone as a flux agent during the smelting process. However, the slag discussed here definitely does not indicate the addition of limestone as a flux agent. Where did the manganese in the slag come from? We consider that there may be two possibilities: one is that the ore used could be a multi-mineral orebody or paragenetic mineral mainly composed of Fe and Mn; the other is that the craftsmen deliberately added manganese ore as a flux agent, mixing the iron ore and manganese ore together during the smelting process.

This raises further questions. For instance, limestone is common in the region, so why did not they choose limestone rather than manganese as a flux agent? Why did they use manganese while limestone was still the norm in central/north China? How did they know to use manganese as a flux agent? Is it the result of innovation or invention? If the ore they used was a multi-mineral orebody consisting of Fe and Mn, where is the mining site for such a multi-mineral orebody? If the craftsmen deliberately added manganese ore, where are the mining sites for the iron and manganese ores? These questions still need further study.

### *Smelting temperature judged from slag composition*

Based on the analysis using SEM-EDS of the 23 smelting slag samples, we know that all the slag is mainly composed of $Al_2O_3$-MnO-$SiO_2$. According to the $Al_2O_3$- MnO-$SiO_2$ diagram, the liquid temperature of the samples was about 1200$^o$C (Fig.12), judging from the average composition of the slag. However, these results do not take into consideration other factors. In practice, the temperature of cast iron smelting when using limestone as a flux agent is above 1400$^o$C, so we consider that it was easier to extract cast iron from iron ores when manganese rather than limestone was used.

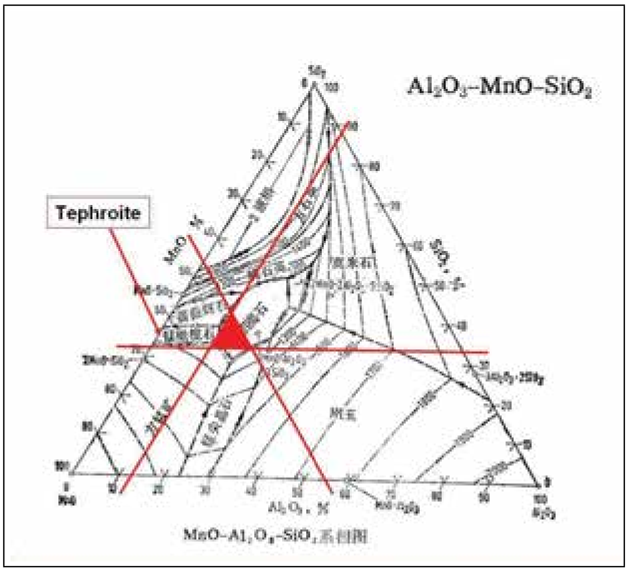


**Figure 12** $Al_2O_3$- MnO-$SiO_2$ diagram (after Slag atlas, 1987, Beijing: Yejin gongye chubanshe) showing that the liquid temperature of the cast iron smelting slag samples analyzed was about 1200$^o$C.

### *Tuyères*

All 23 slag samples were well-melted as observed under mineralographic microscopy, indicating that no other solid residue remained in the slag, a more uniform temperature in the process of smelting, and that blast technology had reached a certain level. We don't know, however, how many *tuyères* and what kind of blast equipment they may have used then.

The typology of the remains of the straight-round *tuyère* indicates a shared tradition with earlier copper and iron-smelting sites in the Guangxi region (Huang, Li 2008, p. 137; Li, Huang, Wan 2007, p. 175), and resembles closely those from South and Southeast Asian ancient iron-smelting sites, such as Ban Di Lung in Thailand (Suchitta 1983, p. 110), Naikund in India (Prakash 1989, p. 307) and so on. This has important implications for understanding cultural interactions between southern China and Southeast and South Asia during the Iron Age.

We know that the Thai/Zhuang people in southern China, northern Vietnam, Laos, Thailand, Burma and northeastern India still share the same basic language. In ancient times, they may have been a medium for cultural interaction between the areas mentioned. Such a new "silk route" requires considerably more interdisciplinary study and international co-operation.

*The dates of the finds*

Dating the finds and sites discussed above is still an issue. The *Yudi Jisheng* indicates the presence of such sites during 1131-1173 A.D in the Southern Song dynasty. Based on finds of large quantities of pottery shards, local archaeologists consider that the sites started in the Tang, flourished in the Song, then came to an end in the Ming dynasty. The patterns of pottery shards (Fig. 4) unearthed at the Gaoling site, however, have led some archaeologists to consider that they date to the Han dynasty [before 220 A.D.] at the latest. Examination with AMS-14C of the charcoal samples directly related to the smelting activities found at the sites should help to clarify some of these issues.

## Conclusions

The slag samples analyzed were cast iron smelting slag. This is the first time that the use of manganese as a flux agent in ancient cast iron smelting has been confirmed in China.

The typology of the remains of the straight-round *tuyère* indicates a shared tradition with earlier copper and iron smelting sites in the Guangxi region, South and Southeast Asia.

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# Metallurgical innovations and pattern of adaptation of iron in early cultures of India

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*ABSTRACT* Iron appears in India in a Chalcolithic context during opening centuries of 2nd millennium BCE without bringing about much change in material milieu. The efficacy of iron as an agent of change has been therefore questioned. The present paper examines the issue of technological innovation and pattern of its adaptation in the early cultures of India.

## The Issues

The advent of iron and steel provided a great impetus to human civilization, though the metallurgical process took a long time to evolve and mature to be truly effective. A comparative assessment of iron objects *vis-a-vis* the status of material remains at particular stages of culture may provide a clue to the degree of impact of technology on society. The present paper proposes to trace the stages of development of iron technology and to assess the role of iron in cultural change. Iron is supposed to be a utilitarian metal with superior strength than copper. Why is it that its impact was so gradual? An answer to such an anomaly lies inherently in the metallurgical development of iron. Firstly, copper is easier to produce on larger scale through casting. Secondly, any bronze even with ten per cent tin alloying is superior to wrought iron as initially produced. Therefore the change from bronze to iron was slow as aptly explained by Taylor and Shell (1988:205-221) in Chinese context, "Two misunderstandings regarding the change over from bronze to iron plague archaeological literature... they are that iron is better than bronze and that the difficulty in smelting iron lies in the high temperature required. In fact it is only steel that is consistently stronger than bronze... Furthermore, a usable bloom, or molten iron, if it contains a large amount of carbon or other impurities can be produced at temperatures close to or even below those needed to melt copper or gold... the difficulty with iron lay not in obtaining high temperatures but in developing the new techniques necessary to hot forge the bloom..." Thus iron required a new kind of technological configuration that necessitated a much longer process of experimentation through trial and error. Iron at early stage remained scarce and of uncertain nature. This resulted into a slow pace of production and adaptation of iron. This issue has been examined in detail by many like Tylecote (1962), Maxwell Hyslop (1974) and Waldbaum (1980: 90-91). They observed that the iron metallurgy initially was more suitable for bronze. This explains a rather slow adoption of iron and the continued use of copper-bronze even after the advent of iron. We propose to examine this at three stages of techno-cultural development in India.

## Early Iron Age

Recent radiometric characterizations suggest that iron first appeared in the Indian subcontinent between 1800-1200 BCE (Table.1). The Early Iron Age (EIA) cultures located in different ecological and geographical parts of the Indian sub-continent may be classified in several zones (zones A to F, Fig.1). These are: (a) the North-western region with cairn burials (b) the Painted Grey Ware (PGW) culture (c) the pre-Northern Black Polished Ware (NBP) culture with BRW-BSW (Black and Red Ware-Black Slipped Ware) pottery traditions (d) Early Iiron Age cultures in Madhya Pradesh (e) Megalithic culture of Vidarbh (f) Megalithic culture of peninsular India. We have sites like Noh, Jodhpura in Rajasthan (belonging to PGW cultural phase (1100-600 BCE) in Indo-Gangetic divide; Prakash, Bahal in Deccan and Kaytha in M.P. (Chalcolithic level); Chirand in Bihar; Dadupur, Raja Nal-ka-Tila, Malhar, Koldihwa, Kausambi, Jhusi, Rajghat and Narthan in Uttar Pradesh, (18/1700-600 BCE); Hatigra, Mangalkot, Mahaisdal, Pandurajar Dhibi (1200-600 BCE) in West Bengal; Naikund, Takalghat-Khapa, Mahurjhari, Hallur, Tadkanhalli, Komaranhalli (1400-6/500 BCE) in Vidarbh and Tamil Nadu (for details see Tripathi 2001, 2008).

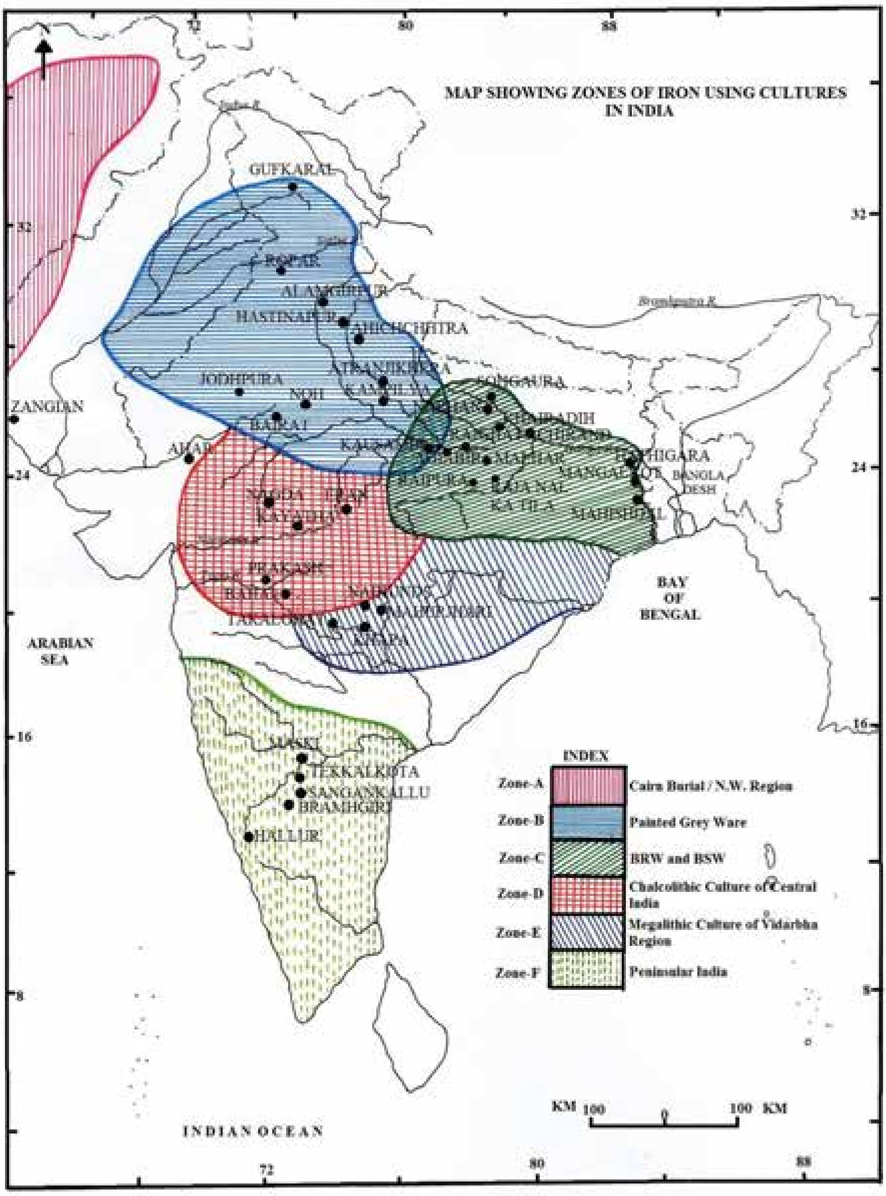


**Figure 1** Map Showing Zones of Iron Using Cultures in India

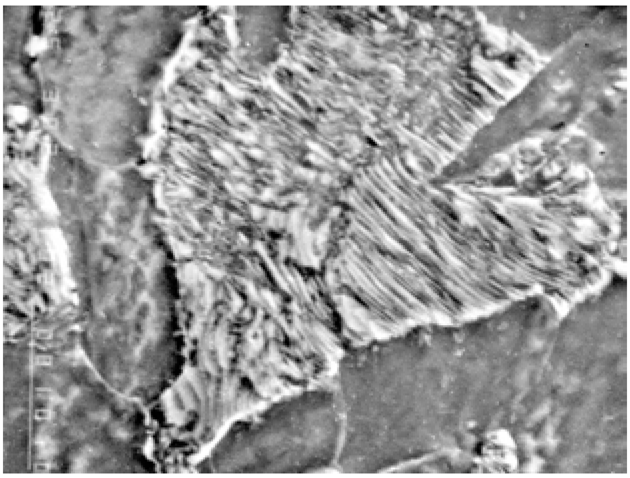

**Figure 2** Electron micrograph of celt, Tadkanhalli

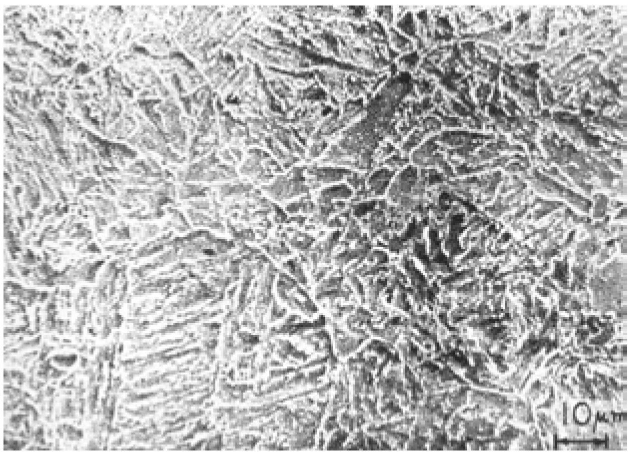


**Figure 3** Tempered martensitic structure of sickle, Pandurajar Dhibi 1000X 15 KV.

An elementary type of iron with slag inclusions was being produced by bloomery process at this stage. The furnaces were not efficient enough to generate sufficient temperature. Hatigra, Pandurajar Dhibi in district Burdwan (West Bengal), have yielded iron in the second phase of the Chalcolithic culture (Period II, B, Figs. 2, 3, respectively) datable to 2940±55 BP (1048 BC) and 2870 ± 30 BP. 970 BC, Period III is dated to 2580 BP (630 BC). The analysed objects of Hatigra (Bengal, 1100-1000 BCE) had Widmanstätten structure due to prolonged exposure at a temperature of about 1200$^0$C followed by slow cooling (Ghosh and Chattopadhyay 1987 p. 88). It is said to be a 'low carbon hypereutectoid steel'. The concentration of carbon on the edges visible in some of the micrographs shows carburization. It may have been incidental due to the technique of repeated heating and hammering in contact of charcoal. The evidence of a dish shaped object from Period II from Pandurajar Dhibi in district Bardwan (West Bengal) is noteworthy in this regard. On analysis, it has been described as a 'dark brown object with yellowish tinge that could easily be confused with copper based objects as work of a copper smith who accidentally seems to have worked it' (De and Chattopadhyay 1989:34). "The specimen could not be sliced with a hacksaw blade as it is extremely hard at the same time brittle". The chemical analysis (wet method) revealed only silicon and iron (De and Chattopadhyay 1989 34, Tripathi 2001, Table 6, 184). They further observed that it is very hard and 'could not be sliced with a hacksaw blade. EPMA revealed cobalt, oxygen, ruthenium, alumina and silica.' The fayalite in large quantity suggests the elementary stage of metallurgy. No carbide or pearlite structure could be detected on etching. High potassium content indicates use of charcoal as fuel.

**Table 1:** Radiocarbon Dates from Iron Age sites

| Sl. No. | Sites | Radiocarbon dates in BP/BC on the basis of half life 5730 ± 40 years | Calibrated Dates- B.C. |
|---|---|---|---|
| **Raja Nal- Ka –Tila** | | | |
| 1. | BS-1378 1996-97 Trench No. U - 19 (6) 1.95-2.00#m With iron | 2626±110 BP<br>676±l10 BC | 822 (773) 486 BC |
| 2. | PRL - 2047 1996-97 Trench No. U-20 (6) 2.08-2.10#m With iron | 2980±90 BP<br>1030±90 BC | 1196 BC- 1188 BC -1164 BC-1143 BC -1132 BC-976 BC -970 BC-930 BC |
| 3. | BS – 1299 1995-96 Trench No. A-l Pit sealed by layer No. (6) With iron | 2914±100 BP<br>960± 100 BC | 1118 (963) 859 BC |
| 4. | BS – 1300 1995-96 Trench No. A-l (6) 2.00#m With iron | 3150±110 BP<br>1200± 110 BC | 1423 (1307) 1144 BC |
| 5. | PRL-2049 1996-97 Trench No. T-19 (6) 2.00#m With iron | 3150±90 BP<br>1200± 90 BC | 1406 BC -1198 BC 1186 BC-1164 BC 1143 BC-1132 BC |
| **Malhar** | | | |
| 6. | BS - 1623, MLR II<br>Trench No. XAl,<br>Layer No. (3)<br>Depth 0.55 cm | 3550 ± 90 | 1886, 1664 1649, 1643 BC |
| 7. | BS - 1593, MLR II<br>Trench No. Al,<br>Layer No. (3)<br>Depth 90-100cm | 3650 ± 90 | 2010 ,2001, 1977, 1750 BC |
| 8. | BS-1590 MLR II Layer No. (4) 80 cm | 3850 ± 80 | 2283, 2248, 2233, 2030 BC |
| **Dadupur** | | | |
| 9. | BS-1822<br>Trench No.<br>DDR-3, A -1 | 3368± 80 B.P.<br>1420± 80 B.C | 1679 (1522) 1422 BC |
| 10. | BS-1759<br>Trench No.<br>DDR-3, A-1 | 3480 ± 160 BP<br>1530 ± 160 BC | 1882 (1685) 1465 BC |
| 11. | BS-1825 (Pit sealed by (12) | 3532 ± 90 BP<br>1580 ± 90 BC | 1739, 1706, 1695 BC |
| **Lahuradewa** | | | |
| 12. | BS-1939 | 2940 ± 100 B.P. | 1205, 1205, 1188 |
| **Jhunsi** | | | |
| 13. | AU/JHS/ 9 2075C-15 (46) 1210 | 2730±90 | 897 (806) 789 BC |
| 14. | AU/JHS/ 12 2077C-15 (49) 1240 | 2900±90 | 1107 (973, 956, 941) 844 BC |
| 15. | AU/JHS/ 16 2081C-15 (53) 1325 | 2780±90 | 966 (830) 799 BC |
| 16. | AU/JHS/ 18 2083C-15 (62) 1520 | 3290±90 | 1597 (1490, 480, 1450) 1400 BC |
| **Aktha** | | | |
| 17. | S-3580 | 3350±160<br>1660 ± 218 | Un calibrated |
| 18. | S-3849 | 3460±180<br>1771 ± 248 | Un calibrated |

Iron first appeared as shapeless bits at Noh in Rajasthan. Within a span of half a century of EIA, finished iron objects appear in several sites. The number gradually increased over the period. In a thick deposit of 2.50m PGW culture dated between 1100/1000- 600 B.C. at Atranjikhera (Gaur 1983) yielded 7, 46 and 81 iron objects, at its three sub-periods, respectively (Table 2). Jakhera, another site nearby has yielded an iron ploughshare along with pieces of slag in the Pre-PGW- Black and Red Ware (BRW). In the PGW the number and type of objects multiply manifolds yielding hoe, sickle, spearhead, arrow-head, dagger, chopper, chisel, axe, nails, rods etc. (Sahi 1994). At Hastinapur (Lal 1954-55) and Alamgirpur in Meerut district iron appears for the first time during the PGW cultural period (Tripathi 2001, fig. 12) A somewhat similar evidence comes forth from Mangalkot (West Bengal) in an otherwise Chalcolithic cultural milieu dominated by Black and red ware. It has been dated to 1300 BCE (Dutta 1992). The iron samples analysed from the site of Hatigra dated 1100-100 BC as noted earlier had Widmanstätten structure due to prolonged exposure at low temperature producing a 'hypo-eutectoid steel'. The analysis indicates carburization (Ghosh and Chattopadhyay 1987).

**Table 2:** Iron Objects of PGW at different sub-phases (Atranjikhera)

| Sl. No. | Objects | Lower | Middle | Upper | Total |
|---|---|---|---|---|---|
| 1. | Arrow-head | - | 7 | 14 | 21 |
| 2. | Spear-head | - | 3 | 5 | 8 |
| 3. | Shaft | 2 | 5 | 3 | 10 |
| 4. | Tongs | - | - | 1 | 1 |
| 5. | Clamp | - | 10 | 11 | 21 |
| 6. | Nail | 2 | 4 | 14 | 20 |
| 7. | Bar/Rod | - | 2 | 5 | 7 |
| 8. | Hook | - | 2 | 5 | 7 |
| 9. | Borer | 1 | 2 | 3 | 6 |
| 10. | Chisel | - | 4 | 2 | 6 |
| 11. | Needle | - | - | 1 | 1 |
| 12. | Axe | - | - | 1 | 1 |
| 13. | Knife | - | 1 | 2 | 3 |
| 14. | Bangle | - | 1 | 1 | 2 |
| 15 | Lumps | 1 | 2 | 4 | 7 |
| 15. | Indeterminate | 2 | 3 | 9 | 14 |
| | **Grand Total** | **8** | **46** | **81** | **135** |

The megalithic burials of southern India at EIA are rich in iron yielding swords, spikes, tridents, horse's bits, and also utensils are found along with usually used shapes found at this period, i.e. arrow-head, spearhead, chisel, axe, fish hook and bangles (Fig. 4). Iron objects from Tadkanhalli, a megalithic site dated by TL to 14$^{th}$-13$^{th}$ BC show steeling with pearlite at grain boundaries (Hari Narain et al. 1998). The megalithic tools from Mahurjhari show high carbon content with evidence of carburization and quenching (Deshpande et al., 2010).

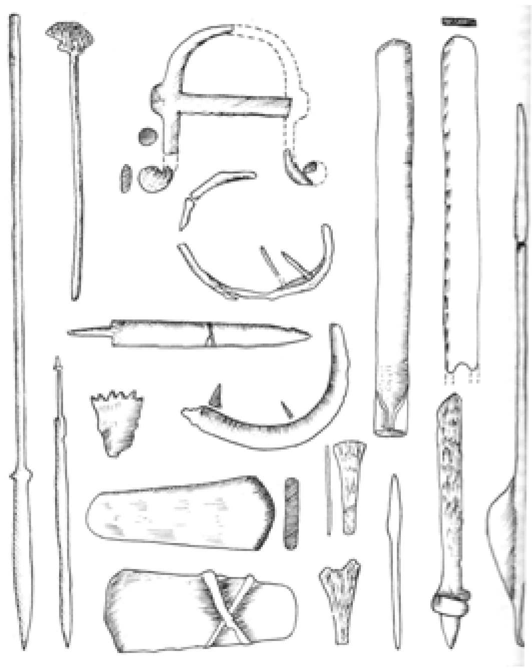

**Figure 4** Iron Objects from Megalithic Burials (Vidarbh Region)

## Middle Iron Age (900 to 200 BCE)

A culture designated as Northern Black Polished Ware (NBPW) culture dominates this stage. This was a period of consolidation of iron technology with steeling and deliberate carburization. A relative increase is recorded in the number and types of iron objects. We see javelins, lances, daggers, blades, and elephant goads along with the earlier types (Tripathi 2001, Figs. 20-24). Agricultural implements become common at this stage.

Though solid-state reduction of iron continues to be the norm of smelting, improvisation in metallurgical technique is clearly perceptible. An iron sickle of Pandurajar Dhibi pertaining to NBP Period was examined. "Electron micrograph obtained at a magnification of 100 X clearly represents its tempered martensitic structure". De and Chattopdhya (1989, 37; Fig. 4.C.) observed, 'it shows non-uniform structure and retained acicularity at certain places, especially around large patches of ferrite areas. Carburization was done during smithy in course of heating and forging of objects. Inside the core, the carbon content that is retained is only 0.22%. But the high level of corrosion that took place over the time must have caused depletion of carbon. There is also an uneven distribution of carbon concentration. It indicates that carbon was more than 0.4% initially.' There are also indications of quenching and tempering. Such conditions were noticed in iron from Senuwar, Narhan, Chirand and Taradih. (Singh and Merkel. 2001-02; Tripathi 2001, PL.X.C, Figs. 24C, and D). Lamination technique was also in practice as seen at Sringverpur (Tripathi, 2001, Fig. 23 A).

**Late Iron Age (C.E.100-600 and beyond)**

**Figure 5** Iron objects (Stage III) Taxila

At stage III, there is not only a proliferation in tool types including some armour grade weapons of high carbon steel at Taxila (Fig.5, see Table 3). A greater proficiency was attained in iron metallurgy. Techniques like lamination and quenching were employed frequently. Hadfield (1913-14) noted high carbon in Taxila iron. He further observed an affinity between Delhi iron and tribal iron objects produced at Mirjati showing continuity in technique. Sisupalgarh in Orissa (datable to 2$^{th}$ -6$^{th}$ CE. Lal, 1949, 95) yielded a caltrop, a weapon to be used in the battlefield to curb the speed of elephants. It is well attested that the ancient Indian smiths at this stage had a thorough knowledge of carbon alloying, case hardening, tempering and lamination (Hari Narain et al. 1998, Fig. 14). These techniques seem to have been purposefully used. For instance, a nail differs in composition from a knife or a dagger. Needless to emphasise that such skills must have been acquired with experience before the craftsmen could venture to take up challenging jobs of manufacturing a 7 ton iron pillar with a high corrosion resistance, having a diameter of 7375 mm at the bottom and 304 mm at the top, weighing approximately 6096 kg. The Delhi Iron Pillar (fig. 6) dated to 4$^{th}$ – 5$^{th}$ century C.E. is a unique example of such a metallurgical skill. It is an excellent quality wrought iron of high purity (99%). It has been examined by many (Bardget and Stanner 1963; Ghosh, 1963; Lahiri, 1963; Balsubramaniam, 2002, 2008). The quality of iron is so good that even after standing in the open for more than sixteen hundred years it still maintains its anticorrosive property. These studies show that ironsmiths had attained mastery over cementing and forge-welding small rods of iron, and strongly forging them to shape such large objects. It also indicates that the ancient craftsman had mastered the operation and technique of control over temperature in furnaces to produce iron of uniform composition on such a large scale. The question that arises at this juncture is about the efficacy of iron technology in bringing about socio-cultural changes.

**Table 3.** Relative Position of Iron Objects at Different Cultural Periods

| Tool Type | Name Of Tool | Early Stage | Middile Stage | Late Stage |
|---|---|---|---|---|
| Hunting Tool | Spear heads | * | * | * |
| | Arrow heads | * | * | * |
| | Points | * | o | o |
| | Socketed tangs | * | o | o |
| | Blades | * | * | o |
| | Spear lances | o | * | o |
| | Dagger | o | * | * |
| | Sword | o | * | * |
| | Elephant goad | o | * | * |
| | Lances | × | × | * |
| | Armour | × | × | * |
| | Helmet | × | × | * |
| | Horse bits | × | × | * |
| | Caltrop | o | o | * |
| Agricultural Tools | Axes | * | * | * |
| | Sickles | * | * | * |
| | Spade | × | * | o |
| | Ploughshare | × | * | o |
| | Hoe | × | * | * |
| | Pick | o | o | * |
| Household objects | Knives | * | * | * |
| | Tongs | * | o | o |
| | Discs | × | * | o |
| | Rings | × | * | o |
| | Spoons | × | * | * |
| | Sieve | × | × | * |
| | Cauldron | × | × | * |
| | Bowls | × | × | * |
| | Dishes | × | × | * |
| Structural and craft tools | Rods | * | o | o |
| | Pins | * | o | o |
| | Nails | * | * | * |
| | Clamps | * | * | * |
| | Chisel | × | * | * |
| | Pipes | × | * | o |
| | Sockets | × | * | o |
| | Plump bob | × | * | o |
| | Chains | × | * | * |
| | Door hooks | × | * | * |
| | Door handle | × | × | * |
| | Hinges | × | × | * |
| | Spikes | × | × | * |
| | Tweezers | × | × | * |
| | Anvils | × | × | * |
| | Hammers | × | × | * |
| | Scissors | × | × | * |
| | Saw | × | × | * |

Definite existence *
Confirmed data not available o

## Discussion: Pattern of technology adaptation and culture change

The interface of iron utilization and material prosperity may help establish a relationship between the two. A brief review of Iron Age Cultures and pattern of utilization of iron at specific stages is called for here.

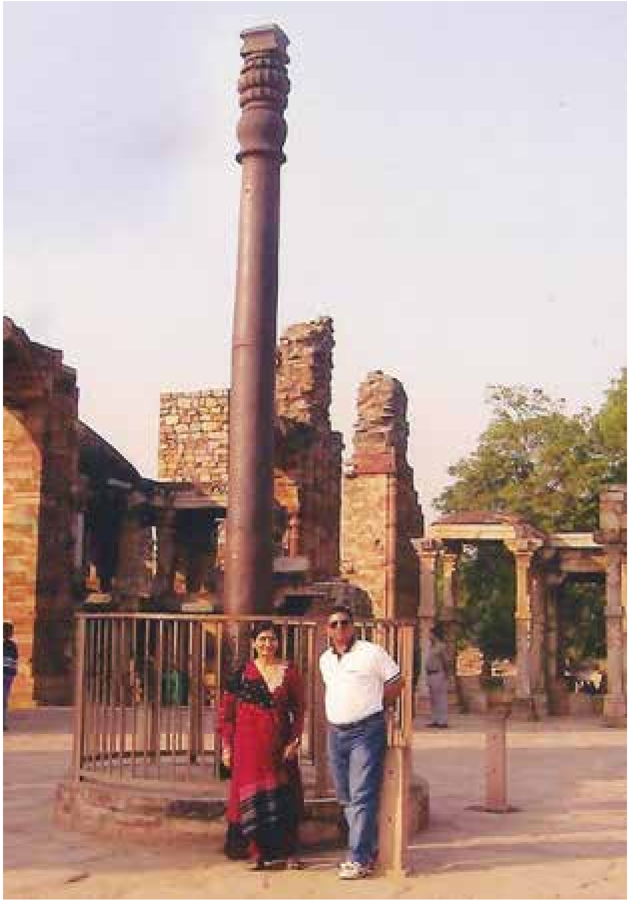

**Figure 6** Vibha Tripathi and R. Balasubramaniam with Delhi Iron Pillar

## Stage I: Age of Commencement

The Early Iron Age settlements are modest sized habitations of thatched roofed huts or sun-baked structures made of mud-bricks. At sites like Kausambi (Sharma 1960) and Hasinapura (Lal 1954-55) towards the later part of this period, rammed roads have been located. Protective bunds and embankments or moats have also been found at sites like Atranjikhera, Jakhera, Kausambi, Sonkh and Eran. It suggests emergence of an organized socio-political system by $8^{th}$-$7^{th}$ BCE.

The economy was predominantly agrarian with cultivation of a variety of grains (Saraswat, 2010). Atranjikhera yielded wheat, barley and rice. In absence of suitable tools and techniques the yield must have been inadequate, as evidenced by cattle rearing and hunting. A near absence of iron ploughshares suggests the use of wooden ploughshare. (The later Vedic texts attest this). Common occurrence of bull figurines and toy carts indicate the significance of cattle.

In the absence of coinage a simple barter system must have been in vogue. Small weights of chert and jasper have been found at Hastinapur which implies some sort of commerce, but what merchandise required such weights is not clear (Ghosh 1973, 10 ). Minor antiquities of this stage are beads of terracotta and objects like points, styli, beads and bangles, stone balls, ivory shell and horn objects. Glass is used for the first time at PGW level, beads and bangles are fashioned with glass.

## Stage II: Middle Iron Age: The Period of Fluorescence

The NBP Ware had a distribution extending from Taxila and Charsadda (now in Pakistan) in the North to Brahmagiri in Karnataka and Anuradhpur (Sri Lanka) in the south; from Prabhas Patan in Saurastra, in the west to Mahasthangarh in Bangladesh, in the east. Chronologically, NBP overlaps with PGW on the one hand, and the Sunga-Kusana period on the other. The earlier chronological bracket of 700/600 to 200 BCE is modified by radiometric dates of 1000 BCE if not earlier, for the beginning of NBPW culture. The culture is harbinger of the second urbanization in ancient India. For the first time, we come across evidence of coinage and writing. The settlements expand with rising population (Fig. 7). Use of baked bricks - haltingly first and more commonly later - fortification of settlements and sanitary arrangements mark the structural activity. At important sites like Hastinapur and Kausambi, remains of larger houses have been unearthed. Kausambi had a double storied house measuring 28’ x 15’ and 16 steps, while in Hastinapur, a long wall has been traced. Lined and unlined drainage system, wells and ring wells have been introduced. Rajghat excavations also revealed a rammed road having a thickness of 33.1 cm. It was made at the late NBP level (Roy 1983, 138). Pataliputra yields a pillared hall with colossal stone pillars, fortification, and drains etc. at the relatively later phase of this period. The Asokan pillars with glossy finish and elegant capital-heads dated to $4^{th}$-$3^{rd}$ BCE are found across the country. Excellent quality iron implements were indeed inevitable in modelling and chiselling of these majestic edifices.

The sophistication in pyrotechnology reached a high standard – the ceramic art specially evolved in the form of NBP Ware having a typical metallic finish. A double chambered kiln was unearthed at Khairadih (Ballia), (Tripathi and Singh 2004). Terracotta figures and pottery are handiworks of specialist class, so are glass, ivory and beads of precious and semi-precious stones. A bead making workshop was discovered at Agiabir, near Varanasi. The Buddhist literature makes frequent references to flourishing trade, both overland and marine. The occurrence of inscribed NBPW at Sri Lanka in 5th century BCE reiterates the growing international trade by 5th-4th BCE.

The political history is witness to rise of historical age marked by rise of Mahajanpadas (states) across India. The fall of Nandas and rise of Mauryan dynasty synchronizes with this period. It hardly needs to be underlined here that the rise of an organized socio-political system had its mark on every sphere of life. Rise of Buddhism and Jainism left a deep mark on every sphere of life.

## Stage III: Late Iron Age: Age of Culmination

This was the era of cultural culmination. The pace of innovations started earlier gained momentum as testified by literary as well as archaeological evidences. The victory pillars being commandeered by the power centres exhibit prowess and technological acumen at the same time. The mighty Kusanas had established themselves in large part of India. The Guptas took India to greater heights subsequently.

The state provided patronage to art- architecture, literature, music, craft, trade and commerce during the Gupta-period. The guilds of traders were well organised and wielded great power in society. It was an era vibrant with activities that took India to unprecedented heights in every sphere of life. How much in it was the contribution of technology may be a debatable issue. It is however, undisputed that science, technology and 'industry' had reached an all time high during this period described by many as Golden Period of Indian history.

## Conclusions

To summarise, we may state that technological skill contributed to economic prosperity. Talking specifically about iron metallurgy, we may say that it took a long time to evolve, as reflected in the scarcity and the elementary nature of iron objects produced in elementary furnaces at low temperature which had little advantage over a good quality bronze having even 11% tin, with a Brinell hardness of 60,000 per sq. inch (PSI.). The hardness increases up to 120,000 PSI. after cold working. Wrought iron, on the other hand has the hardness of only 40,000 PSI. Repeated hammering and heating in contact with charcoal raises its hardness up to 100,000 PSI. The elementary level of metallurgical know-how, coupled with a conservative and sceptical temper of society, explains the reason of late adaptation of iron, for purposes other than weaponry or carpentry at the earliest level. The metallurgy had to attain a high level of efficiency to produce cheaper and affordable objects in sufficient quantity to be socially acceptable, operative and effective.

There appears to be syncretistic growth of technology and social affluence. It may be difficult to establish a direct link between the technology input and socio-cultural development, especially at relatively later stages of emergence with political system and state coming at the helm of affairs. However, at the relatively earlier stages, technology must have played a more crucial role

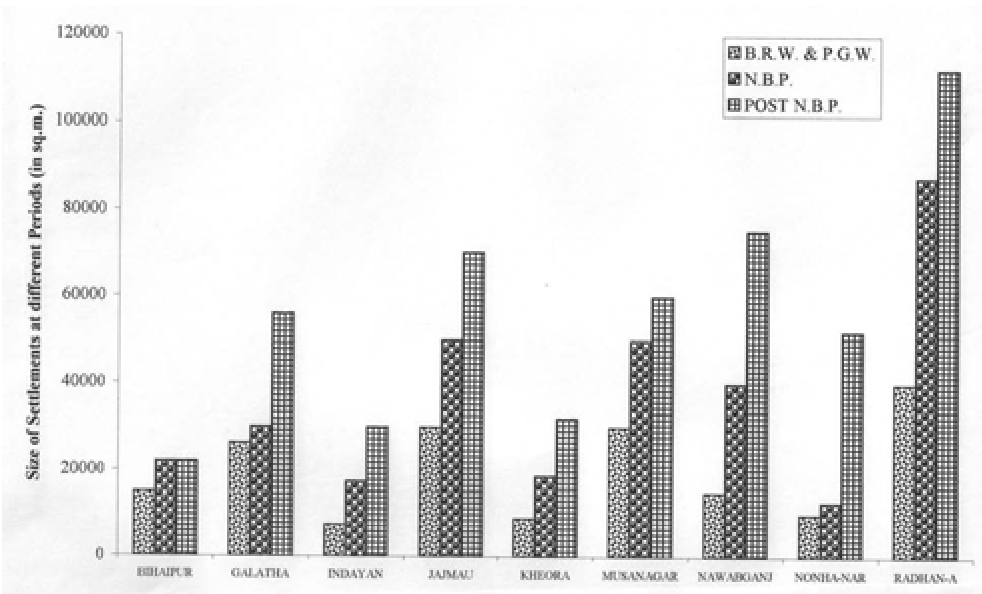


**Figure 7** Relative Position of Settlement Size at Different Cultural Stages in the Ganga Plain

in bringing about prosperity by providing better tools and implements of production that strengthened the economic foundation for future growth. It was truer of iron, the utilitarian metal capable of making a difference in the production mechanism and thereby bringing about prosperity and affluence in society.

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# Improvements in traditional Indian iron making technology

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*ABSTRACT* Iron has been produced and used in India for over 3000 years. Indian tribes preserved the technology of ancient iron making up to the 20th century. In order to reduce the cost and energy requirement and increase the yield of product several improvements were necessary to improve the basic process adopted by the tribals. The National Metallurgical Laboratory of Jamshedpur initiated investigations to understand the ancient iron making process and implemented a number of improvements to make the process a source of livelihood for tribals. Initially a prototype traditional furnace was established to study the effect of different process parameters. The foot driven bellows were replaced by a semi-mechanized air blower, and sal wood charcoal was replaced by charcoal made from eucalyptus or acacia. The ancient iron making process was scaled–up by incorporating the heat recovery system and three semi mechanized air blowers. Hot air was blown into the entire cross section of the furnace through three tuyeres positioned at $120^0$ apart from each other with a view to increase the yield of product from 25 to 54 %.

## Introduction

The Agarias were one of the major tribes of India engaged in the production of iron in central India, eastern Uttar Pradesh, Bihar, and Orissa. The whole family, including women, were engaged in this traditional trade and the technology was maintained as a family trade secret. They moved from place to place and produced iron deep inside jungles. During the 17th and 18th century the iron industry experienced a boost and artisans producing iron and blacksmiths making weapons were kept busy. Iron and steel produced during the 18th century in India were of very high quality and a regular item of export. Iron making was practiced widely in many parts of the country, and employed naturally available iron ore and charcoal for reduction. Such people were called Lohars. This industry was active in various places in U.P., Jharkhand, Bengal, Orissa, Maharashtra, Chattisgarh, Mysore, Assam and Madras. The furnaces were small, up to 30 inches in height, and made of mud, with bellows being used to blow the air. The profile of a typical furnace used at Salem in the early 19th century resembles that of a blast furnace in miniature. The Travel records of Voysey (1823), Buchanan (1807), Hadfield (1912), and Verrier Elwin (1991) clearly show the supremacy of Indian iron and steel technology even in the 18th century.

Charles Wood, who was in charge of the Beypur Iron Works, as reported in a paper by Turner (1894), mentioned that his company could not produce a metal similar to that of the Indian swords used in the Indian Mutiny of 1857. The indigenous iron and steel industry started to decline because of various socio-technical reasons. Unfortunately this art disappeared after the development of a new technology during the 19th and 20th century. Indian metallurgical skills receded to the background, being restricted to the production of utensils, idols, ornaments, industries specializing in exquisite crafts of religious statuary jewellery. The industrial revolution in the 18th century led to Western predominance in materials development and utilization over the rest of the world. The Indian iron and steel industry began to decline in the last two centuries, under the impact of the British rule and the influx of mass scale produced iron and steel of European origin. With the establishment of the Tata Iron & Steel Company Limited (TISCO), there was a gradual extinction of the old indigenous smelting industry carried on by people known as Asur, Lohars, Birjias, Agarias etc. In 1960

Ghosh (1964) and Rao (1963), located a few families of Agarias near Jamshedpur and in Orissa. They observed the operation of three different furnaces at Jiragora and Chiglabecha in Orissa, and at Kamarjoda in Bihar. In 1963 a public demonstration of ancient iron making was organized at National Metallurgical Laboratory, Jamshedpur. Ghosh (1964) published a detailed report regarding the working of such furnaces and their products. In 1981, Prakash and Igaki (1984) located a family of the Mundia tribe at Loharpara in Baster that was smelting iron in that region until recently. In late eighties RDCIS, SAIL (Prasad *et al* 1990) with the assistance of Vikash Bharati, a voluntary organization at Bishunpur, Gumla District, Jharkhand, initiated investigations on the process of iron making practiced by the tribal artisans of Chhotanagpur Division of the then Bihar State and suggested several improvements to make the process a source of livelihood for them. The knowhow of ancient iron making still survives in some of the tribes in this country, especially in the regions of Central and Southern India.

The disadvantages of the old technology of iron making were critically reviewed and the design of the furnace was modified and improved accordingly, to make the process energy efficient, economical and eco–friendly. NML scientists (Vaish *et al 1999*) discussed the historical perspectives and technological considerations to make the ancient process of iron making economically viable and efficient. The kinetic study (Goswami, 2001) on the reduction of low grade iron ore used in tribal iron making by charcoal showed very good agreement with Ginstling-Bronstein model in which diffusion is considered to be the rate controlling step and charcoal is the appropriate selection as a reductant for reducing inferior iron ore. The National Metallurgical Laboratory, Jamshedpur attempted to develop a system to considerably improve the efficiency and yield of ancient iron making process. The incorporation of a heat recovery system and semi-mechanized blowers rendered the process more efficient and eco–friendly. Three tuyeres were positioned at $120^0$ apart from each other for uniformly feeding hot air in the entire cross section of the furnace. The newly developed process was scaled-up and increased the yield of iron from 25 to 54%. Sal wood charcoal was replaced by charcoal made from acacia or eucalyptus, as this charcoal was found to be equivalent to that made with the more expensive sal wood. The improved process makes use of iron ore in the form of composite pellets made of char and ore fines with cowdung as binder. The process has a tremendous advantage for commercialization since the decorative articles made out of this product have a very good export potential.

## Study the primitive technology of iron making

The tribal artisans generally used low grade iron ore (limonite / goethite) available on the surface of the hills (Fig. 1a), and charcoal made from Sal wood for making iron at the tribal site (Fig. 1b).

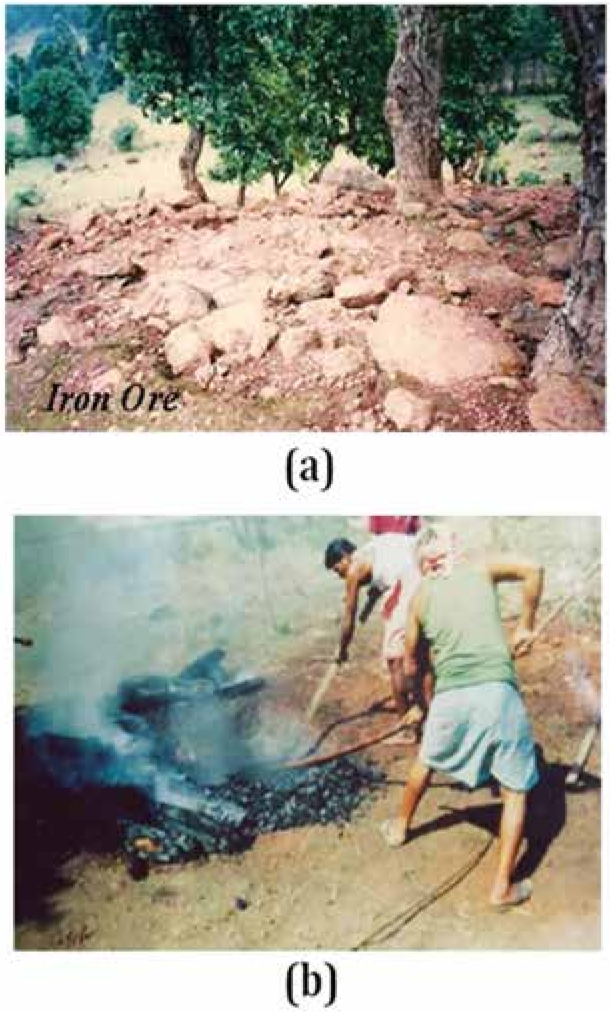


**Figure 1** Illustration of iron ore deposit and charcoal making
(a) Iron ore deposit on the surface of the hills
(b) Charcoal making at Tribal site

## Traditional iron making activities at Hadup Village, Bishunpur, Jharkhand State (India)

The primitive iron–making required the construction of a furnace of stone and clay against a hillock or as a bowl. The open front bottom part of the furnace was closed after the placement of the air blast system and was finally broken when taking out the metal. Locally available iron ores, clay and charcoal prepared from sal wood were used for the production of iron. The furnace was filled with charcoal from the top, lighted up at the bottom, and air was blown through the tuyere by using foot-operated bellows. Bellows made of animal skins were used for air blasting. The charge was a mixture of ore and charcoal. During the air blowing operation the charge level diminishes. After the initial ignition the blowing of air through the charge continued until the operation was over. The dimension of a typical furnace was as follows: around 1 m deep and about two thirds of a meter in diameter. It was filled with iron ore and charcoal in several layers. A tuyere made of clay was inserted from the side or from the top and attached to the bellow. The temperature in the hottest part was around 1200 $^0$C and although reduction took place due to low $P_{O2}$ and high $CO/CO_2$ ratio, the metallic product was not liquid but a spongy mass. The optimal conditions were maintained by empirical experience alone. The slag - mostly fusible ferrous silicate or fayalite (melting at 1170 $^0$C - was caught up in the spongy solid mass, and tapped intermittently or continuously throughout the furnace operation. The measured temperature in front of the tuyere is about 1500 $^0$C. After the completion of the reduction, the leather bellows were removed, the furnace mouth was broken, and the spongy bloom was taken out and hammered gently to squeeze out the slag. The reduced iron in form of porous lump was separated from the FeO rich fayalite ($2FeO.SiO_2$) slag. The iron bloom was then further reheated in a smithy forge to almost white hot (>1250 $^0$C) condition and silica sand was sprinkled on it, to react with the remaining FeO, and to help the formation of $2FeO.SiO_2$ which flows out of the iron block. The refined iron produced in this way could be shaped into the desired products by forging. The microstructure of refined iron consists of ferrite grains, a little pearlite and slag stringers. The traditional process seems to totally follow scientific principles.

## Treatment of sponge iron

The sponge iron retrieved from the furnace was subjected to hammering on a stone. The pieces of sponge iron were then once again reheated in a separate charcoal furnace of the type blacksmiths normally use. The slag had to be squeezed out of the sponge iron by hammering at or above 1250 $^0$C, a process known as forging. About 30-50% of weight loss can be observed in this step, and the iron takes the shape of an implement. A stage of the ancient iron making process at Harup Village, Bishunpur, Gumla District Jharkhand is shown in Fig. 2. The chemical analysis of iron ore from Bishunpur as well as metal and slag produced in primitive iron making furnace are given in Table 1.

Table 1: Typical analysis of iron ore from Bishunpur and the metal and slag obtained in traditional Bishunpur type furnace

| Bishunpur ore lumps | | Metal | | Slag | |
|---|---|---|---|---|---|
| Fe (T) % | 56.35 | C | 0.115 | $SiO_2$ | 31.40 |
| $SiO_2$ % | 2.84 | Si | 0.041 | CaO | 0.43 |
| $Al_2O_3$ % | 4.08 | S | 0.023 | MgO | 0.25 |
| MnO % | Nf | P | 0.021 | FeO | 53.54 |
| S % | 0.004 | Mn | 0.0013 | $Al_2O_3$ | 7.95 |
| P % | 0.119 | -- | -- | -- | -- |

**Figure 2** The ancient iron making furnace at Hadup village, Bishunpur, Gumla district Jharkhand

## Traditional iron making activities at Kondagaon, Bastar District, Chattisgarh State (India)

The furnace used at Kondagaon was similar to the Bishunpur furnace, but the charge is fed through a specially prepared charging bay (inclined at an angle with respect to the horizontal plane to facilitate the feeding of charge materials), and it has a separate slag spout on the side of the furnace. Locally available iron ores and sal wood charcoal were used in the process and clay was employed for the furnace. Initially the furnace was filled up to the top with charcoal, and the mixture

**Figure 3** The ancient iron making furnace at Kondagaon, Bastar district Chhatisgarh

of ore and charcoal, in proportion of 1:2, was spread on the charging bay at 20–25 minutes time interval. Slag in the liquid state was removed several times through the slag spout. The front arch was broken and the lump of reduced iron was taken out with a wooden plank or a bamboo pole after the conclusion of the operation. Fig. 3. The chemical analyses of iron ore from Kondagaon as well as metal and slag produced in the primitive iron-making furnace are given in Table 2. The tribal artisans of the Bastar region have popularised the traditional iron making technology by organising live demonstrations at National and International conferences as well as at Pragati Maidan, New Delhi on special occasions.

Table 2 : Typical analysis of iron ore from Bastar, and metal and slag obtained in the traditional Bastar type furnace

| Bastar ore lumps | | Metal | | Slag | |
|---|---|---|---|---|---|
| Fe (T) % | 60.19 | C | 0.135 | $SiO_2$ | 30.80 |
| $SiO_2$ % | 1.97 | Si | 0.051 | CaO | 0.62 |
| $Al_2O_3$ % | 12.09 | S | 0.021 | MgO | 0.48 |
| MnO % | nf | P | 0.037 | FeO | 56.25 |
| S % | 0.005 | Mn | 0.0069 | $Al_2O_3$ | 6.46 |
| P % | -- | -- | -- | -- | -- |

## Mechanism of reduction of iron ore by carbonaceous reductant in the traditional iron making furnace

In the traditional iron making furnace, the hot ascending gas gives up its heat to the descending charge, while the CO portion of the gas reduces the iron oxides according to its reducing potential at the various temperature levels and is converted to $CO_2$. Considering the reduction reactions with CO at 900 °C in the reduction zone of the furnace, the equilibrium $CO/CO_2$ ratios, CO- utilisation factors $\eta_{CO}$ will be as follows:

| Reactions | Equilibrium at 900 °C | |
|---|---|---|
| | $CO/CO_2$ | $\eta_{CO}$% |
| $3Fe_2O_3 + CO = 2Fe_3O_4 + CO_2$ | 0 | 100 |
| $Fe_3O_4 + CO = 2FeO + CO_2$ | 0.25 | 80 |
| $FeO + CO = Fe + CO_2$ | 2.3 | 30 |

The extent of utilisation, i.e. the percentage CO converted to $CO_2$ is denoted as

$$\eta_{CO}\% = 100\ [\%CO_2 / (\%CO + \%CO_2)]$$

The traditional furnace is a counter current process. The tuyere gas with high CO content comes in contact with the wüstite which needs a very high reduction potential to convert into Fe. The resulting lower potential gas, as it ascends, encounters magnetite and hematite that require a much lesser degree of equilibrium $CO/CO_2$ ratio for reduction to lower oxides. The reaction product of indirect reduction is $CO_2$. If any wüstite remains unreduced in a zone where temperature is higher than 1000°C, the $CO_2$ is reduced by carbon, $CO_2 + C = 2CO - 41.210$

### Advantages of the traditional ancient iron making process

(i) Locally available clay is mainly used for making the furnace and the tuyeres
(ii) The iron made by ancient process is a pure form of iron (wrought iron) with very low C (0.10 - 0.20%).

(iii) The process needs no electric power, no special refractory, no expenditure for the procurement of raw materials and furnace preparation as the entire family, including women, collect the iron ore and participate in furnace making.

## Limitations of the process

The limitations of the traditional ancient processes are:

(i) Continuous air blasting by foot driven leather bellows for 4–5 hours is strenuous.

(ii) Large scale production is not possible since it can produce about 3.5–4.5 kg of metal per heat.

(iii) The productivity of the process is also very low since major loss of iron takes place in the form of FeO in slag.

(iv) A significant amount of heat energy and chemical energy are lost through exit gases from the furnace whose temperature is 550–600 $^{0}$C.

(v) The use of Sal wood charcoal is not suitable from the point of view of environmental management therefore it is advisable to use an alternative reductant namely acacia or eucalyptus charcoal

(vi) It is observed that the degree of ore reduction is less due to low shaft height of the furnace

**Improvements in ancient iron making technology at NML Jamshedpur**

Prior to incorporating several improvements in the traditional iron making process a prototype traditional furnace was constructed at NML Jamshedpur to optimize the process parameters.

## Construction of prototype traditional furnace

A prototype traditional furnace was built at NML by using locally available clay. Extensive experiments were conducted to optimize the following process parameters: ● Type of ore (Bishunpur and Bastar) ● Form of ore (lumps or pellets) ● Type of reductant ● Air flow rate /volume of air blast per unit time ● Type of blower (leather bellows / mechanically driven hand blower)

Table 3 : Typical analysis of metal and slag obtained in traditional Bastar type furnace making use of a hand operated blower, iron ore from Kondagaon and charcoal made from sal tamarind, Jamun and Mahua.

| **Metal Analysis** | | | | |
|---|---|---|---|---|
| | **Sal charcoal** | **Tamarind charcoal** | **Jamun charcoal** | **Mahua charcoal** |
| C | 0.12 | 0.11 | 0.095 | 0.131 |
| Si | 0.045 | 0.038 | 0.039 | 0.042 |
| S | 0.031 | 0.034 | 0.028 | 0.026 |
| P | 0.041 | 0.038 | 0.046 | 0.043 |
| Mn | 0.0071 | 0.0069 | 0.0058 | 0.0069 |
| Slag Analysis | | | | |
| $SiO_2$ | 44.30 | 45.31 | 46.10 | 46.21 |
| CaO | 0.61 | 0.58 | 0.53 | 0.67 |
| MgO | 0.24 | 0.28 | 0.31 | 0.33 |
| FeO | 45.30 | 43.40 | 42.31 | 40.67 |
| $Al_2O_3$ | 6.98 | 8.31 | 7.94 | 7.31 |

The iron making process in the prototype furnace at NML Jamshedpur is shown in Fig. 4. The degree of metallization of sponge iron is low. The metal is probably to some extent re-oxidised in the open atmosphere during the cooling phase. The sulphur and carbon contents in the product are low while $Al_2O_3$ and iron oxides are high. The typical analysis of metal and slag obtained in

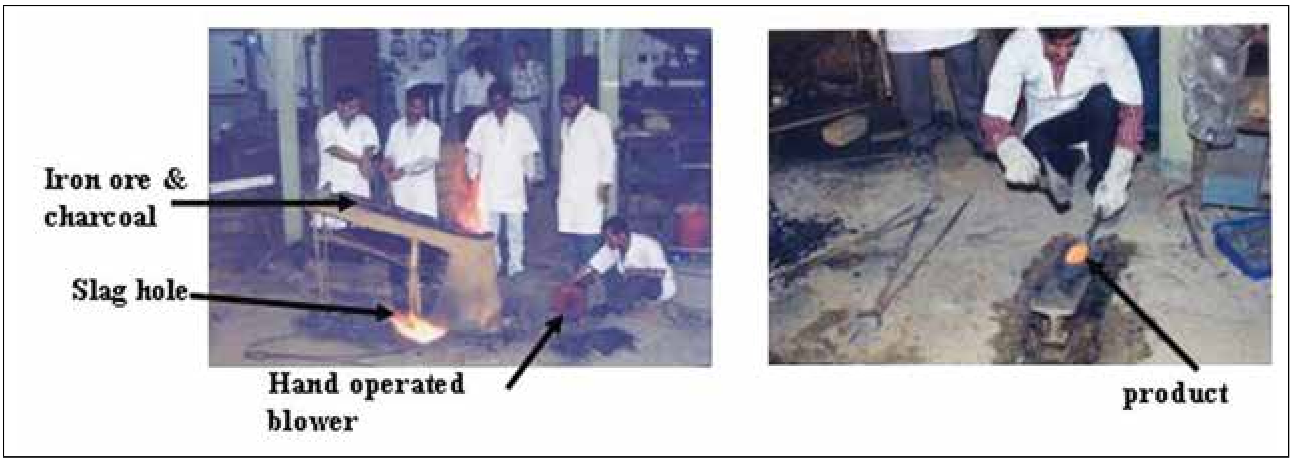


**Figure 4** The iron making process in the prototype furnace at NML Jamshedpur

Table 4: Theoretical & experimental $CO/CO_2$ ratio at different temperatures

| Location | Height from ground level | Range of temp | Theoretical CO /$CO_2$ | Experimental CO /$CO_2$ |
|---|---|---|---|---|
| Flame | -- | 500–600 °C | 1.20 | Not measured |
| Upper | 39 cm | 750–850 °C | 1.85 | 3.0 |
| Middle | 26 cm | 950–1050 °C | 2.60 | 4.0 |
| Lower | 11.5 cm | 1050–1150 °C | 3.0 | 4.5 |
| Tuyere Zone | -- | 1425–1475 °C | 4.0 | Not measured |

the traditional Bastar type furnace, with a hand operated blower, iron ore from Kondagaon and charcoal made from Sal, Tamarind, Jamun and Mahua is given in Table 3. As the total iron percentage is low, more slag formation occurs and as a result the yield is decreased.

The exit gas from the furnace was analysed using Orsat Apparatus especially to determine the percentage of CO and $CO_2$ and to find out the ratio of $CO/CO_2$ at different heights in the furnace. A comparison of theoretical and experimental CO /$CO_2$ ratio at different temperatures along the height of the furnace is given in Table 4. The gas pressure was also measured at different heights in the furnace by using a U-tube manometer.

A thermo couple was inserted in the hole through which air is blown into the furnace. The temperature was found to be about 1450-1500 $^0$C. The temperature in the reheating furnace was also found to be around 1300–1350 $^0$C

## Analysis of Product

The iron made by the ancient process contains slag strewn all over the matrix. The slag content varies from 5-12 % as shown in Fig. 5. The iron contains low carbon and it is ductile in nature. Its hardness (VHN) is of the order of 200-230. The yield of metallic product made by the traditional process is only 20-25%. In the present investigation, an attempt has been made to enhance it up to 50%. Both polarisation as well as immersion tests show that corrosion rates of ancient iron and modern mild steel are almost similar.

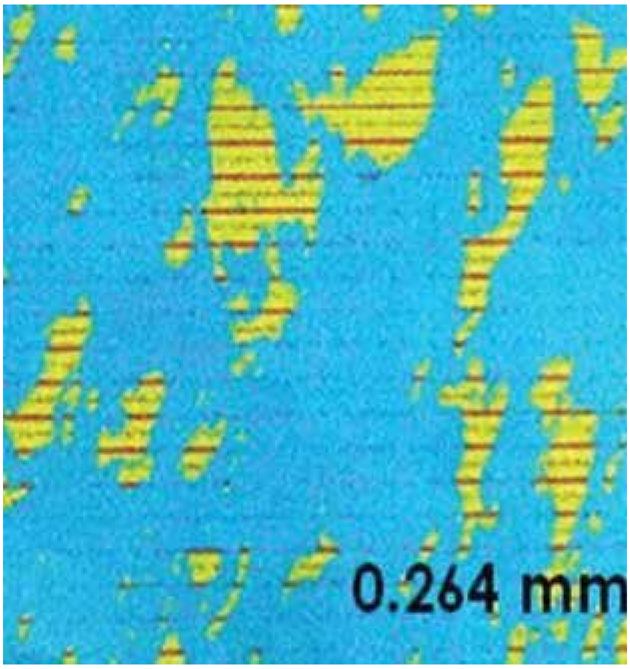


**Figure 5** Typical microstructure of iron made by ancient process showing about 12% slag (yellow regions)

## Improved technology of ancient iron making at NML Jamshedpur

A comparison between primitive technology and improved technology for ancient iron making is shown in Table 5. After considering several disadvantages of the ancient iron making process (see previous section) several modifications were incorporated and the process was scaled–up by 5–6 times.

Table 5 : comparison between primitive technology and improved technology for ancient iron making

| # | Primitive technology | Improved technology |
|---|---|---|
| 1. | One tuyere | Three tuyeres at 120 degrees apart |
| 2. | Sal charcoal | Acacia or eucalyptus charcoal |
| 3. | Cold blast of air | Hot blast of air |
| 4. | Leather foot-driven bellows for blasting cold air into the furnace | Semi – mechanized foot driven system for blasting hot air into the furnace |
| 5. | No incorporation of waste heat utilization system | Incorporation of waste heat utilization system |
| 6. | Charge mix comprised of ore lumps only | Charge mix comprised of composite pellets of even hematite ore and ore lumps |
| 7. | The height of furnace shaft was low | The height of furnace shaft was considerably increased |

## Scale up criteria

The height of the furnace shaft plays an important role in the overall reduction process of iron ore. With very short height, the reaction equilibrium is rarely reached. The enhancement in shaft height increases the average residence time of the reactants and indirectly increases

Table 6 : Scaled up parameters for prototype furnace (Bastar model) established at NML, Jamshedpur and demonstration sites.

| Sl No. | Type of furnace | Furnace cross section | d (cm) | D (cm) | H (cm) | d:D ratio | H/D ratio | Stack angle $\theta^0$ |
|---|---|---|---|---|---|---|---|---|
| 1. | Prototype furnace (Bastar model) | Circular | 16 | 28 | 80 | 0.57 | 2.855 | 85 |
| 2. | Scaled –up ( 6 times) furnace I | Circular | 28 | 48 | 127 | 0.58 | 2.645 | 85 |
| 3. | Scaled – up ( 6 times) furnace II at demonstration sites | Circular | 23 | 46 | 127 | 0.50 | 2.76 | 85 |

the overall reduction of iron ore to metallic iron. The scale up criteria for the traditional iron making furnace at NML Jamshedpur included d/D ratio, H/D ratio, stack angle and volume/kg of iron as mentioned in Table 6. Based on this criteria the Bastar-type furnace was scaled up (up to 6 times) by incorporating a heat recovery system to improve its thermal efficiency. The volume of the furnace was enhanced to six times compared to a conventional furnace by incorporating the following features

- The traditional leather bellows were replaced by semi-mechanized blowers to introduce the required amount of air into the furnace.
- The height of the furnace shaft was almost doubled to increase the average residence time of reactants and the overall reduction of iron ore to metallic iron.
- The conventional salwood charcoal was replaced by char made from acacia and eucalyptus.
- The char made from acacia and eucalyptus was found to have a performance equivalent to that of the expensive traditionally employed salwood charcoal
- The developed process can accept a wide range of raw materials in terms of their physico-chemical properties.
- Even hematite ore with Fe~58 to 60% was successfully used in the form of composite pellets.
- The scaled-up furnace can produce about 15 kg of wrought iron per each run, (total duration is around 4 hours).

## Experiments in scaled up furnaces

The details of the newly developed scaled up system without and with heat recovery are shown in Fig. 6a and Fig. 6b respectively. During the experiments in scaled up furnaces, it was well established that char made from both Acacia and Eucalyptus is a sustainable reductant and a renewable source of thermal energy for ancient iron making. Both Acacia and Eucalyptus are fast growing trees in dry lands and can be planted for making charcoal required for the tribal iron making process. The calorific value of char made from Acacia (7170 kcal/Kg) and Eucalyptus (6720 kcal/Kg) have a performance equivalent to that of sal char (6900 kcal/Kg). In view of heat loss, a heat recovery system has been designed to make use of the sensible heat of exit gases for increasing the blast temperature. This hot air is inserted into the furnace through

Table 7: Typical analysis of metal and slag obtained in scaled–up furnace, and scaled–up furnace with heat recovery system, by making use of charcoal prepared from eucalyptus and acacia

| Metal | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Scaled up furnace | | | | Scaled up furnace with heat recovery system | | | |
| | Using charcoal prepared from eucalyptus | | Using charcoal prepared from acacia | | Using charcoal prepared from eucalyptus | | Using charcoal prepared from acacia | |
| | Bastar ore I | Bastar ore II | Bastar ore I | Bastar ore II | Bastar ore I | Bastar ore II | Bastar ore I | Bastar ore II |
| C | 0.095 | 0.135 | 0.11 | 0.143 | 0.105 | 0.125 | 0.130 | 0.125 |
| Si | 0.035 | 0.049 | 0.038 | 0.053 | 0.031 | 0.048 | 0.041 | 0.048 |
| S | 0.027 | 0.021 | 0.028 | 0.020 | 0.025 | 0.019 | 0.027 | 0.019 |
| P | 0.018 | 0.043 | 0.019 | 0.048 | 0.017 | 0.038 | 0.015 | 0.046 |
| Mn | 0.0018 | 0.0073 | 0.0019 | 0.0084 | 0.0016 | 0.0068 | 0.0015 | 0.0071 |
| Slag | | | | | | | | |
| $SiO_2$ | 38.75 | 39.35 | 39.40 | 40.15 | 43.50 | 44.10 | 45.10 | 46.30 |
| CaO | 8.75 | 10.10 | 8.74 | 10.15 | 8.90 | 10.15 | 9.10 | 10.21 |
| MgO | 2.40 | 1.89 | 2.45 | 1.82 | 2.50 | 2.10 | 2.58 | 1.85 |
| FeO | 35.3 | 37.3 | 34.8 | 36.95 | 30.10 | 33.40 | 29.30 | 31.20 |
| $Al_2O_3$ | 11.45 | 10.10 | 11.34 | 10.35 | 12.10 | 10.40 | 10.74 | 9.85 |

the passage of tuyeres (Fig. 6b). Three semi-mechanized blowers were fitted and hot blast of air was blown at 125 $^0$C into the furnace through three tuyers fitted 120$^0$ apart. The result was a uniform distribution of air through the entire cross-section of the furnace, the reduction of localized hot spots and increased yield of product. Also the flame temperature of exit gases was brought down to less than 450 $^0$C. Further it is important to increase the air blast temperature by further modifying the heat recovery system and bring down the temperature of exit gas to around 300 $^0$C. The product contains elongated slag as shown in Fig. 7. It is of non-corrosive nature and can be used for making several decorative articles as illustrated in Fig.8. The typical analysis of metal and slag obtained in the scaled up furnace, and scaled up furnace with heat recovery system by making use of charcoal prepared from eucalyptus and acacia is given in Table 7.


**Figure 6** Scaled up furnace in operation at NML Jamshedpur
(a) Without heat recovery system and with cold blast of air [Yield using lumps~ 50%]
(b) With heat recovery system and hot blast of air at 125 $^o$C [Yield using lumps ~ 56%]

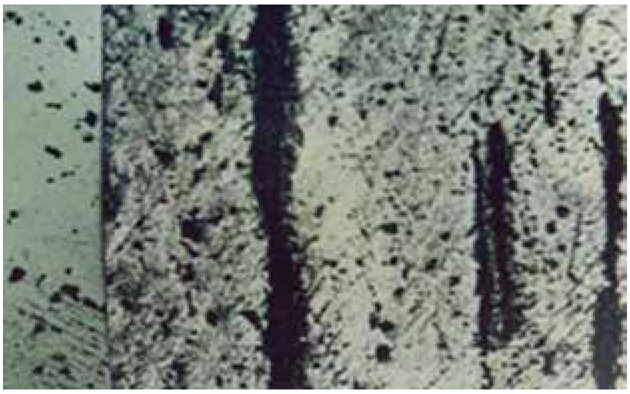

**Figure 7** Metallic iron with elongated slag

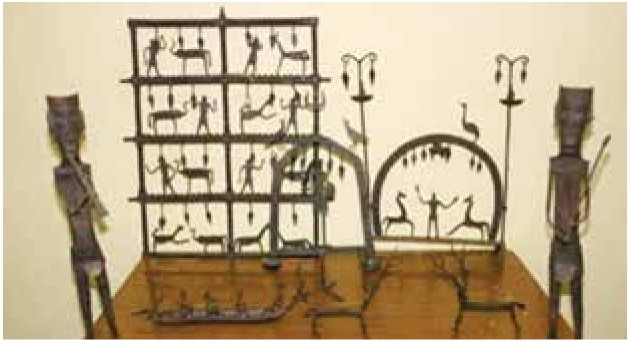

**Figure 8** Decorative articles made of product

## Demonstration of technology for commercialization

The scaled up process of ancient iron making with heat recovery system was successfully demonstrated at NML Jamshedpur to a large number of visitors and entrepreneurs. It was also successfully demonstrated at two tribal sites, namely Tribal Cultural Society, Jamshedpur and Technical Training Institute, Bahanaga, Balasore, Orissa. The product of the process is the value added wrought iron, extremely suitable for making decorative articles that have a good export market. The adaptation of this scaled up process with a heat recovery system shall raise the income and living standards of tribal and rural artisans of our country and preserve the age old technology of iron making.

## Conclusions

- Important aspects of ancient iron making process employed at Hadup village, Bishunpur Jharkhand

and Kondagoan, Bastar, Chattisgarh have been highlighted.

- A prototype traditional furnace for iron making was built at NML and extensive experiments were conducted with a variety of charcoals in order to comprehend the effect of different process parameters on the yield of the product.
- For uniform distribution of air in the entire cross section of the furnace, three tuyers have been fitted at $120^0$ apart to improve the yield of the product.
- A scaled up furnace with heat recovery system and semi-mechanized blowers was constructed at NML in order to improve the productivity of the furnace.
- It is expected that the improved technology of ancient iron making will generate enormous employment for the tribal and rural artisans. The export of decorative articles can boost up their micro – economy .

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# Ancient Indian iron and steel and modern scientific insights

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*ABSTRACT* The metallurgical heritage of India celebrates two ferrous objects- the Delhi Iron Pillar and wootz steel. Modern scientific analysis, using sophisticated tools, has shed further light on the evolution of the materials used to create these. In this paper the materials tetrahedron for the Delhi iron pillar and wootz steel is presented. The composition-microstructure and corrosion resistance relations will be discussed with emphasis on the role of phosphorus in the case of the Delhi Iron pillar. The processing –composition – properties will be described with emphasis on the ultra-high carbon, the effect of vanadium and phosphorus, the thermomechanical treatment and superplasticity for wootz steel.

## Introduction

The iron and steel heritage of India is well documented and is celebrated through historical periods (Ranganathan 1997; Bag 2007; Tripathi 2008). This heritage stretches over three millennia, from the beginning of the second millennium BCE and continuing to the beginning of the second millennium CE.

There appears to be no report of meteoritic iron in India – usually the first encounter of mankind with iron. Bloomery iron production is traceable to 1200 BCE. The Adivasi traditional knowledge of iron making is a living tradition. This method resulted in the Delhi Iron Pillar in 400 CE. This famous pillar has won recognition as an ASM Historical Landmark in 2012.

Surely the most spectacular achievement is the crucible steel from the Deccan datable to 300 BCE. Smith (1963) has recognized this among the four outstanding metallurgical achievements in antiquity. TMS of USA ranked it seventh among the 50 greatest materials moments in history.

The last few decades have seen the use of materials characterization to understand archaeological artefacts. As Cyril Stanley Smith (1965) showed a long time ago, the memory of an artifact resides in its microstructure. It is possible to piece together evidence that the iron was

[1] Ramamurthy Balasubramaniam was Professor of Materials and Metallurgical Engineering at IIT Kanpur and a scholar of eminence. He expired on 9th December, 2009. He produced excellent work in the area of metallurgical research and is widely known as an expert in the field of archaeometallurgy, metallurgical history and corrosion science. He had a deep interest in the field of history of science in general which is reflected in his contribution to Indian wootz steel, corrosion study of famous Delhi Iron Pillar, study of Taj Mahal, a catalogue of cannon in India for the last several years. Prof. Balasubramaniam, an INSA Young Scientist Awardee (1993), was associated with many research programmes of History of Science of the Academy. His untimely death is indeed a great loss for History of Science in India. This paper is dedicated to his memory.

made by smelting iron ore rich in phosphorus and even converse with the Agarias who made the iron and the tribal artisans, who forge welded the blooms. As was observed by Hadfield (1962), this mighty monument - probably made by the tribals of India for their emperor in the 5th century CE - was beyond the capabilities of European iron masters till the end of the eighteenth century. Some of the new knowledge insights gained on the iron pillar and wootz steel are described in the following sections with examples drawn from the researches of the authors.

Archaeometallurgy, pioneered by Smith (1965), has grown beyond his original vision of the microstructure of metallic objects and treating it as a piece of frozen history. Nondestructive testing has been expanded further by three dimensional computer tomography. Extraordinary developments in experimental techniques have enhanced our capabilities in exploring composition, structure, microstructure and texture (Durand-Charre 2004). A recent book by Durand-Charre (2014) deals with the process involved in the forging of the Damascus swords from ultra-high carbon steel.

This paper brings together the scientific investigations by the authors on the Delhi Iron Pillar and wootz steel. It shows that even when historical accounts are not available, the examination of composition and microstructure can provide insights into historical developments. A comparison between the two categories of ferrous materials is also a theme of the paper.

## The Delhi Iron Pillar

### *History: A Tale of Two Pillars*

Historical records about the Iron Pillar are generally meagre (Singh 2006). Often the Delhi iron pillar has been mistakenly called the Ashokan pillar. Figure 1 shows one of the Ashokan pillars**.** It is interesting to trace the transitions in empires, materials, manufacturing, epigraphy, religion and locations. The Mauryan emperor Ashoka (third century BCE) erected sandstone pillars across India to propagate Buddhism. The solid shaft of polished sandstone rises 32 feet in the air. It weighs about 50 tons, making its erection a remarkable feat of engineering. The stones were quarried in Chunnar near Varanasi. The pillars drew their inspiration from Persian, Greek and Egyptian monumental objects, and the capital on top of the column had a lion motif. The Buddhist edicts were written in Mauryan Brahmi. Often the pillars were later moved around. The most famous among them is at Sarnath. For centuries, Ashoka was a shadowy king. James Princep (1837) deciphered an inscription in Brahmi script referring to a king called Devanama Piyadasi (beloved of the gods). In many ways the Mauryan pillar was the inspiration behind the Gupta pillar.

**Figure 1** Ashokan Stone Pillar

### *Epigraphy*

**Figure 2** Delhi Iron Pillar (Balasubramaniam 2002)

Figure 2 shows the Delhi Iron Pillar. On its shaft there is a well preserved inscription in Sanskrit as a panegyric

(Figure 3). The text allows the identification of the origin of the pillar, as it states that the pillar had been erected as a flagpost by Chandra, now identified as Chandragupta II Vikramaditya (c. 400 CE). The pillar originally faced a temple dedicated to Lord Vishnu. Balasubramaniam (2000) used numismatic, archaeological and literary evidence to arrive at this conclusion.

**Figure 3** Well preserved Sanskrit inscription in Gupta Brahmi on the pillar (Balasubramaniam 2002)

### *Manufacturing Technology*

The iron pillar weighs around 7000 kilograms. The iron was produced by solid state reduction in furnaces that may have been capable of producing 40 kg per heat. This would imply that at least 200 furnaces may have operated simultaneously. The iron thus produced was hot forged. The question of how such a massive pillar was actually forged needs to be addressed, as there are differing opinions on this. Anantharaman (1997) has argued that it was forged vertically by patiently piling up pancake after pancake of bloomery iron, and wrought by hammering them, while Balasubramaniam (2002) suggested that it was forged by propping it up in horizontal position.

### *Composition and Microstructure*

Several analyses of the composition of the iron have been carried out (for example Hadfield 1912). They are in broad agreement, indicating very low carbon and almost pure iron. A notable feature was the high phosphorus content. Thus this artifact can be understood as wrought iron.

A recent study by Raj et al. (2005) using in situ metallography on various parts of the Delhi iron pillar indicated a heterogeneous structure. This could be expected due to the forging of a ferrous cake showing microstruvtures more clearly associated with a forged structure. Curiously however, the top of the pillar's ornamental capital and platform displayed characteristics approaching Widmanstätten structures, suggesting faster cooling rates and even some dendritic distribution akin to cast steel. Figure 4 shows the microstructure from the middle portion of the iron pillar undertaken by Raj et al. (2005).

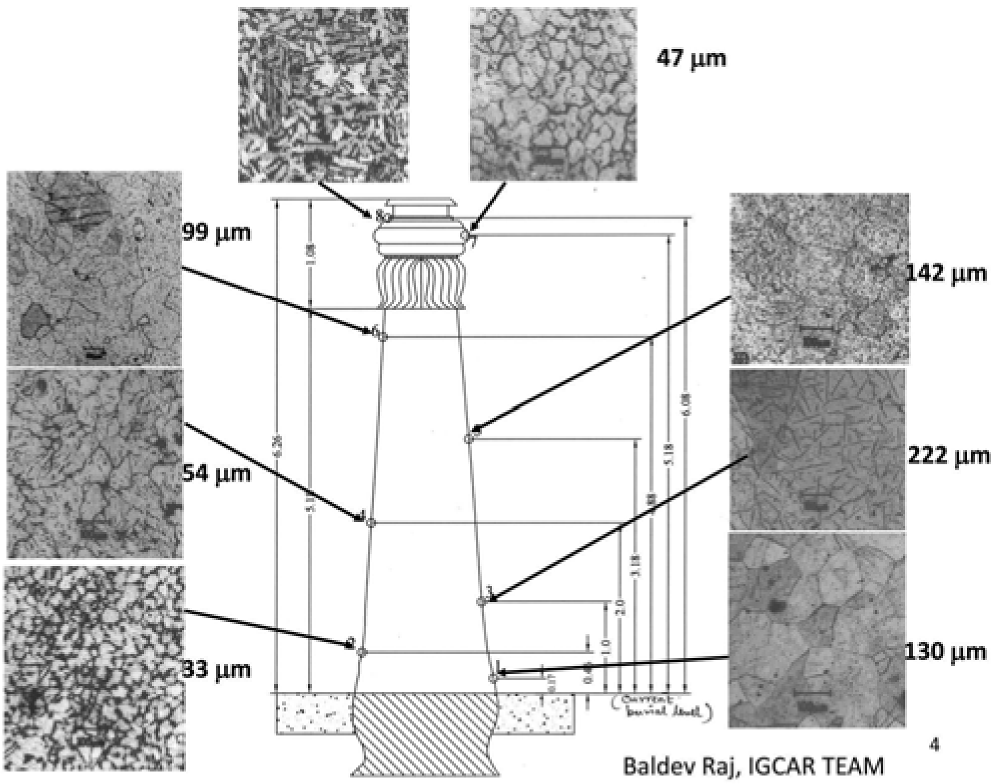


**Figure 4** Microstructural analysis of the Pillar (Courtesy Baldev Raj)

***Horizontal versus Vertical Mode of Inscribing***

For most ancient materials a study of the composition and microstructure allows the description of the process by which the artifact was made. Balasubramaniam (2002) investigated the methodology by which the Delhi pillar was erected, and he went further to explore how the inscriptions were inscribed (Balasubramaniam and Ranganathan 2007, unpublished research; Balasubramaniam and Prabhakar 2007).

There have been two views as to whether the inscription was put up on the pillar before the erection of the pillar or after its erection. Therefore it is important to find out whether the characters were incised on the surface with the pillar in horizontal or vertical position. The term "inscribe" has been used to describe the process by which the characters were engraved on the surface. This term also needs qualification. In the strict engineering sense, inscribing implies an operation of removing metal from the surface and producing the depression, thereby creating the characters of the inscription.

Careful observation of the characters allowed the identification of several locations where the die strike has been struck on the bottom of the characters, so that more material was removed from the lower part of the character. This would provide the first clue that the characters were placed on the pillar with the pillar in vertical position. There are several chips seen on the pillar at the location of the inscription, and these chips are such that the material appears to have been removed from the top to the bottom, thereby indicating that the die was misplaced so that the material was removed from the surface. This seems to indicate that the die used for placing the die mark on the surface was held perpendicular to the surface when the pillar was in vertical position, and the chips were broken from the bottom of the characters. Therefore, this provides the first clue that the pillar must have been already erect when the inscription was die struck.

***Corrosion resistance***

Several investigators have attempted to explain the rustless nature of the iron employed for the pillar. Notable efforts were by Hadfield, the National Metallurgical Laboratory, Jamshedpur (Ghosh 1963), Indira Gandhi Centre for Atomic Research (Kamchi Mudali and Raj 2009) and the Indian Institute of Technology, Kanpur (Balasubramaniam 2002).

The resistance of the Delhi Iron Pillar to corrosion during the 1,600 years or so of its existence is ascribed to the combined influence of a number of normal, favourable factors. Among these the hot climate and the freedom from atmospheric pollution have been held responsible for its corrosion resistance. Secondly, its resistance to rust can be ascribed a progressively decreasing rate of attack due to the building up of a protective layer of oxide and scale during the early years of exposure.

From his studies related to rust characterization, Balasubramaniam (2000) postulated that the corrosion resistance was partly due to the higher phosphorus content and the formation of a protective passive film on the surface (Figure 5) He also discussed the formation of an amorphous oxyhydroxide layer next to the metal-rust surface of the phosphoric iron. Whether the phosphoric nature of the composition of the pillar was an intentional or an intrinsic aspect, linked to the nature of the iron smelting technology practiced at the time, remains an area for further investigation.

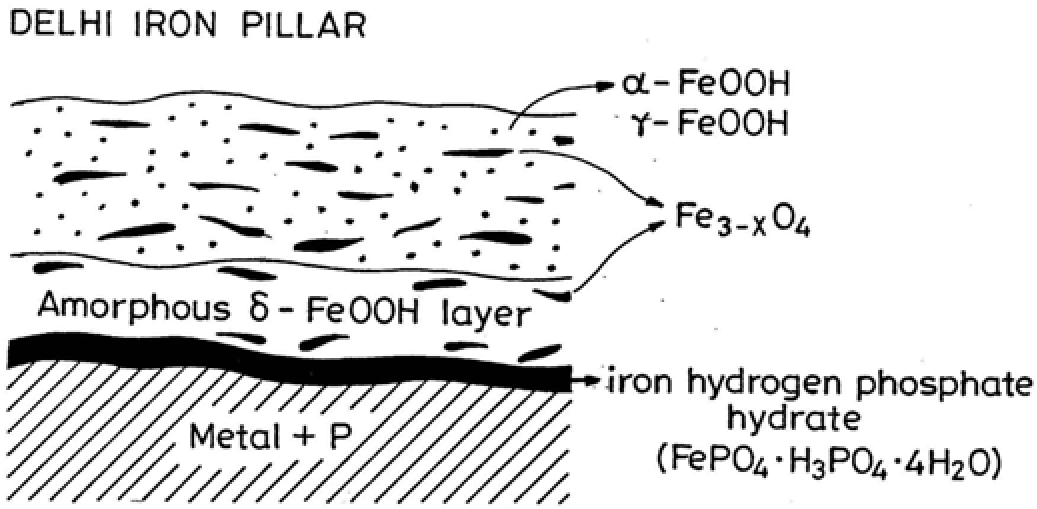


**Figure 5** Schematic of the rust structure formed on the Delhi Iron pillar (Balasubramaniam 2002)

## Indian Wootz Steel

*History*

The term wootz derives from the word for steel ukku, which harks back to Tamil Sangam classics of the Christian era (Srinivasan 1994). There have been numerous European travelers accounts on the making of steel by crucible processes in southern India from about the 17th century onwards (Bronson 1986, Srinivasan and Ranganathan 2014).

One of the marked features from the study of both phosphoric iron and of crucibles used in the making of 'wootz' is the remarkable uniformity in characteristics over different geographic and chronological contexts. For example, in Andhra Deccani wootz crucibles, XRD and scanning electron microscopy indicated similar features such as relics composed of silica, coked rice husks and elastic carbon fibers, originated from the rice husk fibres. and presence of crystalline mullite ( Lowe et al. 1990).

Studies by scientists of the 19th century and later helped to establish that wootz was a steel of a high carbon content of up to 1 to 1.5%. Finds of higher carbon steels have been documented from various sites in Tamil Nadu, Karnataka and Kerala going back to the Iron age and early historic periods (Srinivasan 2007, 2013). Jaikishan (2009) extensively documented surface sites in Northern Telangana in which wootz steel was produced. Subsequently, Srinivasan and Ranganathan have undertaken major surveys in the region, in collaboration under the NIAS –Exeter project (Juleff et al., 2011).

***Microstructure***

The composition of 1.5 per cent carbon in steel is classified as hypereutectoid steel. The microstructure consists of proeutectoid cementite and pearlite. Several investigators such as Verhoeven (2007) have noted the banded structure as an essential part leading to the Damask pattern. This is due to lines of carbides in spheroidal form, and must be arising from high temperature forging, leading to the dissolution of carbides and their appearance at lower temperature aging. Verhoeven (2007) pointed out the extraordinary role of an alloying element like vanadium. This results in microsegregation during solidification leading to the band. Replication of the making of wootz have been carried out by Verhoeven (2007) as well as Wadsworth (2007). The studies on superplasticity of the two phase microstructures have been particularly instructive.

As the composition corresponds to hypereutectoid steel, the microstructure consists of grain boundary cementite enveloping pearlite colonies. Recent metallographic examinations involving three dimensional characterization have proved that each pearlite colony consists of a ferrite crystal and a cementite crystal wrapped around each other. Such a structure represents high surface energy, On thermomechanical treatment it will be broken into spheroids of cementite in a matrix of ferrite, conferring as high strength to the material (Bhattacharya et al. 1992). While this is normal, the distinctive feature of the Damascus sword is the beautiful pattern, that has been attributed to micro-segregation of vanadium in the solidifying steel (Verhoeven 2007). Srinivasan and Ranganathan (2014) have termed vanadium as "magic dust". The superplastic properties of ultra-high carbon steel established by Sherby and Wadsworth (1990) could have contributed to the forgability of wootz at high temperatures.

Recent work (Barnett et al, 2009a) highlighted the role of phosphorus in wootz steel as well. The influence of bands rich in phosphorus on the microstructure of hypereutectoid phosphorus-rich bands are seen to correspond to regions of internal cracking, carbon depletion, and enhanced frequency of spheroidized cementite in place of pearlite.

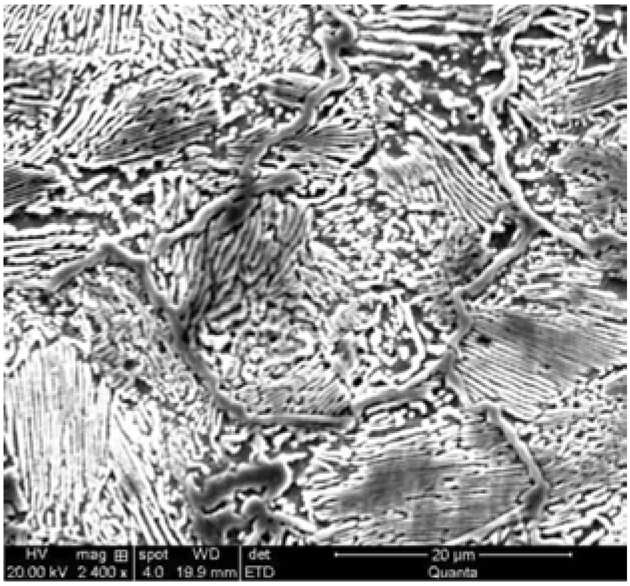


**Figure 6** SEM analysis shows structure of eutectoid pearlite surrounded by a network of cementite (Dixit et al. 2014)

To get an idea of the kind of locally found finished metal artifacts, a knife typically used by the community of toddy tappers in the Telengana region, in the tapping of toddy from the palmyra palm tree, was investigated using metallographic and microscopic study (Srinivasan et al, 2011). Scanning electron microscopy (SEM) was undertaken on a polished cross-section of the blunt edge of the knife as seen in Figure 6. This is a back-scattered electron image which gives an idea of the different phases or constituents in the metal, since the higher atomic weight constituents show up brighter on the micrograph. The structure is clearly one of a high-carbon steel showing a network of cementite around hexagonal grains containing a matrix of lamellar pearlite.

Analyses were also undertaken using Electron Probe Micro-analysis (EPMA-WDS) on some of the slags and crucibles collected from the Telengana region with the cooperation of Jens Andersen at the Camborne School of Mines, University of Exeter. It was possible to separately analyse the glassy constituents and metallic remnants by using a programme of separate standards and calibrations for each, one for oxides and the other for metals, and each measuring about 17 constituents including major, minor and traces. From these preliminary investigations, one trend that is worth mentioning is the growing evidence for the fairly well entrenched pre-industrial use of more efficient high temperature processes, as seen from the finds of very 'efficient' slags and crucibles with very little metallic content left behind in them, and the evidence of very tiny globular 'prills' of ferrous metal remnants with a diameter of less than 10 microns (Srinivasan et al. 2011). One of the specimens of an iron bloom from Telengana (TS-7) was found to contain about 1% phosphorus (Figure 7).

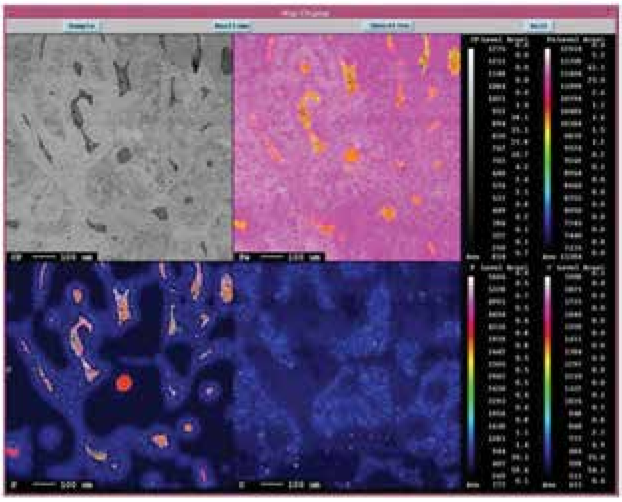

**Figure 7** EPMA-WDS elemental dot map on specimen of ferrous bloom from Telengana (TS-7) found to contain about 1% phosphorus with elemental dot map indicating phosphorus enriched regions (Srinivasan et al., 2011)

***Texture studies***

Crystallographic texture, which is essentially the orientation distribution of crystallites in the polycrystalline materials, is known to be a good indicator of the processing history of the material. A specific arrangement of crystallites can differentiate between a cast and a forged product. The representation of crystallographic texture involves the description of crystal orientations in the bulk specimen frame of reference through pole figures. EBSD offers a more detailed investigation of the microstructure including the information on the orientation of individual grains, and it is accomplished through electron backscattered diffraction (EBSD).

Barnett et al. (2009b) used EBSD to analyse the nature of carbides ptrsent in an ancient wootz steel blade. Bulky carbides, pro-eutectoid carbide along the prior austenite grain boundaries and fine spheroidized carbides were detected.

Dixit et al. (2014) reported detailed texture studies on a wootz toddy tapper blade. The pole figures were determined by X-ray diffraction technique. The texture, as revealed by the (110) and (200) pole figures indicated that the as-cast texture was not destroyed completely due to forging. The volume fractions of the <100>, <110> and <111> fibers were determined to be 7.09, 7.53 and 6.32 respectively. This generally indicates some retention of as-cast texture plus the development of deformation texture.

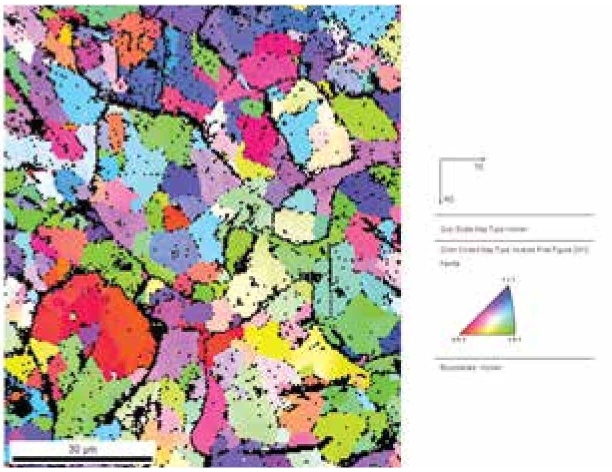

**Figure 8** EBSD micrograph for ferrite. The colour associated with each grain indicates its orientation according to the colour key shown with the unit triangle (Dixit et al.,2014).

## Materials Tetrahedron

The investigations on wootz steel in 19$^{th}$ century Europe led to the foundation of the central paradigm of modern materials science. It is based on the recognition that the processing of a material leads to a microstructure with a definite combination of properties. This set of properties defines the performance of the material. Chaudhari and Flemings (1989) brilliantly captured this in the form of a tetrahedron. It applies equally well to metals ceramics, polymers and composites. Our work has shown that this can be extended to materials from antiquity.

Figure 9 shows the materials tetrahedron for wrought iron. It draws attention to the method of production of wrought iron and the manufacturing methods. It points to the corrosion resistance and the special role of phosphorus.

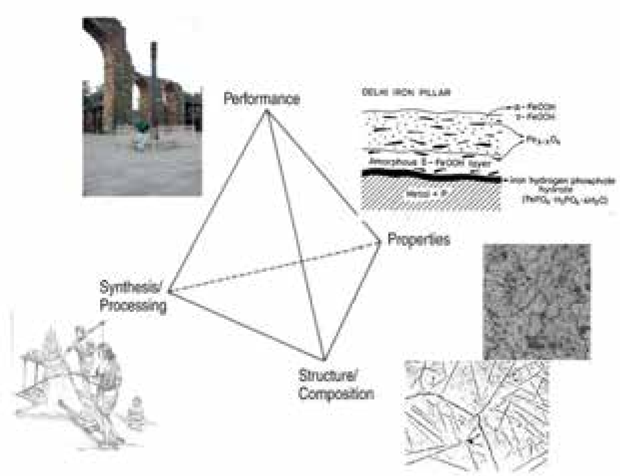


**Figure 9** Materials tetrahedron for wrought iron with Delhi Iron Pillar as the product

Figure 10 shows the materials tetrahedron for wootz steel: individual vertices represent processing, structure, properties, performance and modeling. The facets of the Buchanan furnace, the iron-carbon diagram, the microstructure of the dendrites in the as –cast state and spheroidised cementite in the forged material, the superplastic elongation and the Damascene marks are displayed with emphasis on the interconnections among them (Srinivasan and Ranganathan (2014).

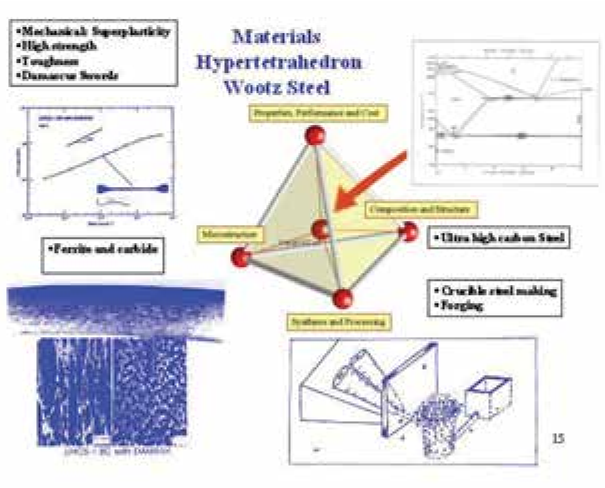


**Figure 10** Materials tetrahedron for ultra-high carbon steel with Damascus swords as the product

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# Section III – Copper Technology

The bronze Fanghu vessel decorated with patterns of birds and phoenixes unearthed from the cemetery of the Guo State of the 9th-8th centuries B.C (M2012:16)

*Shuyun Sun and Jianjun Mei*

# Scientific examination of metal objects from the third excavation of Haimenkou site, Western Yunnan

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*ABSTRACT* The Haimenkou site near the Erhai lake, is located in the Jianchuan County, Yunnan Province, Southwest China. This remarkable site played an important role in the cultural history of the minority in that area, because of some striking archaeological finds, particularly metal objects. Some scholars thought that it marked the beginning of the Yunnan Bronze Culture, however such a view is controversial. In 2008, during the third excavation by the Institute of Yunnan Cultural Heritage and Archaeology, nineteen metal artifacts have been found. In this article, the results of the analysis of seven metal artifacts are presented. They were analyzed preliminarily by using an optical microscope and the scanning electron microscope in order to elucidate the technological characterization and identify the cultural attribution. Copper, bronze and antimony bronzes were identified. They were employed for casting, forging, and cold working after casting. One bracelet found in lower stratum was proved to be wrought iron. This research adds new technical data for the reconstruction of the development of metal technology in ancient Yunnan.

## Introduction

The Haimenkou site, an ancient bronze cultural site close to the Erhai lake, is located in the Jianchuan county, western Yunnan (Fig.1). It played an important role in the cultural history of Yunnan and was striking for the well preserved large scale wooden architecture built at the waterfront. After the first and second excavations in 1957 (Yunnan Provincial Museum, 1958) and 1978 (Yunnan Provincial Museum, 1995), the dates of the site and the metal objects have generated considerable discussions. In 2008, approved by the China National Bureau of Cultural Heritage, the Institute of Yunnan Cultural Heritage and Archaeology has carried out the third excavation at Haimenkou site which was declared one of the top ten archaeological discoveries in China. There were nineteen metal objects unearthed in this excavation including bracelet, chisel, copper ingot, bronze needle, drill, knife, arrowhead, bell, awl etc (Institute of Yunan Cultural Heritage and Archaeology et al., 2009).

The relationship between unearthed metal objects and stratum was not clear after the first excavation due to various reasons. One wooden peg from the ruin was dated by C14 to 1150±90 BC and it belongs to the late Shang dynasty, but whether the wooden peg and the metal objects were unearthed from the same stratum or not, was not specified in the excavation report in 1957.

**Figure 1** Location of the Haimenkou site

Bronze objects were unearthed from the third and fourth cultural layer respectively during the second excavation. One wooden peg from the fourth layer was dated to 645±75 BC. The composition and microstructure analysis of the bronze from the fourth layer show that it also belongs to the late Spring and Autumn period (Li and Han, 2006).

The third excavation was comprehensive and large-scale. The Haimenkou site had a long duration from the late Neolithic to the Iron age. The wooden peg passed through many layers, therefore the wood C-14 dating cannot be effective. The bronze and iron objects were unearthed from the fourth, fifth and sixth cultural layer respectively located in the central part of the ten layers indicating that the metal objects belong to different periods and had a long history. This is the most important discovery revealed by the third excavation which enriched the understanding of the Haimenkou site.

Seven metallic artifacts - including two bracelets, one chisel and one copper ingot from the fourth layer, one copper ingot from the fifth layer, one iron bracelet and one copper ingot from the sixth layer - were sampled for studying the microstructure and composition in order to elucidate the technology and determine the cultural attribution. Although the metal objects were excavated from the mud, they were well preserved and showed very little corrosion.

Samples were mounted, ground and polished in the Institute of Historical Metallurgy and Materials Laboratory at the University of Science and Technology, Beijing. The polished sections of the copper-based samples were etched with a $FeCl_3$+HCl+alcohol solution and iron sample with a $HNO_3$+alcohol solution (4% $HNO_3$) to reveal the microstructures. The etched samples were examined and photographed with both a LeicaDM4000M metallurgical microscope and a Cambridge S-360 scanning electron microscope (SEM). Compositional analysis was conducted on the polished and un-etched sections in the SEM by using a Tracor Northern 524X energy-dispersive spectrometer (EDS).

## Chemical composition of the copper-based alloys

Table 1 shows the elemental analysis results of the six copper-based alloys. The number ④,⑤,⑥ represent the fourth, fifth and sixth cultural layer respectively.

Four copper-based samples from the fourth layer were analyzed. The compositional results show that one chisel and one ingot are unalloyed copper, two bracelets are Cu-Sn alloy which are low tin bronze with 4.9% and 8.5% tin. The unalloyed copper objects and Cu-Sn alloy were unearthed from the same layer, and show different composition and properties.

Four copper-based samples from the fourth layer were analyzed. The compositional results show that one chisel and one ingot are unalloyed copper, two bracelets are Cu-Sn alloy, i.e. a low tin bronze with 4.9% and 8.5% tin. The unalloyed copper objects and Cu-Sn alloy unearthed from the same layer show different composition and properties.

Han Rubin analyzed one chisel (chisel 220), unearthed from the first excavation, which is made of unalloyed copper (Cu), the material is the same as that of the chisel analyzed in this research. Another bracelet (CHT2:3(27) from the second excavation was made of a Cu-Pb alloy (Li and Han, 2006), different from the bracelets in the third excavation.

Composition analysis shows that the ingot from the fifth layer is unalloyed copper.

It is notable that the ingot from the sixth layer is a Cu-Sb alloy with 93.5% copper and 5.3% antimony. This kind of alloy was not common in ancient southwest China and was so far the first instance from the Haimenkou site.

As can be seen from the above analysis, there are three pieces made of unalloyed copper (chisel 1, ingot 2), two Cu-Sn alloys (bracelet1) and one Cu-Sb alloy (ingot1). 5% of the objects are unalloyed copper and 50% copper-based alloys and the alloy proportion is not stable. In comparison in the third excavation the number of bronzes is larger than that of the unalloyed copper objects in the first and second excavation. Also some high tin bronzes containing over 12% of tin were unearthed. Additionally, there is no leaded alloy from the third excavation, while some lead was detected in the bronzes from the first and second excavations.

**Table 1** Composition of the copper-based alloys from Haimenkou site

| Lab No. | Primary No. | specimen | Analysis result | | | | Remarks |
|---|---|---|---|---|---|---|---|
| | | | Cu | Sn | Pb | Sb | |
| 9910 | 2008JHAT1901④:2 | bracelet | 93.6 | 4.9 | 0.2 | | Cu-Sn alloy, coldworking after hot-forging, equiaxed grains and twinned grains, many slip lines. |
| 9912 | 2008JHAT2104④:18 | chisel | 99.1 | 0.1 | | | Cu, hot-forging, equiaxed grains and twinned grains. |
| 9913 | 2008JHDT1103⑤:6 | copper ingot | 97.4 | 1.5 | | | Cu(Sn), coldworking after casting, slip lines |
| 9914 | 2008JHDT1304④:2 | bracelet | 90.8 | 8.5 | | | Cu-Sn alloy, cold working after hot-forging, equiaxed grains and twinned grains, many slip lines. |
| 9915 | 2008JHAT2002④:2 | copper ingot | 97.7 | | 1.3 | | Cu (Pb), casting |
| 9916 | 2008JHAT2004⑥:4 | copper ingot | 93.5 | | | 5.3 | Cu-Sb alloy, cold working after casting, slip lines. |


**Figure 2** Bracelet (9910), equiaxed grains and twinned grains structure with slip lines

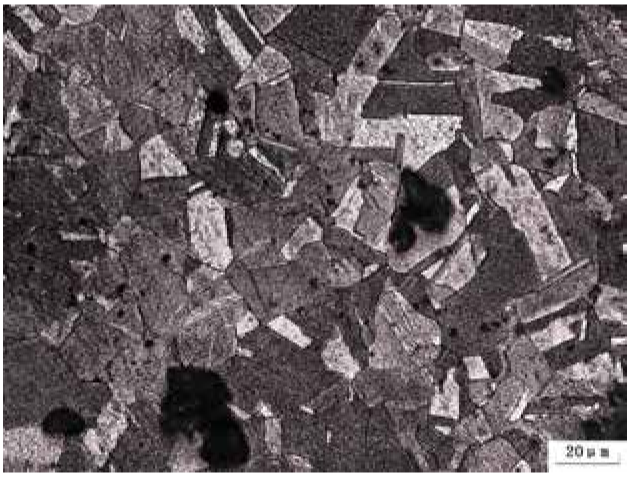


**Figure 3** Chisel (9912), equiaxed grains and twinned grains

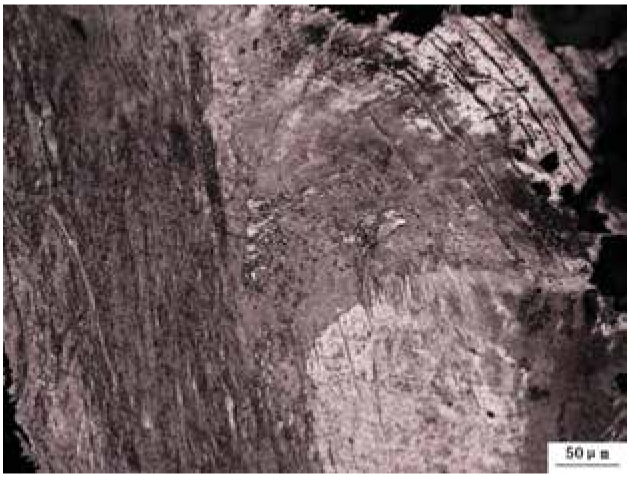


**Figure 4** copper ingot (9913), as-cast microstructure with slip lines

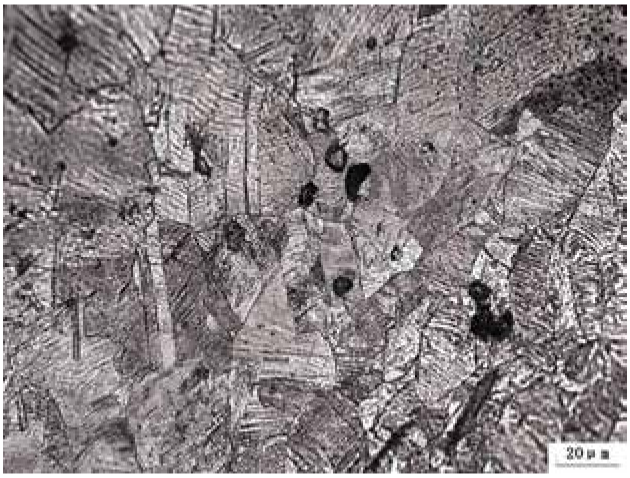


**Figure 5** Bracelet (9914), equiaxed grains and twinned grains structure with slip lines

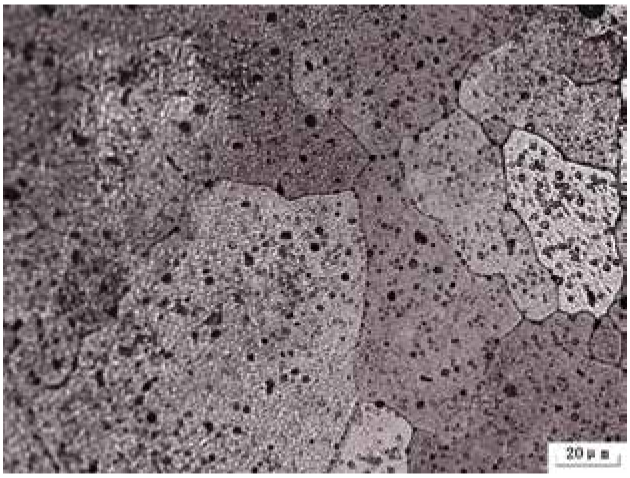


**Figure 6** Copper ingot (9915), as-cast microstructure, the black spots are lead particles

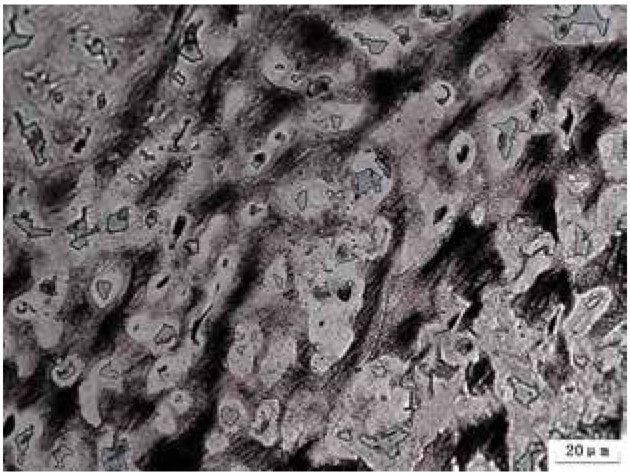


**Figure 7** Ingot (9916), as cast-dendritic microstructure with eutectoid structure and sulphide inclusions

## Microstructure of the copper-based alloys

Six copper-based samples were examined and photographed with a LeicaDM4000M metallurgical microscope. The examination results are summarized in Table 1. Following are the metallographic photos.

According to the examination results, the microstructure of the copper-based samples can be generally divided into two categories: casting and casting with hot-forging. Two samples taken from the bracelets (9910, 9914) unearthed from the sixth layer have a microstructure of cast bronze with equiaxed grains, twinned grains and slip lines (Fig.2, Fig.5). The equiaxed grains and twinned grains have also been observed in the microstructure of the unalloyed copper chisel (9912) unearthed from the fourth layer, which indicate the object had been hot-forged (Fig.3). The chisel is bar-shaped with one curved side and hammering marks on the surface. Hot-forging could appropriately increase the tools strength and improve the properties of the metal objects. The copper ingot (9915) unearthed from the fourth layer has the microstructure of as-cast structure, without any traces of further working (Fig.6). The slip lines identified in the microstructure of the copper ingot (9913) (Fig.4) suggest that the object had been worked after casting. The ingot (9916) from the sixth layer shows an as-cast microstructure with eutectoid structure and slip lines indicating that the eutectoid structure is an antimony-rich phase (Fig.7).

To sum up, the six samples unearthed from the third excavation in the Haimenkou site include two bracelets which had been cold worked after hot-forging, one hot-forged chisel, and three cast copper ingots. Both bracelet and chisel were hot-forged or cold worked after hot-forging. Consequently, all of these objects from the Haimenkou site show a diverse metal working technique.

Five copper-based objects unearthed from the second excavation were analyzed in 2006, and showed that the technology of manufacture included casting, hot-forging, cold working after hot-forging. It was therefore identical to the working techniques of the samples analyzed in this research.

## Microstructure examination of the iron bracelet

The iron bracelet was excavated from the sixth layer, and was the metal object unearthed from the lowest layer, indicating the earlier period culture. It was analyzed by metallographic microscope and SEM-EDS. The results showed high Fe and low Si content, with small amounts of Al and Mg and Ti and a ferrite matrix (Fig.8). In addition, FeO and silicate inclusions extending along the working direction indicate that the bracelet is wrought iron (Fig.9). This iron bracelet, small and simple-shaped, was hot-forged and this removed part of the inclusions and improved the mechanical properties. It indicates that the technology of smelting iron was still in the initial stage. In central China, the iron bar unearthed from the Liuhecheng bridge site, Jiangsun province, was made of wrought iron dated to late Spring and Autumn to early Warring States period (Chen and Han, 2007). Compared to this iron bar, the iron bracelet from Haimenkou site had a relatively pure composition and high quality. Iron objects were seldom found in the bronze age of western Yunnan.

## Stone mould

One piece of battle-axe stone mould (DT1003⑤:1)was unearthed from the fifth layer in the third excavation. Another piece of battle-axe stone mould was unearthed in the first excavation but no precise report of the unearthed layer exists. Both pieces of the mould were made of sandstone with slight cracks and soot traces, indicating that they had been used in the casting process. In the ruin, some copper ingots and ore were also found, proving that the Haimenkou site was probably an ancient smelting workshop. Stone moulds were either unearthed from the Dahuashi site, Longling county (Wang, 1992) and Hejiashan site, Midu county (Zhang, 2000), and indicate that stone mould casting was prevalent in western Yunnan at that time.

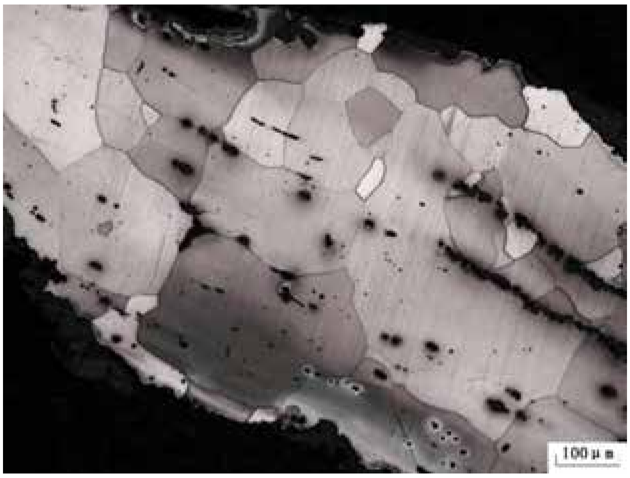


**Figure 8** Typical microstructure of wrought iron showing ferrite matrix and inculsions

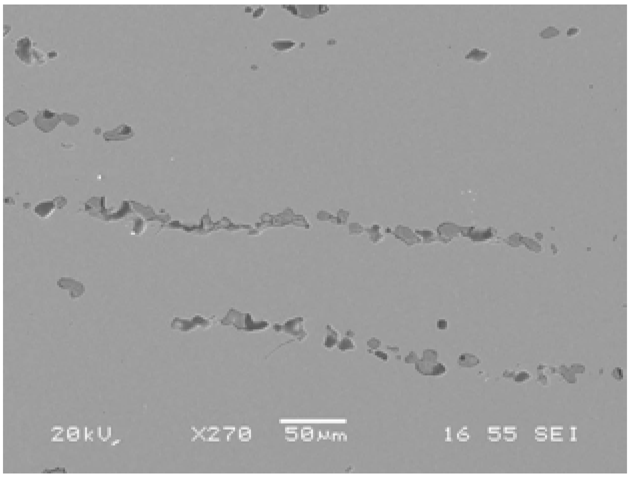


**Figure 9** FeO and eutectic silicate inclusion

## Discussions

The fourth and fifth cultural layers belong to the early stage of Yunnan Bronze age which extends from 3,100 to 2,500 years ago; the sixth cultural layers belong to the early or middle period of the Yunnan Bronze age which extends from 3,800 to 3,200 years ago (Institute of Yunnan Cultural Heritage and Archaeology et al., 2009). According to the composition and microstructure observation, it is concluded that the Haimenkou site began in the late Neolithic Age, continuing through the early Bronze Age to middle period, and finally developed into the early Iron age.

The ingot unearthed from the sixth layer is a copper-antimony alloy, which was a kind of special alloy in ancient China. The copper ware unearthed from the Hejiashan site, Midu county, dating from late Spring and Autumn to middle Warring States period is lead-antimony-arsenic-copper alloy with a content of 20.3% Sb (Li and Yun, 2008). Antimony containing alloys were also found in eastern and southern Yunnan, and date from Warring States to early western Han Dynasty. In northwestern China, copper-antimony alloys were found in the Siba culture of the Huoshaogou site (Sun et al., 2003) and in the Keliya site in Xinjiang ( Qian and Sun, 2006)

Antimony, a brittle metal, often showing a silver-white luster, exists mainly in stibnite ($Sb_2S_3$) as a sulphide. In early times it was difficult to smelt pure antimony from the ore (Moorey 1985). The antimony in these early metal artifacts probably comes from minerals that contain Pb, Sb and As, which do not separate completely from each other under primary smelting conditions. Antimony can also be extracted from panabase ($Cu_8Sb_2S_7$) and jamesonite ($Pb_2Sb_2S_5$) during the smelting of copper or lead.

Wrought iron was first found in the central plain in the 9th century BC to 8th century BC (Chen and Han, 2007), subsequently bloomery technology appeared in some other parts of China. Accordingly, this iron bracelet unearthed from the sixth layer should not be earlier than this period. It is notable that the iron bracelet was excavated from the sixth layer which was the lowest layer in which there were metal artifacts, therefore further investigation is necessary to make sure whether the cultural layers have been disturbed. If the layers were not disturbed, the metal objects unearthed from the sixth layer should date from late Spring and Autumn to early Warring States period.

Additionally, one bronze bell (AT1901⑥:1) unearthed from the sixth layer is similar to the chime which was common in central China, belonging to the period from Spring and Autumn to Warring States.

Stone moulds were separately unearthed from the fifth layer in the third excavation and in the first excavation. There were also stone moulds excavated from the Aofengshan site, Jianchuan county which is close to the Haimenkou site. All of these stone moulds were battle-axe moulds made of sandstone. Their typology indicates that the fifth layer of the Haimenkou site and Aofengshan site was probably in the same period in which battle-axes were cast from stone moulds. The Aofengshan site was dated to the Warring States period which corresponds to the sixth layer in the Haimenkou site, starting from the late Spring and Autumn period. This date seems therefore to be reasonable.

Of the four copper-based objects unearthed from the fourth layer two are unalloyed copper, and two bronzes. The manufacture is different. The period of the fourth layer should be later than the fifth layer dated to the Warring States. There were also some small metal objects with the characteristics of early bronze unearthed from the fourth layer. Therefore, the fourth layer should date from the Warring States to the middle of the Western Han dynasty.

According to the analysis and C-14 data, the metals objects unearthed from the second excavation are to be dated to the late Sping and Autumn period. The wrought iron bracelet from the sixth layer and the Cu-Sb alloy from the fifth layer in the third excavation also indicate that the metal objects should date back to the late Spring and Autumn period. It is concluded that the Haimenkou site was one of the earliest Bronze Age sites in western Yunnan, and that they played an important role in the history of the Yunnan Bronze culture.

It is difficult to define the date of an archaeological site disturbed by external factors. Except for the analysis the only dating element is the identification of the type of metal objects. Of course, this cannot be considered the date of the whole Haimenkou site. The date will be finally determined when other experts from different fields give more elements to identify the date of the Haimenkou site.

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# Multiphase microstructures on late imperial Chinese brass coins


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*ABSTRACT* Thirty-five brass Chinese cash coins from three different reigns and of distinct provenances were studied to characterize the composition of Chinese coins in the period from the 17th to the 19th century. Energy-dispersive X-ray fluorescence spectrometry (EDXRF) of the coins surface as well as energy-dispersive micro X-ray fluorescence spectrometry (micro-EDXRF) of small cleaned areas on the coins rims was performed to obtain elemental composition. Optical microscopy (OM) and scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS) were used to examine their microstructures. For a few selected coins, micro X-ray diffractometry (micro-XRD) was used to identify less common phases in brasses. Results showed that these brass alloys (Cu-Zn) frequently contain up to 3 wt.% Sn or the corresponding value in Sb, have highly variable Pb content (from *n.d.* up to 14 wt.%) and although Fe and As appear mainly as minor elements, their content in the last reign rises up to 6 wt.% and 4 wt.%, respectively. The coins present very typical fine-grained as-cast microstructures, which could be interpreted by binary (Cu-Zn) and ternary (Cu-Zn-Sn) equilibrium phase diagrams, the latter explaining the main microstructural differences due to Sn or Sb in these brasses. Fe and As rich phases were observed in a few coins of later reigns.


## Introduction

Cash coins are part of the Chinese cultural heritage, and were commonly used in every-day commercial trades (Hartill, 2005). These round coins with a central square hole are successors of the ring coin – which was a round disc with a central round hole - and appeared in the late Zhou dynasty (1050-771 BC). They were adopted as official currency over all other forms of coin after the Qin dynasty's emperor Qin Shi Huang Di monetary system reform in 221 BC (Hartill, 2005). Henceforward they remained the ordinary currency in China for over 2000 years, with only little changes in the production process. As such, they are a suitable study object, for they bear witness over the rise and fall of empires, commercial trades and raw material exchanges, and can be considered as one of the records in the development of metallurgical production in China.

They had been preceded by coins of different shape such as the spade and knife, their shape and size was quickly seen as practical, both in manufacture and use. The amount of metal required was drastically reduced, and this decreased the production cost, leaving more metal for the production of weapons and religious objects (Thierry, 1992; Rawson, 1993). The central hole allowed easy post-casting processing and handling. The first items possessed one or more pictograms on one side, indicating production site or attributed value. From the Tang dynasty (618-907 AD) onwards the monetary system was changed and the pictograms were substituted by characters on one or both sides of the coin, and in specific locations on its field (Burger, 1976).

They were first cast in wood or stone moulds, but soon the artisans found that the time they spent carving these materials was not profitable because the moulds were highly perishable when used for metal casting. Therefore clay moulds, easy to shape or to be imprinted, were adopted (Thierry, 1992). In the 17$^{th}$ century sand moulds started to be used: a mixture of fine grained sand and charcoal was easily reused and "unbreakable". As with clay moulds, a positive mould - the mother cash – is imprinted upon the sand surface, creating a negative mould. The imprints are connected by channels so that the liquid metal fills all the details. When cold, the moulds are disassembled, the sand recycled and the coins are cut from the coin "trees". The single pieces are filed away and imperfections removed from the surface (Song, 1637).

The characterization of the cash coins gives an insight into the compositional alloy changes throughout the years or over the same time period in different provinces. Simultaneously, microstructure observation permits the investigation of corrosion behaviours for conservation purposes. Although several studies on Chinese cash composition were carried out, very few discussed microstructural aspects (Lei, 2003). In this study, the chemical and microstructural composition of 35 brass cash coins belonging to the Macau Scientific and Cultural Centre's Museum (CCCM) was obtained.

The coins were acquired in 1999, at Macau, China. Some information on each coin is available - name, production period and mint, face value – but it is not certain. All coins belong to the Qing dynasty: six are attributed to the reign of Kang Xi (1662-75 AD), thirteen to the Qian Long reign (1736-95 AD), and sixteen to the Jia Qing reign (1796-1820 AD). The coins whose microstructures are discussed in this study are shown in Fig. 1.

## Methodology

The coins are part of a museological collection, therefore the guideline adopted was that of minimum intervention, in order to avoid the cutting or deep polishing of the pieces. After processing an archaeological sample that was already broken in two pieces, it was found that the compositional and microstructural results of the radial cut and of the polished outer rim were very similar. This is understandable because of the small volume and thickness of the objects. Data was collected from small polished rim and surface areas trying to minimize the intervention on the coins. Each coin was mounted in epoxy resin and subsequently polished to obtain a clean, roughly elliptical, ≈2 mm$^2$ area.

The elemental composition of the coins surface was determined by EDXRF and the polished area was analysed by micro-EDXRF prior to the mounting in resin. The same area was also used to observe all microstructures by OM. On 11 selected coins SEM-EDS analyses were carried out for the microstructural

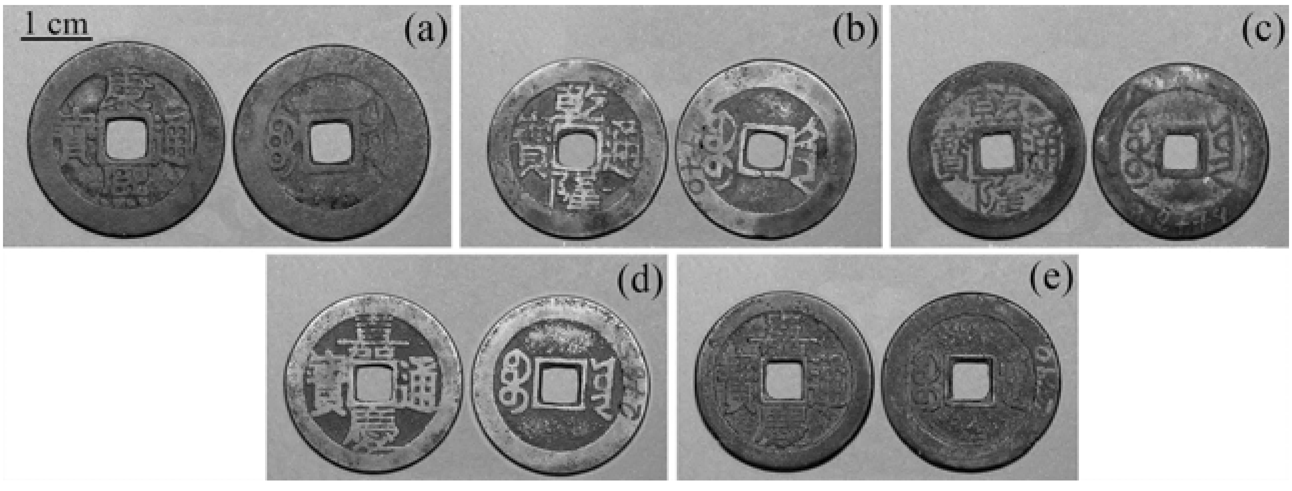


**Figure 1** (a) Coin no. 2710 (Kang Xi Tong Bao, 1681-1703AD); (b) Coin no. 2770 (Qian Long Tong Bao, 1736-95AD); (c) Coin no. 2774 (Qian Long Tong Bao, 1736-95AD); (d) Coin no. 2785 (Jia Qing Tong Bao, 1796-1820AD); (e) Coin no. 2790 (Jia Qing Tong Bao, 1796-1820AD).

characterization of the alloy phases and inclusions. Four coins were also analysed by micro-XRD to confirm the presence of phases recognised by OM and SEM-EDS.

Surface composition was obtained by using a commercial EDXRF spectrometer KEVEX 771. Both faces of the coins were analysed without preparation. The useful area of the equipment is circular and measures about 8 $cm^2$. Primary radiation originates from an Rh tube, and two secondary targets were used to produce the incident radiation for each of the two conditions used: silver (35kV tube voltage; 0.2mA current intensity) and gadolinium (57 kV tube voltage; 1mA current intensity). Spectra were collected for 300 seconds. This instrument allows the detection of elements with Z ³ 9. The semi-quantification was obtained through the fundamental parameter method combined with a calibration obtained using the certified reference material C1103 (National Bureau of Standards, Washington DC).

An ArtTAX Pro commercial micro-EDXRF spectrometer with a Mo X-ray tube was used to analyse the cleaned areas. The primary X-radiation beam has a micro spot of less than 100 µm in diameter, created by a set of polycapillary lenses. The precise position of the analysed area is controlled by a camera that shows a magnified image of the region under investigation. Elemental composition was determined with the WinAxil software (Canberra, 2003). The certified reference material C1103 (National Bureau of Standards, Washington DC) was used to determine the accuracy and precision of the method. Details on the equipment as well as on the analytical procedures were previously published (Figueiredo, 2007; Bronk, 2001). The spectra were collected for 250s at 40kV tube voltage and 500 mA current intensity. To account for heterogeneities, three different spots per coin were analysed and the average was used.

A Leica DMI5000M microscope with a digital camera was used to observe and capture the coins cross-section images in bright field (BF), dark field (DF) and polarized light (POL) both in unetched and etched conditions (with an aqueous ferric chloride (Voort, 1984). The LAS V2.6 software used with the microscope allows image acquisition at different Z-positions to obtain a single focused composite image from various depths.

Some coins were observed and analysed using a scanning electron microscope Zeiss DSM962 with secondary electron (SE) and backscattered electron (BSE) detectors and an Oxford Instruments INCAx-sight energy dispersive spectrometer (EDS), which detects elements with Z ³ 6. Most of the polished areas, in non-etched conditions, were previously gold coated to reduce charging effects during examination. The elemental X-ray maps show how the elements are associated in the metallic matrix. Semi-quantification of the detected elements was calculated through a standardless analytical method based on a ZAF correction procedure.

Four X-ray microdiffraction analyses were made with a Bruker AXS D8 Discover diffractometer. The model possesses a Cu tube and a GADDS detector with a Göbel mirror system. The calculated irradiated circular area is of about 1.2 $mm^2$. The analytical conditions were an angular variation of 12º-105º, 40 kV tube voltage and 40 mA current intensity.

## Results and discussion

The surface EDXRF analysis identified copper-based alloys with Zn as a main element. Other elements such as Pb, Sn, Sb, Fe and As are sometimes present in variable amounts. Although there is a slight superficial enrichment in Cu and Pb (< 5%), the micro-EDXRF results obtained from the clean metal area were similar to the EDXRF results (see Fig. 2), which is explained by the thin alteration layer on these coins. In this paper, all compositions are given in weight percent.

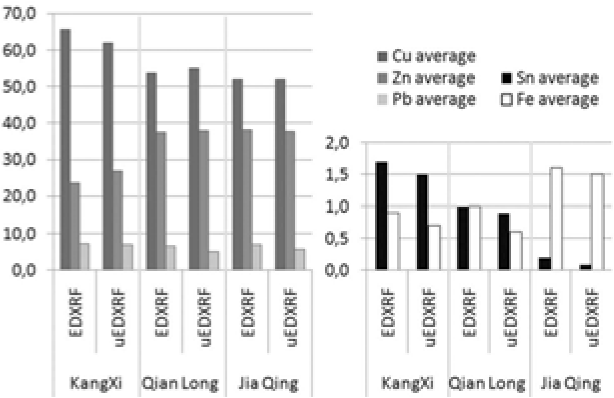


**Figure 2** Average contents of major and of some of the minor elements during the three reigns (EDXRF and m-EDXRF)

The dimensions of the coins, the average contents obtained by micro-EDXRF, and their standard deviations are presented in Table 1. The results are comparable to previously published studies (Dai and Zhou, 1992; Wang *et al.*, 2005). There is a tendency over time to a decrease in Cu and Sn contents, while there is an increase in Zn and Fe. Pb values vary from nil to 14% even within the same period.

The coins have typical as-cast microstructures with dendritic primary phase morphology, segregations and microporosities. Their optical microscopy interpretation is, however, rather difficult, because of the fine microstructure. Also, the most frequent Cu-Zn phases present (a and b) are quite similar in colour (yellowish), and require frequent etching for a better distinction.

**Table 1** Diameter and average elemental composition (wt.%) of the coins by micro-EDXRF. Elemental content standard deviations (STD) for each reign are also present

| Reference | Reign | Diameter [cm] | Cu [%] | Zn [%] | Pb [%] | Sn [%] | Sb [%] | Fe [%] | As [%] |
|---|---|---|---|---|---|---|---|---|---|
| 2710 | | 27.5 | 56.6 | 29.2 | 10.2 | 2.5 | 0.8 | 0.6 | 0.2 |
| 2723 | | 24.5 | 46.9 | 51.6 | 0.4 | n.d. | n.d. | 1.0 | n.d. |
| 2728 | Kang Xi | 27 | 65.0 | 24.0 | 7.2 | 1.8 | 0.9 | 0.6 | 0.2 |
| 2733 | | 26.2 | 65.3 | 23.4 | 7.0 | 1.7 | 1.4 | 0.6 | 0.2 |
| 2736 | | 26 | 61.5 | 32.7 | 3.3 | 0.7 | 0.3 | 0.8 | 0.6 |
| 2737 | | 27 | 78.6 | 3.5 | 14.3 | 2.1 | n.d. | 0.4 | 1.0 |
| Average | | | 62.3 | 27.4 | 7.1 | 1.8 | 0.9 | 0.7 | 0.4 |
| *STD* | | | *10.5* | *15.6* | *4.9* | *0.7* | *0.5* | *0.2* | *0.4* |
| 2758 | | 24.5 | 53.0 | 35.0 | 8.3 | 2.9 | 0.3 | 0.3 | n.d. |
| 2761 | | 23.5 | 49.8 | 36.8 | 12.0 | 1.0 | 0.2 | 0.6 | n.d. |
| 2762 | | 25 | 54.6 | 39.1 | 5.5 | 0.2 | 0.1 | 0.6 | n.d. |
| 2763 | | 27.2 | 68.2 | 29.9 | 0.8 | n.d. | n.d. | 0.5 | 0.5 |
| 2764 | | 24.5 | 53.9 | 38.3 | 6.1 | 1.3 | 0.1 | 0.3 | n.d. |
| 2766 | | 26.5 | 65.5 | 32.6 | 0.7 | n.d. | 0.3 | 0.4 | 0.4 |
| 2767 | Qian Long | 24.5 | 46.9 | 41.3 | 6.6 | 2.1 | 0.2 | 1.8 | 1.2 |
| 2770 | | 25.2 | 55.3 | 35.0 | 7.0 | 2.1 | 0.2 | 0.3 | n.d. |
| 2772 | | 24 | 46.7 | 47.9 | 4.2 | n.d. | n.d. | 1.3 | n.d. |
| 2773 | | 23.1 | 53.7 | 38.1 | 6.6 | 0.9 | 0.1 | 0.3 | n.d. |
| 2774 | | 24.5 | 48.1 | 46.7 | 4.1 | 0.4 | n.d. | 0.9 | n.d. |
| 2775 | | 24 | 49.6 | 45.0 | 4.7 | n.d. | n.d. | 0.5 | 0.2 |
| 2776 | | 25 | 58.8 | 32.5 | 8.0 | 0.2 | 0.2 | 0.2 | n.d. |
| Average | | | 54.2 | 38.3 | 5.7 | 1.2 | 0.2 | 0.6 | - |
| *STD* | | | *6.7* | *5.6* | *3.0* | *1.0* | *0.1* | *0.5* | |
| 2777 | | 25 | 64.4 | 30.1 | 2.4 | n.d. | 1.3 | 1.0 | 0.6 |
| 2782 | | 23 | 52.9 | 35.4 | 6.6 | n.d. | 1.0 | 1.5 | 2.7 |
| 2783 | | 24 | 46.8 | 42.9 | 7.0 | n.d. | n.d. | 1.8 | 1.6 |
| 2785 | | 25 | 52.3 | 30.8 | 9.7 | n.d. | 3.3 | 2.3 | 1.6 |
| 2786 | | 24 | 59.0 | 39.1 | 1.4 | n.d. | n.d. | 0.5 | n.d. |
| 2787 | | 24.2 | 55.2 | 34.4 | 7.1 | 0.5 | n.d. | 1.6 | 1.0 |
| 2788 | | 25.5 | 55.1 | 35.8 | 7.6 | n.d. | n.d. | 1.4 | 0.2 |
| 2789 | Jia Qing | 24.5 | 51.3 | 36.9 | 8.8 | 0.8 | n.d. | 1.7 | 0.6 |
| 2790 | | 25 | 53.8 | 38.0 | 6.8 | n.d. | 0.6 | 0.1 | 0.6 |
| 2791 | | 23.5 | 43.7 | 50.8 | 4.4 | n.d. | n.d. | 1.2 | n.d. |
| 2792 | | 24.5 | 53.6 | 34.1 | 6.6 | n.d. | 0.4 | 0.8 | 4.1 |
| 2793 | | 25 | 53.2 | 31.4 | 10.0 | n.d. | 3.4 | 0.3 | 1.7 |
| 2794 | | 25.5 | 56.1 | 34.7 | 7.0 | n.d. | n.d. | 0.8 | 1.1 |
| 2796 | | 25.1 | 45.6 | 52.0 | 0.7 | n.d. | 0.1 | 1.5 | 0.1 |
| 2799 | | 24 | 43.2 | 49.5 | 4.9 | n.d. | 0.3 | 1.4 | 0.2 |
| 2802 | | 23.5 | 61.8 | 32.7 | 4.8 | 0.3 | n.d. | 0.4 | n.d. |
| Average | | | 53.0 | 38.0 | 6.0 | 0.5 | 1.3 | 1.1 | 1.2 |
| *STD* | | | *6.0* | *7.1* | *2.7* | *0.3* | *1.3* | *0.6* | *1.1* |

STD – standard deviation
n.d. – not detected

The coins were classified in 6 groups, according to the main brass phases of the Cu–Zn system present: α, α+β, α+γ, β, β+γ and α+β+γ. The presence of other elements triggered the appearance of more phases (rich in Fe or Pb) and S-rich inclusions, which were investigated but not considered while grouping the coins. An example of each group is presented below (except for the simple monophasic a or b structures).

Coin no. 2790 has a typical α+β brass structure: an α phase Widmanstätten structure in a β phase matrix. Both phases are yellowish in OM-BF, but the β phase turns darker after etching, allowing a clear distinction between the two (Fig. 3). SEM-EDS analysis showed the β phase to be richer in Zn than the α phase, and it was noticeable in OM that the β phase corroded preferentially. This leads to a Zn leaching with Cu redeposition (pink colour in OM-BF) in its place. This selective corrosion process is called dezincification and happens due to the Zn lower Fe-rich standard reduction potential compared to Cu.

A grey Fe-rich phase observed in OM-BF, was later identified by micro-XRD as a-ferrite.

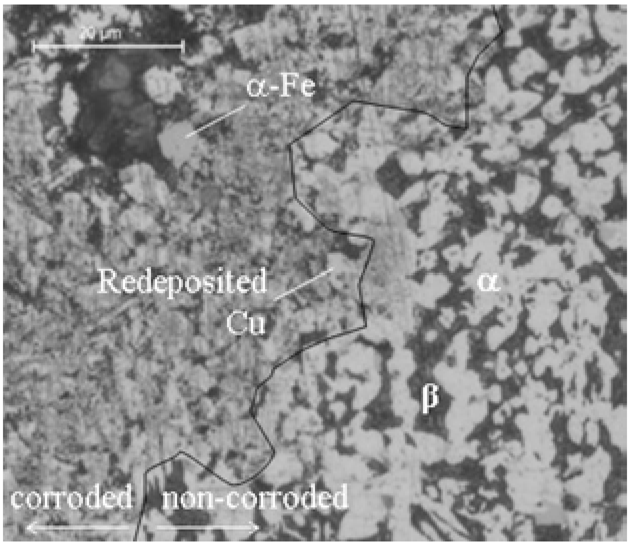


**Figure 3** Coin no. 2790 detail: **α+β** structure (OM – BF, etched)

The microstructure of coin no. 2774 is β+γ, in which the γ phase precipitates at β phase grain boundaries. In OM-BF the two main phases are discernible especially after etching: the β phase turns darker, while the γ phase is still light grey. In backscattering electrons (BSE), where phases with higher atomic number appear brighter, Pb globules stand out, but there is a scarce contrast between β and γ phases. EDS analysis showed that the β phase (spot 6 in Fig. 4-b) has a lower Zn content than the γ phase (spots 2, 3 and 4 in Fig. 4-b). The latter also presents some Sn. In spite of the higher Zn content of the γ phase, the β phase is preferentially corroded, which may be due to the Sn influence in the γ phase.

A dark-grey phase, rich in Fe and with some As (EDS of spot 1 in Fig 4-b) is precipitated inside the γ phase. Consulting the Cu-Fe and the As-Cu-Fe phase diagrams, it was assumed to be ferrite (α-Fe) or/and an iron arsenide ($Fe_2As$), which was later clearly identified in other coins by micro-XRD.

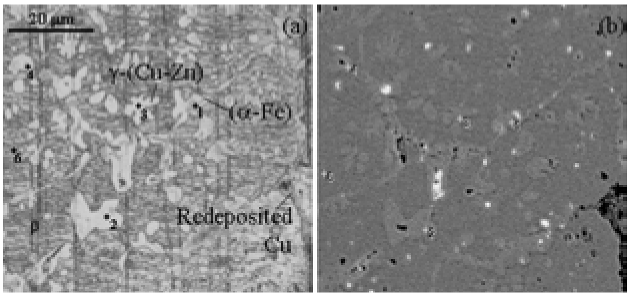


**Figure 4** Coin no. 2774 detail showing a **β+γ** structure: (a) OM-BF, etched; (b) SEM-BSE

The microstructure of coin no. 2710 did not fit the binary Cu-Zn phase diagram: although its Zn content is below 30%, a significant light grey phase in OM-BF was observed. A micro-XRD analysis of the region indicates the presence of a γ-brass phase. It only appears with ca. 50% Zn content in binary Cu-Zn alloys. Nevertheless, the microstructure has an α+β eutectoid in a primary a phase matrix, with some dispersed Pb globules (Fig. 5).

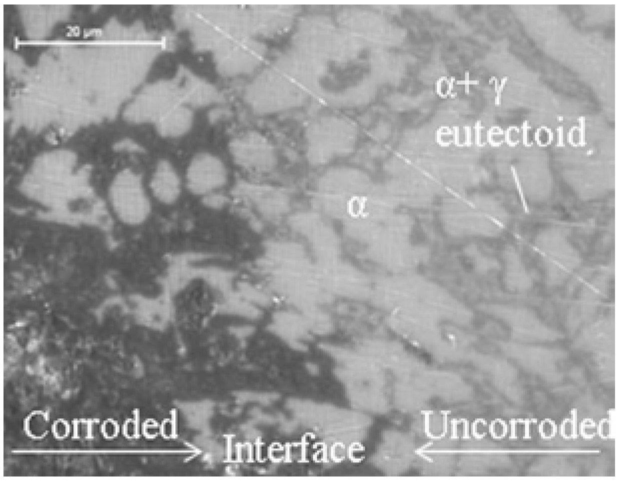


**Figure 5** Coin no. 2710 detail: **α+γ** structure (OM, Polarized – non-etched)

SEM-EDS analysis showed that, although the Zn content is practically identical in both phases (29.9 % and 28.4 % for α and γ, respectively), the γ phase is four times richer in Sn (1.7% and 7.6% for α and γ, respectively). Therefore, the Sn content seems to promote the appearance of the γ phase in the case of lower Zn contents in brasses. Looking at the metal/corrosion interface, the γ phase seems to corrode preferentially with sporadic copper redeposition (Fig. 5).

The next microstructure presented shows α+β+γ brass-phases (coin no. 2770). In Fig. 6 (OM-BF), the a grains are visible in a β phase matrix. It also shows that the γ phase is finely distributed between them. Phases α, β and Pb-rich globules are clearly visible with the SEM (BSE mode), but the γ phase is scattered: EDS quantifications in this phase were impossible to perform due to its small dimensions. Once more, the β phase seems to corrode preferentially, by dezincification with consequent Cu redeposition, as shown in Fig. 6.

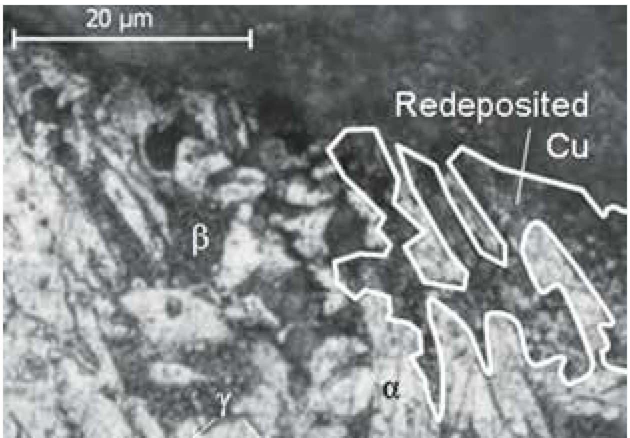


**Figure 6** Coin no. 2770 detail: **α+β+γ** structure (OM, BF- etched)

Finally coin no. 2785 exemplifies other phases occurring in these coins. The maps in Fig. 7 show the elemental distribution of a selected area: brighter spots indicate higher concentrations. The matrix is constituted by α and γ phases. The latter contains Sb, which was found to promote the appearance of the γ phase with lower Zn contents, as seen in coin no. 2710 in the case of Sn. Small interdendritic Pb globules and microporosities were observed. Other phases sometimes present in these coins are ferrite (α-Fe), as primary dendrites, and iron arsenide ($Fe_2As$), both identified by micro-XRD. They appear dark-grey in OM-BF. Segregation occurs even within these phases, as noticeable in the As mapping: this element is more concentrated around the Fe-rich dendrites (Fig.7). This layer could be a result of a (α-Fe+$Fe_2As$) divorced eutectic, according to the binary phase diagram As-Fe (Okamoto, 1991) and the ternary phase diagram As-Cu-Fe (Raghavan, 1992). The α-Fe also seems to be more susceptible to corrosion than α-Cu.

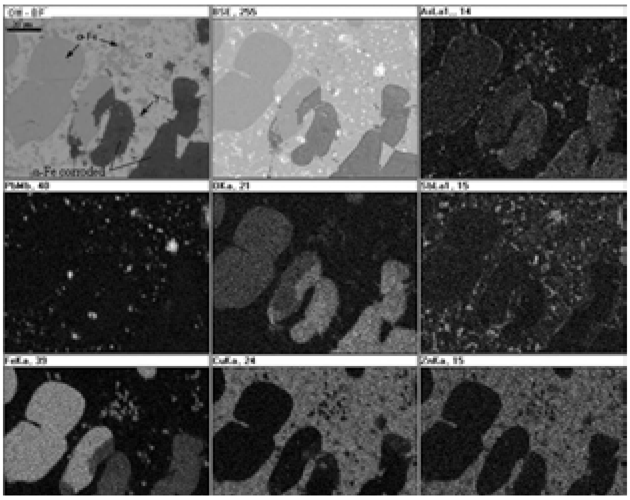

**Figure 7** Coin no. 2785 detail: SEM element mapping in EDS mode

In general, these observations show that the usual phases in binary Cu-Zn brasses (α, β and γ) cannot be explained just by the Zn content or the Zn/Cu ratio. Both Sn and Sb seem to promote the appearance of the β, and especially of the γ phase, with lower Zn contents than expected by the Cu-Zn phase diagram. These two elements (Sn and Sb) are distributed in a similar way within phases and seem to have the same microstructural effects in the alloys. Elements like Pb, Fe and As tend to promote other phases (non-existent in binary brasses) and do not change significantly these alloys: Pb concentrates in Pb-rich globules, while Fe forms primarily ferrite (α-Fe), or in the presence of As, also an iron arsenide ($Fe_2As$). Pb and Fe-rich phases oxidize preferably when exposed to aerobic environments, turning darker but remaining un-depleted, while the $Fe_2As$ phase seems to have better corrosion resistance than α-ferrite.

In order to verify the correlation between the compositions of the coins (obtained by micro-EDXRF) and the major brass phases observed, an isothermal section of the Cu-Zn-Sn ternary phase diagram at 450 ºC (Furtado, 2010) was used (Fig. 8). Due to similar microstructural effect and atomic mass proximity, a Sn equivalent content given by Sn+Sb was used to represent the coin compositions in this diagram. The Cu-Zn-Sn phase diagram is in good agreement with the phase constitution of the observed coin microstructures. Individual phase compositions measured by SEM-EDS are also in reasonable agreement with the equilibrium phase composition.

Kangxi coins can be interpreted mainly as α+γ brass microstructures with the exception of two coins, one monophasic α and the second biphasic β+γ. Qian Long coins are more scattered, presenting all the groups, except for α+γ. Jia Qing coins have mostly α+β brass structures and a few α, β, β+γ and α+γ.

Dezincification happens in many of the coins and can explain the differences in Zn content observed in the micro-EDXRF and EDXRF results.

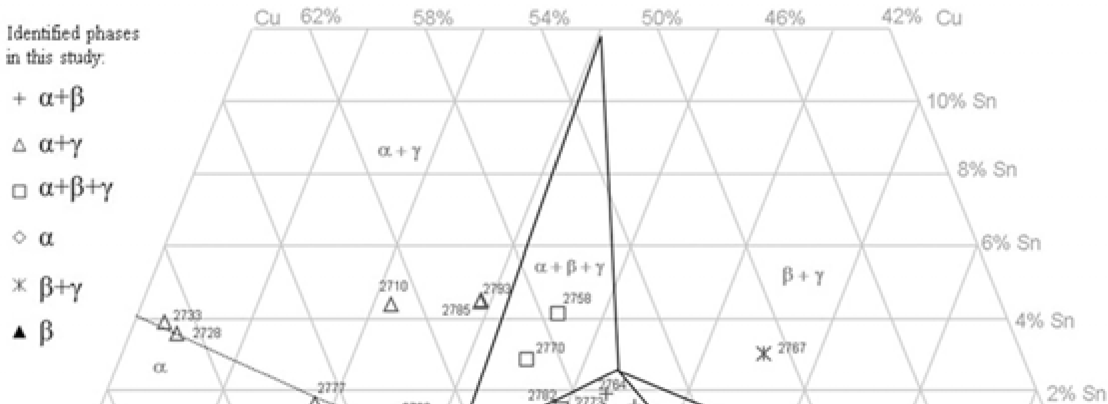


**Figure 8** Coin elemental distribution in a partial isothermal section of Cu-Zn-Sn phase diagram at 450 ºC (adapted from [Furtado, 2010]). Coin no. 2737 (α phase) is not represented here due to its low Zn value (outside the boundaries of this diagram)

## Conclusions

Although Chinese coins were made in a very consistent way, by casting liquid metal into sand moulds in which an imprint of a coin had been previously made, their composition is quite variable, even within the same time frame. This can be due to numerous factors as for instance mint location, issues per year, raw material availability and official regulation for economic measures, to name a few.

In the studied coins there is tendency to a decrease in the average Cu content and an increase in Zn when comparing the coins of the Kang Xi reign (1662-75 AD) with those of the two following reigns (1736-1820 AD): this may be related to Cu supplies shortness during these later reigns (Peng, 1965). The average Pb content varies between 5-8% and this metal may well have been added to improve the alloy fluidity and reduce the raw-material cost, due to its low melting point and cheapness. There seems to be a trend towards Sn decrease over time, while on the other hand, the Fe average content is higher in the last reign (Jia Qing), probably because of the use of unrefined minerals or scrap metals, employed to reduce the production cost.

The fine and porous microstructures observed are in conformity with the as-cast method used in China for casting coins: no indications of thermal or mechanical operations were detected. The major phases encountered are explained by the binary Cu-Zn system although the appearance of beta and gamma phases in the case of lower Zn contents lead to the use of a ternary phase diagram Cu-Zn-Sn, that explained the major phases present in coins. A ternary phase diagram for As-Cu-Fe (Raghavan, 1992) helped to clarify Fe and As-rich phases, identified by micro-XRD. Minor elements were found to be in association: Sn-Sb and Fe-As, have the same microstructural effects and appear concentrated in the same phases, which simplifies the microstructure interpretation. Fe appears as small to large dendrites of ferrite, and when - in the presence of As - an iron arsenide forms around the Fe-rich phase. Pb occurs mainly as small Pb-rich globules.

The small composition variation between the surface and clean metal usually shows a Cu enrichment and Zn depletion explained by the phenomenon of dezincification (Zn loss with Cu redeposition), observed in all coins. There is also a tendency to a superficial enrichment in Sn and Fe.

For coins made of brass containing tin, the following sequence of corrosion resistance was observed: $\alpha > \gamma > \beta$. This is not a common sequence for binary Cu-Zn alloys in which the observed corrosion resistance is $\alpha > \beta > \gamma$. In the case of these particular coins it was observed that Sn promotes β and/or γ phases in high zinc brasses, and those phases corrode preferentially in the long term. Pb-rich globules seem to oxidize faster, but Pb is not leached out. Fe-As rich phases are also susceptible to easy oxidation and acquire a dark colour. Fe is eventually leached out of the alloy.

This study intends to contribute to the knowledge of the Chinese metallurgy in numismatics. The characterization of the microstructural constituents and the long term corrosion behaviour observed in these coins is also significant for the preservation of this cultural heritage.

## Acknowledgements

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# Simulating investigation of the casting techniques for casting ancient Chinese bronze coins of the Han Dynasty


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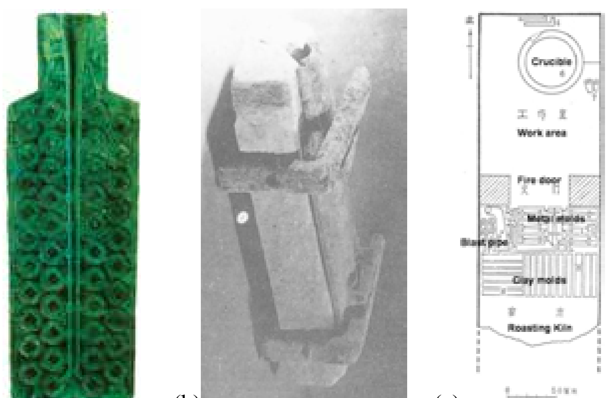
*ABSTRACT* At the time of the Han Dynasty (206 B.C.-A.D. 220) in ancient China there existed two important techniques for casting bronze coins: stack-casting and bunch-casting. In this paper, computer simulation of the casting processes was used to study how different the mold filling process of these two kinds of techniques for bronze coins were, and how the mold materials influence the mold filling capacity in bunch-casting. Based on the results, we discuss the differences between these two kinds of casting techniques and the reason why they played different important roles during the Han Dynasty period in the casting of bronze coins.


## Foreword

At the time of the Han Dynasty (206 B.C.-A.D. 220) in ancient China there existed two important techniques for casting bronze coins: stack-casting and bunch-casting. In the bunch-casting technique, cavities were symmetrically laid out one by one on both sides of the sprue. The mold material could be stone, clay or metal. Up to 62 bronze coins could be cast at one time. In the stack-casting techniques, some pieces of clay molds made from the same metal model were stacked up with one pouring cup and sprue. According to the data from archaeological excavations, more than one hundred coins could be cast at one time.

The mold material for bunch-casting could be clay, stone or metal (The Shaanxi Branch of the Chinese Coin Association 1992). Only a few clay-molds were found. Stone molds had been mainly used by the early Western Han (206-118 B.C.). More than one hundred bronze molds have been found in China, but also a few iron molds are known. 41 pieces of bronze molds and 102 clay molds for bunch-casting were unearthed from a kiln in Chengcheng, northern Shaanxi province in China in 1979 (see figure 1) (The Joint Archaeological Team of CPAM of Shaanxi Province 1982, p. 23-30). The casting mold consisted of one metal and one clay part. 42 or 30 coins could be cast at one time. The archaeologists dated them to 118 - 113 B.C. A large number of clay molds for casting metal molds have been found on several central government mint sites in Xi'an, the capital of the Western Han Dynasty.

About 370 stack-casting molds and more than one thousand small fragments were unearthed from a kiln in Xi'an, Shaanxi province, China in 1958 (see figure 2). They belong to the Xin Dynasty (AD 8-23) (The Shaanxi Province Museum 1959，p.12-13). In one whole stack-casting mold, 46 piece molds were stacked up, and reached a total height of 39 centimeters. 184 bronze coins could be cast at one time.




(a) (b) (c)

**Figure 1** (a) Bronze-mold, (b) casting mold and (c) drawing of kiln, unearthed from Chengcheng, northern Shaanxi province in China in 1979. 118 - 113 B.C

Many factors influenced the casting process, including the mold material and its physical parameters, the gate system, the pouring temperature and rate of the molten metal and so on. All these factors act on a casting contemporarily. The advanced computer simulation allowed the visualization of the casting process. In this paper, the computer simulation of the casting processes was employed to determine how different the mold filling processes for bronze coins was when these two kinds of techniques were applied, and how the mold materials influenced the mold filling capacity in the bunch-casting method.

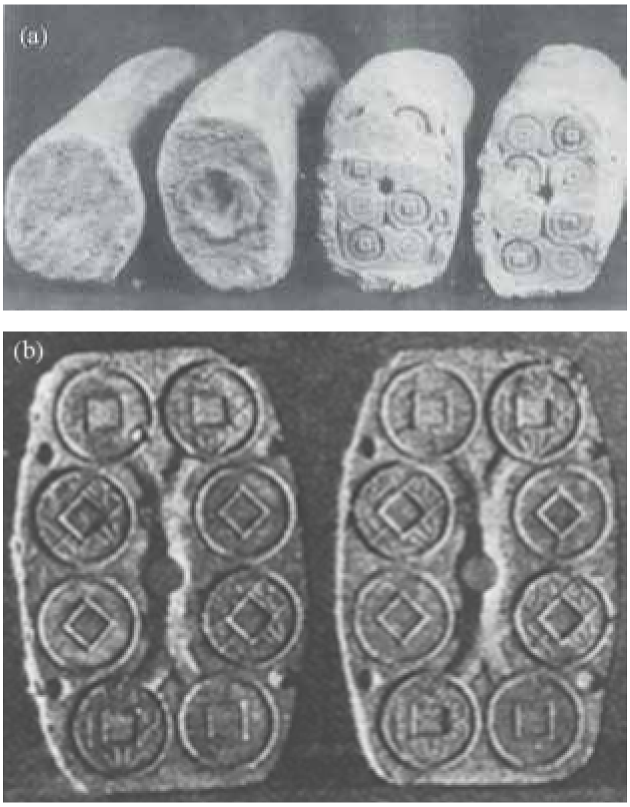
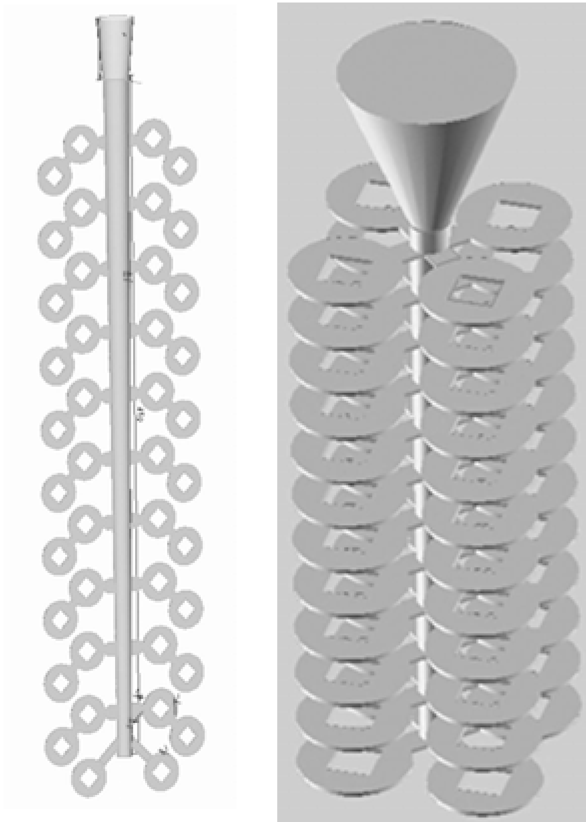


**Figure 2** (a) casting molds (b) pieces of mold unearthed from a kiln in Xi'an, Shaanxi province, China in 1958. AD 8–23

## CAD models and conditions of the computer simulation of casting processes

The size of a mold cavity for coins is similar for the majority of coins in the Han Dynasty period: diameter 2.6 cm; thickness: 0.1 cm; length of square side 1 cm. The size of the bunch-casting gating system is based on bronze molds unearthed from Chengcheng, northern Shaanxi province in 1979 (The Joint Archaeological Team of CPAM of Shaanxi Province 1982, p.26). The size of the stack casting gating system is based on a bronze model for making clay molds, collection of Shanghai Museum (Lian 2008, p.58).
CAD models show in figure 3.



(a) (b)

**Figure 3** Sketches of CAD models a. For a bunch-casting filling process; b. For a stack-casting filling process

The coins' composition is based on the average values of 83 bronze coins of the Western Han (Zhou 2004, p. 36-39). The percentages are 82.62 % Cu，9.51 % Pb，3.91 % Sn and 0.95 % Fe. C93500 from the Metals Handbook, with 85 % Cu，5 % Sn，9 % Pb and 1 % Zn, is the alloy which is closest to this composition. Its physical parameters were used in the computer simulation of casting processes (see table 1) (American Society for Metals 2004, p.561-562).

At the time of the Han Dynasty, various different bronze-mold compositions were used: in most cases copper was between 50-90%, lead was between 5-30%, and tin was between 5-20%. In the computer simulation of casting processes, C93500 with 85 % Cu，5 % Sn，9 % Pb and 1 % Zn was used for the metal-molds, ceramic-mold was used for the clay-molds, and talc was used for stone-molds. See table 2 for their physical parameters.

The pouring temperature is 1100℃, and the pouring speed is 10mm/s.

The casting simulation software ADSTEFAN, manufactured by Ibaraki Hitachi Information Service Co. Ltd. in Japan, was used in this study. The ADSTEFAN consists of Pre-treatment, Post-treatment and Solver modules, that are able to calculate flow, solidification, mold temperature, stress etc.

**Table 1** Physical parameters of Bronze coin

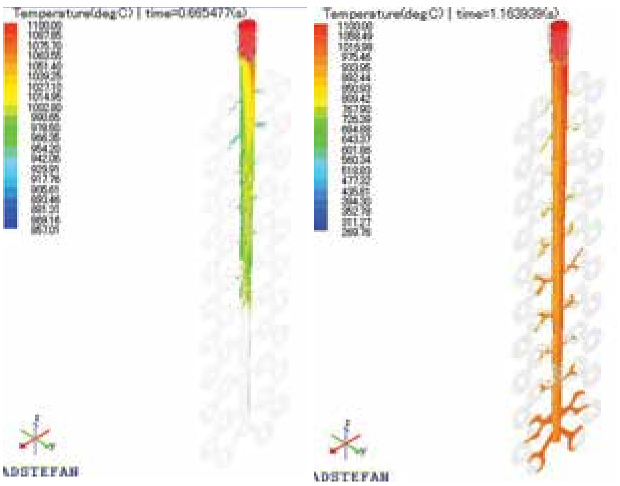
| Density | Specific heat | Thermal conductivity | Latent heat | Kinematic viscosity | Liquids | Solidus |
|---|---|---|---|---|---|---|
| kg/m$^3$ | kJ/(kg K) | W/(m K) | KJ/kg | m$^2$/s | K | K |
| 8870 | 0.376 | 71 | 300 | $1\times10^{-6}$ | 1273 | 1123 |

**Table 2** Physical parameters of casting molds

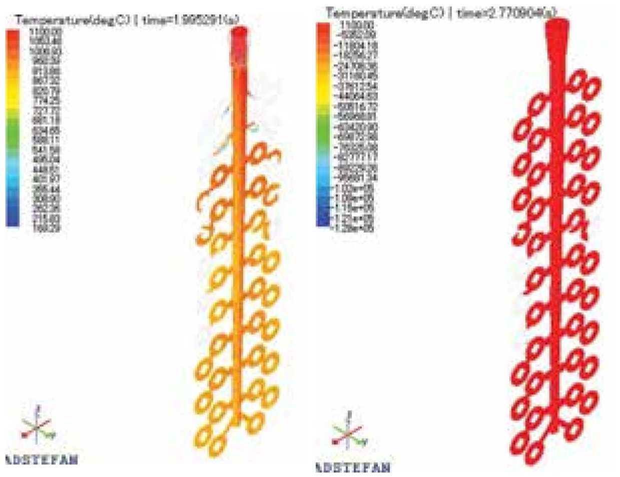
| Name | Density kg/m$^3$ | Specific heat kJ/(kg K) | Thermal conductivity W/(m K) |
|---|---|---|---|
| Bronze-mold | 8870 | 0.376 | 71 |
| Stone-mold | 2980 | 0.88 | 38 |
| Clay-mold | 3260 | 0.98 | 16 |

## Computer simulation of the mold filling process

### 1 Computer simulation of the mold filling process in the case of bunch-casting



(a) Filling time: 0.67 seconds (b) Filling time: 1.16 seconds

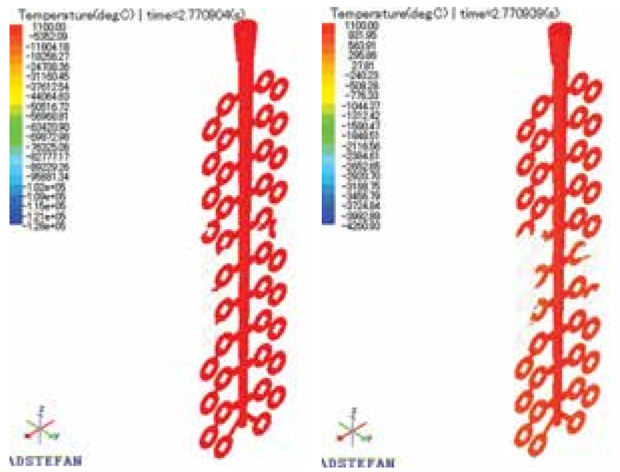


(c) Filling time: 2.00 seconds (d) Filling time: 2.77 seconds

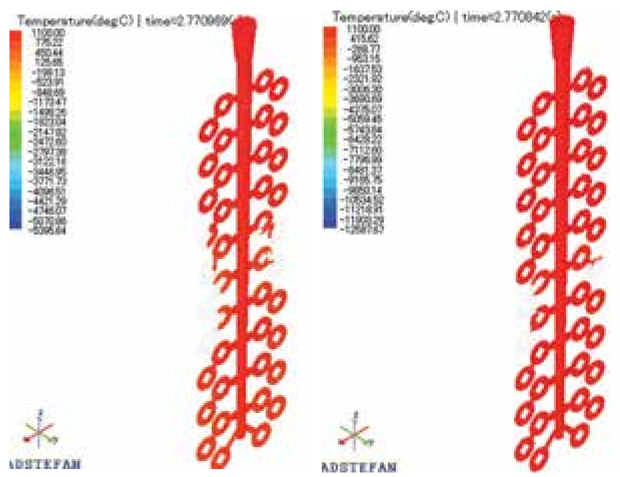
**Figure 4** Computer simulation process of bunch-casting for a bronze-clay pieces mold (mold material: bronze and clay)

Figure 4 shows the computer simulation process of bunch-casting for a bronze-clay pieces mold. The process does not show a good sequence, i.e. a sequence that should begin from the lower layer to the upper side. The upper layers began to be filled while some cavities of the lower layers were still unfilled. This caused the division of the flow of molten metal and a casting defect at the level of the middle layer cavities. The filling processes for different mold materials, such as bronze, stone or clay, are similar. Only the degrees of casting defects were different.

### 2 Results of the usage of different mold materials for bunch-casting



(a) mold material: bronze and clay (b) mold material: bronze



(c) mold material: stone and clay (d) mold material: clay

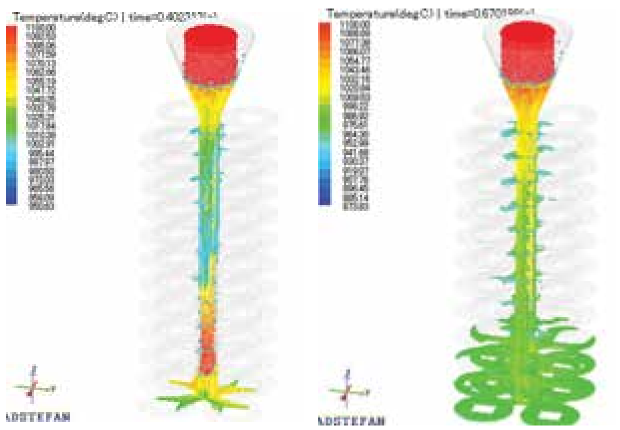
**Figure 5** Filling results of different mold materials for bunch-casting, the molds were all preheated to 150°C

The filling results of different mold materials for bunch-casting are shown in Figure 5. According to the computer simulation results, the filling performances for different molding materials of stone, metal and clay were different: the stone mold was the worst, the clay mold the best. When the mold was preheated to 150°C, the filling processes improved and more coin cavities were filled. The rates of finished product in the case of the metal- or of the clay molds were higher than those obtained from the stone mold.

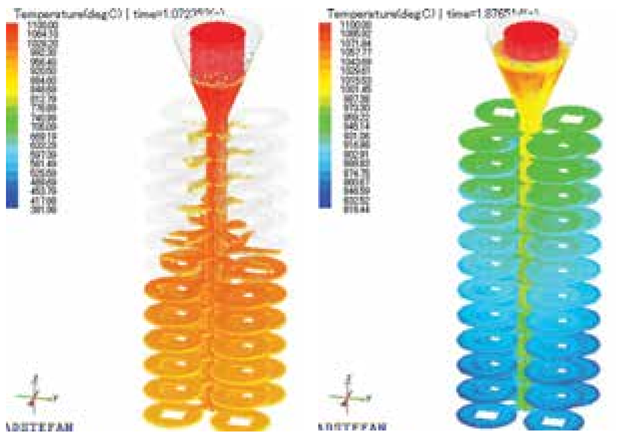
**Table 3** Filling results of different mold materials for bunch-casting

| Molding Material | Preheating mold condition | Number of unfilled coins/ Total coin cavities | A rate of misrun defect |
|---|---|---|---|
| Bronze-clay | Preheated to 150℃ | 7 / 42 | 17 |
| Bronze-bronze | Preheated to 150℃ | 11 / 42 | 26 |
| Stone-clay | Preheated to 150℃ | 10 / 42 | 24 |
| Clay-clay | Preheated to 150℃ | 4 / 42 | 10 |
| Bronze-clay | No preheating, 20℃ | 12 / 42 | 29 |
| Bronze-bronze | No preheating, 20℃ | 17 / 42 | 40 |
| Stone-clay | No preheating, 20℃ | 12 / 42 | 29 |
| Clay-clay | No preheating, 20℃ | 10 / 42 | 24 |

### 3 Computer simulation of mold filling process in the case of stack-casting



(a) Filling time: 0.40 seconds (b) Filling time: 0.67 seconds



(c) Filling time: 1.07 seconds (d) Filling time: 1.88 seconds

**Figure 6** Computer simulation process of stack-casting

Figure 6 shows the computer simulation process of stack-casting. A good sequential filling process from the lower layer to the upper layer can be recognized and all coin cavities are filled.

## Results and discussions

### 1 Comparison between stack-casting and bunch-casting

Under the same mold material and preheating conditions, the stack-casting method showed a good sequential filling process from the lower layer to the upper layer and all coin cavities were filled with molten metal (see figure 6.d). Bunch-casting did not work in the same way. The upper layers began to be filled, while some cavities of the lower layer were still unfilled. This caused a division in the flow of molten metal and a casting defect in the middle layer (see figure 4.d).

In the bunch-casting process, mold cavities were vertical and the mold was 41.5 centimeters high. Some of the cavities were connected with other cavities, and then to the sprue, but in the stack-casting process, the mold cavities were horizontal and the mold was 16.9 centimeters high, only 41% of the bunch-casting height. Here all cavities were connected to the sprue. By using the same mold material and with the same pouring conditions, molten bronze took 1.06 seconds to fill to the bottom cavity and its temperature decreased to about 900°C, and the total mold filling time in bunch-casting was 2.4 seconds. In the case of stack-casting, molten bronze took 0.38 seconds to fill to the bottom cavity and its temperature was above 1000°C. The total mold filling time was 1.65 seconds. Stack-casting could fill faster and had a lower heat loss. So its filling efficiency was higher than that of bunch-casting.

The production efficiency of stack-casting was lower than that of the metal-mold casting, but stack-casting was more easily controlled and higher quality coins could be cast at one time, than in the case of metal-mold casting, a method which is still highly technically demanding in modern society. For this reason the stack-casting method was used by private and state government workshops in the period of the early Western Han (206 B.C.-A.D.8) Dynasty. However, in the middle and late Western Han Dynasty, only the central government could cast coins but the whole country needed large numbers of coins. The metal-mold bunch-casting method was able to meet the requirement of rapidity and lower cost. In the Xin Dynasty period (A.D.9 - A.D.23), the high quality of coins became the most important factor, and stack-casting was readopted.

### 2 Comparison of the different mold materials for bunch-casting

When molds were preheated, the clay-clay pieces mold showed the best filling performance; the bronze-clay pieces mold followed in efficiency, and then came the stone-clay pieces mold, while the bronze-bronze pieces mold was the worst.

When molds were not preheated, the clay-clay pieces mold still showed the best filling performance; the bronze-clay pieces mold and the stone-clay pieces mold followed showing the same filling performance; the bronze-bronze pieces mold was again the worst.

The filling rates of the group in which the molds had been preheated were higher than those in the group without preheated molds. The preheated clay-clay pieces mold had the best filling performance; the bronze-bronze pieces mold without preheating was the worst. When a mold was preheated, the casting defect rate of a bronze-bronze mold was reduced from 40% to 26%; while that of a clay-clay pieces mold was reduced from 24% to 10%. The filling performance of all these materials could be improved by preheating the mold. This happened because the temperature gradient between molten metal and mold was reduced while preheating a mold. The heat conduction rate between molten metal and mold was reduced and therefore the solidified precipitates appeared later. The solid phases would block the pouring channel, and the casting defects appeared.

The mold material and its physical parameters influence the casting process observably according to the computer simulation results. Molds with higher heat preservation properties and a higher warming up temperature will show a better filling process. The clay mold was the best. The metal mold was better than the stone mold. The bronze-clay pieces mold was better than the bronze-bronze pieces mold.

The rate of faulty castings with the bronze-clay pieces mold was 17%; that of bronze-bronze pieces mold was 26%. In comparison with the bronze-bronze mold, the metal-clay mold improved the filling performance. This was one reason why ancient craftsmen of the middle-late Western Han Dynasty replaced the bronze-bronze pieces mold with the bronze-clay mold.

## Conclusions

1. The stack-casting method is better than the bunch-casting under gravity casting. The stack-casting shows a good sequential filling process from the lower layer to the upper layer and all coin cavities are filled by the metal, but the bunch-casting behaves in a different way. The upper layers begin to be filled, while some cavities of the lower layer are still unfilled: This causes the division of the flow of molten metal and a casting defect in the middle layer.
2. The mold material and its physical parameters visibly influence the casting process. Molds with higher heat preservation and a higher warming up temperature will perform better in the filling process. The clay mold was the best. The metal mold was better than the stone mold. The bronze-clay pieces mold was better than that bronze-bronze pieces mold.
3. Preheating the mold improved the filling performance.

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# A preliminary study on solders and soldering methods of ancient Chinese bronzes (9th Century B.C. - 3rd Century A.D.)

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*ABSTRACT* Recent research has revealed that soldering was an important technique used in the fabrication of ancient Chinese bronzes and its appearance can be traced back, at least, to the Western Zhou period (11th-8th centuries B.C.). In this paper, six solder samples as well as the relevant bronze objects were examined using optical microscope, scanning electron microscope (SEM), X-ray energy dispersive spectrometry (EDS) and X-ray diffraction spectrometry (XRD). The results indicate that the solders dating to the Late Western Zhou period (9th-8th centuries B.C.) are mainly Pb with a small amount of Sn and As; while those dating to the period between the Warring States and the late Eastern Han Dynasty (5th century B.C.-3rd century A.D.) consist of Pb-Sn alloys. It has also been found that soldering methods are distinct in different periods. From the late Western Zhou period (9th-8th centuries B.C.) to the Warring States period (5th-3rd centuries B.C.), the soldering method was as follows: first, to cast a tenon at the relevant position of bronze body; then, to pour molten solder into the mortise in appendage; finally, to connect the tenon with the mortise before the solder solidified. In the Eastern Han Dynasty (1st-3rd centuries A.D.), two bronze parts were directly connected by molten solder, without casting a tenon and a mortise. Interfacial reaction between Sn-Pb solder and bronze substrate is also discussed in the paper.

## Introduction

Recent archaeo-metallurgical research has shown that bronze soldering technology started in ancient China no later than the late Western Zhou period (9th – 8th centuries B.C.) and developed in many aspects from the Spring and Autumn period to the Warring States period (8th – 3rd centuries B.C.). Bronze objects with clear signs of using solders have been found recently in Beijing, Henan and Hubei. Solders taken from more than 10 bronze vessels were subjected to scientific analysis, revealing a significant change in their materials from the Spring and Autumn Period (8th – 5th centuries B.C.) to the Warring States (5th – 3rd centuries B.C.), with Sn or Pb being replaced by Sn-Pb alloys (He and Jin 2000; HPM 1989). However, generally speaking, research on soldering techniques in ancient China is still far from adequate. In this paper, the soldering techniques and the interface reaction between the solder and the bronze matrix are discussed through the scientific investigation of 6 soldered bronze vessels, with a focus on their chemical compositions and microstructures.

## Samples and research methods

### *1. Samples*

Table 1 presents some general information about solder samples taken from 6 ancient bronze vessels. Among them, 2 are dated to the late Western Zhou period (9th-8th centuries B.C.), 3 to the period from the late Spring and Autumn period to the Warring States period (6th-3rd centuries B.C.), and 1 to the Eastern Han Dynasty (1st-3rd centuries AD).

**Table 1 Solder samples taken from 6 ancient bronze vessels**

| Nos. | Sample names | Dates | Unearthed places | Notes |
|---|---|---|---|---|
| 1 | *Fanghu* (rectangular wine container decorated with birds and phoenixes) M2012:16 | Late Western Zhou Dynasty, 9th-8th centuries B.C. | The cemetery of the State of Guo, Shangcunling, Sanmenxia, Henan Province | Solder used at the connecting point between the ears and the body |
| 2 | *Fanghu* M2012:25 | Same as above | Same as above | Same as above |
| 3 | *Gaidou* (Hemispherical bowl with a lid) M72:3 | Late Spring and Autumn period to Early Warring States period, 6th-5th centuries B.C. | Tombs in Zhouzhuang, Xintai, Shandong Province | Solder used at the connecting point between the plate and the foot |
| 4 | *Jian* (big basin) 7:344-3 | Warring States period, 5th-3rd centuries B.C. | Tombs in Gaozhuang, Huaiyin, Jiangsu Province | Solder from the tenon at the bottom of the Jian |
| 5 | *Jian* (big basin) 7:344-1 | Same as above | Same as above | Solder filled in the foot of the Jian |
| 6 | Coin Tree Ssyh-3-1 | Eastern Han Dynasty 1st-3rd centuries A.D. | A tomb in Shitangxiang, Mianyang, Sichuan Province | Solder on the leaves |

***2. Research methods***

Samples were mounted in polyester resin on their sectional way, then the resin block were ground against wet silicon carbide papers and polished by using diamond powder paste. Lead samples were polished at room temperature by using chemicals consisting of 30ml HCl, 10ml $H_2O_2$ and 60ml $H_2O$. Etching reagents were selected according to the different materials. Lead samples were etched with a $H_2O_2$-acetic acid solution ($H_2O_2$:$CH_3COOH$=1:3), while Pb-Sn samples were etched with an acetic acid–nitric acid–glycerine solution ($CH_3COOH$:$HNO_3$:$C_3H_8O_3$=1:1:8), and bronze samples were etched with a 3% $FeCl_3$·HCl alcohol solution. After etching the samples were examined under a microscope (Leica DM400M).

Compositional analyses were carried out by using a JEOL JSM-6480LV Scanning Electron Microscope (SEM) equipped with a NORAN System Energy Dispersive X-ray Spectrometer (EDS), with a working condition of 20kV for voltage and 50 seconds for counting. Normally, the average value of two or three measurements at different areas of a sample was taken as its composition, while point-scanning measurement was used for analyzing inclusion particles.

Phase components of the solders were tested by using a Japan MXP21VAHF rotating anode X-ray diffractometer with Cu target. The working conditions were as follows: voltage 40kV, current 200mA, and power 8000W.

## Investigation and analysis results

***1. Samples of the late Western Zhou Dynasty (9th – 8th centuries B.C.)***

**(i) Soldering method**

Many bronze vessels of the late Western Zhou dynasty were found at the cemetery of the State of Guo in Shanglingcun, Sanmenxia, Henan province (HPIA 1999). Some of them have clear signs of soldering. For example, a Guo Ji (虢季) Fanghu (a rectangular container with an inscription of Guo Ji) (M2001:92) and a Fanghu decorated with birds and phoenixes (M2012:16) (Fig. 1). The observation of the bronze Fanghu vessel (M2012:16) indicates that its ears were already broken off and solder residue was found at the two tenons in the relevant position on the body of the Fanghu. Clearly, low melting-point solder was used to connect the ears to the vessel body. The soldering process might have been like this: the melted solder was poured into the mortise in the ears and then the mortise was connected with the tenon at the relevant position of the vessel body before the solder solidified (Fig. 2).

**Figure 1** The bronze *Fanghu* vessel decorated with patterns of birds and phoenixes unearthed from the cemetery of the Guo State of the 9th-8th centuries B.C. (M2012:16)

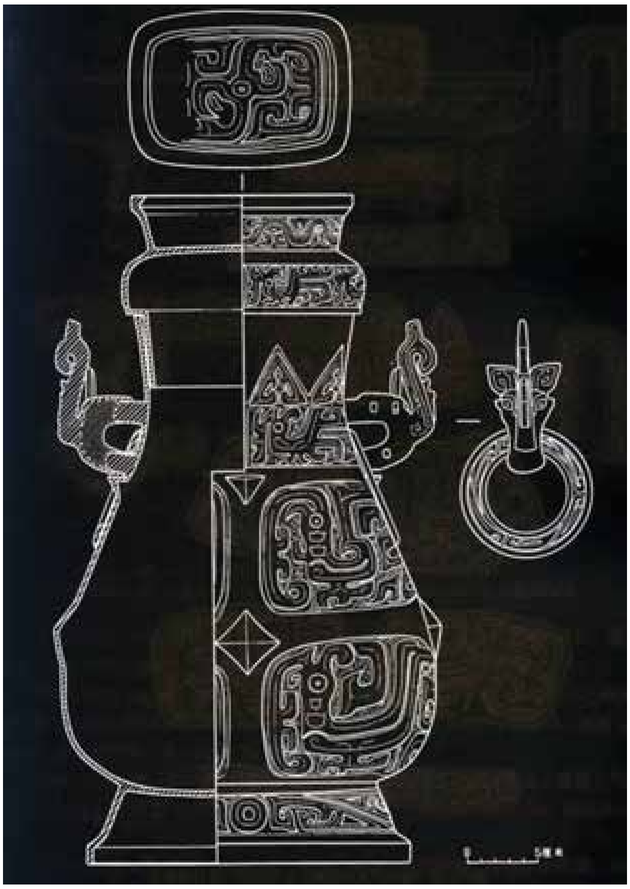

**Figure 2** Drawing of bronze *Fanghu* vessel (M2012:25) shows connecting method between vessel body and ear appendage

### (ii) Solder analysis

The solder samples were taken from the connecting areas between the ears and the body of the two *Fanghu* vessels. The analysis results are given in Table 2.

**Table 2 The analysis results of two solder samples of the $9^{th}$ -$8^{th}$ centuries B.C.**

| Nos. | Sample names | Pb% | Sn% | Cu% | O% | As% |
|---|---|---|---|---|---|---|
| 1 | *Fanghu* vessel (M2012:16) | 97.9 | 0.7 | 1.4 | tr. | tr. |
| 2 | *Fanghu* vessel (M2012:25) | 89.7 | tr. | 1.9 | 8.4 | tr. |

Note: "tr" in the table indicates that the element was identified, but the percentage is very low.

Table 2 indicates that the two solder samples are mainly lead with a small amount of copper, tin and arsenic as their impurities, most likely originating from the lead ore. It should be noted that the sample No. 2 was heavily corroded.

## 2. *Samples of the late Spring and Autumn period and the early Warring State period ($6^{th}$-$5^{th}$ centuries B.C.)*

### (i) Soldering method

Many bronze vessels were unearthed from the cemetery of the late Spring and Autumn period and the early Warring State period in Zhouzhuang, Xintai, Shandong province. Over ten vessels showed the traces of soldering, as revealed by the separation between the appendages and the vessel body. For example, in the case of a Gaidou vessel (M72:3), its foot was already broken from its bowl-shaped body (Fig. 3). The broken surfaces clearly revealed that they were connected through a tenon on the bottom of the vessel and a mortise on the foot.


**Figure 3** Bronze *Gaidou* vessel (M72:3) unearthed at Zhouzhuang, Xintai, Shandong province showing the connecting method between its foot and bowl-shaped body.

### (ii) Solder analysis

Solder sample (No.3) was taken from the connecting point between bowl and foot of the Gaidou (M72:3). The sample was corroded and compositional analysis revealed that it contains 93.9% Pb, 0.9% As, 5.2% O. Microstructure examination showed a cast structure with precipitated phases distributed along grain boundaries (Fig. 4). The SEM-EDS analysis indicated that the phases were compounds of Pb and As (63.0% Pb, 34.3% As, 2.7% O).

**Figure 4** Microstructure of the No.3 sample taken from the solder of the *Gaidou* vessel (M72:3), showing a lead cast structure with precipitated phases being distributed along the grain boundaries.

### 3. *Samples of the Warring States period (5th-3rd centuries B.C.)*

#### (i) Soldering method

A total of 176 bronze vessels were unearthed from a tomb (HMM 1988) of the Warring States period at Gaozhuang, Huaiyin, Jiangsu Province. Recently, when these vessels were restored in the Nanjing Museum, it was found that, on several vessels, the appendage was soldered onto the main body. Some appendages were already broken off, showing clearly the presence of solder as well as the soldering structure (Figs. 5 and 6). Two samples were taken for analysis. Sample No.4 was taken from the solder connecting the bottom and the foot of a bronze Jian vessel (7:344-3), while sample No.5 comes from a further bronze Jian vessel (7:344-1). The most likely soldering method was to pour melted solder into the mortise on the foot and then to attach the foot to the pre-cast tenons on the vessel body.

**Figure 5** Pre-casting tenons on the body of a bronze *Jian* vessel recovered at Gaozhuang, Huaiyin, Jiangsu province.

**Figure 6** Pre-casting tenon and mortise seen on body and foot of a bronze *Pan* vessel found at Gaozhuang, Huaiyin, Jiangsu province.

#### (ii) Solder analysis

The analysis results of two Gaozhuang samples are given in Table 3, and show that the two solder samples are Pb-Sn alloys.

Sample No.4 contains 46.3% Pb and 52.1% Sn, and is slightly different from the eutectic composition of Pb-Sn alloy under equilibration condition (38.1% Pb and 61.9% Sn). The eutectic has the lowest melting point, of around 183.3$^{o}$C, and is widely used as solder materials in modern times. The melting point of the solder No.4 is higher than that of the modern solder by about 50-90$^{o}$C, but it still can be considered as a solder with a relatively low melting point. It should be noted that this solder also contains a small amount of Cu (1.6%), which seems to come from the bronze vessel body, made of a Cu-Sn-Pb alloy (65.3% Cu, 18.1% Sn and 12.7% Pb).

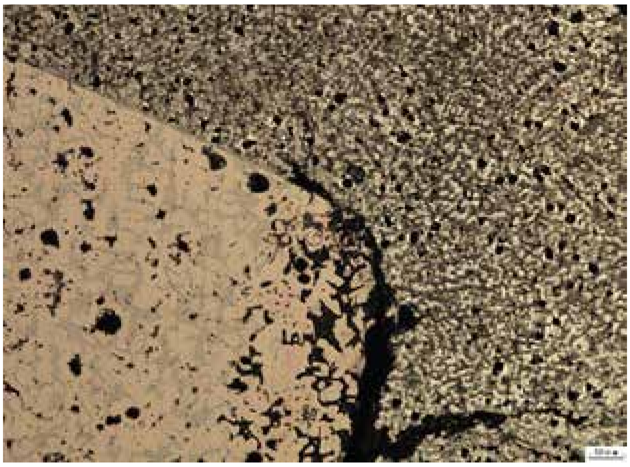

**Figure 7** Microstructure of the joining area between the solder and the bronze body of the *Jian* vessel (No.4 sample, 7:344-3).

Figure 7 shows the microstructure of the joining area between the solder and bronze body of sample No.4. The lower part on the left shows the cast bronze structure of the body, while the upper part on the right shows the Pb-Sn dendrites of the solder, with the dark-grey phase being the α solid solution and the white-grey phase the β solid solution. A dark film of Cu-Sn seemed to have formed at the interface between the bronze body and the Pb-Sn solder. It contains 42.1% Cu and 53.8% Sn. Some small dark Cu-Sn blocks are also visible within the solder region, and they contain 35.0% Cu and 65.0% Sn (Fig. 8). As an inter-metallic compound in the Cu-Sn alloys, the η phase contains 39% Cu and 61% Sn. We suggest that the dark Cu-Sn

**Table 3 The analysis results of two solder samples of the 5$^{th}$ -3$^{rd}$ centuries B.C.**

| Nos. | Sample names | Sample location | Analysis area | Cu/% | Sn/% | Pb/% | O/% | Others/% |
|---|---|---|---|---|---|---|---|---|
| 4 | *Jian* (big basin) 7:344-3 | Solder at the bottom of the *Jian* | body<br>solder | 65.3<br>1.6 | 18.1<br>52.1 | 12.7<br>46.3 | tr<br>tr | S: 0.4<br>S: tr |
| 5 | *Jian* (big basin) 7:344-1 | Solder filled in the foot of the *Jian* | solder | 0.0 | 21.4 | 68.1 | 5.9 | Al: 4.6,<br>Si: 0.3 |

Note: "tr" in the table indicates that the element was identified, but the percentage is very low.

areas observed in the interface and solder region are actually η phases.

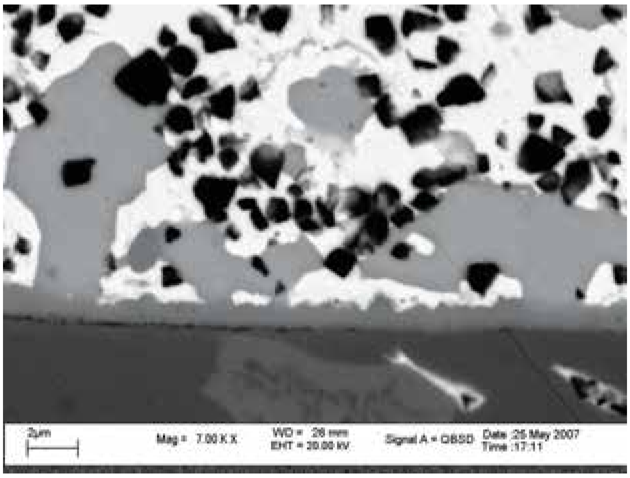


**Figure 8** Cross-sectional back-scattered electron image of SEM of the No.4 sample showing the interface between the solder and the body of the *Jian* vessel (7:344-3)

The sample No.5, taken from the solder filled in the foot of the *Jian* vessel (7:344-1), is shown to contain no Cu, suggesting that there were no exchanges through contact between the bronze body and the solder. Table 3 also shows the presence of O, Si and Al in the sample, probably due to the influence of corrosion, and to some particles embedded in the soft substrate of Pb-Sn solder during the grinding and polishing processes.

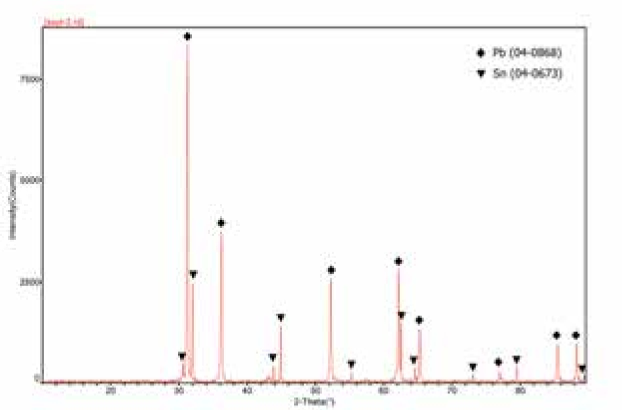


**Figure 9** The X-ray diffraction pattern of the No.5 solder sample taken from the *Jian* vessel (7:344-1)

In order to define the solder components of the bronze vessels from Gaozhuang, Huaiyin, X-ray diffraction analysis (XRD) was carried out on sample No.5. The XRD pattern shown in Figure 9, indicates that the solder is composed of lead and tin, but not of α and β phases. The explanation for this is that both α and β phases are solid solutions. When a small amount of Sn is dissolved in the α phase, it can not change the original lattice constant of lead. Therefore, X-ray diffraction analysis failed to identify lead and α phase as well as Sn and β phase. But according to the SEM-EDS results, the tin-rich β phase contains 4.40% Pb, while the lead-rich α phase contains 2.97% Sn. This demonstrates that the solder used for the *Jian* vessel was composed of α and β phases.

### *4. Samples of the late Eastern Han Dynasty (3rd centuries A.D.)*

**Figure 10** Bronze coin tree unearthed from a tomb of the late Eastern Han dynasty (3rd century A.D.) in Shitang, Mianyang, Sichuan province.

**Figure 11** The broken leaves soldered to the coin tree.

A single solder sample (No.6) was taken from a coin tree unearthed from a tomb of the 3rd century A.D. in Shitang, Mianyang, Sichuan province (Figs. 10 and 11) (Sun and He 2007). The leaves were directly connected to the tree branches by using solder (Fig. 12). This soldering technique shows no signs of using the tenon and mortise method, and is totally different from the five samples discussed above.

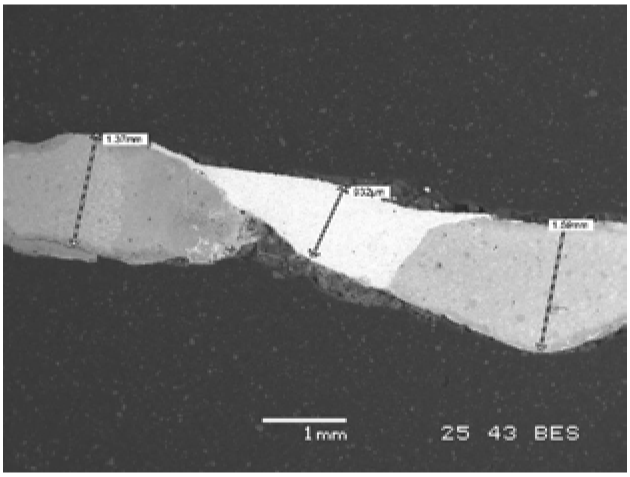


**Figure 12** Secondary electron image of SEM of the No.6 sample cross-section covering the soldering area of the leaves in the bronze coin tree (Ssyh-3-1): The bright area in the middle position is solder, while the dark-grey areas in both sides are bronze leaves.

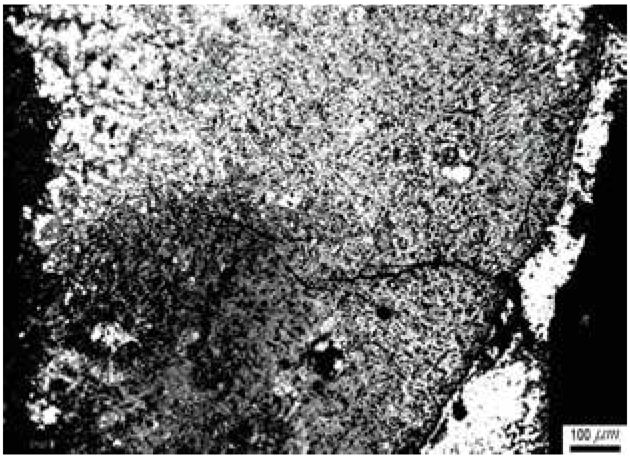


**Figure 13** Microstructure of the No.6 sample showing the joining area between the solder (right) and the body (left) of the bronze coin tree.

The SEM-EDS analysis shows that sample No.6 contains 60.9% Pb and 35.3% Sn, presenting a sharp contrast to the modern Pb-Sn solder with eutectic composition (38.1% Pb and 61.9% Sn). The examination of its microstructure reveals the existence of clear borders between the solder and the bronze leaves. The bronze leaves at the joint points are in a heavily corroded state (Fig. 13). The solder and the bronze body are not detached, thus indicating the solidity of the soldering. The microstructure of sample No.6 (solder only) shows a cast structure of Pb-Sn dendrites in a well developed state, where the dark phase is α solid solution and the white phase is β solid solution (Fig. 14). The compositional analysis also shows that the solder contains 3.8% Cu, which could be due to the diffusion of Cu from the bronze body to the solder through interface reaction. The small dark blocks were also observed to scatter across the α and β phases (Fig. 15). As discussed above, they are most likely η phases, an inter-metallic compound of Cu-Sn. However, the SEM- EDS analysis shows that the average composition of the dark blocks is as follows: 32.0% Cu, 46.5% Sn and 21.5% Pb. This indicates that they not only contain Cu and Sn, but also Pb, which might come from a part of lead-rich α phase surrounding the dark blocks. Probably because of the presence of Pb, the proportion of Cu and Sn of the dark blocks is quite different from that of the η phase.

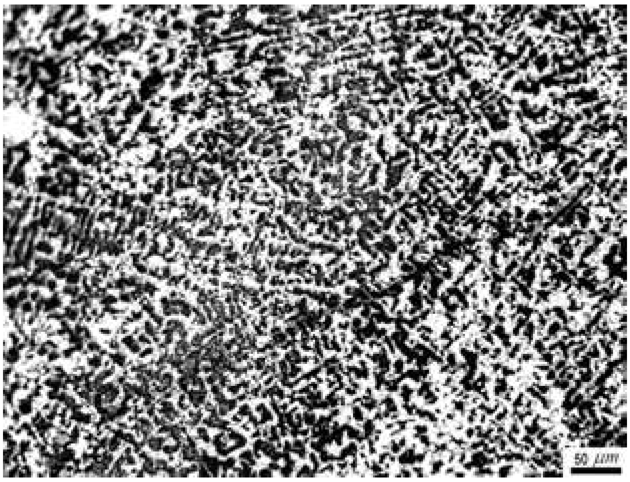


**Figure 14** Microstructure of the No.6 sample (solder only) showing a casting structure of Pb-Sn dendrites: the dark area is α solid solution, while the white area is β solid solution.

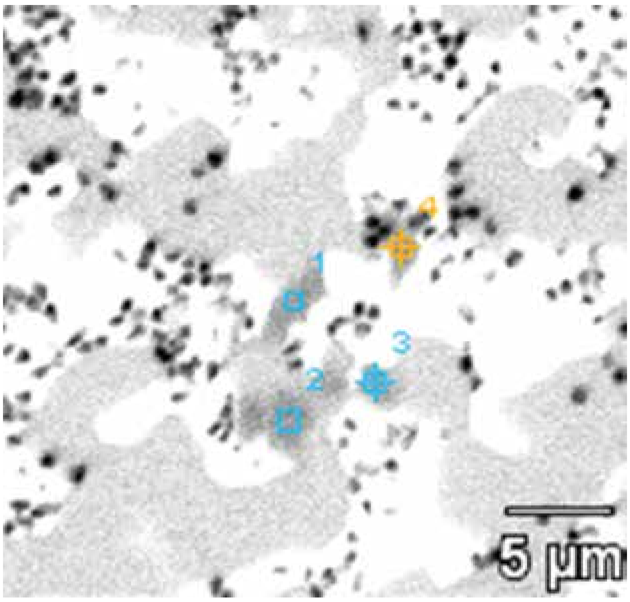


**Figure 15** SEM-EDS analysis of the No.6 sample (solder only) showing the composition of η phases: Average value of four analysis areas is: 32.0% Cu, 46.5% Sn, and 21.5% Pb.

**Table 4 Other analysis results of ancient solders found in China**

| Objects (Nos.) | Materials | Sn (%) | Pb (%) | Others (%) | Dates | Sites | References. |
|---|---|---|---|---|---|---|---|
| *Ding* vessel M2:34 | Solder | 98.3 | | | 6th-5th Centuries B.C. | The Xiasi Tomb, Xichuan, Henan province | He and Jin 2000 |
| *Gui* vessel | Solder between the handle and the body | 3.2 | 88.8 | Zn: 2.4, Ag: 0.3 | 8th-5th Centuries B.C. | Zhengzhou, Henan province | Same as above |
| *Lei* vessel YYM2:1 | Solder between the ear and the body | | 100 | | 8th-7th Centuries B.C. | The Shanrong Tomb, Yanqing, Beijing | Same as above |
| *Lei* vessel YYM18:1 | Same as above | 89.3<br>83.4 | | Cu: 10.7<br>Cu: 11.6, Fe: 5.0 | Same as above | Same as above | Same as above |
| *Lei* vessel YYM250:1 | Same as above | 6.1<br>5.6 | 91.8<br>91.9 | Fe: 1.6, Al: 0.5<br>Fe: 1.8, Al: 0.5 | Same as above | Same as above | Same as above |
| *Zhongjia* (Rack for hanging bells) | Solder on the groove in Rack | 36.9 | 58.5 | Cu: 0.23, Zn: 0.19 | 5th-4th Centuries B.C. | The tomb of Marquis Yi of Zeng, Suizhou, Hubei province | HPM 1989 |
| *Zhongjia* (Rack for hanging bells) | Same as above | 39.1 | 60.1 | | Same as above | Same as above | Same as above |
| Drum | Solder below the dragon head | 93.4 | 5.9 | | Same as above | Same as above | Same as above |
| *Zun* vessel | Solder in the foot of the vessel | 53.4 | 41.4 | Cu: 0.38, Fe: <0.01 | Same as above | Same as above | Same as above |
| *Jianfou* vessel | Solder below the dragon head | 90.9 | 0.5 | Cu: 0.03, Fe: <1 | Same as above | Same as above | Same as above |

## Summary and discussions

### (i) Soldering method

This study has revealed a significant change in the development of the soldering methods in the time from the late Western Zhou dynasty to the late Eastern Han period. From the late Western Zhou to the Warring State period (9th– 3rd centuries B.C.), the soldering method was characterized by the use of tenon and mortise. The process might have had the following steps: first, tenons were made during the casting of the vessel body; secondly: melted solder was poured into the mortise in the appendages; thirdly, the appendages were connected to the tenon of the vessel body. In some cases, the soldering join obtained by this method was not so strong, leading to the detachement of the appendages from the body. During the Eastern Han Dynasty (1st -3rd centuries A.D.), the soldering method appeared to have gone through a significant transformation, to a direct process involving the application of a low-melting-point solder to the parts that needed to be connected. This soldering method is similar to the modern one. Because of the use of low-melting-point solder, the soldering joins seem to be relatively strong.

### (ii) Soldering materials

The analyses of the six solder samples in this study have revealed a significant change in the soldering materials, from Pb (containing a small amount of As, Sample No.1 to No.3) to Pb- Sn alloys, during the early Warring States period (5th century B.C.). This observation is in consistence with other analysis results listed in Table 4. As we can see, the solders of the Spring and Autumn period (8th – 5th centuries B.C.) were mainly Pb or Sn; Pb-Sn alloys became predominant solders since the early Warring States period, while Sn solders with a small amount of Pb continued, in some cases, to be used. It should be noted that Pb-Sn alloys have melting point lower than that of Pb or Sn and that they offer a stronger soldering performance. Therefore, the appearance of Pb-Sn alloys as soldering materials represents an important development in the history of metal technology in ancient China.

### (iii) Interface reaction

The issue of the existence of Cu-Sn compounds in the soldering interface in the ancient solder samples may be explained according to modern research on soldering technology. The compounds that formed (or grew) at the interface between a Pb-Sn solder and a copper substrate have been studied in many papers (Grivas, *et al.* 1986; Prakash and Sritharan 2001; Tu and Zeng 2001; Ahmed, et al. 2004; Qi, *et al.* 2006; Qi, *et al*. 2007). It has been shown that when molten Pb-Sn solder was in touch with the copper substrate, Cu would diffuse into the solder and react with the Sn, leading to the formation of some sorts of inter-metallic Cu-Sn compounds at the interface. From the copper substrate to the solder, thin layers of $Cu_3Sn$ (ε phase) and $Cu_6Sn_5$ (η phase) would be observed at the interface, showing a clear growing trend towards the molten solder. These studies provide a good explanation for the identification of Cu-Sn phases in the ancient solder samples, as discussed in the preceding sections.

## Conclusions

The solders dating to the Late Western Zhou period ($9^{th}$-$8^{th}$ centuries B.C.) are mainly Pb with a small amount of Sn and As, while those dating to the period between the Warring States and the late Eastern Han Dynasty ($5^{th}$ century B.C.-$3^{rd}$ century A.D.) consist of Pb-Sn alloys. It has also been found that distinct soldering methods were used in different periods. From the late Western Zhou period ($9^{th}$-$8^{th}$ centuries B.C.) to the Warring States period ($5^{th}$-$3^{rd}$ centuries B.C.), the soldering method was as follows: first, to cast a tenon at the relevant position of bronze body; then, to pour molten solder into the mortise in appendage; finally, to connect the tenon with the mortise before the solder solidified. In the Eastern Han Dynasty ($1^{st}$-$3^{rd}$ centuries A.D.), two bronze parts were directly connected by molten solder, without casting a tenon and a mortise.

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# Metallographic study of 27 metallic artifacts unearthed from two sarcophagus tombs at Beipiao, Liaoning Province


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*ABSTRACT* In 1965，two sarcophagus tombs found in Baipiao (北票), Liaoning province, were excavated. According to the historical records (晋书) and from the seals unearthed from them archaeologists believe that these were double burials, for husband and wife, of the minister of war (大司马). This is the first time that an important tomb clearly dated to the northern Yan period (4th century -5th century AD) has been excavated. The two unearthed tombs have rich finds. They have been studied in close cooperation with archaeologists to ascertain the manufacturing technology of the metal artifacts excavated from the tombs and compared with the vast majority of metal artifacts from tombs in the Liaoning Provincial Museum collections warehouse, in order to fully reveal useful information on metal artifacts. A small amount of metal from the tomb could be sampled for study. Great attention was paid to the ferrous artifacts. Most of them were used habitually in every day life. We took a limited number of samples: 27 metallic artifacts, including 5 bronze vessels, 5 iron tools, 5 iron weapons, 4 iron objects and 2 iron plates, 3 silver and 1 gold pieces, a belt buckle and belt hook with gilding, and 1 fragmented glass bead. The 27 metallic objects excavated from the Fengsufu tombs show that the quality of the 5 bronzes was good. For the production of high tin bronze objects quenching was employed. 16 iron and steel samples were taken from pig iron, decarburized steel in solid state, puddling steel, sandwiched steel, quenched steel products, and from a forged iron mirror. Mercury gilt bronze belts, silver-copper and gold-silver alloys, and imported glass ware from the West were identified. In particular a pair of horse stirrups with a wooden core covered with gilt copper, has been for the first time recovered from an excavation. These results confirm that the making and using of metal is characteristic for this culture and technology, and provide new information on the development of economy and society of the Northern Dynasty in 4th-5th century.


In 1965，two sarcophagus tombs found in Baipiao (北票), Liaoning province (辽宁省) were excavated. These graves are located around 21 km north-west of the Beipiao county at the eastern foot of the Jiangjun mountain (Fig.1; Li Yaobo 1973).

According to the historical records (晋书) (Jin Shu 1974) and from the unearthed seals (Fig. 2) (Li Yaobo 1973) archaeologists interpreted these tombs as a double burial, for husband and wife, of the minister of war (大司马). The owner of grave No.1 named Fengsufu (冯素弗), had notable achievements and a high position in the Northern Yan (北燕) state. He died in 415 AD (Jin Shu 1974). Many artifacts have been recovered from these two tombs. This is the first time that such an important tomb that can be clearly dated to the northern Yan period (4th century -5th century AD; Li Yaobo 1973; Xu Bingkun 1996) has been found.

We invited the archaeologists of the Liaoning province Museum to co-operate with us in the study of the manufacturing technique of the metallic artifacts unearthed from the tombs of Fengsufu and his wife. Most metallic artifacts are still preserved in the storeroom of the Museum. We took a limited number of samples: 27 metallic artifacts including 5 bronze vessels, 5 iron tools, 5 iron weapons, 4 iron objects and 2 iron plates, 3 silver and 1 gold pieces, 1 belt buckle and 1 belt hook with gilding, and 1 fragmentary glass bead have been studied by metallography . Each sample was mounted and polished. They were then etched with different etchants. A Neophot 21 optical microscope was used to observe the microstructure of iron and bronzes samples. The chemical composition of bronze, gold, silver and glass bead samples was determined by SEM/EDS.


**Figure 1** Location of the FengSufu and Lamadong Tombs on the Liaoning province map

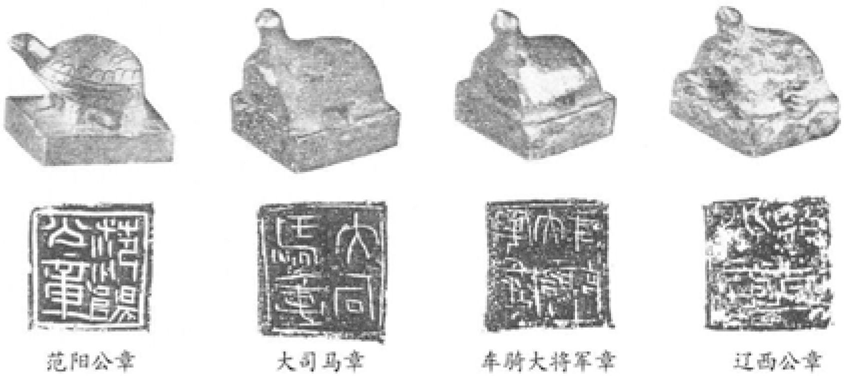


**Figure 2** Several seals excavated from the FengSufu tombs

## Experimental results

1) The analysis results of 5 bronzes have shown that 4 samples show Cu-Sn-Pb cast microstructures, (alpha and some delta phase). The Sn content was 5-7% and the Pb content was around 5%, the remainder being copper. The micro constituents were well distributed. There were a few casting defects and inclusions, but the casting is of high quality (Fig. 3 and Fig.4). The chemical composition and microstructure of two samples from a vessel with a handle and the matching lid are similar. Some strain lines were seen. The vessels showed cooking traces on the surface. This indicates that these were objects for use and not just ceremonial items. Two other samples taken from a Fu (釜), (a kind of cauldron used in ancient China), and a Zeng (甑), (a rice steaming utensil), did not show traces of use. Archaeologists had supposed that they were produced only for burial, and the results of our analysis confirmed this hypothesis. For the funerary objects high quality bronzes were used, as it was suitable for the importance of the grave owner (Fig.5 and Fig. 6).
The sample of the Bo (钵) is made of a CuSn alloy containing around 24.4% Sn (beta phase). The microstructure shows the high temperature phase of a bronze in the beta region that can be readily worked. If allowed to cool slowly to room temperature, the bronze would have decomposed into alpha and delta phases and it would be impossible to work, but the beta phase could be retained by quenching. This preserved the high temperature phase and produced a martensitic structure; the typical beta bronze resembles gold. The very golden 5100 Bo (钵) was formerly thought to be gilt because of its color. The microstructure of the 5100 Bo sample

(Fig.7) shows the typical development of the beta – quenched bronze structure. Small islands of α phase that often follow the grain boundaries of the previous high temperature β grains, present before quenching the alloy, can be also seen. The 5100 Bo with 0.1 cm thick wall was forged and the traces of working can still be seen on the inside wall of the vessel.

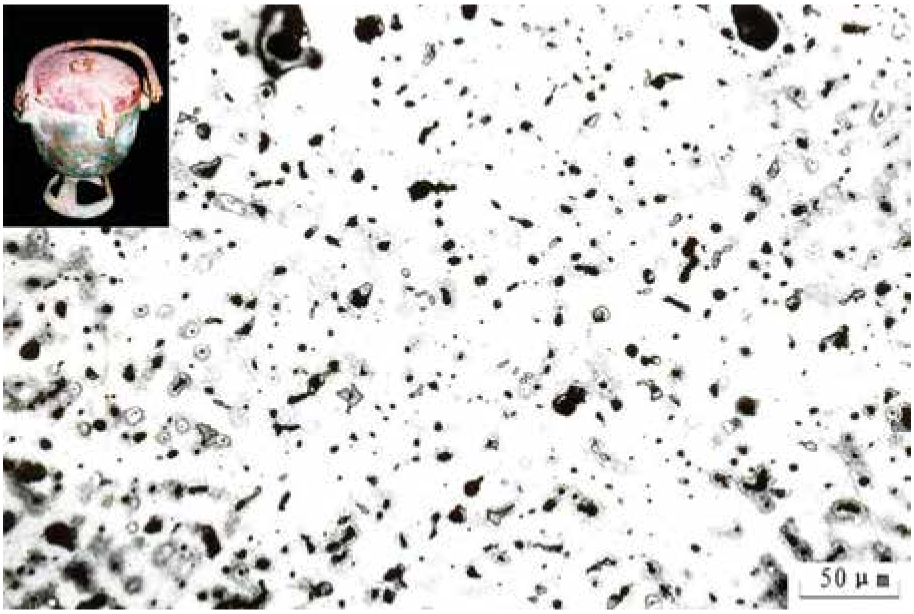


**Figure 3** Microstructure of vessel 5089.2. Composition: 4.8% Sn, 5.9 % Pb, 89.3 % Cu

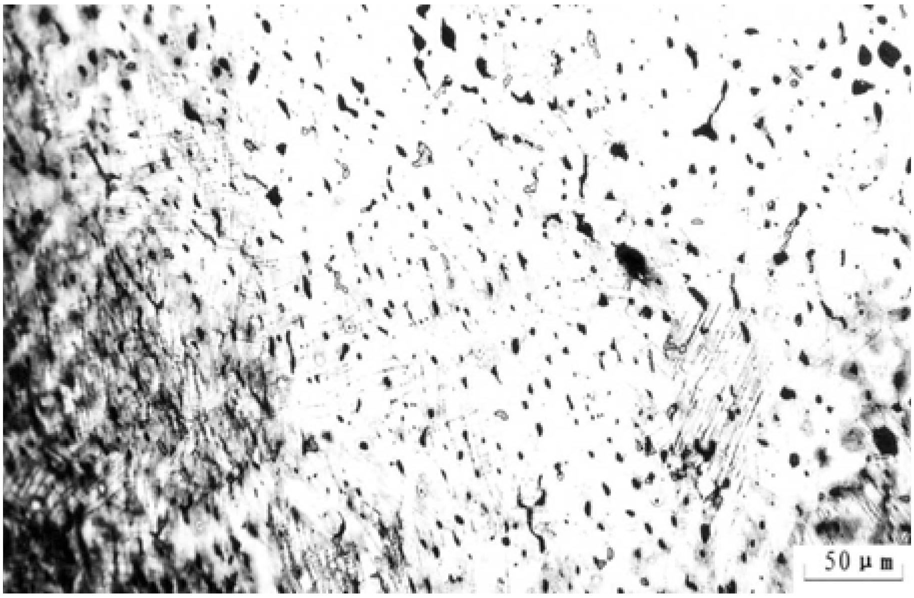


**Figure 4** Microstructure of vessel 5089.1. Composition: 5.9%Sn, 5.0% Pb, 89.2% Cu

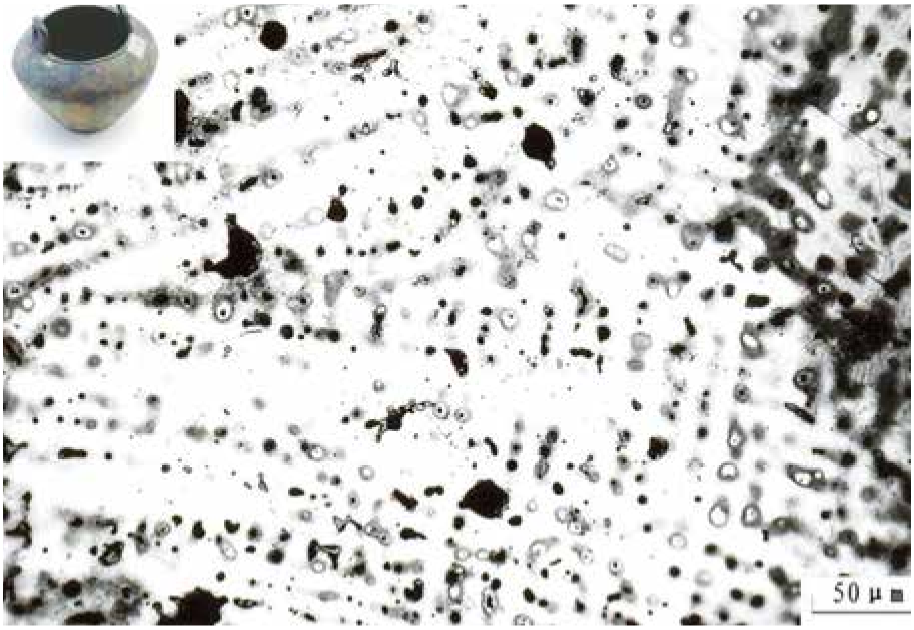


**Figure 5** Microstructure of 5090 Fu (釜). Composition: 6.4%Sn, 5.0%Pb, 88.6%Cu

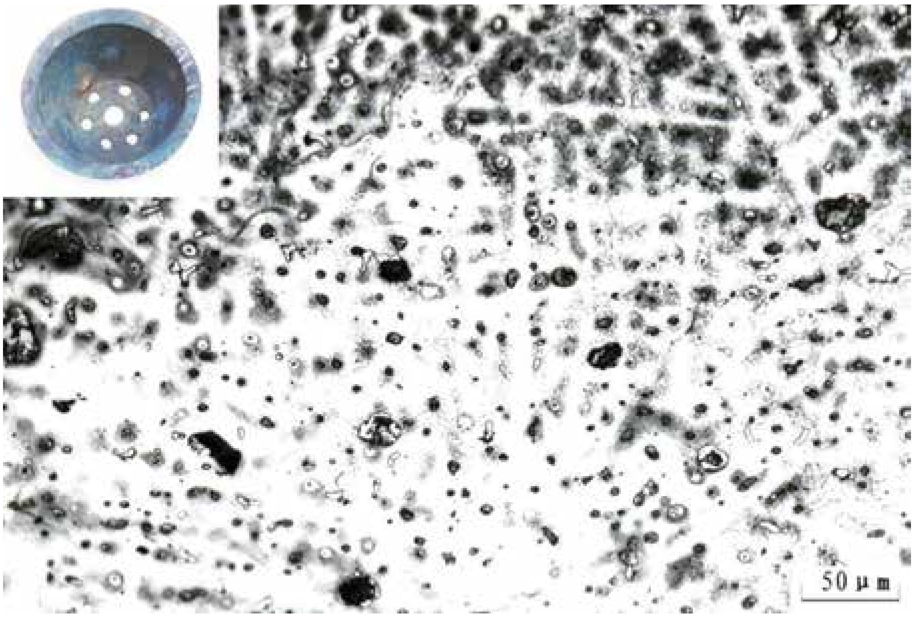


**Figure 6** Microstructure of 5091 Zeng (甑). Composition: 6.9%Sn, 3.6%Pb, 89.5%Cu

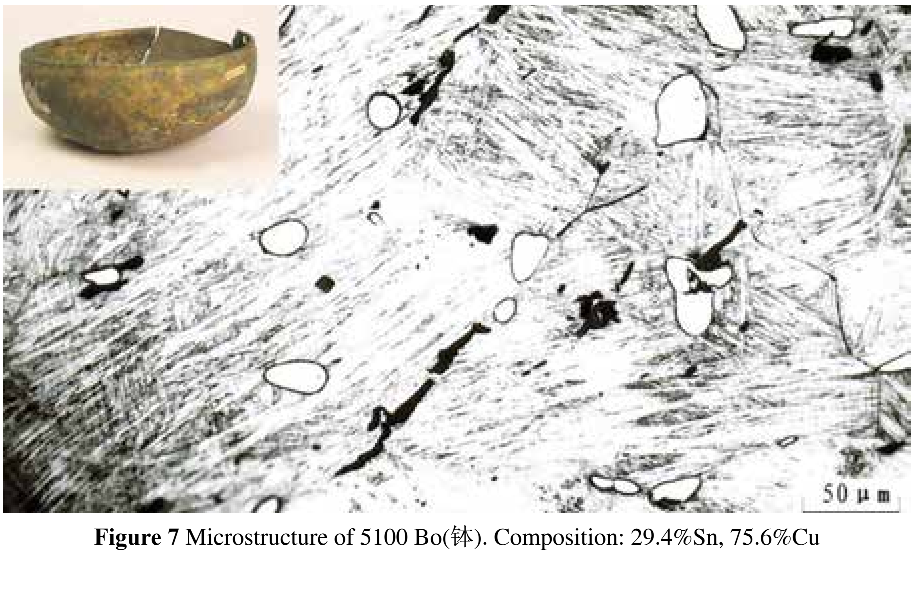


**Figure 7** Microstructure of 5100 Bo(钵). Composition: 29.4%Sn, 75.6%Cu

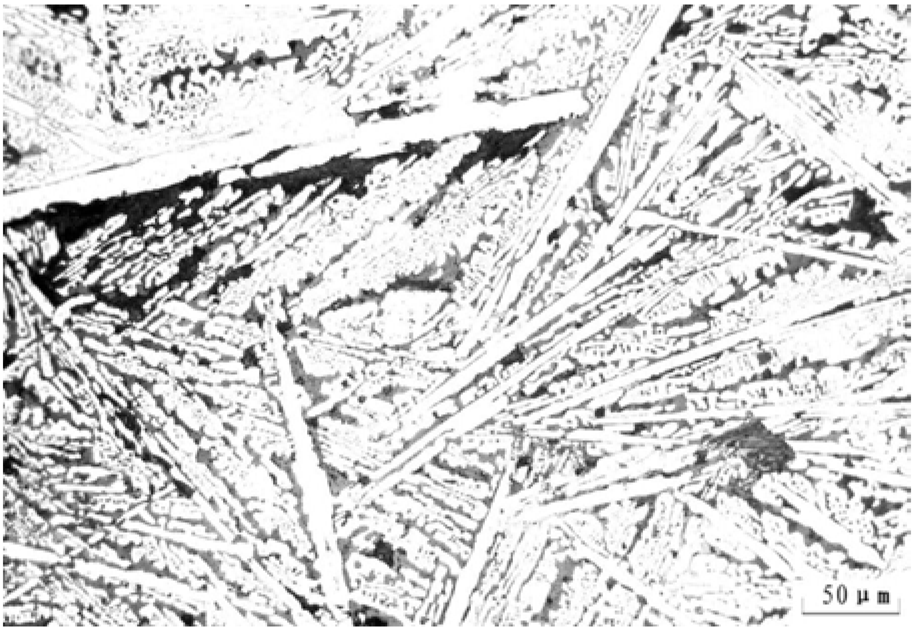


**Figure 8** Microstructure of ironware stand: cementite and ledeburite

2) There are over 230 ferrous artifacts from these graves, including an iron cuirass, a sword, 14 knives, a spear, 130 arrowheads, 8 whistling arrows, a mirror, an iron horse harness and many pieces of a corroded iron armour. We selected 16 iron objects for metallography. The number is limited, but the results can reflect the iron and steel manufacture technique of this period.

   The metallographic samples have shown that a flag stand is made of cast iron, (Fig.8), while 5 tools had been made by a simple economic process of decarburization of steel. Iron was cast into thin strips or plates, and then decarburized in solid state into steel, which was then used as raw material for forging. Ancient Chinese craftsmen invented the technique of casting liquid iron to produce farm tools and created the annealing process to improve the brittleness of cast iron. The cast iron could then be widely used in the development of the society.

   The analysis of the excavated ironware shows that on iron objects diagnostic casting mould lines can be recognized. The metallographic studies indicate that the iron artifacts have a homogeneous microstructure with few inclusions. The carbon concentration on the surface of the iron pieces is low and there is no graphite or very little graphite precipitation, except for a very little remain of a cast iron structure. We found that the overall structure of the 5 iron tools is that of steel and 5117 arrow head (Fig. 9, 10 and 11). One chisel (5074) has as sandwiched structure with a piece of steel in the center and two pieces of wrought iron outside. The inclusions in the two regions are different, and the chisel is a good quality tool.

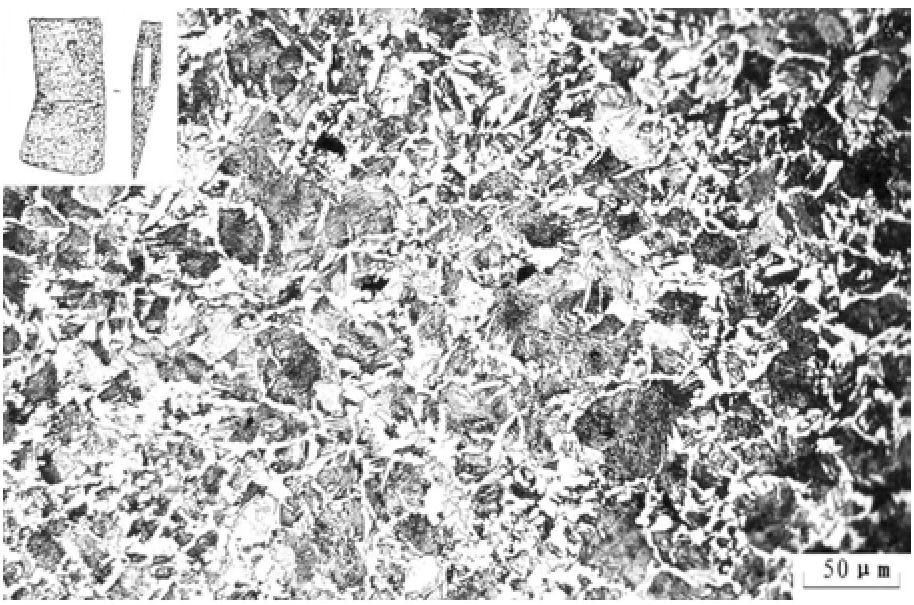


**Figure 9** 5073 axe. The microstructure shows that it is pearlite and ferrite with more than 0.6% C


**Figure 10** 5067 saw fragment. The microstructure shows ferrite and pearlite with around 0.4% C

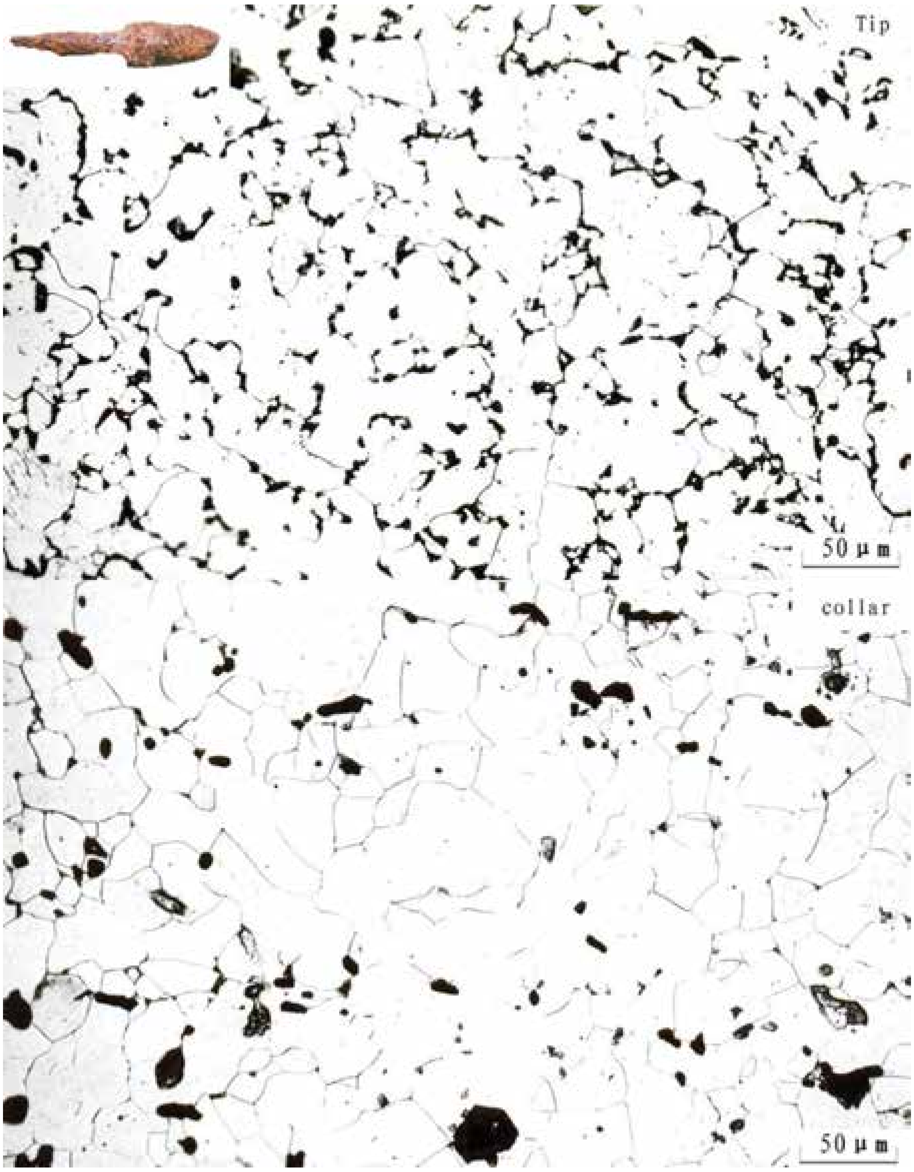


**Figure 11** 5117 arrowhead. The microstructure shows that it is decarburized steel


**Figure 12** L13-2 saw fragment. The microstructure shows puddling steel with elongated single phase inclusions along the working direction, with a carbon content of 0.2%-0.6%

10 iron artifacts showed different carbon contents, produced by puddling, and followed by forging and folding until the desired result was achieved. In the steel matrix there is a large number of inclusions, elongated in the direction of working, as shown in fig.12.

A more advanced steel making process, which first appeared in the 2nd century BC and was very popular by the 2nd century AD, was puddling. In the puddling process pig iron was first heated in air, by using the combustion heat of carbon to raise the temperature. This brought the iron to a pasty state and when the mixture was stirred in air, the carbon in the liquid iron was oxidized. As the temperature increased, the carbon content of austenite gradually fell. Oxidation of silicon and manganese in pig iron formed silica inclusions and iron oxide. If the stirring continued in the semisolid state, the result was low carbon wrought iron, but it was also possible to stop before decarburization was complete, to obtain medium or high carbon steel. The steels obtained by puddling pig iron were stacked and forged, probably with repeated hammering.

In 10 artifacts excavated from these graves numerous very thin silicate string inclusions were found. They were produced from pig iron that had undergone fusion. The chemical composition of these inclusions includes aluminum, silicon, phosphorus, potassium and manganese and the elements are uniformly distributed, as demonstrated by the SEM-XEDA examinations. The iron mirror was made by the puddling process and represents a new forging variety of steel among the unearthed objects (Fig. 13). On the other hand, the microstructure of 5120.2 sword shows that it is partially martensitic quenched steel (fig.14).

The making of steel by puddling was one of the most important inventions in human history, and this cannot be overemphasized. Commenting on the application of the puddling process, James E. Gordon, a historian, remarked: "The cheapening and improvement of iron and steel during the 18th -19th centuries was the most important events of its kind in history" (T. Ko 2002). The 18th and 19th century events he refers to are puddling (1783), the Kelly-Bessemer (1856) and the open hearth (1860) steel making processes. (Ko 2002 and Tylecote 1992)

3) Two excavated gilded belt buckles have been examined by SEM-EDX to look for the presence of mercury in the gold-silver alloy. The thickness of the gilt layer is of about 20 μm, but the matrix is copper with less than 2% of lead. (Fig. 16) The microstructure shows that the buckles were produced by heating and annealing. They have a crystallized structure with twinned grains and small particles of lead. 3 silver pieces i.e. 5116, L9-1, and L9-2 were made of a Ag-Cu alloy and the Cu contents varied between 1.2%, 2.9%, and 6.4%, respectively. The L13-3 gold foil on the artifacts surface was an Au-Ag alloy.

4) The 5114 glass bead was made of glass with Si-Na-K-Ca system. Other similar glass pieces have been excavated from this grave.

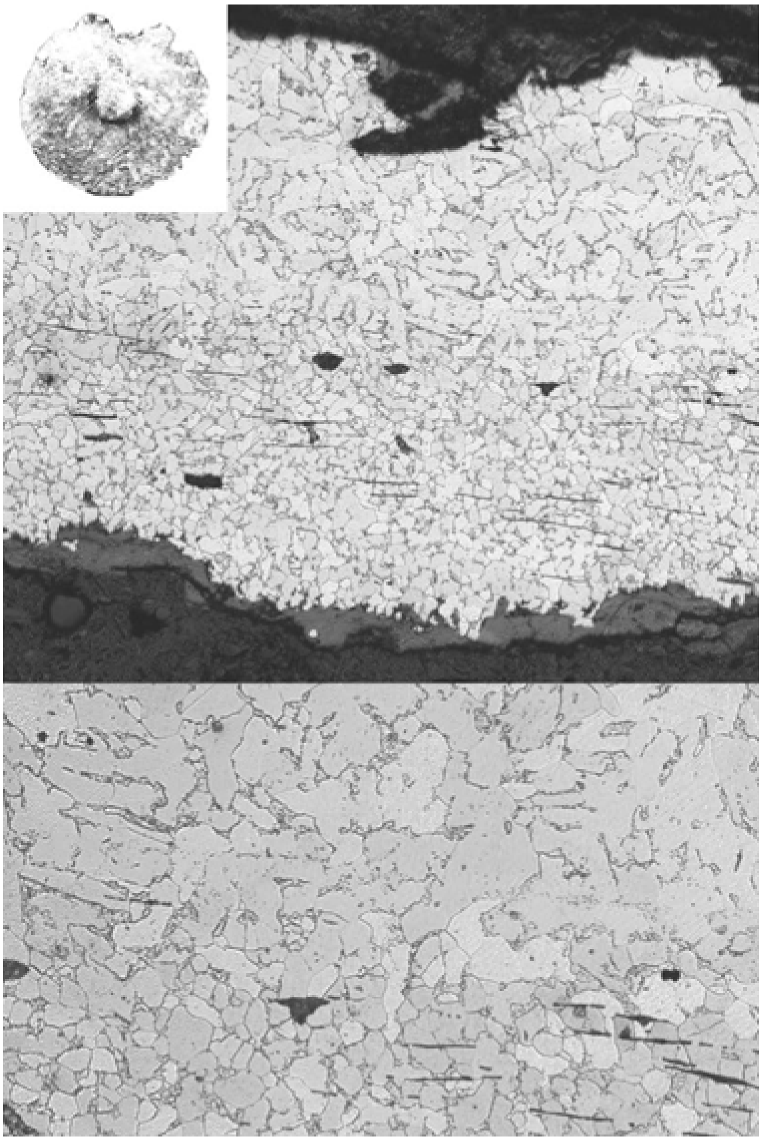

**Figure 13** 5072 iron mirror with inlaid gold inscriptions. The microstructure shows that it is puddling steel with 0.15% C

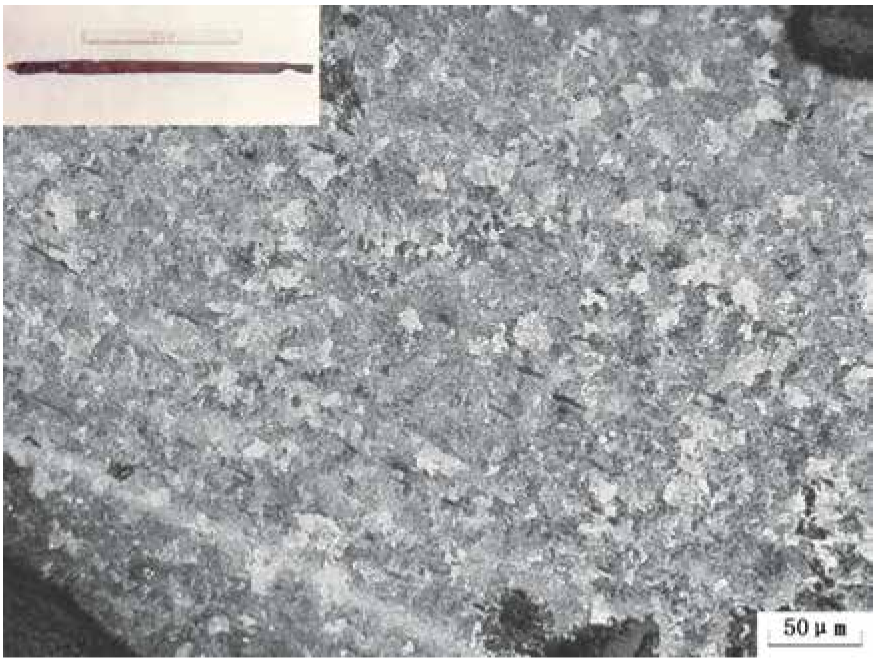


**Figure 14** 5120.2 sword. The microstructure shows a quenched martensite structure

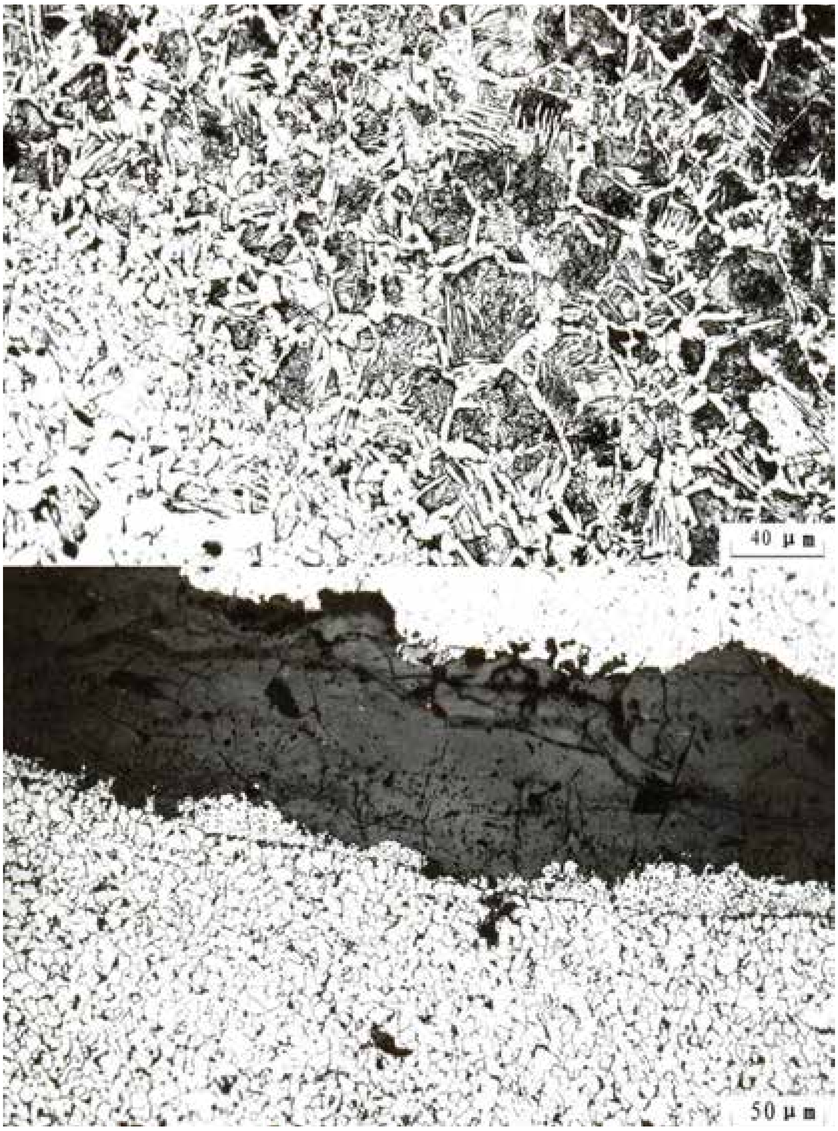


**Figure 15** L2 knife's microstructure shows that there are two different materials forge welded together. Between them a clear boundary line with different carbon content and cracks is visible

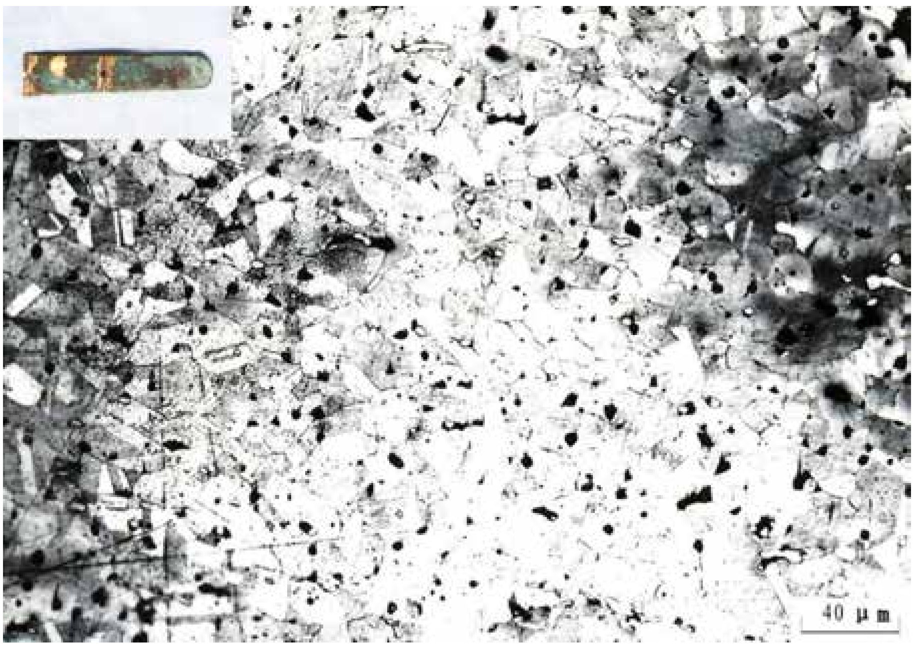


**Figure 16** 5118 gilded buckle. The microstructure shows a recrystallized structure with twinned grains and small particles of lead (2 %)

## Discussion

The contemporary iron making and steel technique employed for the manufacture of the metal objects found in the unearthed tombs of Lamadong, Beipiao city, Liangning province, were used as comparison. The tombs of the Xianbei tribes in the Lamadong village, Beipiao city, Liaoning province have been excavated during five campaigns between 1992 and 1998. (Liaoning 2004). Because of the importance of the Xianbei tribes in the history of China, the archaeological project was awarded a price as one of top ten archaeological finds in 1996. The Lamadong graves are situated about 1.5 km north of Beipiao city and 1.2 km south east on the Daling River, and cover a total area of 6600 square meters. Over 350 tombs of Xianbei tribes have been found and excavated (Liaoning 2004). 39 samples from 24 tombs, taken from six kinds of typical artifacts have been selected and examined by metallographic analysis (Chen Jianli 2007).

A summary of the main results of both analyses is as follows.

1) Great attention must be paid to the ferrous artifact buried in each tomb. Most of them were habitually used in every day life. One of the important features is that in the burials ferrous weapons have been found. These include long or short sword, spear, arrowhead, and ring handle knives or farming implements, i.e. ploughshare, moldboard, sickle, U-shaped shovel and tools, and there are also some cases of iron cuirasses and many armours. This demonstrates that the owner of the grave was both a commoner and a noble man that combined farming with warfare. (Chen Jianli 2007)
2) The quality of tools, such as that of 4 axes and of 4 chisels is very good. They have been made by the process of steel making from cast iron, by decarburizing in solid state and by puddling. The 7139 chisel unearthed from M368 tomb in Lamadong and the 5074 chisel from the Fengsufu tomb were made by the sandwiching method, and they are functional and suitable for use. This method was simple, economical and easily applicable, the quality was high enough for their purposes, the plates could be easily transported and traded. It is possible that the Xianbei people used these materials to work them themselves, and to manufacture their products. 9 farming implements excavated from the Lanmadong graves have been also examined. They include two ploughshares made of pig iron. A U-shaped implement and the 7130 adze (M70: 6) were found to have the hardness of malleable iron, with some snowflake graphite embedded in a ferrite matrix. As their microstructures clearly show, these artifacts have been annealed (Chen Jianli 2007).
3) The production technique of 4 swords from both graves also demonstrates the good performance of the smiths. They were made by puddling and have different carbon contents and grains size. The 5120.2 sword was quenched. 2 knives unearthed from grave M308(7124) in Lamadong and L12 from the Fengsufu tombs have been also examined. Their microstructures show that they are made of two different materials, forge welded together. Among them there is an obvious boundary line with a different carbon content and cracks (Fig. 15). This demonstrates that the steel making technology was still not established. On the other hand the 7126 arrowhead (M379: 13) unearthed from Lamadong was found to have the hardness of malleable iron. The 5117 arrowhead found in the Fengsufu tomb was made of steel decarburized in solid state (Fig. 11). In general the arrowheads were in good condition. How did they make good quality products? How can we explain it?
4) The iron semi-products have been excavated in both sites. There were two kinds of raw materials: one made by puddling steel and the other by steel decarburized in solid state. Where did they come from? We will have to find the ancient smelting site or the workshops near these sites in the Liaoning province by co-operating again with archaeologists.
5) When the metal is heated to a temperature above the critical point and then rapidly cooled, the procedure is called quenching.
   Chinese ancient books on quenching recorded "water and fire together as quenching". The analysis of excavated iron weapons and tools dated around the 4th century BC demonstrates that they have been quenched. The identification of many unearthed steel objects shows that quenching became popular in the 1st century BC. Jia ying (2004) tested two swords of the Spring and Autumn Period, belonging to the Wu state (about 6th BC), and they showed the quenched microstructure of a copper-tin alloy. Yao Zhihui (2006) tested a bronze sword belonging to the late Warring States (dated around the 3rd century BC), unearthed in Chongqing, and also this one had been quenched. Wang Jinchao et al. (2007) conducted a microstructural identification on eight copper bowls, plates and other utensils. All of them were high tin bronze quenched products belonging to the Southern dynasty hoard, unearthed at Jiangdu Town. Originally the 5110 quintana bowl was supposed to be gilt, but also this piece was a high tin bronze, produced by quenching. A large proportion of quenched CuSn bronze has been rarely identified and some of these cases may be fortuitous, but it is possible that they were made on purpose. A clear account of the historical and traditional processes is

given on a bronze ring,(响铜) in its production the forging process was an important part.

As Chadwick's experiments on 5-30% tin bronze forging showed (1939), in a copper-tin binary alloy there are two different zones in which the bronze is ductile: one with 18% or less of tin in the bronze at a temperature range of 200-300° C, and a second one containing 20-30% of tin in the bronze at a the temperature range of 500-700°C. The first alloy mainly consists of alpha phase, the second is mainly composed of β or γ phases. The studies of Kennon (1972) and of other scholars on binary alloy bronze showed that with a tin content of 21.82% and 23.88%, respectively, needles of β martensite developed when the bronze was heated to 675°C and 780°C, and then quenched in cold water at 20°C. The quenching of a bronze alloy improves the hot workability of a high tin bronze alloy that can be then forged into the desired objects. This technique results from the empirical knowledge of the ancient craftsmen. The bowl 5110 from the Fengsufu tomb, contains 24.4% of tin. The thickness of the wall is 0.1 cm and the vessel was forged after quenching.

## Conclusions

27 metallic samples from objects excavated from the Fengsufu tombs show that the quality of 5 bronzes was good and that one example of high tin bronze was made by quenching and forging. 16 iron and steel pieces were made of pig iron, decarburized steel in solid state, puddling steel, sandwiched steel, quenched steel and an iron mirror by forging. Mercury gilt bronze belts, silver-copper and gold-silver alloys, and imported glassware from the West have been identified. A pair of horse stirrups with a wooden core covered by gilt copper have been also found for the first time on excavation. These results confirm that the making and using of metal is characteristic for this culture and technology, and provide new information for the study of the development of economy and society in the $4^{th}$-$5^{th}$ century of the Northern Dynasty.

The results indicate that most of the artifacts buried in the tomb were made by relatively high-level skill. It is important to note that the technique employed for the making of farm implements and weapons created a very significant condition for a rapid development and expansion of the economic and military superiority of the Xianbei people.

The Xianbei tribes played an important role in spreading the advanced iron technology from central China to neighboring people through wars, migration, presents and robbery and then disseminated them to the southeast. The multidisciplinary study of the smelting technology of the $5^{th}$ century furnishes more new evidence and information. Cooperation in archaeometallurgical research is essential for good results in the research. The impact of the historical development of ferrous technology on society must be further studied.

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# Section IV – Tin and Zinc

18th Century bidri flask with silver and brass inlays, from the Bidar region (BN1878.1230.758) height 30 cm (copyright Trustees of the British Museum)

*Susan La Niece*

# Resource areas of tin for ancient cultures of India (prior to 6th century BCE)

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*ABSTRACT* Scarcity of tin in ancient cultures was a worldwide phenomenon. This led to the hypothesis that in antiquity, especially during the Bronze Age, tin was traded to India. However, explorations conducted in different parts of India, right from the British period, identified several areas with occurrences of a variety of tin ores. Interestingly, many of these deposits are located in close proximity of ancient sites belonging to different cultural horizons. In the light of this, there is now a need to re-examine the occurrence and utilization of tin in India in antiquity. There appears to be a possibility of utilization of some of these occurrences because of their geographical proximity, evidence of ancient mining and prevalence of pre-industrial exploitation, including panning, in many of these areas. The present paper proposes to draw the attention of scholars towards this fact.

## Introduction

India has been considered a country with scarce tin deposits, but analytical examinations of a large number of ancient copper artifacts from different cultures revealed that tin alloying was prevalent in ancient India right from the Chalcolithic period. Talking of tin utilization and its resources in ancient India, we are faced with questions like: which were the sources of tin for the early cultures? Was tin imported through long distance trade or could be procured locally? Earlier, it was thought that tin was imported from Northwestern Iran, Afghanistan, Central Asia, and South-East Asia (Marshal 1931, 434; 1951, 566; Crawford 1974; Ratnagar 1981, 94; Rajpitak and Seeley 1982, 26-31). Marshal (1951, 566) and Warmington (1974, 274) suggested import of tin from the Mediterranean through trade on the basis of a reference in '*The Periplus of the Erythrean Sea*' that mentioned the export of copper, lead and tin to Barygaza, Muziris and Nelcynda from Egypt in the early centuries AD (Schoff 1912, 77-79). Chakrabarti (1979, 61-74) reviewed the problem of tin and pointed out the Indian tin deposits as an important source for Indian bronzes. Cleuziou and Berthoud (1982, 114-119) re-assessed the evidence regarding the early tin and concluded that western Afghanistan might have been the source of tin for the bronzes of the Harappan civilization. Some scholars attributed the occurrence of tin in the Gangetic plains to South-East Asia (Shrimali 1976; Rajpitak and Seeley 1982, 26-31). It was postulated that tin was a product of the contemporary South-East Asiatic trade through lower Bengal. However, we propose to draw attention of scholars to recent discoveries of tin deposits in India (Fig. 1). In several such areas there also exists a long tradition of retrieving tin from placer deposits. Possibly some of these tin deposits were exploited in antiquity. The accounts of the Geological Survey of India have reported tin from many localities in Andhra Pradesh, Arunachal Pradesh, Bihar, Chhattisgarh, Gujarat, Haryana, Jammu and Kashmir, Jharkhand, Karnataka, Maharashtra, Odisha, Rajasthan, Sikkim, Tamil Nadu, Uttarakhand, Uttar Pradesh and West Bengal (Krishnaswamy 1988; Babu 1994, 35-67; Upadhyay 2003, 125-137; 2007, 135-149). There is a need to take a fresh look at these tin deposits, with a view to explore the possibility of their utilization by the ancient cultures in the vicinity. The present paper proposes first to take a close look at the geological evidence of tin and then at the archaeological evidence in the nearby areas. This may reveal whether there existed a possibility of their utilization by the ancient cultures. It may not be possible to suggest a definite exploitation of these deposits in antiquity at the present state of our knowledge but some of these occurrences may prove to be significant if dating of old workings for tin and further in-depth researches are conducted in future.

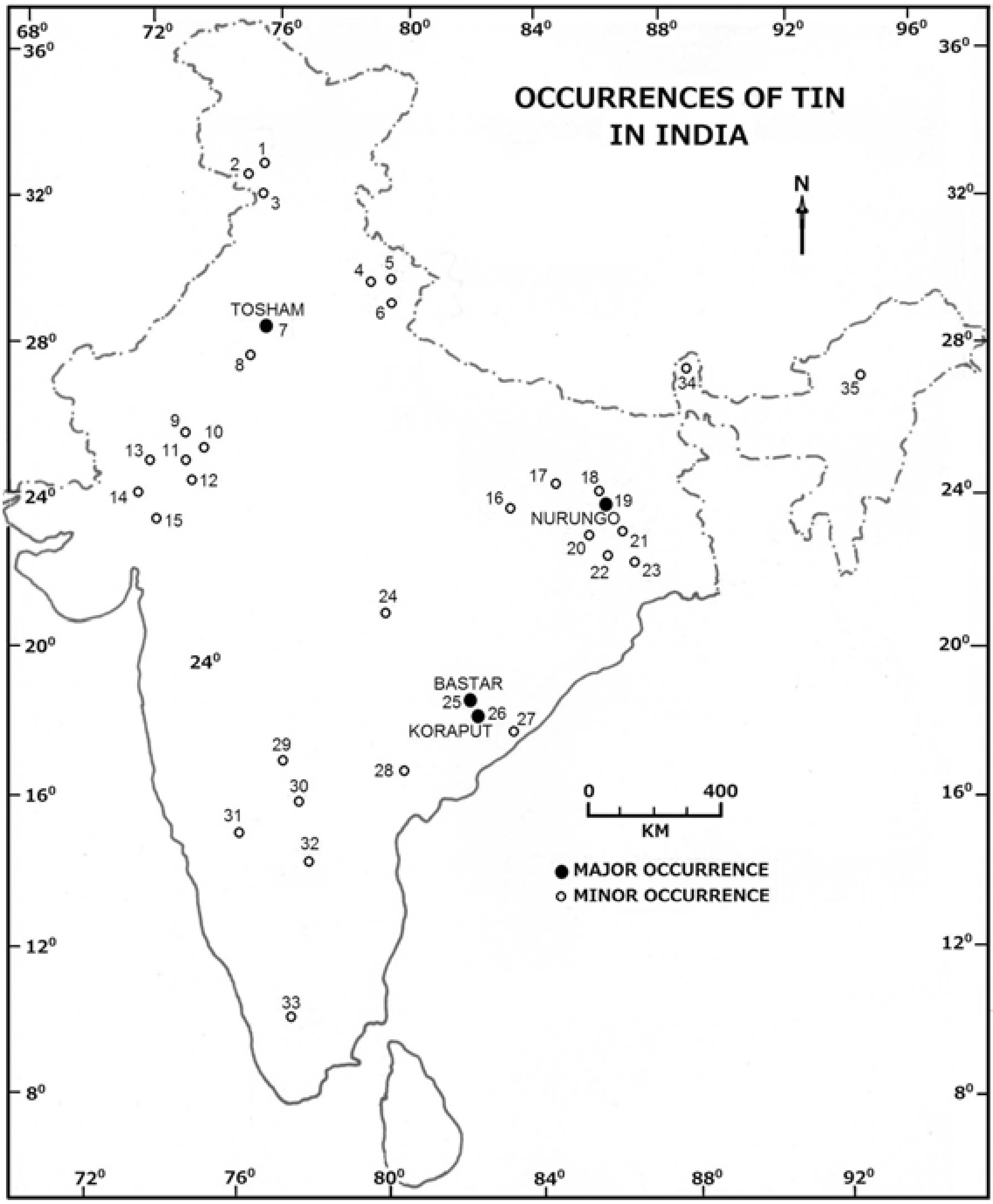


**Figure 1** Map showing location of tin deposits in India (Upadhyay 2007)

## The Bronzes in the Harappan Zone and Probable Resources

In the Harappa civilization, tin bronzes were more common than other alloys (Agrawal 2007, 188). Harappan bronze objects include tools, weapons, utensils, statuettes and jewellery. This civilization showing sudden advancement in the field of copper alloying yielded the largest range in the content of tin - ranging from 1 per cent to 26 per cent (Chakrabarti and Lahiri 1996, 45-62). An artefact from Mohenjodaro (DK 9567) analysed by C.H. Desch and E.S. Carey, University of Sheffield, showed 26.9 % of tin (Mackey 1938, 481).

Regarding the major source of Harappan copper, Sanaullah pointed out that the copper mines of Rajasthan are the nearest source of copper for the Harappans. He says, “The Rajputana mines are not only the nearest of all to Harappa and Mohenjodaro, but also fulfill the test for the key elements, i.e. nickel and arsenic. It is very likely, therefore, that these mines supplied the bulk of the metal for the Indus valley” (Sanaullah in Vats 1940, 379). Regarding the source of tin he thinks that Iranian sources, such as that of the Khorasan and Kara Dagh districts, were the main source of tin for the Harappan bronzes (Sanaullah, in Vats 1940, 378-382).

The Harappans had established contacts with Afghanistan (an outpost of Harappan civilization), Iran and Central Asia (between Bukhara and Samarkand), i.e with regions that possess tin deposits. The newly found evidences worth mentioning here are several tin bearing localities of Rajasthan, Gujarat and Haryana fall well within the Harappan zone (Table 1). It is just possible that some of these deposits were tapped by the Harappans or their Chalcolithic neighbourhood. Many of these localities also have copper deposits with evidence of ancient mining (Fig. 2).

The above table demonstrates tin mineralization in the Ajmer, Alwar, Bhilwara, Jalore, Jhunjhunu, Nagaur, Palli and Udaipur districts. It is important to note that many of the tin bearing localities fall within copper bearing areas. In the Jhunjhunu district, high abundance of tin (0.174 to 0.372%) in granites and granite porphyry is reported from Jhunjhunu, Nand Pahari, Nehra Pahari, Mahakhar, Rijani hill and surrounding areas (28°00’-28°15’: 75°15’-75°40’) (Kochhar *et al*. 1991, 99; Babu 1994, 58). Ancient copper mines such as the Khetri Copper mine (Madhan-Kudhan Deposit) (28°03’35”-28°04’45”:75°47’40”-75°46’45”) and the Kolihan Mine Block (27°59’-28°02’:75°46’-75°47’) in the Jhunjhunu district are located close to tin deposits. Indication of tin mineralization is found in the Kolihan copper mine area (Raghunandan *et al*. 1981, 72-73).

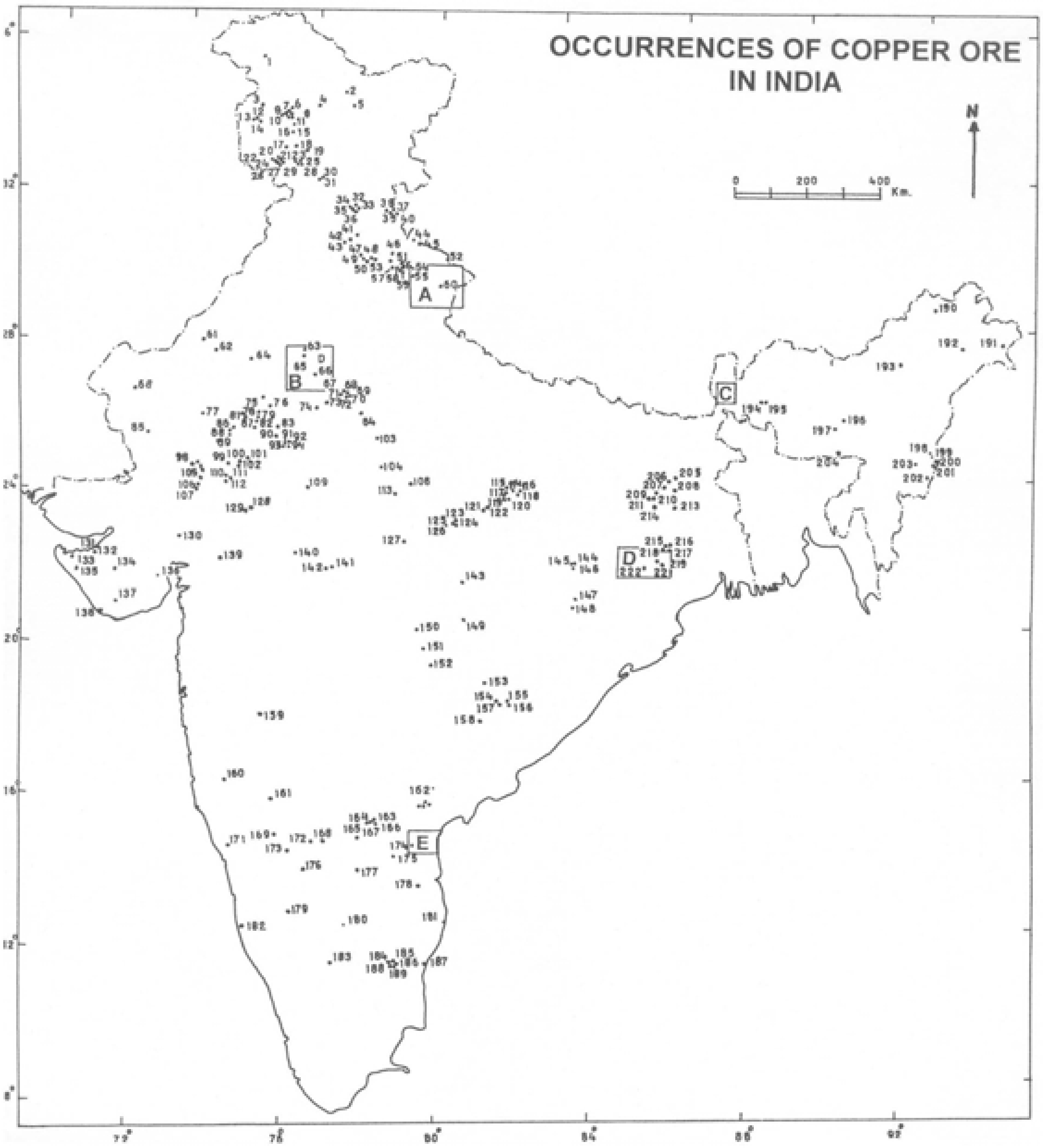


**Figure 2** Map showing location of copper deposits in India (Upadhyay 2007)

**Table 1** Occurrences of Tin in Rajasthan, Gujarat, Haryana and Jammu and Kashmir (in and around Harappan Zone, India)

| District/ State | Locality |
|---|---|
| Jhunjhunu, Rajasthan | Jhunjhunu area, Nand Pahari, Nehara Pahar, Mahakhar, Rijani hill and surrounding areas (28°00'-28°15': 75°15'-75°40") |
| Ajmer and Pali districts, Rajasthan | Pipaliya-Govindgarh, Karnos-Somel-Babra, Chitar-Sendra- Ramgarh |
| Alwar, Rajasthan | Bandraul |
| Bhilwara-Udaipur, Rajasthan | Soniana (25°09':74°28'), Paroli, Potlan – Devaria (25°12':74°02'), Nathdwara (24°56':73°52'), Rajko - Sujanpur |
| Jalore, Rajasthan | Kotra Khambi and Korana areas |
| Nagaur, Rajasthan | Degana |
| Bhiwani, Haryana | Tosham (28°51':75°56'), Khanak and Rewasa. |
| Palanpur (Banaskantha), Gujarat | Hosainpura (24°16':72°36') |
| Himatnagar (Sabarkantha), Gujarat | Nadari (24°00':73°00') |
| Doda, Kathua and Udhampur district, Jammu and Kashmir | Dudu, Gandhtop, Binkindra peak, Khobbi, Jamotha and Kaplas Granite (1000 – 2500 ppm tin) |

In the Bhilwara and Udaipur districts, tin mineralization is reported from different localities. Large crystals of cassiterite are found in the Soniana (25°09': 74°28') mica mine in the Bhilawara district. Pegmatite of Paroli and quartz veins of Rajko-Sujanpurcontain tin –tungsten mineralization. The main area of tin mineralization is bounded by 25°05' to 25°55' N and 74°20' to 75°45'E. Pegmatites of Devra-Paroli-Baguder contain tin. Even the stream sediment sampling carried out along the Banas river tributaries indicated tin values up to 1200 ppm in the Paroli area (Babu 1994, 59-60). Large number of old workings of copper ore with abundant slag heaps are reported in the tin bearing area of Bhiwara district. Tin has also been reported in the Potlan-Devaria (25°12': 74°02') and Nathdwara (24°56': 73°52') areas of the Udaipur district (Babu 1994, 59). In this area there are evidences of old mining activity in the copper-lead-zinc deposit of Dariba (24°57':74°08') - Rajpura (24°58':74°08') - Bethumni (25°04':74°11'). In the Jalore district, tin mineralization in quartz veins is reported about 20 km SW of Bhadrajan (25°36': 72°54'). The mineralized area lies between lat. 24°45' to 25°47' N and long. 71°45' to 73°00'. The quartz cassiterite veins are more pronounced at Kotra, Khambi and Korana areas. Tin content in these veins ranges from 1000 to 3000 ppm (Babu 1994, 60). The Chalcolithic culture of Ahar / Banas flourished in this eco-zone mainly along the Banas river. Finding of six Harappan beads at Ahar anciently known as Tambavati (a city of copper) suggest a contact with the Harappan sites.

In the Palanpur (Banaskantha) district, tin mineralization as cassiterite is encountered near Hosainpura (24°16': 72°36'). Here large crystals of cassiterite associated with gadolinite are found in tourmaline – bearing pegmatites (Holland 1904, 43; Clegg 1944, La Touche 1918, 477; Babu 1994, 63-64). Extensive ancient working for copper-ore with large slag heaps are found in the Ambamata or Ambaj area (24°19'-24°24':72°48'-72°51'). The granite massif near Nadri in Himatnagar (Sabarkantha) district yielded significant values of tin. Cassiterite crystal aggregate has been found in quartz veins south of Nadri (Babu 1994, 64). Copper is reported from several localities in the Sabarkantha district.

In Haryana, tin is reported in Tosham (28°52':75°55'), Khanak and Rewasa areas in Bhiwani district. The tin of the Tosham area has been located over a length of about 1300 m. Primary mineralized tin ore of Tosham has been estimated to be 23,440.000 tons. According to the Indian Minerals Year Book, 1993, in the Tosham area about 19.88 million tons of 0.17% Sn grade and 3.67 million tons of 0.19% Sn grade of ore have been established (Kochhar *et al*. 1991, 99, 102 and 104; Babu 1994, 45, 59). Tosham area is also known for copper and traces of old working is also found in the Khanak area. Copper deposits with large number of old workings, slag heaps and ancient smelting crucibles/ *cupellae* were found at various localities such as Khodana (28°26':76°06) Narnaul (28°03':76°06'), Balana (28°17':76°04'), Dadhor (28°16':76°03') etc. very close to the Tosham tin bearing area (Raghunandan *et al*. 1981, 188-189; (*Rec. Geol. Sur. Ind.*, 115(1), 142). Tin alloying is not common in Copper Hoard objects. It is important to note that a Copper Hoard axe (Sn 0.55%) from Hansi (29°06':76°00') located very close to Tosham tin deposit, and two axes (Sn 2.68% and 0.1%) from Rewari hoard (28°12':76°40') not far from Tosham showed considerable amount of tin contents.

In view of the close proximity of Harappan sites rich in copper - bronze objects and copper and tin deposits, it may be construed that some of these tin deposits located near ancient copper mines might have been easily exploited by the Harappans. Significantly enough the Ganeshwar (27°40':75°50')- Jodhpura (27°31':76°05') complex sites of Rajashan which yielded thousands of copper objects are close to copper deposits of the Jhunjhunu, Sikar and Jaipur districts and not far from the Tosham tin deposit. Indication of accidental tin alloying has been noted in two copper objects from Ganeshwar belonging to 4th-3rd millennium BCE (Chakrabarti and

Lahiri 1996, 35). This site is located in the vicinity of ancient copper mines and also close to tin bearing localities of the Jhunjhunu district. In view of this, the possibility of use of local resources by the Harappans cannot be altogether ignored.

## Tin in Chalcolithic Cultures of Deccan and Central India

Bronze objects are reported from the Chalcolithic sites of Daimabad, Jorwe, Nevasa, Navdatoli and the Megalithic site of Khapa. The rhinoceros figure of the Daimabad hoard contains 6.51% tin (Yule 1985, 100). The content of tin in the objects of the Chalcolithic cultures varies from 1.78 – 4.37 per cent. It is noteworthy that Megalithic sites like Mahurjhari, Bhagimohri, Khairwada, Raipur and Borgaon of Vidarbha region have yielded a few specimen of high tin bronzes (Srinivasan 2010, 239; Park and Shinde 2013, 3814).

**Table 2** Occurrences of Tin around Deccan and Central India

| |
|---|
| **Maharashtra (District Bhandara)**: Goberwahi area (21°31’30”:79°43’45”) |
| **Chhattisgarh (District Bastar - Dantewara):** “Bastar Tin Province” (18°30’-19°00’: 81°15’-82°15’) - (Tongpal-Mundval Sector, Katekalyan sector, Bacheli - Degalras sector). |
| **Odisha (District Koraput - Malkangiri):** Mundagudda - Maithili area (18°35’-18°40’:81°54’-82°11’) Mundagudda, Mittiguda, Kurumapalli, Dammaguda Mohopodar, Bajaripodar, Vedurpalli, Salimi, Kamarpalli, Sirkuppa, Mongerguda Tentuligumma (18°45’:82°08’) etc. |

The Harappan legacy of tin was hardly perceptible in the objects from Jorwe, Nevasa and Navdatoli. The tin deposits of Mukargavi, Kanhalli-Manglur, Malgatti and Halampur in the Gulbarga district (Table 3) are close to Jorwe (19°33’:74°17’) and Nevasa (19°34’:74°54’) and are well connected through the river. Tourmaline bearing pegmatite at Manglur assayed 1000 ppm of tin content. Excavations at Navdatoli yielded lapis lazuli beads from all four periods. The tin bearing area of Goberwahi (21°31’30”:79°43’45”) in the Bhandara district is the nearest known source of tin (Table 2). Significantly, lapis lazuli also occurs near Bhamasur hill in Bhandara district. The tin deposit of the Bhandara district might have been exploited by the Megalithic community of the Vidarbha region. The Megalithic sites of Mahurjhari (21°14’:79°30’), Borgaon and Khapa (20°55’:78°57”) etc. are not far from the Goberwahi tin deposit. The tin deposits of Bastar - Dantewara and Koraput – Malkangiri could also serve as resource zone for tin for the ancient settlements of Deccan and southern India. The tin province is spread over an area of more than 1000 sq. km. It is bounded by lat. 18°30’ to 19°00’ and long. 81°15’to 82°15’. The tin ore of Bastar-Dantewara has been estimated 28,894,653 tons (Babu 1994, 181). Panning of cassiterite by tribals had been prevalent in Bastar – Dantewara district till recently (Fig. 3). The tin mineralization of Koraput – Malkangiri is mostly confined to an area lying within lat. 18°35’ to 18°40’ and long. 81°54’to 82°11’ in the Mundaguda – Maithili- Salini area. The total area of mineralization is spread about 170 sq. km (*Indian Minerals* 1982, 36(4), 8). From this area 12,692 tons of tin ore and 34.6 tons of tin metal of proved category reserves have been estimated till 1990 (*Indian Minerals* : Year Book 1993).

**Figure 3** Panning for cassiterite in Bastar, Chattishgarh, India (Courtesy Paul Craddock, British Museum, London)

### Tin in Neolithic-Chalcolithic and Early Iron Age Cultures of Southern India

Sharada Srinivasan investigated the tradition of high tin bronze working in southern India. “The earliest report on bronzes with a high percentage of tin in south India comes from the study of Breeks (1873, 94) on the bowls uncovered from the cairn burials of the Nilgiris in Tamil Nadu. A few bronze bowls were found to contain about 23% and others 30% tin. Tin bronze vessels of 22-30% tin have been found in the Iron Age megalithic burials of Tamil Nadu belonging to first millennium BC from Adichanallur, Maula Ali, Coimbatore, and also the Nilgiris (Leshnik 1974). As early as 1940’s Paramasivan (1941, 418) conducted a metallurgical investigation on a bowl from Adichanallur, Tirunelveli district. This was found to contain 23% tin, with the microstructure substantially different from ordinary low tin bronze” (Srinivasan 1998, 241). At Brahmagiri (14°48’:76°48’), district Chitradurga, Karnataka, a bronze rod/pin (Neolithic-Chalcolithic) yielded 9% tin (Chakrabarti and Lahiri 1996, 76). One wonders about the probable source of tin for these sites. The table below (Table 3) shows tin deposits in southern India.

**Table 3** Occurrences of Tin in Southern India

| District/ State | Locality |
|---|---|
| Anantapur, Andhra Pradesh | Nayaniveripalli, Korrepadu and Bandaripalli |
| Khammam, Andhra Pradesh | Nandipadu, Chunnambatti, Lankalapalli, Narayanapuram and Chittapareddipalem |
| Visakhapatnam, Andhra Pradesh | Aduamunda Area, Aruku and Gairiveeddi |
| Dharwar, Karnataka | Dambal area (15°13’:75°45’), Nabhapur and Attikatti, |
| Gulbarga, Karnataka | Mukargavi, Kanhalli-Manglur, Malgatti and Halampur |
| Raichur, Karnataka | Gabbur-Sirwar area (16°00’-16°30’:77°00’-77°30’) |
| Chitradurga, Karnataka | Challi, |
| Salem, Tamil Nadu | Tiruchengodu |
| Tiruchi, Tamil Nadu | Kadavur (19°36’:78°15’) and Ururakarad area |

Tin deposits of the Dharwar and Raichur districts of Karnataka and Anantapur districts, in Andhra Pradesh (Tab. 3) are the nearest known resource areas for the site of Brahmagiri. At Sirwar in Raichur, a pegmatite traversing biotite granite assayed 1000 ppm of tin content (Babu 1004, 64). In the Dharwar district, minute grains of cassiterite associated with native copper and silver were detected by Foote (1874, 140) in the streams draining the northern portion of the Kapatgod range near Dambal (15°13’:75°45’) (Ball 1881, 315; La Touche 1918, 77; Babu 1994, 64). Sharada Srinivasan has reported the finding of slags containing 5 % of tin from the slag heaps near the old copper working at Kalyadi (13°14’:76°09’), district Hasan, Karnataka (Srinivasan 1997, 136). “.... 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, which points to exploitation of indigenous sources of tin. Malroney (1975, 36) 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” (Srinivasan 2013, 737). It is possible that some locally available tin deposits may have been smelted in this copper mining area to produce bronze objects. In Dharwar, a number of small pits and shafts representing ancient workings are present at many localities between Nabhapur and Attikatti, NW of Venkatapur and SE of Hosur (Babu 1994, 64). Tin is also reported at a place 25 km east of Gadag. In the Ananatapur district, Andhra Pradesh, cassiterite grains have been found in the panned concentrates of streams collected about 2 km west of Nayanivaripalli and 1.25 km east of Korrepadu (Babu 1994, 65-66).

Regarding the bronze object of Adichanallur (08°50’:76°40’) situated in the district of Tirunelveli, Tamil Nadu, the tin deposits of Kadavur (10°36’:78°15’) and Ururakarad area in the district of Tiruchchirappalli, Tamil Nadu, may also be considered the nearest resource area of tin. E.L.G. Clegg had reported that a sample containing wolframite found near Kadavvur analysed 3.15% tin (Clegg 1944 quoted in Rajarajan 1976, 19).

**Table 4** Occurrences of Tin around Ganga Plains

| District/ State | Locality |
|---|---|
| Almora, Uttarakhand | Jalali, Dhamera, Ghugati, Chaura and Pali-Ira area |
| Chamoli and Pauri, Uttarakhand | Dudhatoli hill, Kotibagar |
| Sonbhadra, Uttar Pradesh | Mahwaria (24°14’:83°18’) Nerueadamar (24°18’:83°22’) Harnakachar (24°15’:83°23’) Bagarwa (24°18’:83°17’) and Baghisoti (24°21’:83°26’) areas |
| Gaya, Bihar | Chakrabanda (24°30’:84°28’), Dhakanawha (24°32’:84°27’), Dhanras (24°33’:84°27’) and Kanchanpur (24°23’:85°41’30”) |
| Giridih-Hazaribagh, Jharkhand | Nurungo area (24°09’30”-24°11’: 86°04’-86°06’), Semritari (24°39’:85°50’), Pihira (24°38’:85°52’), Chappatand (24°42’:85°53’30”), Purgo (24°10’:86°08’) and Nimatanri area (24°33’-24°45’: 85°49’-86°00’). |
| Ranchi, Jharkhand | Paharsingh (23°22’:85°42’), Johana Sili and Tatti |
| Singhbhum, Jharkhand | Kalikapur |
| Bankura, West Bengal | Chhendapathar (22°15’: 86°45’) and Kuilkapal areas |
| Purulia, West Bengal | Belamu (23°28’:86°03’), Amra-Telmatia (23°32’30”:86°40’30”), Ramachandrapur (23°35’:86°49’), Hansapathar (23°38’:86°39’45”), Parga, Damrughutu areas, Jabarban hills near Maramu, Taherbera and Hanksara villages (23°10’-23°30’: 85°00’-85°05’) |
| North Sikkim | Singhik (27°31’03”:88°33’13”) - Chungthang (27°36’20”:88°39’) area and Chungthank-Lachen (27°42’:88°32’) - Lacheng (27°41’:88°45’) areas |
| West Sikkim | Chitre |

## Tin in the Cultures of the Ganga Plains

There are sufficient examples to say that tin was frequently used in Chalcolithic and pre-NBPW phase in the Gangetic plains. Analyses of copper objects from Atranjikhera in the upper Ganga plain, from Narhan, Senuwar, Sonpur and Taradih in the middle Ganga plain, from Pandu Rajar Dhibi, Dihar, Bahiri and Mangalkot in the lower Ganga plain, showed 0.8 -22.2% of tin (Chattopadhyay 2004; Upadhyay 2006, 87-108).

In absence of evidence of international trade during the Chalcolithic and pre-NBPW cultural phases of Gangetic plains, one may have to pay attention to the mineral deposits located around the region which were used by people for variety of minerals through the ages.

In the hilly tracts around the middle and lower Ganga plain occurrences of tin are reported from various localities (Table 4), like the Gaya, Hazaribagh-Giridih, Ranchi, Singhbhum, Purulia and Bankura districts. These districts are also known for their copper deposits and ancient mining. The Nurungo tin bearing area is spread over about 55 sq km around Nurungo village of Giridih district. Old workings for tin (still undated) are reported from this area (McClelland 1850, Mallet 1874, Clegg 1944, Datta *et al*. 1969). Taradih (24°42': 85°00'), an important Neolithic - Chalcolithic settlement of the Gaya district, yielded a fishhook containing 22.2% of tin (Chattopadhyay 2004, 74). This site is situated close to tin deposits of this district.

Tin mineralization in an area of c. 4 km x 0.3 km is found near Chakrabanda (24°30':84°28') in Gaya district. The old workings though not dated for tin-ore are located in this very area (Murthy 1967, 31). A Copper Hoard bar-celt (Sn) from Chhotanagpur region yielded 0.9% of tin (Chakrabarti and Lahiri 1996, 89). In the lower Gangetic plains several objects from Pandu Rajar Dhibi (23°35':87°39'), Bahiri and Mangalkot(23°33':87°55') showed over 10% tin content in the Chalcolithic phase (Chattopadhyay 2004). These sites are close to the tin deposits of Purulia and Bankura districts of West Bengal (Table 4). In Purulia district, the main area of tin mineralization is bound by lat. 23°10' to 23°30' and long. 85°00' to 86°05'. In this area, the skarn rock at Belamu, Maramu and Taherbera analysed 0.22%, 0.37% and 0.63% tin content respectively (Baidya 1981, 403-404). Pegmatites of this area assayed 0.04 to 0.12% tin (Kar and Ghosh, 1984). It seems that the ancient Bengal (Vanga) was famous for its tin deposits. It is likely that the exploitation of tin from the Vanga region (West Bengal and adjoining district of Jharkhand such as Giridih, Ranchi and Singhbhum) could have given the name *vanga* to tin. Tin is called *vanga* in several alchemy texts like Rasaratnakara (7th century), Rasahridaya (11th century), Rasarnava (12th century), Rasendrachudamani (12th-13th century), and Rasaratnasamuchchaya (13th-14th century). The Arthashashtra of 4th century BCE and the other medieval texts mentioned above suggest that tin deposits of the Vanga region could have been tapped in ancient time. Copper deposits of district of Purulia, Bankura of West Bengal, Hazaribagh-Giridih district of Jharkhand and Gaya district of Bihar – all very close to the tin deposits of the respective district - have evidence of ancient mining. At Katchanar (24°32':84°24') in Gaya district traces of malachite and azurite associated with tin ore have been observed in an abandoned trench. These facts are significant in the present context.

## Observation and Conclusions

The rich literary sources of India amply demonstrate familiarity with tin (Sanskrit *Trapu*) right from the Vedic period (Pre - 1000 BCE). *Trapu* finds mention in Yajurveda (*trapu ch me yajnen kalptam*, Yajur. 18.13). Atharvaveda mentions *trapu* as an important metal (Atharv. 11.3.7-8). Kautilya's Arthshashtra (4th century BCE) clearly suggests the local production of *trapu* (Arth. 2.12.25; 2.17.15). The Arthshashtra also mentions at length about tin ores, their properties and the proportions in which copper-tin-silver and lead are to be alloyed for minting coins.

Geological evidence shows that tin-ores have not only been found in small pockets in several remote parts of the country, but have been worked. Up to 19th century pre-industrial exploitation of tin has been prevalent at Nurungo in the Giridih district, Jharkhand. Old workings for tin have been found in this locality. Mallet (1874, 23-44) reported the pre-industrial activity. Another early report related to pre-industrial activity in this area is that by J. McClelland who visited the place in 1849. He reported that the aboriginal tribes "Kols" accidentally dug up tin ore, believing it to be iron ore. The tribal mistook this white metal for silver after smelting it (McClelland 1850). Hunter (1877, 158-60) also reproduced the McClelland's report in detail.

As early as 1881, in Chhattisgarh Valentine Ball drew attention to the prevalence of pre-industrial tradition of tin smelting in the Bastar area. Even until about two decades ago, in the Bastar region, tin was recovered through manual digging and hand panning (Fig. 3). The panning technique is the same as used for gold panning. In India, river sand containing gold, tin and even iron were also separated from river sand through a tedious process of panning till recent times. Most of the gold bearing area of India had a long tradition of placer mining and panning for gold. Gold panning is well documented from Bhandara (Maharashtra) Bastar – Dantewara (Chhattisgarh), Chhotanagpur region (Chhattisgarh and Jharkhand), Purulia (West Bengal) and the Dambal area in the Dharwar district. Considerable tin deposits are also located in all these areas. The panning tradition that was prevalent in different parts of India for retrieving gold from placer deposits has a hoary antiquity as is evident from the literary accounts. We get clear reference to the washing and cleaning of gold in Vedic text Satpath Brahmana (c. 1000 BCE) and Buddhist text Anguttar Nikaya (c. 4th century BCE). Panning for cassiterite in bamboo pans and winnows was widespread for tapping of placer deposits of Bastar province up to the last decade of the 20th century. There are many placer deposits of tin but the placer mining activity leaves little evidence behind it. We may not be far-fetched in presuming that in ancient times tin was procured from different deposits in the same way as gold in these regions.

In the light of the facts noted above, a rethinking on the issue of the resource area of minerals, especially tin is overdue. Tin mineralization is reported near many copper bearing localities in India. Though yet to be dated precisely, several tin deposits are known to have been worked in the past as suggested by the old workings. It is possible that artisans of early cultures were familiar with some of the neighbourhood deposits and could easily utilize them. Further in-depth study is required to pinpoint the date and precise nature of exploitation of these tin deposits.

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# Sources of zinc in early India: the evidence of numismatics, trade and lead isotope analysis

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*ABSTRACT* A limited programme of lead isotope analysis was undertaken on early Indian zinc coins and the zinc alloy *bidri* ware. The lead isotope ratios for the coins form a very tight cluster in contrast to those for the *bidri* which are much more dispersed. Subsequent numismatic work on the coins suggests that they were minted in the north west of India where recent geological exploration has identified likely centres for early non-ferrous smelting including zinc. The coins are likely to be of Medieval date and are thus the earliest coins of zinc found anywhere in the world,

Continuing work on Post Medieval international maritime trade in metals has made it clear that already by the early 17th century zinc was being imported into India from China. Indeed Indian zinc does not seem to have featured in later international trade and production in the 17th and 18th centuries was probably very limited.

## Introduction

The excavations carried out at the zinc mines at Zawar in the Aravalli Hills of Rajasthan in the North West of India (Fig.1) during the 1980s and 1990s revealed the true scale of this enterprise (Craddock et al. 1998a). The extent of the remains at Zawar together with the numerous interim reports published on the site have rather overshadowed the potential existence of other sources of zinc exploited in India in the past. However, at the commencement of the project lead isotope analyses of Indian zinc artefacts, both coins and *bidri* wares were undertaken in the expectation that they would prove to be of zinc from Zawar. When it became clear that this was not the case and that moreover the zinc in the items selected could not have come from anywhere in the Aravalli Hills, in which Zawar and the other metal mines investigated in the project lay, the information was put to one side for later investigation. Over the years more information has been amassed on the coins to suggest that they are likely to be Medieval in date (Cribb, 2014) and thus there must have been other sites producing zinc contemporary with Zawar. By the Post Medieval period, historical, geological and scientific studies combine to show that zinc was coming from a variety of sources both within and without India.

[1] Sadly, Noel Gale died on the 3rd February 2014, within days of the submission of the final version of this paper on which he had been very actively working. We would like to dedicate this paper to his memory and in recognition of the great contribution he made to archaeological science.

## Analytical

Lead isotope analyses were performed on a small selection of punch-marked silver coins, zinc coins and *bidri* ware to try to identify both the zinc and the silver variously produced at Zawar, Dariba and Agucha. The silver will be discussed in the main monograph on the Indian metals project and in this paper only the zinc coins and *bidri* wares will be considered. Lead isotope analyses were made in the Isotrace Laboratory, Oxford, housed at first in the Department of Earth Sciences and later within the Nuclear Physics Laboratory. From 1985 to 1989 a single collector 12" radius thermal ionisation magnetic dispersion mass spectrometer was used in the dynamic mode, with online data reduction by computer. From 1990 onwards thermal ionisation mass spectrometric analyses were made using a computer controlled magnetic sector, multicollector, double focussing VG Isolab mass spectrometer employed in the static mode. In both cases a silica gel activator on a rhenium ionisation filament was used. The isotopic analyses were normalised using many repeat measurements of the NIST lead isotope standard SRM981, resulting in measured isotopic ratios accurate to ± 0.1% at the 2 standard deviation level. The lead analysed was extracted and purified from small samples dissolved in HCl or $HNO_3$ in ultra clean Class 100 over-pressured laboratories. Lead for mass spectrometric analysis was extracted in a state of high purity by anodic electrodeposition (Arden and Gale 1974), or by ion-exchange separation of the lead from all other matrix constituents using the special ion-exchange resin SrSpec according to the method described by Gale (1996). All chemistry was conducted in Class 100 clean rooms, using ultra pure reagents, with a total blank less than 1 nanogram of lead (see Gale and Stos-Gale 2000 for further details).

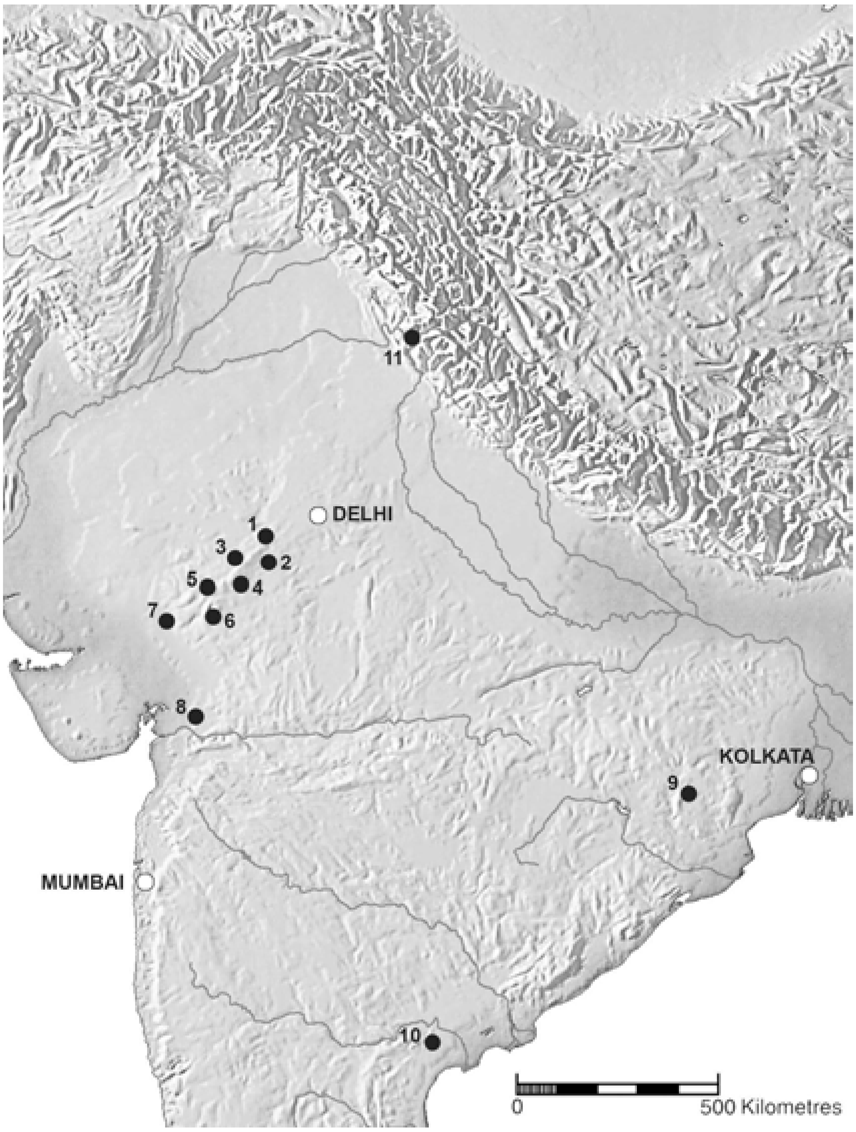


**Figure 1** Location of some of the principal sites from which lead isotope data is discussed in this section. 1 Khetri; 2 Daribo Nola; 3 Khankaria; 4 Dariba; 5 Pipalwas; 6 Zawar; 7 Ambaji; 8 Amba Dongar; 9 Amjhore; 10 Agnigundala; 11 Kwanu

Fig. 1 shows the localities of some of the sites from which ore samples were obtained for lead isotope analysis. The work reported here should be regarded very much as preliminary, since only a few analyses were performed on the ores, slags and metal from the mines investigated as part of this project (Table 1). Most certainly a systematic sampling programme would need to be performed to establish the true range of lead isotope ratios in the various minerals exploited at each of the three major mines investigated in this project as well as samples from the mines at Ambaji and Singhana-Khetri. In addition a more general programme of survey and sampling should be undertaken along the lines of that initiated some years ago in the Aravalli Hills by J.E. Ericson and K.T.M. Hegde (Hegde and Ericson 1985; Ericson and Shirahata 1985), whose lead isotope data have also been used here (Table 2). These produced samples of minerals from a number of major mining and smelting sites (Fig.1) including Ambaji and Deri (Cu-Pb), Zawar (Zn-Pb), Pipalwas (Cu) near Udaipur, Dariba (Pb-Cu) and Kankaria (Pb-Cu) near Ajmer. The latter is close to the lead mines at Taragarh Hill (Krishnaswamy and Sinha 1988, 279) described by Capt. Dixon (Percy 1870, 293-4). Further north the mines at Daribo Nola and Kho Dariba (Cu) near Jaipur (Ball 1881, 259, where the mines are called Daribo) and Khetri and Ghatiwali (Cu) were sampled. The principal metals believed to have been produced at these sites are shown here in the brackets. The lead isotope compositions measured by Ericson and colleagues for Ambaji, Zawar, Dariba and Agucha are similar to those reported in Table 1.

The data from some other related lead isotope projects have been used here (Table 3). These include the survey of South Indian bronzes (Srinivasan 1999) which used our as then unpublished data but also included the analysis in the Isotrace laboratory by Srinivasan of nine galena samples from the central Indian copper - lead mines at Agnigundala (Fig.1), and a single analysis of galena (Venkatasubramanian et al. 1982) from the fluorite deposits of Amba Dongar, in the Baroda District of Gujarat on the northern most section of the Western ghats of the Deccan (Krishnaswamy and Sinha 1988, 279) and three galena samples published as coming from Anijhor in the Shabad District of Bihar (Mookerjee 1964; Balasubrahmanian and Chandy 1976). This is

**Table 1** Lead isotope values from Ambaji, Zawar, Dariba and Agucha. Those with numbered references are the British Museum surveys and excavations, the others are mainly from Mookerjee (1964)

| Inv. Nos. etc. | Site | Find Spot | Material | Main Constituent | 208Pb / 206Pb | 207Pb / 206Pb | 206Pb / 204Pb |
|---|---|---|---|---|---|---|---|
| AGUCL1 | Agucha | | ore | galena | 2.22970 | 0.96581 | 16.049 |
| 43612V | Agucha | Well Section | metal | lead | 2.22418 | 0.96283 | 16.094 |
| 43613T | Agucha | Well Section | metal | lead | 2.22827 | 0.96430 | 16.094 |
| 26259Z | Agucha | Old Workings II: Incline | ore | galena | 2.23146 | 0.96502 | 16.044 |
| 26270Y | Agucha | Old Workings: Incline | ore | galena | 2.23419 | 0.96634 | 16.075 |
| AMB1 | Ambaji | | ore | PbS / ZnS | 2.09020 | 0.86951 | 18.003 |
| 21895S | Ambaji | tip nr. Jain temple | slag | Pb-rich | 2.14843 | 0.90079 | 17.313 |
| 33524Y | Ambaji | tip nr. Jain temple | slag | Pb-rich | 2.14883 | 0.90085 | 17.318 |
| 28491S | Zawar: Balaria | mine | ore | ZnS | 2.20051 | 0.94685 | 16.614 |
| 28495V | Zawar: Balaria | mine | ore | ZnS | 2.21119 | 0.95244 | 16.461 |
| BALM1 | Zawar: Balaria | | ore | PbS / ZnS | 2.20230 | 0.95048 | 16.397 |
| BALL2 | Zawar: Balaria | | ore | PbS / ZnS | 2.20800 | 0.95200 | 16.470 |
| BALL3 | Zawar: Balaria | | ore | PbS / ZnS | 2.19100 | 0.94600 | 16.530 |
| BALL4 | Zawar: Balaria | | ore | PbS / ZnS | 2.19600 | 0.94600 | 16.550 |
| BALL5 | Zawar: Balaria | | ore | PbS / ZnS | 2.20500 | 0.95100 | 16.400 |
| 33525W | Zawar: Zawar Mala | mine | ore | PbS / ZnS | 2.20195 | 0.94760 | 16.604 |
| 33501Q | Zawar: Zawar Mala | Mine: ZW/LW/87/50 | ore | PbS / ZnS | 2.19648 | 0.94324 | 16.661 |
| 26001X | Zawar: Mochia | mine | ore | PbS / ZnS | 2.20495 | 0.95004 | 16.493 |
| 26002V | Zawar: Mochia | mine | ore | PbS / ZnS | 2.19909 | 0.94345 | 16.640 |
| 21939U | Zawar: smelting site | Smelting Site 19 | slag | Cu-rich | 2.19244 | 0.94290 | 16.730 |
| 26074W | Zawar: smelting site | Smelting Site 14, layer 3 | slag | Pb-rich | 2.20259 | 0.94806 | 16.575 |
| BAX1 | Zawar: smelting site | | retort filling | Zn-rich | 2.20646 | 0.94931 | 16.601 |
| BAX2 | Zawar smelting site | | retort filling | Zn-rich | 2.19700 | 0.94677 | 16.523 |
| DARM1 | Dariba | | ore | PbS / ZnS | 2.23060 | 0.96600 | 16.048 |
| DARL2 | Dariba | | ore | PbS / ZnS | 2.21500 | 0.96100 | 16.140 |
| DARL3 | Dariba | | ore | PbS / ZnS | 2.20900 | 0.96300 | 16.180 |

more usually known as Amjhore, in the Rohas District of Bihar, and has pyrite deposits that have been worked in the recent past for sulphuric acid manufacture. Although some lead zinc mineralisation does occur at Amjhore and is believed to extend over approximately 100 sq. km, it is nowadays considered as an uneconomic deposit. However, any ore deposit considered as uneconomic by modern standards cannot necessarily be excluded as a source in ancient times, but there is no indication of early exploitation (Raghunandan et al. 1981).

More recently lead isotope analyses were performed at the British Geological Survey at Keyworth, Nottingham (Table 4) on three samples collected in 2009 from sites in the Tons valley separating the states of Himachal Pradesh and Uttaranchal in North West India (Figs. 1 and 2).

**Figure 2** The Tons Valley at Kwanu where zinc smelting retorts were found in the 1970s.The slag sample came from the west (left) bank of the Tons just across from the arable land. (P.T. Craddock / BM)

**Table 2** Lead isotope ratios from some mine sites in the Aravallis. (from Ericson and Shirahata 1985)

| Location | Region | No | Ore Type | 208Pb / 206Pb | 207Pb / 206Pb | 206Pb / 204Pb |
|---|---|---|---|---|---|---|
| Ambaji | Gujarat | 1_1 | Chal+gal+sphal | 2.1596 | 0.90405 | 17.315 |
| Ambaji | Gujarat | 1_31 | Mal | 2.1494 | 0.89936 | 17.127 |
| Ambaji | Gujarat | 1_33 | Mal | 2.1528 | 0.90247 | 17.337 |
| Deri | Rajasthan | 3_5 | Gal | 2.1573 | 0.90343 | 17.280 |
| Deri | Rajasthan | 3_3 | Ferr quartz | 2.1593 | 0.90263 | 17.292 |
| Dariba Nola | Rajasthan | 10_2 | Gal+pyr | 1.8440 | 0.51670 | 33.390 |
| Ghatiwali | Rajasthan | 7_1 | Gal+pyr | 1.0910 | 0.39760 | 45.910 |
| Khankaria | Rajasthan | 11_9 | Mal stains | 2.2284 | 0.96301 | 16.122 |
| Khankaria | Rajasthan | 11_6 | Serp | 2.2050 | 0.95757 | 16.269 |
| Khetri | Rajasthan | 4_6 | Quartz acid | 2.0407 | 0.74702 | 21.311 |
| Kumbhariya | Rajasthan | 2_10 | Talc | 2.1509 | 0.90165 | 17.358 |
| Pipalwas | Rajasthan | 14_9 | Gal | 2.2445 | 0.98443 | 15.682 |
| Pipalwas | Rajasthan | 14_9 | Gal in cl sch | 2.2457 | 0.98449 | 15.688 |
| Rajpura Dariba | Rajasthan | 16_18 | Gal | 2.2345 | 0.96543 | 16.061 |
| Rajpura Dariba | Rajasthan | 16_18 | Gal | 2.2297 | 0.96441 | 16.056 |
| Rajpira Dariba | Rajasthan | 16_10 | Gr sch | 2.1580 | 0.92708 | 16.800 |
| Zawar | Rajasthan | 12_5 | Gal | 2.2031 | 0.94671 | 16.583 |
| Zawar | Rajasthan | 12_4 | Gal+quartz | 2.1977 | 0.94778 | 16.593 |

chal=chalcopyrite; gal=galena; sphal=sphalerite; mal=malachite; quartz=quartzite; ferr quarz=ferruginous quartzite; pyr=pyrite; serp=serpentinite host; quartz acid=quartzite acid leach; talc=talc chlorite schist; gal in cl sch=galena in chlorite schist; gr sch=graphitic schist host

**Table 3** Lead isotope ratios from galena samples from sources beyond the Aravallis, including Agnigundala, Andhra Pradesh (Srinivasan 1999); Amba Dongar, Gujarat (Venkatasubramanian et al 1982) and Amjhore, Bihar (Balasubrahmanian and Chandy 1976)

| No. | Location | Region | Pb 208/206 | Pb 207/206 | Pb 206/204 |
|---|---|---|---|---|---|
| 1 | Agnigundala | Andhra Pradesh | 2.17031 | 0.94146 | 16.699 |
| 2 | Agnigundala | Andhra Pradesh | 2.16910 | 0.94075 | 16.727 |
| 3 | Agnigundala | Andhra Pradesh | 2.16874 | 0.94079 | 16.721 |
| 4 | Agnigundala | Andhra Pradesh | 2.17334 | 0.94176 | 16.745 |
| 5 | Agnigundala | Andhra Pradesh | 2.16646 | 0.94023 | 16.717 |
| 6 | Agnigundala | Andhra Pradesh | 2.16899 | 0.94080 | 16.728 |
| 7 | Agnigundala | Andhra Pradesh | 2.16722 | 0.94053 | 16.708 |
| 8 | Agnigundala | Andhra Pradesh | 2.17385 | 0.94212 | 16.726 |
| 9 | Agnigundala | Andhra Pradesh | 2.17206 | 0.94186 | 16.716 |
| | | | | | |
| | Amba Dongar | Gujarat | 2.07 | 0.84 | 18.57 |
| | | | | | |
| | Anijhor | Bihar | 2.1422 | 0.8915 | 17.51 |
| | Anijhor | Bihar | 2.1467 | 0.8959 | 17.59 |
| | Anijhor | Bihar | 2.1483 | 0.8736 | 17.40 |

**Table 4** Lead isotope values from slag and minerals collected at Kwanu, Uttaranchal

| Sample name | 208Pb / 206Pb | 207Pb / 206Pb | 206Pb / 204Pb |
|---|---|---|---|
| Slag (Tons river) | 2.02791 | 0.82136 | 19.4008 |
| Slag (mine) | 2.06367 | 0.84056 | 18.8400 |
| Pyrite (mine) | 2.07648 | 0.84449 | 18.7416 |

The lead isotope compositions for the various ore, slag and metal samples are plotted in Fig. 3. The isotopic compositions of ores from the mines at Zawar, Dariba and Agucha form quite tight groups and are close together. On the basis of both plots the lead isotope fields of Dariba and Agucha overlap and cannot reliably be separated. Again on the basis of both plots the lead isotope data (LIA) for ores from Zawar are separable from the nearby LIA for the ore deposits of Agucha, Dariba, Agnigundala and Pipalwas, and are completely separable from the LIA of the ore deposits of Ambaji, Amba Dongar and the Tons Valley sites. The very few available results from the major copper producing areas of Khetri and Daribo Nola are very different (Table 2), and their plotted ratios would lie quite outside the field of compositions covered by Fig.3. The copper / lead deposits of Ambaji and Pipalwas have lead isotope compositions separable from those of Zawar, Dariba and Agucha. Lead isotope compositions for slags and retort fillings from Zawar overlap the isotopic compositions of ores from the Zawar mines. In a similar way lead metal excavated from a well section at Agucha, radiocarbon dated to the third century BC, has isotopic compositions overlapping with the ore from Agucha.

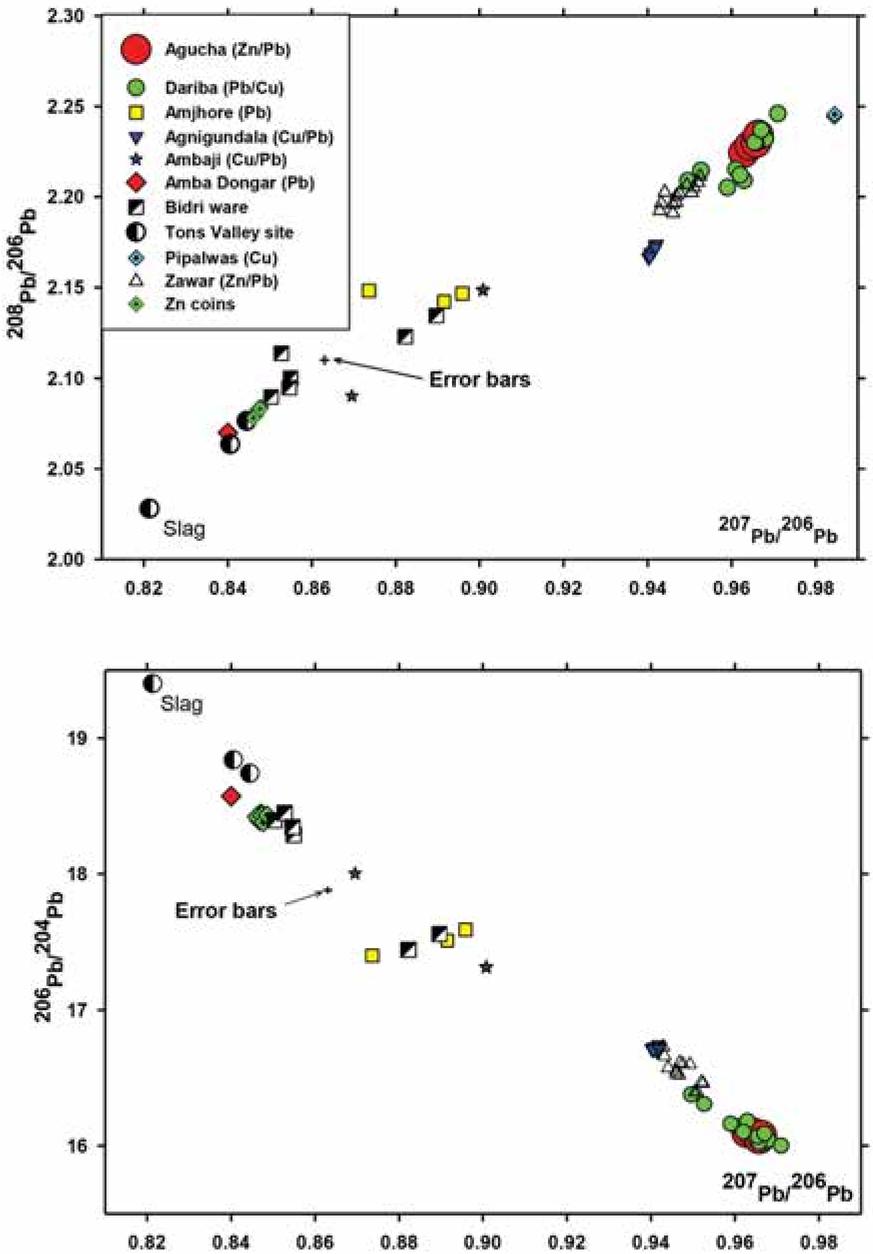


**Figure 3** Lead isotope plots of some of the principal sources of zinc, copper, lead and silver worked in the past, together with those of a selection of zinc coins and zinc -based *bidri* ware

## Zinc coins

Coins made of 'white metal', usually assumed to be lead or pewter are surprisingly widespread. They tend to be at the low end of the numismatic range both in value and quality and thus have not received so much attention as their silver contemporaries. India is no exception and chemical analysis has revealed that some of the white metal coins are in fact made of zinc, usually with a little lead that is likely to have come with the zinc ore.

One group of these zinc coins (series A; C & M Reg. 1889, 1203. 49-58) was found at Nadaun on the Beas river in Himachal Pradesh, to the east of the Tons valley. Another group (series B; Fig. 4, C & M Reg. 1892, 0207. 46-51) was acquired from the collector C.J. Rodgers as part of a group of coins from the Punjab including some coins of the kings of Kangra, now in Himachal Pradesh (Rodgers 1895). A few years previously Rodgers had been conducting excavations in Kangra for the Punjab Archaeological Survey. A third group (series C;Fig. 5, C & M Reg. 1900, 0805. 1-15) was donated to the British Museum by the government of N.W. Provinces and Oudh, the area which included Uttar Pradesh, the Punjab and Himachal Pradesh. The fourth group (series D) was said by its donor to have been found between Agra and Mathura in Uttar Pradesh. Although there was a lack of precision in the provenance of series B and D; Fig. 6, C & M Reg. 1877, 0707.1-18), their context places them in the same broad region of the other two series, so all four series can be said to have originated in the north western part of India.

**Figure 4** Zinc coins from North West India, Series B, C & M Reg. 1892, 0207. 46-51, (A. Milton / BM)

**Figure 5** Zinc coins from North West India, Series C, C & M Reg. 1900, 0805. 1-15 (A. Milton / BM)

The size of the zinc coins of all series suggest that they were made using the same production technique, and were of the same size as the base silver coinage circulating in North-West India during the medieval period. These base silver coins, known as *jitals*, were in circulation from the twelfth to fourteenth centuries AD (Tye and Tye 1995). Their designs, often featuring a horseman on one side and a bull on the other, were derived from the silver coinages of the Shahi kings who ruled in Afghanistan and Pakistan from the ninth to eleventh centuries AD. Inscriptions on the *jitals* were written in Arabic or Sanskrit, sometimes both. The inscriptions often copied the original Shahi-period Sanskrit inscriptions, but also added the name of the local ruler responsible for their issue.

**Figure 6** Zinc coins from North West India, Series D, C & M Reg. 1877, 0707. 1-18. (A. Milton / BM)

The thick round-edged fabric of the zinc coins of series A, B and C, are closest to the *jital*s issued by the last three coin-issuing kings of Kangra, in the Himachal Pradesh region where the series A coins were found. Series A and B coins were both acquired in groups containing *jital* coins issued by the kings of Kangra, suggesting that group B also came from the same region. Group C were donated by the administrative authority which also governed the Kangra region. Group D coins were found further south, in the region where *jitals* with the horseman and bull issued by the sultans of Delhi were in circulation during the thirteenth century.

These links between the zinc coins and the *jitals* of the Kangra kings offer the only evidence for their chronology. Unfortunately there is no consensus on the dating of the Kangra kings who issued *jitals*. There are at least 12 Kangra kings named on *jital* coins (Jha and Garg 1991, 22; Tye and Tye 1995, 99–101), but some names may represent more than one king. The chronology of the Kangra *jitals* was originally proposed by Cunningham (1894, 99–108) as dating from the fourteenth until the seventeenth century. Gupta (1985, 39–43) rejected Cunningham's dating by drawing attention to the reference to four types of Kangra *jital* coins in the money manual *Dravya Pariksha* written in AD 1318 by the Delhi mint master Thakkura Pheru (Agrawal 1969, 109). There are surviving coins which seem to match three of the types mentioned by Thakkura Pheru. These are among the earliest Kangra coins, suggesting that their issue began in the thirteenth century. It also suggests that the remaining recorded issues of Kangra coins were issued immediately after Thakkura Pheru wrote his manual, i.e. through the fourteenth century. Gupta, however, still suggested that some late issues of Kangra *jitals* were produced in the sixteenth century.

More recently Jha and Garg suggested a modified version of Gupta's analysis, but also places the last issues in the sixteenth century (p. 40). One of the hoards of Kangra coins examined by Jha and Garg contained coins of almost all the Kangra kings, including the kings responsible for coins with the thick rounded-edged fabric. This hoard also included coins of three Delhi sultans, Balban (1266–87), 'Ala-al-din Khalji (1295–1315) and Muhammad bin Tughlak (1325–51), suggesting again that the Kangra kings were ruling in the thirteenth to fourteenth centuries.

The Kangra coinage should therefore be dated like the other *jital* issues of North India between the twelfth and fourteenth centuries. The evidence of Thakkura Pheru's manual suggests that Kangra *jital* production only began during the thirteenth century. The relationship between the zinc coins and the Kangra issues therefore suggests that their production was inspired by the later Kangra *jitals*, so probably should not be dated earlier than the fourteenth century and might be dated later. They are, however, unlikely to have been issued much later as the *jital*-like designs would not have been readily available as prototypes after the fifteenth century. There is no evidence in the designs of the zinc coins to link them with any state authority, so they could be unofficial coins or religious coin-like objects.

## Analysis and Source

Approximately 40 coins were semi-quantitatively analysed by energy dispersive X ray fluorescence, which showed the majority of the zinc coins had between one and three percent of lead, which is likely to be associated with the zinc ore rather than represent a separate addition. From these, 11 coins with lead contents between one and two percent were selected for lead isotope analysis together with those of two coins from a hoard purchased in London, and once claimed to be of the 4-5th centuries AD, but now believed to be medieval, and to come from the Deccan (Srinivasan 1999, Table 1). The lead isotope data for the zinc coins are given in Table 5 and plotted in Fig 3.

**Table 5** Lead isotope values of the selected zinc coins

| BM CM Reg. | 208Pb / 206Pb | 207Pb / 206Pb | 206Pb / 204Pb |
|---|---|---|---|
| 1877, 0707. 2 | 2.08174 | 0.84710 | 18.446 |
| 1877, 0707. 5 | 2.08311 | 0.84722 | 18.443 |
| 1877, 0707. 6 | 2.07993 | 0.84672 | 18.389 |
| 1877, 0707. 8 | 2.08191 | 0.84698 | 18.418 |
| | | | |
| 1889, 01203. 49 | 2.07870 | 0.84620 | 18.423 |
| 1889, 01203. 51 | 2.08429 | 0.84791 | 18.401 |
| 1889, 01203. 55 | 2.08365 | 0.84773 | 18.423 |
| 1889, 01203. 56 | 2.08319 | 0.84757 | 18.385 |
| 1889, 01203. 57 | 2.07809 | 0.84607 | 18.419 |
| | | | |
| 1892, 0207. 51 | 2.08360 | 0.84735 | 18.428 |
| | | | |
| 1900, 0805. 4 | 2.08312 | 0.84767 | 18.379 |
| | | | |
| Seeley coin | 2.08775 | 0.84857 | 18.431 |

Although coming from a variety of locations the coins have a remarkably consistent lead isotope signature. Thus it is likely that the zinc for all these coins came from the same ore source. The tightly grouped LIA for these zinc coins lies far from the LIA for Zawar in Fig.3 and makes it abundantly clear that the coins were not made from zinc coming from the Zawar ores, or anywhere in the Aravallis. Note, the coins are not of identical chemical composition, for example, those in the 1900, 0805. 1-15 group also have small amounts of iron and copper not detected in the other coins. However these small differences in chemical composition could easily arise from different parts of the same ore deposit or a different smelting / refining procedure.

The lead isotope of the coins plot in the vicinity of the single geological sample from Amba Dongar (Venkatasubramanian et al 1982) and also to the mineral samples from the Tons Valley. The Amba Dongar ore deposit itself is not a zinc ore deposit, but rather a fluorite / carbonate deposit. Moreover the coins plot only *in the vicinity* of the Amba Dongar ore deposit; the

LIA of the coins are in fact separated in both diagrams from the LIA for the single Amba Dongar mineral analysed. Recent archaeological surveys have located early lead / zinc mines near Godhra at Panj Mines which lies approximately 60 km East North East of Baroda and at Kadwaj (73$^{0}$ 46$^{|}$ E 22$^{0}$ 29$^{|}$ N) and at Jhabua (73$^{0}$ 47$^{|}$ E 22$^{0}$ 30$^{|}$ N) all in the Panch Mahals District of Gujarat (Upadhyay 2007). However, surveys undertaken by the first and fourth authors failed to locate any evidence of zinc production at these mines.

The Tons Valley sources (Fig. 1) appeared initially to be more promising. Not only do the coins seem to emanate from that region but deposits of copper, lead and zinc ores with evidence of early working have recently been identified in the Tons Valley near Chakrata in the Dehradun District of Uttaranchal (unpublished Vedanta geological survey report) and zinc mining was also reported in the Kullu valley, from which the Beas river flows (Anon. 1908). In addition, a retired geologist, R.C. Dey described zinc smelting retorts, very similar to those from Zawar, which he had found many years before at Kwanu, a small settlement in the Dehradun District besides the Tons River (Dey 2008) (Fig.2). The dimensions of the Kwanu retorts match those of the large retorts at Zawar which were in use in the 16$^{th}$ century. A very brief survey of the area conducted in 2009 by the first and fourth authors failed to relocate the retorts, but did find evidence for early mining and smelting of copper or lead ores, which provided the samples for the Tons Valley lead isotope data (Table 4). The lead isotope values for one of the two mineral samples are fairly close to those of the coins in the upper diagram but are completely separated in the lower diagram. The other Tons River mineral sample has LIA which are well separated from the LIA for the coins in both diagrams, whilst the LIA for the slag sample from the Tons River valley are vastly different from those for the coins in both diagrams (Fig. 3). It may safely be concluded that the lead isotope data excludes the Tons Valley sites at Kwanu as a source of zinc for the zinc coins.

## Bidri

*Bidri* is an alloy of zinc with about 5% of copper from which a variety of hollow ware items, including small boxes, hookah bases, bowls etc, were cast, inlaid with silver and given a distinctive black patina (Fig. 7). Production probably began at Bidar in the Deccan in the 15th century AD (Stronge 1985; Lal 1990). The material is unique to India, and being predominantly of zinc, the possible association with Zawar is obvious. However, there are problems, *bidri* has always been produced by Moslem craftsmen in styles that owe more to Iran than India, and more specifically there is no record of *bidri* ever having been made in Rajasthan.

**Figure 7** Flask of *bidri* ware (V & A 1479-1904, Stronge 1985, Cat. 2, pp. 39-40), dated to the mid 17$^{th}$ century. *Bidri* is an alloy of zinc with copper, inlaid with silver and then patinated. (V & A)

Samples were selected from a group of *bidri* items in the collections of the Victoria and Albert Museum at a time when a more extensive sampling programme was being undertaken for elemental analysis (La Niece and Martin 1987). *Bidri* wares are difficult to date stylistically and 'old' pieces only survive from the 17$^{th}$ century and most are from the 19th century. The six pieces (described and illustrated in Stronge 1985) were chosen as the oldest, are stylistically dated to the 17th or 18th century and are likely to have been made in the Deccan. There is a potential problem in that *bidri* is an alloy and the lead in the small percentage of copper must contribute to the overall lead content. However, the lead isotope data presented in Table 6 and plotted in Fig. 3 show that none of the zinc could have come from either the Tons Valley sites or from Zawar (see below).

**Table 6** Lead isotope values of some pieces of *bidri* ware dated to the late 17th or 18th centuries

| Type and Reg. | Date | 208 / 206 | 207 / 206 | 2.6 / 204 |
|---|---|---|---|---|
| Bowl 1S 10-1973 | Early 17$^{th}$ century | 2.0896 | 0.8503 | 18.392 |
| Ewer 1479.1904 | Mid 17$^{th}$ century | 2.1137 | 0.8527 | 18.447 |
| Pan box 1S 17-1970 | 18$^{th}$ century | 2.1000 | 0.8549 | 18.286 |
| *Huqqa* base 1S 39-1976 | 1750-1800 | 2.0947 | 0.8546 | 18.343 |
| *Huqqa* base 856.1874 | 1700-1750 | 2.1229 | 0.8822 | 17.441 |
| Carpet weight 1S 46.1977 | Late 17$^{th}$ –early 18$^{th}$ century | 2.1344 | 0.8896 | 17.558 |

It is now apparent that very substantial imports of zinc from China to India were being made in the vessels of the European trading companies from the early 17th century (Souza 1991). For example, there are Portuguese records of Chinese zinc being brought into Goa, the nearest sea port to Bidar, in the 18th century and being used in part to mint low denomination coins locally known as *bazarucos* (Yih and Kreek 1993). Although most of the zinc was used in the manufacture of brass some was used for the production of *bidri* (Ball 1886). Thus all the pieces sampled here are likely to have been made when Indian production was already in sharp decline. However, it still seems inherently probable that Indian zinc was used at the inception of the *bidri* manufacture, either from Zawar or from sites in the north west.

## Conclusions

As with many other areas, lead isotope analyses have shown that the metal supply situation was much more complex in the past than hitherto understood. At the start of our investigations at Zawar back in the 1980s we believed the site to be the earliest and only major source of zinc in India prior to the 19th century. Similarly the distinctive *bidri* wares were quintessentially Indian and it was logical to assume that the zinc came from Zawar (as it actually does now, possibly for the first time in centuries!). Thus the lead isotope analyses were carried out to confirm our hypotheses, and when this failed explanations were sought in the material rather than the hypotheses. Clearly, we argued, both the coins and the *bidri* wares selected must be relatively recent and to have been made of European zinc, imports of which are recorded from the early 19th century (Craddock 2013). However, the closely clustered lead isotope compositions of the coins suggested a single source, which would be rather unlikely if they were made from a general stock of imported metal.

The recent study of the coins has now shown that their appearance associates them with the late coins of the kings of Kangra (Himachal Pradesh), which were issued in the thirteenth to fourteenth centuries AD. They are thus of some importance in their own right as the earliest zinc coins in the world. The only other early artefacts made of zinc are also from this general region. They include a series of heavily inlaid zinc vessels of which a collection is preserved in the Topkapi Museum in Istanbul (Atil et al. 1985; Rogers and Ward 1988). They are believed to be of mid 16th century date and stylistically are likely to have come from East Iran or Afghanistan. A semi-quantitative analysis showed them to be of zinc with about a percent of lead and traces of silver (Craddock et al. 1998b). Some brass astrolabes made in Lahore in the early 17th century contain so much zinc (typically between 40-50%, Newbury et al 2003) that the brass is very likely to have been made by adding copper to molten zinc, rather than by the traditional cementation process of reacting copper metal with powdered zinc minerals in which the maximum zinc content is approximately 33% (Craddock et al. 1998b).

The lead isotope values of the *bidri* wares are more dispersed, suggesting a number of sources, in turn raising the possibility that the metal could have been imported. The study of the early Indian metal trade is very incomplete, but where documentation does survive it suggests that non-ferrous metals, including zinc, were usually imported into India rather than exported as might have been expected given the precocious production of zinc in India. For example, recently published documents from the Cairo *Geniza* give detailed descriptions of the trade across the Arabian Sea from Aden to India in the 11th century AD (Goitein and Friedman 2008). There is one account describing the establishment of a foundry in Kerala, southern India, for making typical Islamic brass vessels and lamps to order from Aden (p.555, FN 11). What is significant is that the metals copper and 'yellow copper' (i.e. brass, the alloy of copper and zinc) had to be sent from the Middle East to India.

Somewhat later Marco Polo on his return journey from China sailing up the west coast of India reported that brass, silver and gold were all imported into the ports of Thana, near present day Mumbai, and Cambay in Gujarat together with *tutty* at Cambay (Latham 1972, 266, & 267). *Tutty* is not defined there but earlier in his account Polo gave a detailed description of the production of *tutty* at Kerman in Iran where there can be no doubt that *tutty* was zinc oxide (Latham 1972, 39)

The first direct European trade with India began in the 16th century and through that century was largely conducted in Portuguese vessels based at settlements such as Goa, Seurat and Diu on the west coast of India. Zawar would then have been at the peak of production and it is likely that the Portuguese were trading zinc from Zawar but unfortunately the surviving documentation of all Portuguese trade is very poor. By the early 17th century the English and Dutch Companies had begun trading with India, largely supplanting the Portuguese, and from their much more complete records it is clear that right from the start Chinese zinc was finding a ready market at Indian ports including those in the north west, closest to Zawar (Morse 1926, 185; Prakash 1984; 2007). Furthermore, there is no record of Indian zinc ever featuring in international maritime trade from the late 16th century on. The probable cause for this lies in the political and military situation in Mughal India

(Tod 1978; Hooja 2006). After the battle of Haldigathi in 1576 Mewar, in which Zawar was situated, was defeated and occupied by the Mughals, but a long guerrilla campaign was carried on before a peace treaty was finally signed in 1615. During these forty years of incessant turmoil, raids, reprisals and counter raids when settled conditions and organised trade were severely disrupted in Mewar, it is very likely that a high technology process such as the distillation of zinc would have ceased. As a consequence India's supply would have been severely curtailed. However the demand for zinc was still there and the newly established European maritime trading companies were able to make up the deficiency with imports of Chinese zinc. For a variety of reasons this was likely to have been cheaper to produce than the Indian zinc (Craddock and Zhou 2003; Zhou et al. 2012), and when production commenced again at Zawar the market had been irretrievably lost. Survey of the remains of zinc production at Zawar shows that the distinctive late retorts are only found in a few areas and nowhere form the massive heaps produced by the earlier process carried on in the 14th to 16th centuries. Thus it seems that zinc production was only carried on at a much reduced level before ceasing completely in 1812 during the Maharatta wars (Tod 1978; Hooja 2006), and that probably Zawar itself was a major producer only between the fourteenth and sixteenth centuries AD.

The export of zinc from China expanded enormously through the 17th and 18th centuries, with much of it destined for India and only to a lesser extent to Europe. From the early 19th century European zinc came to dominate world trade only in turn to be overtaken by other sources around the world, notably in North America and Australia,. From the mid-20th century India became a major producer, with the mines of the Aravalli Hills of Rajasthan, including Zawar again in operation.

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# Bidri ware and its black patina

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*ABSTRACT* Bidri ware is a well-known class of inlaid metalwork used to make such items as decorative jugs, huqqas and other containers, produced in India from the 17th century or earlier and which is still being made today. The early history of bidri ware is not certain though the class as a whole is well studied and published, for example by Stronge (1985), Lal (1990) and Craddock (2005). The cast white metal of the objects is an alloy of zinc; the inlays are silver, brass or gold. The distinctive feature of bidri ware is its matt black patina which was the main focus of this research. None of the commonly occurring zinc compounds is black and no adequate explanation for the colour of the patina has yet been published. The patina is easy to produce in the laboratory on alloys of zinc with 2-10% copper, falling within the $\varepsilon + \eta$ phase field of the binary copper-zinc equilibrium diagram, but it does not form on pure zinc or on brass (La Niece and Martin 1987). This study employed Field Emission Scanning Electron Microscopy with Energy Dispersive X-ray spectrometry (FE SEM-EDX) and X-ray diffraction (XRD) analysis to determine not only the chemical composition of the patinas, but also the morphology and distribution of the component particles. As a result it is now proposed that it is the ability of the patina particles, by reason of their small size and acicular form, to absorb light which gives the appearance of a matt black surface, rather than the existence of additional components within the patina.

## Introduction

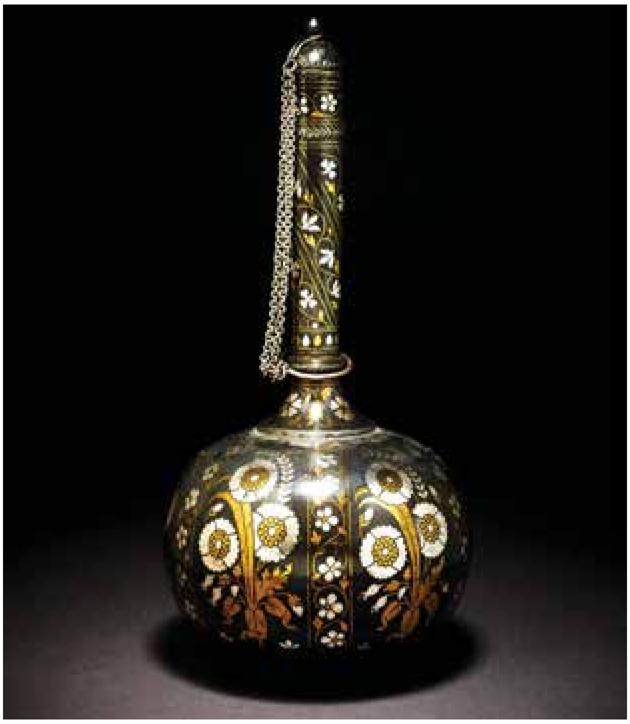

**Figure 1** 18th century bidri flask with silver and brass inlays, from the Bidar region (BM1878,1230.758) height 30 cm [copyright Trustees of the British Museum]

Bidri ware, with its characteristic rich black patina appears to be unique to India (figure 1). The origins of the craft are still uncertain, with some traditions attributing it to the 15th century Bahmani kingdom, but no documentation has been found before the mid-17th century (Stronge 1985, Craddock 2005). A range of items has been made of bidri ware including jugs, huqqas, boxes and furniture fittings. The production centres for this craft were Bidar, Hyderabad, Lucknow, Purnea and Patna and it is thought to have derived its name from the town of Bidar, north-west of Hyderabad (figure 2). There are several collections in museums outside India as well as major collections in the sub-continent.

The materials used to make bidri ware are consistent in all the accounts. It is a cast zinc alloy, inlaid with silver and sometimes brass or gold, and its main characteristic is its black patina, which contrasts with the bright polished inlays. Zinc came to be used as a metal on its own very late in the history of metallurgy. The reason, of course, is that smelting zinc ores such as sphalerite in a simple shaft furnace similar to those used at early periods to smelt metals such as copper, tin and lead results in the volatile zinc oxidising in the flue and being lost. In India the production of metallic zinc was mastered around one thousand years ago, which is earlier than elsewhere in the world and zinc was being produced at Zawar from *c*. 1000 AD using retorts to trap the volatilised zinc. However, recent work has established that production at Zawar is likely to have been severely disrupted, if not discontinued for long periods after the late 16th century (Craddock *et al.* this volume; Craddock 2013). Craddock points out that from

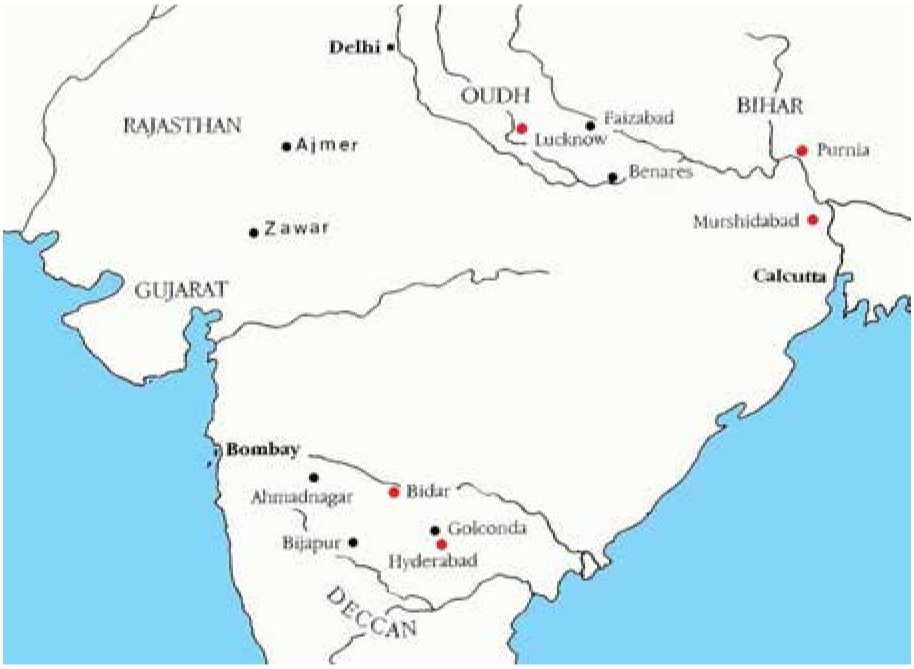


**Figure 2** Map showing the main bidri producing centres marked red

the early 17th century it is clear that the European trading companies were importing Chinese zinc into India in considerable quantities and this is likely to be the source of the zinc in the 17th and 18th century bidri wares.

Zinc is well known for its resistance to corrosion. It forms a pale grey/white protective layer, usually of zinc oxide and hydroxide, which reduces the rate of any further corrosion of the surface (Chivers and Porter 1994). The black patina on bidri ware also seems to protect it from unattractive corrosion growths under a range of normal atmospheric conditions but the unexplained aspect of this protective patina on bidri is its deep black colour: no zinc corrosion products are black. The patina of bidri has been the subject of a number of recent studies using surface techniques such as SIMS (secondary ion mass spectrometry) and SAM (scanning Auger microscopy) for example Paparazzo *et al.* (1998) and Beardmore *et al.* (2007), but the understanding of the patina has not significantly advanced. However, a number of consistently occurring components of the patina have been identified and these are discussed below.

## Manufacture of Bidri Ware

Bidri ware is cast and is made today by sand-casting, as illustrated by photographs taken at the Gulistan Bidri Works in Hyderabad by Rachel Ward (figures 3-4); it is also well illustrated by Untracht (1969) and Craddock (2005). The sand casting ‘flask’ is a two-part metal frame that forms the sides of the mould. The two halves of the frame are laid onto boards and rammed full of a mixture of sand and a binder. The surface is scraped flat and dusted with a release agent. A model, also coated with a powder release agent is embedded between the two halves then removed, leaving a hollow impression of the shape required. The two halves are then put back together and the frame is tightly bound together to prevent it slipping during the casting process. The frame is tilted at an angle to allow the molten zinc alloy to be poured into the ingate seen on the front face of the frame, while allowing gases to escape. Interestingly, earlier references to the contemporary casting of bidri ware describe it as being made by the lost-wax process rather than sand-casting (Mukharji 1886, p.41-42: Yazdani 1995, p.20).

The as-cast surface is cleaned by scraping and filing, then it is polished. This finishing process is important to the final result: the as-cast surface of the metal does not take on the decorative patina if the surface casting skin is not removed. The prepared surface is temporarily coloured by immersion in a copper sulphate solution, which allows the craftsman to see where he has drawn the design for engraving, and this colorant can be washed off in water after the inlay is complete. The inlay metals identified analytically on late 20th century pieces examined in this study were silver and brass. Some items are said to be inlaid with gold rather than brass, and gold may have been used in earlier periods or for important commissions, but its use has not been confirmed analytically. The inlays are applied either as wires into engraved grooves, or as thin cut-out sheet metal. Mukharji (1886, p.42) describes how a small piece of paper is placed over the cavity engraved to take the sheet metal inlay and rubbed to provide a pattern from which to cut out the metal sheet. The inlays are gently hammered into the engraved design and the inlaid surface is then carefully smoothed and polished. The patination of the items is carried out once the inlays are in place and the items are fully finished: any further mechanical working after the patination stage would risk damaging the thin patina.

**Figure 3** Sand casting workshop, Hyderabad 2008 [copyright R. Ward]

**Figure 4a** Sand casting at the Gulistan bidri works in Hyderabad a) outer frame for the moulding, known as a flask. [copyright R. Ward]

**Figure 4b** Sand casting at the Gulistan bidri works in Hyderabad. b) the sand-casting flask assembled, with the ingate at the front [copyright R. Ward]

## Bidri Alloy Composition

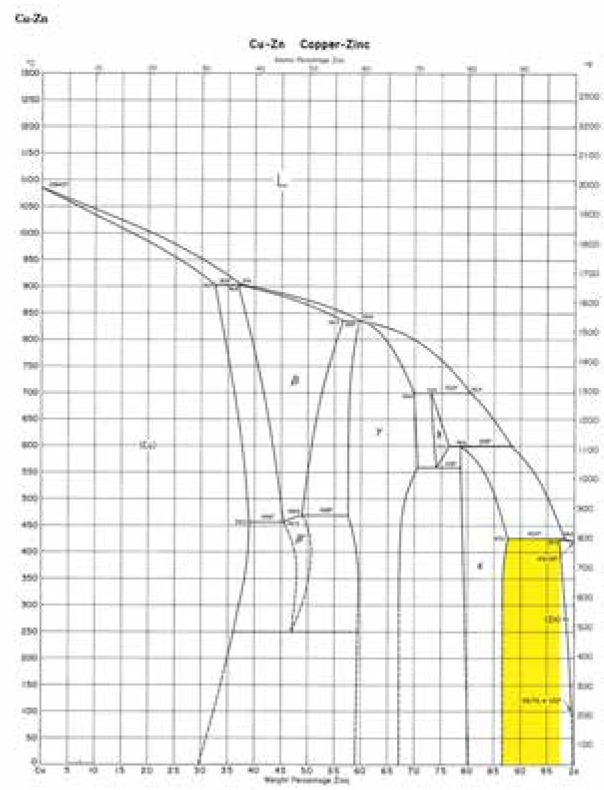


**Figure 5** Copper-zinc binary equilibrium diagram with the composition range of bidri alloys indicated by the yellow zone [after *M. Hansen and D.T. Hawkins*]

It is well established that bidri is an alloy of zinc with some copper (for example Roberts-Austen 1892, Buchanan 1928, Gairola 1956 and Untracht 1969). Martin analysed 27 bidri items in the collections of the Victoria & Albert Museum dating from the 18th to 20th centuries by atomic absorption spectrometry (La Niece and Martin, 1987). The results confirm that all are high zinc alloys with between 2 and 10% copper, with the majority between 2 and 5% copper. Lead, tin and iron are sometimes mentioned in the literature, but do not appear consistently and are probably accidental ingredients. Lead is a common impurity in zinc ores but Martin considered that levels above 3% were probably too high to be contributions from the ore. Four of the 27 items analysed contained more than 3% lead and a source of these other elements might be from recycling of metal, especially items with tin-lead soft solders, or even white metal items which were mistaken for zinc.

An examination of the copper-zinc equilibrium diagram (figure 5) is relevant to the understanding of the bidri alloy. The small amount of copper added to the molten zinc will enter into solid solution to a maximum of about 2.7%, the remainder of the copper forming intermetallic compounds with the zinc.

## Patina and Experimental Replication

The traditional patination process uses the soil from beneath the mud-brick walls of the fort of Bidar city which is said to have special oxidizing properties. The soil is boiled with ammonium chloride and the products are dipped into the solution or, in some accounts, the mixture is applied as a poultice to the items. Almost at once the zinc alloy turns black but the silver inlay and, interestingly, the brass inlay is unaffected, even though brass is also an alloy of zinc and copper, but containing more copper than zinc.

The main significance of the soil around the fort used in the traditional recipes is that it is saturated with salts because the walls are commonly used as a latrine. An adequate chemical substitute for the soil is to make a solution of potassium nitrate (1 part), ammonium chloride (4 parts) and sodium chloride (1 part) in hot water. The temperature of the solution is said to have a marked effect on the rate at which zinc and zinc alloys react and perhaps more importantly for the production of a decorative patina, the form and adherence of the corrosion layer (Chivers and Porter 1994, p. 175-176). The craftsmen often rub over the finished pieces with a vegetable oil which serves to enhance the black appearance (Mukharji 1886) and will also provide some protection against damage by corrosion. The patina is relatively resistant to corrosive attack, but storage in damp conditions will cause unattractive blistering of grey/white corrosion that is not easily remedied and can lift the inlays, although it is said that minor losses of patina can be restored by rubbing in the hands.

A set of zinc alloy discs, made by following the traditional recipes (approximately 7% copper and 93% zinc) was sand-cast by Terry Jones at the Slade School of Art, and finished by the author by grinding and polishing to remove the as-cast surface skin before patinating the experimental pieces in the chemical solution described above.

## Analysis

The two main methods of examination and analysis used in this study were Debye Scherrer Powder X-ray diffraction (XRD) using the standard ICDD database for crystallographic pattern matching, and a Hitachi S-4800 Field Emission Scanning Electron Microscope (FE-SEM) operated at 20 kV to provide high resolution images of the patina structure, with Energy Dispersive X-ray (EDX) compositional data obtained using an Oxford Instruments INCA EDX microanalysis system with an INCAx-act Silicon Drift Detector (SDD). The SEM-EDX was calibrated using a pure cobalt specimen.

XRD analysis of samples of the black patina taken from these experimental pieces and from historic bidri items (La Niece and Martin 1987, p.99) identified the three main crystalline components of all the object and experimental patinas analysed:-

*Simonkolleite*, zinc hydroxychloride ($Zn_5(OH)_8Cl_2$): ICDD powder diffraction file 7-155

*Zincite*, zinc oxide (ZnO): ICDD powder diffraction file 5-664

*Cuprite*, copper I oxide ($Cu_2O$). ICDD powder diffraction file 5-667

The two zinc compounds identified are white in colour and cuprite appears reddish, so these results do not directly explain the black colouration of the patina. The copper II oxide *tenorite* (CuO) does appear black, and had been expected to be present, but it was only rarely found in the patina, along with other occasional finds of silver chloride and lead compounds. To provide more information, the experimental patina was examined using FE SEM-EDX.

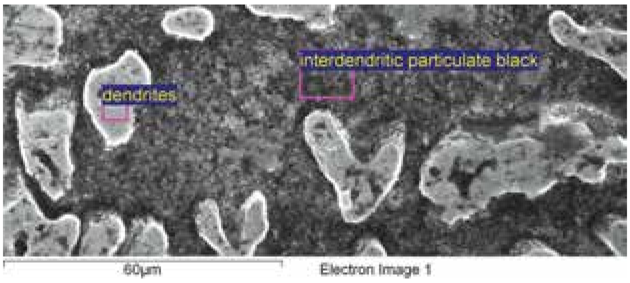


**Figure 6** SEM secondary electron image showing the dendrites (raised features) and interdendritic zone in the patinated surface. The areas analysed and reported in Table 1 are marked [copyright British Museum]


**Figure 7a** SEM Secondary electron image of a part-patinated piece of experimental bidri alloy. Scale 400 microns

The depth of the patina was measured in cross-section using the SEM and found to be only of the order of three to ten micrometres thick. The cast metal has the expected dendritic structure when examined at magnification, but it is too fine to be discernible to the naked eye and visually the patina appears completely homogenous. The areas of the patina analysed by

EDX (Table 1) are indicated on the SEM secondary electron image of the patinated surface (figure 6). The SEM was used to directly compare the unpatinated and the patinated areas on an experimental bidri alloy disc, the surface of which had been partly masked during the patination process to leave an area free from patina (figure 7 a). The alloy composition of the unpatinated surface is approximately 4% copper and 96% zinc. Compositional maps of the distribution of copper, chlorine and oxygen, detected by EDX in the zinc alloy, are illustrated in figure 7 b-d. The white/red areas indicate high concentrations, green, low and blue is the lowest. It can be seen that unpatinated metal, as expected, has little oxide and even less chloride on its surface. The dendrites are slightly cored and revealed by their enhanced copper content. The copper is less pronounced in the unpatinated zone. In the patinated area the dendrites were found to contain 12-30% copper and the interdendritic phase 2-5% copper. Conversely, the chlorine is concentrated in the interdendritic zones whereas oxygen is relatively evenly distributed across the patinated area. At a magnification of 10,000 times it is possible to resolve the structure of the loosely packed acicular particles in the interdendritic zone. They are extremely fine, *c*. 1 micron long and *c*. 0.1 micron thick, with no flat reflective surfaces (figure 8).

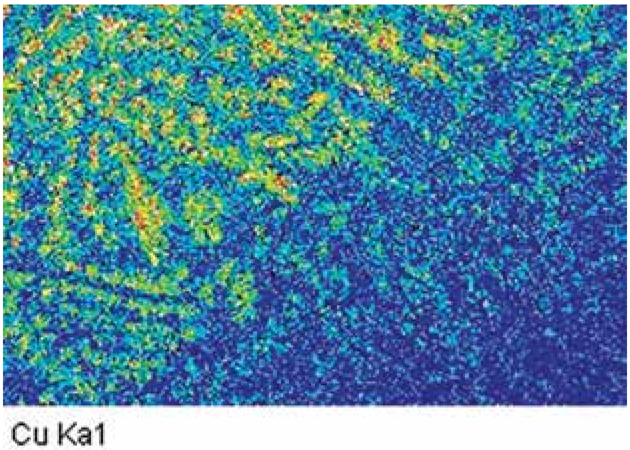


**Figure 7b**

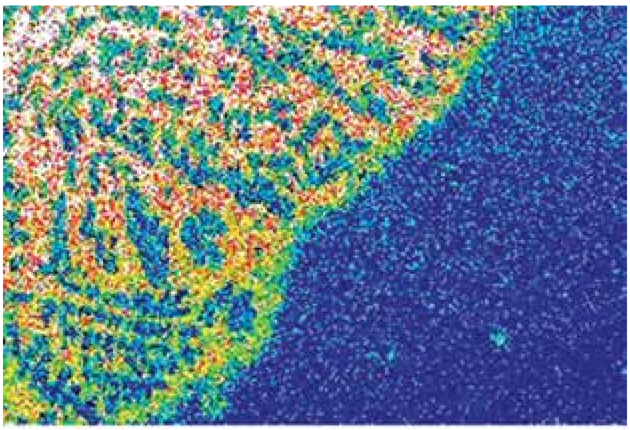

**Figure 7c**

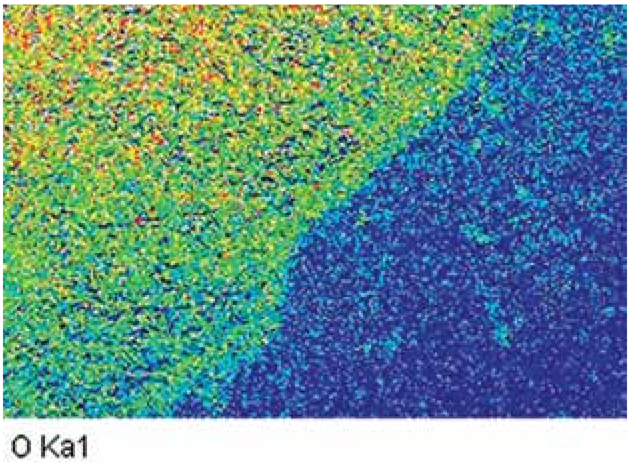


**Figure 7d** 7 b-d SEM-EDX element maps of the area in 7a. In these false colour images the white/red areas indicate high concentrations, green is low, and blue is the lowest. Note 7 b shows the high concentration of copper in the dendrites, particularly in the patinated area [copyright British Museum]

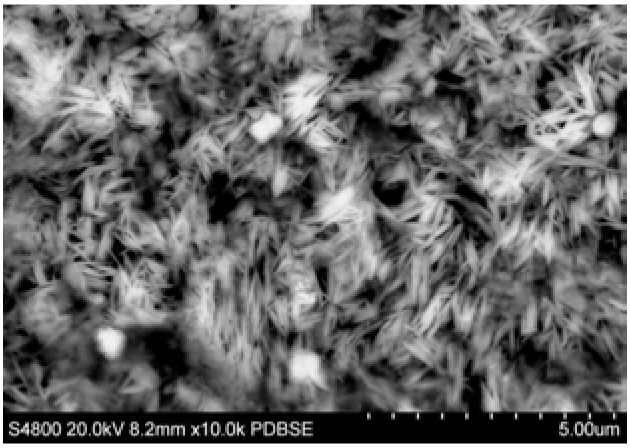


**Figure 8** SEM back scattered electron image of the patina particles in the interdendritric area, taken at 10,000 times magnification showing their fine, *c*. 1 micron long and c. 0.1 micron thick, loosely packed, acicular structure. There are some rounded particles of lead chloride (patches of bright appearance) and some local charging of the image [copyright British Museum]

**Table 1** Bidri Semiquantitative Analysis

| Area analysed | Cu wt% | Zn wt% | Cl wt% |
|---|---|---|---|
| unpatinated metal | 4 | 96 | trace |
| patina in interdendritic zone | 5 | 80 | 15 |
| patina on dendrite | 28 | 71 | 1 |

## Discussion and conclusions

The copper content in the bidri alloy is low, and all studies indicate that 2-10% copper is the required composition range for patination. This composition falls precisely within the eta + epsilon phase field of the binary Zn-Cu equilibrium diagram and it is concluded that this is the critical phase of the alloy for patina formation. It is suggested that the patina-forming mechanism is the preferential dissolution of zinc from the cast bidri alloy by ammonium chloride together with the oxidation of the copper-enriched surface by potassium nitrate, forming cuprite, zincite and simonkolleite.

The original study (La Niece and Martin 1987) using the SEM available at that time, was not able to resolve the structure of the patina and it was suggested that the patina contained additional, unidentified colouring phases that were amorphous and thus not susceptible to XRD analysis. In this recent study, the high resolution and magnifications achievable using a SEM with a field emission gun meant it was possible to resolve the fine structure of the patina (figure 8) and to map the elemental distributions (figure 7). As a result it is now proposed that it is the ability of the patina particles, by reason of their small size and acicular form, to absorb light which gives the appearance of a matt black surface, rather than the existence of additional components within the patina. This proposal is consistent with the results of studies of Japanese shakudo alloy (Murakami 1993, Kitada 2006) which have established that it is the development of the fine particles forming the patina of the distinctive copper-gold alloy of shakudo which makes it appear deep black even though the components of the patina are cuprite and fine metallic gold particles, neither of which are intrinsically black. In conclusion it is proposed that the eta + epsilon phase of the zinc-copper alloy is the critical factor for providing a microstructure susceptible to the formation of patina particles which absorb visible light and hence appear matt black. The results indicate that future research into bidri ware should look at the morphology of the patina particles and how they contribute to the low reflectivity and correspondingly high absorption of visible light.

## Acknowledgements

Thanks are owed to British Museum colleagues, Paul Craddock for his encouragement in this study, Nigel Meeks for sharing his expertise in SEM imaging and analysis and Rachel Ward for photography. Also to Susan Stronge, the curator of the bidri collection at the Victoria & Albert Museums, London and to Graham Martin for AAS analysis and continuing interest in bidri patina.

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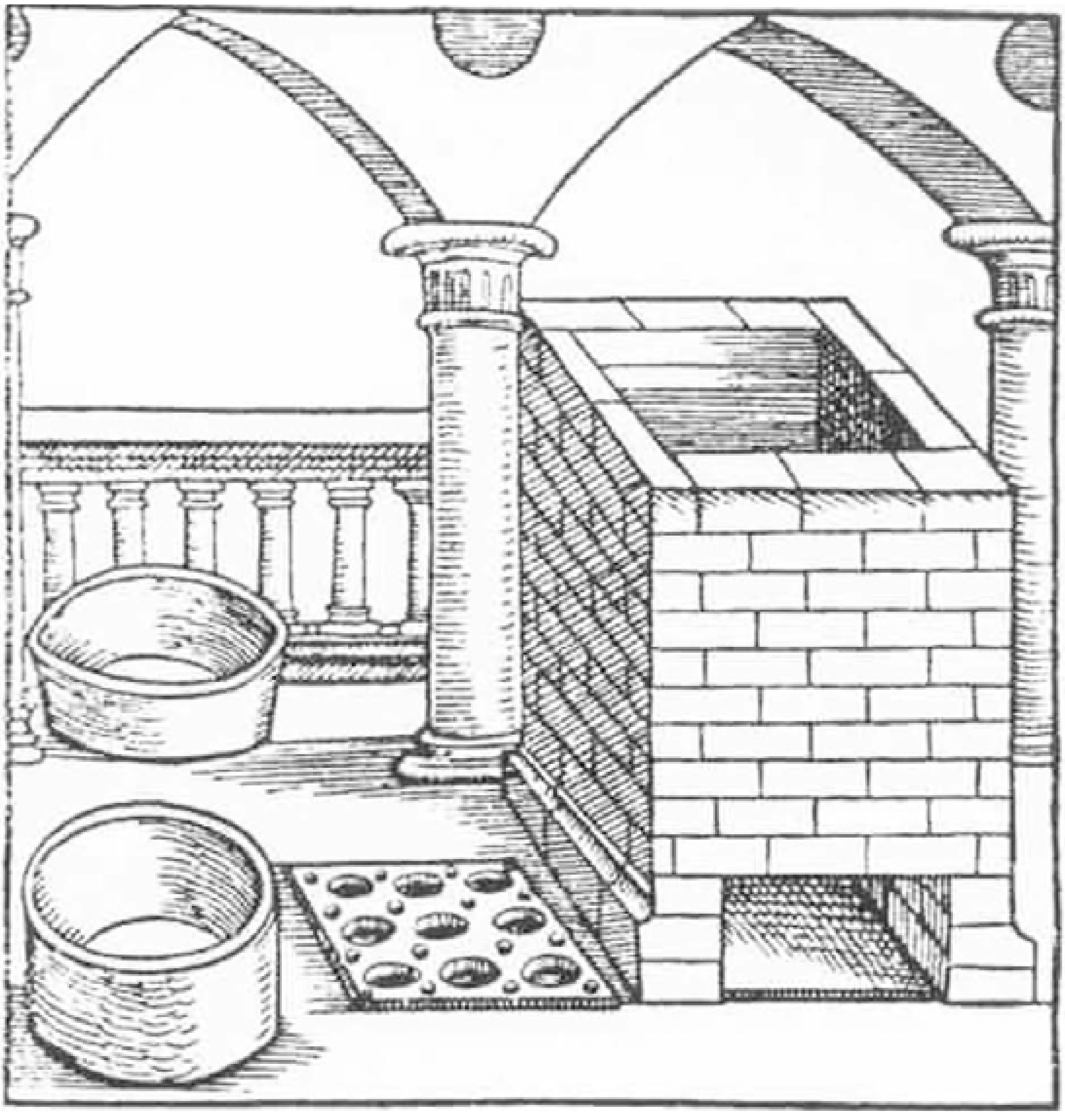
# Section V – Crucible Steel and Weapons



A furnace possibly in the form used for the production of crucible steel in medieval Iran and the surrounding region. Illustration from Jabir ibn Hayyan (see Russell, 1994, The Alchemical Works of Geber, 241).

*Brian Gilmour*

# New evidence for the early making and heat-treating of crucible steel: Kindi's iron treatise

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*ABSTRACT* An almost unknown treatise describing the making and heat-treating of steel made in small clay crucibles by the famous Iraqi scholar Ya'cūb al-Kindī (*c.* 800-870), hereafter referred to as Kindi, has recently come to light. This treatise was evidently compiled as a kind of technical appendix to Kindi's well-known sword treatise - written in Baghdad for al-Mu'tasim, the 3rd Abbasid Caliph (832-841). This gives details of many places, in the Middle-East and further afield, where crucible steel was made and compares the qualities of the metal from different places, but gives no information about how it was made, and very little about how it was treated (Hoyland and Gilmour 2006). This puzzling aspect of Kindi's first treatise is explained by the content of his second treatise on this subject which contains nine recipes for crucible steel and various details about how this should be heat-treated. The aim of this paper is to look at the content of Kindi's second treatise, to see how it compares to other surviving medieval and earlier descriptions or recipes for the making of crucible steel and the ways in which it was heat-treated, and also to consider the possible origin of Kindi's information and the antiquity of this method of steel making[1].

## **Introduction and background**:

We do not have very much evidence of how or when the exploitation of iron on any scale began, nor is it very clear when and how the production technology behind the development of steel making developed. Nevertheless it was clear to researchers, even a hundred years or more ago, that this technology developed along rather different lines in different regions of western, central and eastern Eurasia.

Once the use of iron became more widespread we also begin to get a few mentions of iron from written sources, but these mostly do little more than tell us that it existed and was of some importance. It is not until Kindi's sword treatise in the earlier 9th century that we finally can find enough surviving contemporary information to enable us to construct a framework for how iron and steel was made and exploited over much of the known world at that time. It is of great value not only for the light it throws on the Middle East and greater Iran, but also on India, and is also by far the most informative medieval source for understanding iron and steel manufacture and use in Europe. In his sword treatise Kindi is essentially giving us a snapshot of sword manufacture in the mid-ninth century Muslim world.

Kindi's sword treatise also tells us that steel-making and use had by then become specialised in different ways in different regions with crucible steel-making being by then in use in various parts of the Middle-East and central/southern Asia, as compared with the continued development and use of bloomery steel in Europe. However it is clear from other, less detailed written sources that crucible steel-making was already a well developed technique by early in the first millennium, if not before. By far the earliest description of the making of crucible steel is a single recipe written in Greek and attributed to the 2nd century Alexandrian scholar Zosimos of Panopolis (now Akhmim in northern Egypt).

'Take soft iron [malleable iron with low carbon content], four *librae*, cut it into small pieces; then take the date's peel that Arabs call *elileg*, 15 parts of weight and 4 parts of weight of *belileg*, without its core, i.e. its

[1] Kindi's sword treatise, its translation and contribution to the background study of early iron and steel into which it fitted has already been discussed in some detail (Hoyland and Gilmour 2006, Gilmour 2009). The aim of the present paper is to focus on 'work in progess' on the study of the recently rediscovered second Kindi treatise on iron and how it compares to other technical accounts of early crucible steel-making, as well as how it contributes to this area of study.

skin only, and also 4 parts of weight of *amblag*, emptied in the same way, and two parts of female *magnesia* of the glass maker, of which I told you previously; crush everything together but not too finely and mix with 4 *librae* of iron. Then, throw it into a crucible and smooth well the place for the crucible before heating it. In fact, if you neglect to do so as to ensure, that it does not move and stays there, it will cause problems during the melting process. Then add the charcoal and stimulate the process, until the iron melts and the (organic) substances are pushed into it. Four *librae* of iron require 100 *librae* of charcoal.

Remember that, if iron is relatively soft, there is no need for *magnesia* but only for the other substances [organic material]. In fact, *magnesia* makes it excessively dry and brittle. But if it is soft, it is necessary to use only that (*magnesia*), because it is better than anything else.

What we are doing today is the primary operation, worthy of a King, and creates marvellous swords. It was discovered by the Indians, then transmitted to the Persians and in fact from there it arrived to us' (translation by A Giumlia-Mair: see Giumlia-Mair and Maddin 2004, 132-133; but also see Berthelot, 1888 (reprint 1967), III, 332, Zosimos, Technical Treatises, V, 5)

We can summarise this recipe as:

'Take:

4 pounds of soft iron pieces
15 parts by weight of *elileg**
4 parts by weight of *belileg**
4 parts by weight of *amblag**
[*different organic components from date palms]
2 parts glass workers magnesia

Mix, then put into a crucible and heat until the iron [by now steel] is molten.

Zosimos also notes that this text is part of a batch which originated in Persia and which were 'translated under Philip's reign, King of Macedonia' which would place it to sometime between the time of the death of Alexander the Great in 323 BCE and the annexation of Greece following the end of the Macedonian dynasty at the Roman victory of the Battle of Pydna in 168 BCE (Giumlia-Mair 2009, 42; Giumlia-Mair and Maddin 2004). It is difficult to determine which of the King Philips of this period is being referred to, but in any case it seems likely that crucible steel making was already a well-established technology at least by the beginning of the 2nd century BCE.

Following this there are no known surviving descriptions for the making of crucible (or any other) steel before a description in the 'Book on Iron' attributed to the 8th century Iranian scientist Jabir ibn Hayyan (known in the West as Geber) which only survives as an extract quoted in the 14th century by Izz al-din al-Jildaki (d.1342):

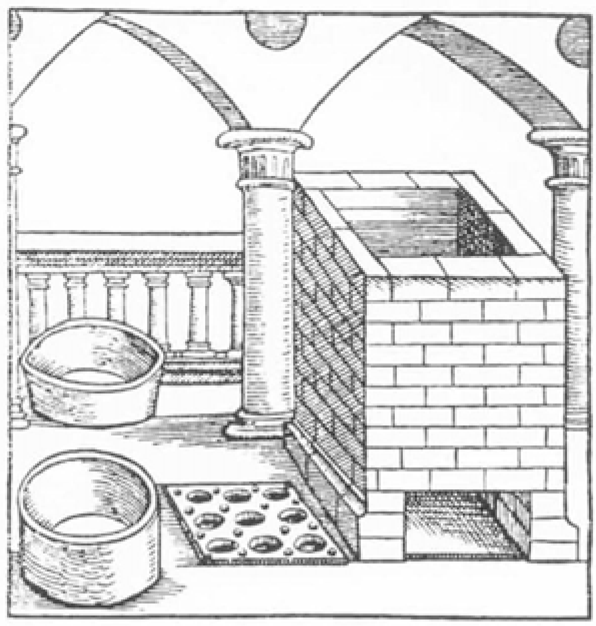

**Figure 1 (a)** A furnace possibly in the form used for the production of crucible steel in medieval Iran and the surrounding region. Illustration from Jabir ibn Hayyan (see Russell, 1994, The Alchemical Works of Geber, 241)

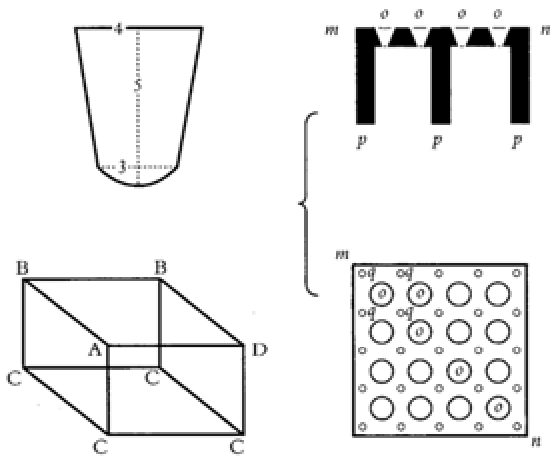

**Figure 1 (b)** Sketch from Massalski (redrawn) of crucible steel furnace he observed in Bukhara in 1840 (see Hoyland and Gilmour 2006, 119, Fig 18; Allan and Gilmour 2000, 535-539)

'Know, o brother, that your companions are those who cast iron in furnaces made specifically for it, after extracting it from its mine as yellow earth (the ore) in which scarcely visible veins of iron are mixed. (Beforehand) they put it in furnaces to smelt it and they set up over them powerful bellows from all directions after pounding these ferrous earths (ore) with a little of oil and alkali. And they fire it with hot coals (charcoal) and firewood and they use bellows on it until they find it has melted and that (as metal) its body and substance has become free from that earth. Next they let it out in drops through holes like strainers in those furnaces. Thus that melted iron is purified, and they induce (cast) it to become rods from that earth, and they transport it to the horizons and countries (i.e. far and wide) and the people use it for whatever human benefits they require.

As for steel specialists, they take the rods of (cast) iron and put them in (crucibles in) furnaces that are suited to the steel-treatment that they have in mind. They apply or blow fire to the furnaces for a long time (to the cast iron in the crucibles) until it becomes (molten) steel like bubbling water. They feed this with glass, oil, and alkali until there appears from it light in the fire and it is purified of much of its blackness by strong (or continuous) melting for the duration of a night and a day. They continue to watch its swirling for signs until its good condition is clear to them and (this is judged by) the radiance that shines from it. Then they pour it through channels so that it comes out as though it were running water. Then they solidify it like rods or in (moulding) pits of clay crucibles. It comes out as refined steel like ostrich eggs, and they manufacture from it swords, helmets, spear-heads and many other implements'[2].

Until the recent re-appearance of Kindi's second treatise on iron the only other main written source[3] for early crucible (or any other) steel was a chapter on iron in the book on mineralogy – the 'Sum of Knowledge about Precious Stones' – written by Muhammad ibn Ahmad al-Biruni (c 975-1050) probably towards the end of his life. This text is an undifferentiated mixture of much earlier (*c* 6th century) written information, mostly relevant to the Middle East, and contemporary (11th century) oral information from the general region – mostly north India – near his base at Ghazna in what is now eastern Afghanistan. Fortunately his descriptions from written sources can be matched to material from late pre-Islamic and early poetry, brought together by the 19th century German scholar Friedrich Schwarzlose, enabling the beginnings of a framework to be suggested for iron and steel manufacture and use in the Middle East in the late pre-Islamic and early Islamic period (see translation and commentary in Hoyland and Gilmour 2006, 148-174).

This is very helpful in understanding Kindi's sword treatise as it gives us some of the background to the manufacture of the iron and steel for swords in the Middle East, information that Kindi leaves out in his much more wide-ranging description which is mainly relevant to contemporary (i.e. earlier 9th century) practices. Biruni's iron chapter also gives some useful clues about the identity of some of the earlier sword-making centres in the regions further east, places not mentioned by Kindi, although probably already important by his time. For instance it now seems likely that one of the sources of high quality Indian steel and swords that were being brought to the Middle-East in Kindi's time was Kanauj in the Ganges region of central northern India. Biruni's text on iron is also particularly useful because he also uses information which must have come from earlier written sources (which unfortunately he does not name) when he mentions sword types such as the Mashrafi, from the Levant, which were much vaunted in late pre-Islamic and early Islamic poetry, but are unknown to Kindi.

## Kindi's treatise on the making and heat-treating of crucible steel

Among the many treatises composed by Kindi, preserved and listed by the bibliographical compiler Ibn al-Nadim (d. 380/990), are a series of miscellaneous works on things such as jewels, stones, glass, dyes, including two works relating to iron: 'the kinds of swords and iron' and 'that with which swords and iron are treated so that they are not broken or blunted'. The first of these clearly refers to Kindi's well known sword treatise which has also been referred to – in a note added to the Leiden manuscript version of this treatise – as 'On the description of swords and their kinds, which should be preserved' (Hoyland and Gilmour 2006, 8), the second referring to Kindi's treatise on iron crucible steel making and heat-treating.

This second treatise is the subject of ongoing research leading on from the recent translation of Kindi's sword treatise and related texts (Hoyland and Gilmour 2006) and the aim here is to serve as a progress report with the aim of giving some of the detail and the wider significance of what it means to the understanding of the manufacture of early crucible steel and the uses to which it was put, as well as suggesting where Kindi may have got his information.

There seems to be a widely held view that early crucible steel was made with the sole aim of producing sword blades or related artefacts with 'watered' patterns on their surfaces after suitable final polishing and etching, although there seems to be no real evidence to support this assumption. However it is clear from Biruni's chapter on iron that there were two main

2 This is a slightly simplified or interpretative version of the more literal translation given in Hoyland and Gilmour 2006, 144-145.

3 Four crucible steel recipes, plus some details on related heat-treatments are quoted in *c.* 1200 by Murda ibn Ali al-Tarsusi in his long treatise 'How to stay alive in battles' but it is clear that this and the surviving part of another crucible steel recipe – known as the Berlin mss – were simply extracts from Kindi's second treatise (Hoyland and Gilmour 2006, p 10-11. parenthesis).

varieties of crucible steel known at that time, one of which (after suitable finishing treatments) resulted in a watered or watery pattern, while the other resulted in a plain, i.e. pattern-free surface (Hoyland and Gilmour 2006, 164). The crucible steel recipes given in Kindi's second treatise can also be categorised in this way.

Overall Kindi's second iron treatise contains nine recipes for crucible steel as well as 28 assorted recipes and methods for heat treating (this) steel, the two main categories of crucible steel being as follows:

| | |
|---|---|
| Crucible steel recipe 1: | Crucible steel recipe 8: |
| [general purpose 'tool' steel] | steel for Indian swords |
| Take *narmahan* (soft iron) pieces | Take 1 *manna* (~ 2lb) in |
| add equal quantities of (inorganics): | small pieces each of: |
| Male magnesia (?$MnO_2$) and | *Narmahan* (soft iron) |
| Coral | *Shaburqan* (cast iron) |
| Tincal (borax - $Na_2 B_4 O_7$ ) | |
| Then add equal portions of | Add (inorganics): |
| (organics): | 1 *dirham* of magnesia |
| African rue salt | 5 *dirhams* of Andarani |
| Gall nuts | 6 *dirhams* of Khurasani |
| Acorns | borax |
| Mollusc shells | Plus (organics): |
| Plus some unsalted kernels | 2 *dirhams* myrobalan |
| Spanish flies | [cherry or plum stones] |
| [a well known aphrodisiac bitter | and a handful of sieved |
| *cantharides* made of | pomegranate peel |
| beetles wings] | It is melted as an egg |
| | [-shaped ingot] |

**Figure 2 (a)** Corroded remains (in the foreground) of a egg-like crucible steel ingot of approx 8th to 11th century date from Banbhore on the mouth of the River Indus; (a) as displayed in Banbhore Museum

**Figure 2 (b)** Enhanced to show better the form of the ingot: ingot measures approximately 5mm across (see Hoyland and Gilmour 2006, 122, fig 12)

## Discussion and interim conclusions

Two main conclusions have emerged from this research so far and these can be summed up as follows.

It has long been known and recognised that the main ingredients in the making of early crucible steel – as can be seen in the recipes given here – were of two types. The first involved the mixing of pieces of 'soft' (bloomery) iron together with organic matter (as the reducing agent to convert the iron into steel) together with other ingredients to aid this process. However this first process was varied, it seems inevitable that it would have resulted in a plain 'tool' steel, probably of excellent quality, but pattern-free since the iron pieces forming the raw material in the crucible would have been smelted at too low a temperature to allow the reduction and take up of small quantities of elements such as vanadium which are now thought to be responsible for the formation of the familiar watered patterns seen in crucible steels.

On the other hand for the second process the main raw materials to produce the liquid steel were 'soft' (bloomery) iron and 'hard' (cast) iron, the latter providing the carbon necessary to convert the former to steel. In this case the cast iron may well have been smelted at a high enough temperature and in reducing enough conditions for a proportion of (pattern-inducing) alloying impurities such as vanadium to be reduced into the metal, rather that ending up in the slag during smelting. This would in any case always have been dependent on the presence of impurities like this in the ore used to smelt the cast iron in the first place.

The other, perhaps rather more tantalising conclusion is the possible antiquity of these crucible steel-making processes, and hence the way(s) in which steel-making may already have become highly specialised by around the middle of the first millennium BCE.

If we combine the details of the crucible steel recipes we now have from Kindi's second ironworking treatise with the few early clues we already have from Biruni's iron chapter, combined with the references to early steel of this kind from pre-Islamic and early Islamic poetry, we can see that these recipes are likely to have been circulating in the eastern Mediterranean region between the late 6th and early 9th centuries. More specifically it would appear that Kindi knew of the 6th century Mashraf industry of southern Syria, and this may have been the source of some of the recipes he gives.

These recipes may in fact be much more ancient than this, given their remarkable similarity to the single surviving crucible steel recipe of Zosimos. Some, if not all, of these recipes may have been written down and have been quite widely known from at least the 2nd century BCE if not earlier. In this context it is noticeable that the description of cast iron and crucible steel making from Jabir ibn Hayyan's 8th century 'Book on Iron' (see above) is quite different in style and may owe little to this earlier tradition and may have been more of an 'eye witness' account.

More clues are slowly emerging as to the existence and detailed workings of crucible steel-making in the Classical and later Antiquity in the Eastern Mediterranean region. These are both in the form of written texts and archaeological evidence, such as the recent identification of a probable 4th century crucible steel hinge block from the Nabataean Temple complex at Khirbet –et-Tannur, about 25km south-east of the Dead Sea (Gilmour 2013, 139-143). This itself is a likely product of the Mashraf industry, which was situated in the Hawran region some 250 km to the north along the King's Highway, the ancient principal north-south route of this region (see McKenzie *et al* 2013, Vol. 1, xxvi, Map 3). Work on assembling the snippets of information from both Kindi and other sources is ongoing and it is hoped that this will start to make better sense overall in the near future.

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# Crucible steel in medieval European and Indian swords

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*ABSTRACT* Specimens from many swords of the Viking period (between the 9th and 11th centuries CE) with "Ulfberht" or related inscriptions have been studied by metallography in the Wallace Collection, as well as by WDXray spectroscopy at the National Physical Laboratory.

The steel that the makers of some of these swords used was a hypereutectoid steel which does not resemble any other swords made in Western Europe either before or afterwards. It was during this period that a Viking trade route between the Baltic Sea and Iran flourished, and the manufacture of these swords ceases when this route is closed. Their origin appears to be an early form of crucible steel from Central Asia.

There are, it may be observed, numerous written references to Indian swords by Medieval European writers, suggesting that another trade route (probably via Muslim Spain) was bringing the knowledge of Indian steel to Europe.

Many counterfeits of these swords were made, with variant spellings of the name "Ulfberht". None of these, nor indeed any later medieval swords (after 1000 CE) so far examined, show the use of hypereuctoid steels, so it may be deduced that their metallurgy correlates with the different spellings of the maker's name.

Some examples of Indian arms and armour (including a number from the Arsenal of Hyderabad) have been examined by metallography; the results of which are contrasted. Their microstructures show different forms of crucible steel, which have been further improved by various methods of heat-treatment.

## "Ulfberht" swords

There are around 100 swords with 'Ulfberht' - or variants on this name - inlaid into the blade. These have been found scattered all over Northern Europe. The largest concentration is in Scandinavia and the Baltic Sea, although it has been suggested that if *Ulfberht* was their maker then on linguistic grounds the source of their manufacture should lie in the Rhineland (Müller-Wille 1970). From the different forms of these swords, *Ulfberht* would have been active for 300 years, so it has been suggested that perhaps this was a family of smiths rather than an individual, or the name was a trade mark of some sort.

Some very early quantitative analyses of Viking-age swords have been undertaken. A number of swords were analysed for Petersen (1919). The highest carbon content (0.75%C) of those tested was 4690, an VLFBERH+T sword from Aker, Hedemarken. This has been examined again more recently.

## Swords with the inscription +VLFBERH+T

The first four of these results were presented at a British Museum conference in 2005 and published two years later (Williams 2007a). Since then the author has examined many more of these swords. It seems that those swords upon which the maker's name is spelt as +VLFBERH+T formed a metallurgically distinct group, with a much higher C% than other swords. Of them some were hypereutectoid, and the others eutectoid (Williams 2009).

Out of these 14 swords, 9 are made of hypereutectoid steel, or steels hypereutectoid in places. The others are all made of eutectoid steels, which might of course have come from a steel hypereutectoid in other places. So all 14 could have been made from a crucible steel, whatever the source of that might have been.

Swords with variant spellings show a wide variety of microstructures, but **none** of them have steels that are hypereutectoid.

*1. Museum for Hamburg History*

(M.1152, 11th century). An analysis (by one Dr.Schindler) was published in a Festschrift edited by Jankuhn (1951, 224). It was found to have a carbon content of 1.2%. No metallography was published, and the very high carbon content was not remarked upon.

*2. Württemburg Landesmuseum, Stuttgart, inv.no. WLM 1973-70*

The microstructure taken from a half-section at the broken end, consisted of pearlite and cementite, some at grain-boundaries, and some in needle-like form. This was made from a billet of steel which had been folded twice and forged out into a blade. The presence of these cementite needles may have led to a certain brittleness in the blade, as its end had been broken off. Its carbon content is around 1.2% - 1.4%.

*3. Museum für Hamburgische Geschichte; inv. no.1965/124*

Another river find, from the Elbe, from the same museum as #1.

A sample taken from the damaged edge, shows a microstructure of mostly fine pearlite with some cementite at grain boundaries, but no visible slag inclusions. Another taken from near the centre, at the broken tip, shows a microstructure of very fine pearlite. This is a steel of perhaps 1% carbon, or more, and so it is almost certainly a *hypereutectoid* crucible steel.

Microhardness centre 337-388; average = 355 VPH.
edge 439-476; average = 463 VPH.

It seems that this blade underwent more hot-working than sword # 2, and perhaps had a lower carbon content, for no cementite was observed in the form of needles within the prior austenite grains, but only at grain boundaries, or as laths, in a more equiaxed form. By contrast, the sword #4 seems to have undergone a little *too much* hot working. Electron microanalysis suggests that the inclusions are iron oxide. These three swords were published in Williams (2007a).

*4. Solingen, Deutsches Klingenmuseum; inv. no.1973.w.5*

A sample taken from the damaged edge shows a microstructure of what seems to have been pearlite which has been mostly divorced into carbide particles, and a network of particles outlining the prior pearlitic areas. There are very few slag inclusions.

Microhardness 243-277; average = 258 VPH.

This seems to be a steel which has been annealed, or undergone an excessive amount of hot-working. Since it seems unlikely that any sword would be intentionally softened by annealing, one may speculate that this was another *hypereutectoid* steel but it was somewhat overheated in working.

*5. Oslo Historisk Museum c. 4690 inventory*

It has an inscription which may be read as + VI F B E R H + T

Average surface hardness (body) 130 –180 VPH (nearer edges) 220-310 VPH.

An analysis of samples from this sword (by Refsaas) was published in Petersen (1919). The cavities left by his sampling are still visible on the surface of the blade. They were taken from the middle of the blade, which might explain why the carbon content in the published analysis (0.75%C) does not tally with that expected from the microstructure of the edge.

A sample was taken from the edge, at the broken end of the sword tip.

The microstructure consists mostly of pearlite, in areas surrounded with a network of cementite. In places, this cementite appears as laths within the areas of pearlite; in other places, the network has broken up into globules. There are a few slag inclusions. In parts, away from the edge, there are areas of ferrite also. These seem to become more frequent as one moves towards the areas from where the samples were taken.

This appears to be a *hypereuctectoid* steel, in places, which has undergone considerable hot-working (or even perhaps a deliberate anneal to soften it) which has caused the cementite to spheroidise in some parts. This may also have led to surface decarburisation, deliberately or accidentally. It may explain why the carbon content, according to combustion analysis of samples away from the edge, is only 0.75%C; but away from the surface, according to the microstructure, it is well over 1.0%C.

These results were sufficiently surprising to lead us to seek some_confirmation from another analytical technique, namely WDX carried out at the National Physical Laboratory, Teddington (thanks to Dr.Dipak Gohal).

*WDX microanalysis:* The carbon content from point analyses varied from 0.59% to 2.33%. An average of 15 points gave 1.4 %C, which is in accordance with the microstructure here.

*6. Bergen Historisk Museum 882*

It has an inscription which may be read as V L F B E R

H +…
[Read as VLFBERH+T by Lorange (1899)]
Three specimens were taken;

(i) A specimen from the body of the sword was examined. The microstructure consists of areas of fine pearlite, with a network of cementite, and no visible slag inclusions. This is a *hypereutectoid* steel of carbon content at least 1%.
Microhardness range 253 – 308 VPH. (average = 282)

(ii) Two smaller flakes from the edge were also examined. The microstructure of one consists of areas of fine pearlite, with some ferrite grains near the surface, and no visible slag. The microstructure of the other consists of areas of fine pearlite, with a network of cementite and some ferrite grains near the surface. There are also some unusual features, which on repolishing and re-examination at a higher magnification, turned out to be cavities, some of which still contain graphite flakes, and some of which are empty. In the surrounding area, the microhardness is higher there.This would appear to be the relic of an area of very high carbon content, which has contained primary graphite.

Local decarburisation near the surface might have occurred during forging.

Microhardness range 226-279 VPH.

*WDX microanalysis:* The carbon content from point analyses in the middle of sample (ii) varied from 1.72% to 8.96%. However, avoiding primary graphite, an average of 9 points gave 2.7 %C. This suggests an area which originated as **cast iron**.

*7. Bergen Historisk Museum 1483*

Only part of the inscription can now be read; …H + T
The microstructure consists of areas of fine pearlite, with a network of cementite, and only very few slag inclusions. This is a *hypereutectoid* steel of carbon content at least 1%.
Microhardness range 295-360; average = 327 VPH.

WDX microanalysis: The carbon content from point analyses varied from 1.22 to 2.69%, but, avoiding dendrites, an average of 6 points gave 1.3 %C, which accords with the microstructure.

*8. Bergen Historisk Museum 3149*

It has an inscription which may be read as V L F B E R + H T or V L F B E R H + T – two specimens were taken:

(i) from the edge
The microstructure consists of areas of fine pearlite, with numerous small equiaxed grains of ferrite and very few inclusions, which are not elongated, but there is no cementite network. This area is a medium-carbon steel of perhaps 0.5% overall. Local decarburisation must have occurred during forging. A low forging temperature might explain the small ferritic grain size.
Microhardness range 220-274; average = 231VPH.

(ii) from the body
The microstructure consists of areas of fine pearlite, outlined with a network of cementite, and no visible slag inclusions. This part is a *hypereutectoid* steel of carbon content at least 1%, which has been subsequently annealed.
Microhardness (Vickers, 100g load) range 204-286 VPH.
The lower carbon content of the edge may be the result of an imperfectly melted and homogenised crucible steel, or decarburisation due to excessive hot-working.
WDX microanalysis: The carbon content from point analyses varied from 1.09% to 6.19%. An average of 9 points gave 1.7 %C, if the $Fe_3C$ dendrites were avoided altogether.

*9. Helsinki Kansali Museum 9164:3*

from Eura. It has an inscription which may be read on one side as

+VL F …E R H +T; the character between F and E might be read as **b** or a distorted B.

The microstructure shows large areas of pearlite, of a feathery appearance, and almost irresolvable. There are no visible slag inclusions, nor areas of ferrite.

Microhardness range 417-476; average = 447 VPH.

The absence of slag inclusions may be significant. *If* this is another *hypereutectoid* steel, that has undergone some form of accelerated cooling, to form irresolvable pearlite (or perhaps even upper bainite) then the absence of visible proeutectoid cementite might be explicable.

Samuels (1999) shows a photomicrograph of a 1.0 %C steel which has been isothermally transformed at 450ºC for 1 minute to produce a fine pearlite/bainite microstructure with a hardness of 425 VPH.

A similar microstructure is also shown in a 17th – 18th century Indian sword from Hyderabad (see below); one specimen #10 showing very fine pearlite of 370 VPH. This is presumed to have been made much later from another crucible steel.

*10. Helsinki Kansali Museum 2548:839*

from Laitila. It has an inscription on one side which may be read as +VLFBERH+T .

The microstructure shows large areas of pearlite, lamellar in some places, but irresolvable in others. Some ferrite is present near one end of the sample as equiaxed grains, and in other places within the pearlite areas in a Widmanstätten formation.

There are also a number of large, irregular, slag inclusions.

This is a rather unusual microstructure, but it seems to be a steel of *varying carbon* content which has undergone a rapid air-cool.

Microhardness range 236-286; average = 269 VPH.

Out of these 10 swords, 8 are made of hypereutectoid steel, or steels hypereutectoid in places. Of the others, two specimens (#9 and #10) are eutectoid steels, and the carbon content of one (# 9) cannot be accurately determined, but was probably at least eutectoid. And, of course, the eutectoid steels might perhaps have come from a steel hypereutectoid in other places

It would have been very tempting to try and counterfeit these valued blades, and many

other workshops seem to have followed similar methods, which were already well-established in Europe.

Swords with their maker's name as a variant spelling show more diverse microstructures. The methods of their manufacture, the hardnesses attained, as well as the variant spellings, together suggest that they may well have come from other workshops, which were endeavouring to copy the high-carbon blades of the original "Ulfberht" workshop. One possible way would have been by welding small pieces of bloomery steel onto a billet of iron, and forging that into a blade before quenching it. The sharp edge that could be formed might well fool the less discerning customer, but with a depth of only a few millimetres it would not have survived many sharpenings.

## Summary

1. These H+T swords do not resemble later European swords in any way.
2. The making of H+T swords ceases around the time that the Volga trade route closes; this linked the Baltic to areas where crucible steel was made.
3. Only the H+T swords show hypereutectoid steels – none of their copies do.
4. There are written references in Indian swords in medieval Muslim Spain – collected by Dinnetz

Of course, a crucible steel does not have to be hypereutectoid – some of these H+T swords are eutectoid – as are many much later Indian swords.

## Muslim Spain

There are literary sources to support the contention that swords of crucible steel were appreciated in medieval southern Europe. The Franks valued Saracen swords, and one of Charlemagne's vassals captured '*spatha india cum techa de argento parata*" –Indian sword with a siliverscabbard

Count Eccard of Mâcon left a '*spatha indica*' an Indian sword in his will, as well as '*tabulas saraciniscas*' – Saracen pictures.

It has been suggested by the historian who collected these references (Coupland 1990) that this referred to a Saracen sword, but it may just as well have meant what it said, an Indian sword.

Dinnetz (2001) has collected numerous literary references to these blades in medieval Spain. We may quote, among others,

(i) Ibn al-Labbana (eleventh century) who referred to 'Indian swords'.
(ii) Abu Bakr al-Sayrafi (twelfth century) who suggested that Indian (*hinduwani*) swords should be used because they were sharper than other swords and better able to pierce the heavy armour worn by the Christian soldiers.
(iii) Al-Zuhri (twelfth century) who said that Seville produces 'Indian steel'.
(iv) Ibn-Abdun (twelfth century) who said that makers of scissors, knives, scythes etc. in Seville may only use [materials translated as] steely iron *mudakkar* or cast steel *amal al-tara'ih*.
(v) Ibn Hudhayl (fourteenth century) who described Frankish swords as *mudakkar* with 'steel edges on an iron body, unlike those of India'.

## Indian swords

An opportunity arose through the kindness of the family of the Nizam to examine a number of broken blades from the princely armoury of the Nizams of Hyderabad.

| Specimen | object | microconstituents | C% | VPH |
|---|---|---|---|---|
| 1 | dagger | F + P | 0.4 | 280 |
| 2 | dagger | F + P | 0.1 | 170 |
| 3 | sword blade | P + F | 0.5 | 210 |
| 4 | sword blade | TM | (0.9) | 515 |
| 5 | sword blade | P + C | 1.0 | 260 |
| 6 | sword blade | TM | (0.8) | 550 |
| 7 | sword blade | vfP | (0.9) | 300 |
| 8 | sword blade | TM + F | 0.8 | 410 |
| 9 | sword blade | F | 0 | 170 |
| 10 | sword blade | vfP | 0.8 | 370 |

The carbon contents are estimated; those in brackets, after normalisation.

The metallography of these specimens has been described elsewhere (William s, 2007b). A further group of samples from Hyderabad swords has recently been studied. Only the blades, and a shield, are discussed here.

| | | | | |
|---|---|---|---|---|
| 12 | shield | C + TM | > 1.0 | 455 |
| 13 | sword blade | F + P | 0.2 | 215 |
| 14 | sword blade | vfP | 0.8 | 290 |
| 15 | knife | C + P | > 1.0 | 415 |
| 18 | knife | F + P | 0.1 | 140 |

F = ferrite, P = pearlite, TM = tempered martensite, C = cementite, vfP = very fine pearlite

So 7 out of 10 of the swords (plus a shield and a knife) from the princely Arsenal of Hyderabad seem to have been made of crucible steels. None of them display the segregation of cementite that would have led to a “wootz” pattern, although the shield does. One out of the 10 is a wrought iron, and the remaining 2 are steels of low- to medium-carbon content. In each case, a sample was taken showing a complete cross-section.

Even accepting that this sample of swords would probably have been of higher quality than average, it is still remarkable that so many display such excellent metallurgy. Hyderabad may well have been making the best blades in India because of the decline of the Mughal Empire. If these blades were made for the retainers of the Nizam they are indeed of very high quality.

Numbers 4, 6, and 10 have all undergone some form of heat-treatment to increase their hardness from its already respectable level to a truly impressive one.

Hyderabad 12
is a segment from the rim of a circular shield.

A specimen was detached and mounted so that the shield was examined in section.

The microstructure consists of a groundmass of a ferrite-carbide aggregrate. This is irresolvable in places, and granular in others, but does not show a lamellar arrangement visible anywhere. (It might be tempered martensite)

Part of the cross-section occupied by cementite particles arranged in rows. This is evidently a *crucible steel* (perhaps between 1% and 1.5%C) which has undergone some form of heat-treatment to harden it. The parallel rows of the cementite suggest the original existence of a surface pattern.

Microhardness (Vickers, 100g) range 423-476; average = 455 VPH

Hyderabad 13
is part of a single-edged knife-blade.

A specimen was detached and mounted so that the blade was examined in cross-section. The microstructure consists of a fairly uniform mixture of fine-grain ferrite and pearlite (corresponding to a steel whose carbon content varies from 0.3% - 0.5%C) with very few, small, irregular inclusions. Could this be a 19th century European ingot steel? The photomicrograph was taken at about the mid-point of the blade.

A smaller specimen was mounted separately for microhardness testing.

Microhardness (Vickers, 100g) range 204-236; average = 215 VPH

Hyderabad 14
is part of a single-edged knife-blade.

A specimen was detached and mounted in two parts so that the blade could be examined overall in cross-section. The microstructure consists of uniform very fine pearlite, with a very few isolated grains of ferrite (corresponding to a steel of perhaps 0.7% - 0.8%C), and no visible slag inclusions. So this may well also have been a *crucible steel*.

A smaller specimen was mounted for microhardness testing.

Microhardness (Vickers, 100g) range 266-308; average = 292 VPH.

Hyderabad 15
is part of a single-edged knife-blade. Fig.1

**Figure 1** Blade no. 15 from Hyderabad

A specimen was detached and mounted in two parts so that the blade could be examined overall in cross-section. The microstructure consists of a groundmass of fine pearlite, with parallel rows of cementite particles. These rows extend to the cutting edge without appearing to be packed more closely at the edge, Fig.2

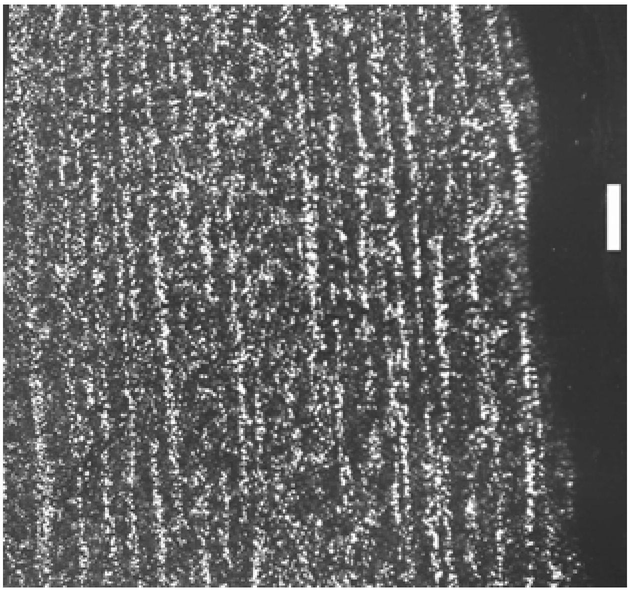

**Figure 2** A cross-section of blade 15 showing parallel rows of cementite inclusions in a dark-etching groundmass. Where these lines intersected the surface of the blade, a pattern could be generated after suitable etching.

but they are further apart at the back of the blade. Fig.3

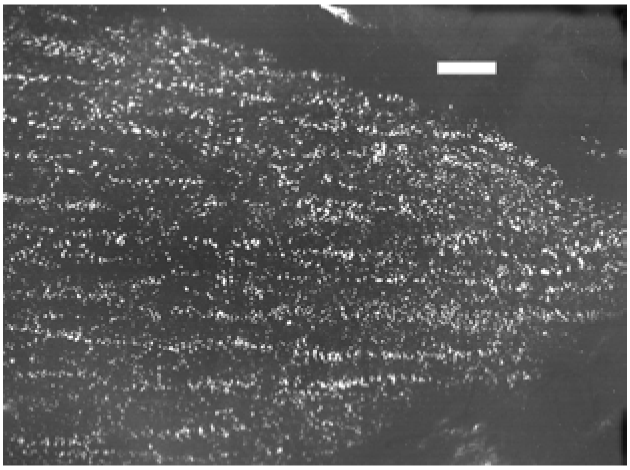

**Figure 3** A cross-section of blade 15 near to the edge. Note that the rows of cementite have not been moved together by forging. The edge has been formed by grinding

This is evidently a crucible steel (perhaps between 1% and 1.5%C) which has been forged to shape and the edge then finished by grinding. The parallel rows of the cementite suggest the original existence of a surface pattern where they intersected the surface. Fig.4

Microhardness (Vickers, 100g) range 397-434; average = 416 VPH

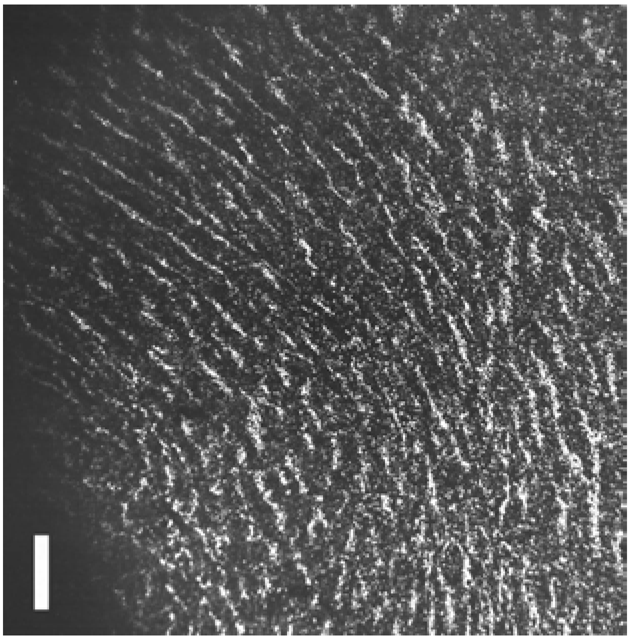

**Figure 4** A cross-section of blade 15 near to back showing the rows of cementite having been spread out by forging.
Scale bars 50 microns

Hyderabad 18

is part of a (two-edged) knife blade.

The microstructure is a fairly uniform mixture of ferrite and divorced carbides (corresponding to a steel of perhaps 0.1% - 0.2%C) with carbide–free bands in the center of the cross-section. Traces of a “ghost” microstructure are visible within the ferrite grains. After etching with Oberhoffer’s reagent, these features are accentuated. This knife has evidently been made by piling pieces of high-phosphorus and low-phosphorus iron together and forging them into a piled structure.

Microhardness (Vickers, 100g) range 129-185; average = 140 VPH .

The best examples of both show some form of heat treatment being employed. Retained austenite might pose a problem in steels of the highest C% - it is possible that an isothermal transformation was employed rather than a full quench. One may speculate that this was the secret of the swords ascribed to the smith known as Asadollah.

## Conclusions

Crucible steel is frequently discussed as if it were a single entity. It is becoming clearer - and conferences like this one have done much to clarify this - that there are many different methods of making it, with many different results.

Initially, it may have started as a means of "improving" a bloom by reheating it in a covered container, perhaps with medicinal herbs to help it recover its strength. Certainly, some loss of slag, and some gain in carbon would have improved the bloom, and encouraged the ironmasters to persist with the use of this technique. With longer periods of time in the crucible, enough carbon might have been absorbed to lower the temperature at which iron will start to liquefy (γ iron with 1% C at around 1350ºC, with 1.5%C at around 1250ºC). An ingot liquefied in places might have been the starting point for some of these Viking swords. Complete melting leading to an entirely homogenous product would have been a later development.

Ironically, the patterned swords esteemed in later centuries were the product of a less homogenous ingot – their "watered-silk" patterns depended on a very high C% and segregation of the cementite. The more splendid patterns may have been attained at the expense of the swords' toughness.

Those swords which were homogenous and successfully heat-treated seem to have been of a lower C%, which would have required a higher temperature to make. Without a distinctive surface pattern (other than a sort of "satin chrome" finish after etching), they may have commanded a lower price, despite being mechanically superior. What heat-treatments patterned swords were subject to is a topic for further research.

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# The analysis of Indian arms and armour at the Wallace Collection, London

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*ABSTRACT* The Wallace Collection in London contains nearly 1,000 items of princely historic Indo-Persian and Ottoman arms and armour, many made of 'watered' crucible steel (*wootz*). This paper gives an overview of the metallurgical research being carried out in the Collection's Conservation Department towards an illustrated scholarly catalogue to replace at last the current small un-illustrated 1914 publication. This work is on-going, but some interim results were presented at BUMA VII, including the results of XRF analysis, and the use of optical microscopy to investigate the way in which bloomery-iron was often combined with *wootz* for both practical and decorative purposes.

This paper is intended to be an overview of certain aspects of the research into Asian arms and armour currently being carried out in the Conservation Department of the Wallace Collection, Hertford House, London.

The Wallace Collection is home to the largest collection of Indian and Indo-Persian princely historic arms and armour on display in the whole of London. It opened to the public as a national museum in 1900, but began life as a private collection of paintings and art objects, assembled throughout the 18th and 19th centuries by four generations of the Hertford family and Sir Richard Wallace, illegitimate son of the last Lord Hertford. Wallace died in 1890 and his widow in 1897; their only son having pre-deceased them, the principal part of the family's art collection was bequeathed to the British nation, with the proviso that it should never be 'mixed' with any other works of art. The Collection today, therefore, is static; nothing has been added to it since 1890, and it therefore (importantly) contains no 'modern' fakes or forgeries. Even more significantly, most of the Indian arms and armour collection is known to have been acquired not by Richard Wallace but by his father, Lord Hertford, who died in 1870… so we can be fairly certain that relatively few of our Indian arms, armour and related works of art can have been manufactured later than 1870. In this respect the Wallace Collection has a considerable advantage over many other museums which have continued to acquire works of art throughout the 20th century, some of which are now turning out to be modern-made fakes.

For some time now, members of the in-house Conservation Department, in co-operation with a number of other scientific agencies and institutions, have been undertaking scientific analysis of the Armoury collection, and have also occasionally examined items from important collections in India and elsewhere. Techniques used so far have included optical microscopy, X-ray fluorescence spectroscopy (XRF) and (most recently) neutron diffraction. The results of this work, together with the culmination of nearly six years of conservation and detailed photography recording nearly 1,000 individual works-of-art, armour and weapons, will eventually be brought together to create a richly-illustrated scholarly catalogue of the Wallace Collection's Indian, Middle-Eastern and Ottoman arms and armour, designed to replace at last the old, small, un-illustrated and woefully out-of-date 1963 catalogue, itself a virtual reprint of the very first edition produced in 1914. The work of research and scholarship towards this new catalogue is on-going, but some of the interim results of the work to date was presented at the Buma VII conference in Bangalore in 2009.

Due to its small staff, restricted space, and inevitable budegetary constraints, the Wallace Collection is limited in what scientific analysis and research can be carried out in-house. The Conservation Science laboratory at Hertford House is not large and does not benefit from any individual funding of its own. The Conservation Department itself only consists of a conservation manager, one metalwork conservator, one furniture/woodwork conservator, and a conservation technician. Even so, with occasional assistance from interns and with the guidance of archaeometallurgist Dr. Alan Williams, the Department nevertheless maintains a research programme that belies its small size.

Although large and immediately impressive, it should be noted that the Armoury at Hertford House is also limited in certain ways. It was assembled predominantly as an art collection; neither Lord Hertford nor his son Sir Richard had any interest, so far as we know, in the military history of either Europe or the East. Their principal concerns were those of art connoisseurs, and the European and Oriental Armouries of the Wallace Collection are therefore found to contain arms and armour chosen predominantly for its fine craftsmanship and 'decorative art' characteristics. Many of the items on display were intended not for war but for parade, hunting and sport, or were made as 'high status' objects intended to reflect and enhance the social prestige, wealth and good taste of their owners. The weapons and armour of ordinary soldiers feature barely at all, and this can consequently sometimes 'skew' a researcher's perception. For example, the fact that a very high proportion of our 18th and 19th-century Indian blades appear to be made of 'watered' crucible steel (Verhoeven, Pendray and Peterson, 1992) does not necessarily mean that 18th and 19th-century 'working' armouries in India contained the same high proportion of such weapons.

The modern Wallace Collection Conservation Department (as distinct from its forerunner, the old 'Craftsmen's Workshop') was founded in the 1970s, but it is only in the last decade or two that its role in both carrying out, and publishing, scientific research has developed. Until relatively recently its resources for doing so were limited in the extreme. However, in 2006 the Collection was fortunate to acquire a hand-held portable XRF scanner, the X-MET3000TXR, made by Oxford Instruments. Surface-analysis by XRF is not suitable for historic ferrous metals but can be extremely useful as an approximate guide to the elemental content of non-ferrous metals. Its use has already radically corrected our knowledge in certain areas of the Collection… for example, XRF surface-analysis of much of the sculpture collection has confirmed that as is the case with most contemporary pieces analysed up to now , many magnificent Renaissance 'bronzes' were actually made using copper/zinc alloys… they are, in fact, cast-and-chased brass.

We have found XRF to be also particularly useful for finding out the composition of non-ferrous alloys prior to conservation treatment. Positive and detailed identification of the metal alloy is obviously of considerable use in deciding which conservation treatments should be used. For example, the heavily-tarnished foil-metal scabbard-mounts of a 19th-century Indo-Persian dagger (Wallace Collection inventory number OA2171) were surface-analysed using the XRF scanner and found not to be white metal, as the conservator had assumed from the tarnish, but a copper/zinc alloy (62% Cu/33% Zn). This information resulted in a significant change to the proposed treatment. Furthermore, although of limited use in the investigation of an Armoury collection chiefly comprising artefacts made from ferrous metals, XRF analysis has nonetheless sometimes been found to be useful in researching the construction and composition of decorative non-ferrous elements of armour.

The analysis of mail armour (often erroneously known as 'chain mail') has long been of interest to us. Although much research still remains to be done, aspects of European mail have been examined and analysed in some detail since the 1930s, but very little investigative work at all has been carried out on Asian mail (Edge, 2001). A recent Wallace Collection special exhibition on the history, construction and conservation of European and Eastern mail armour (Edge, 2010) provided new impetus for further research, however. Very little analytical work has ever been carried out on Indian butted-link patterned iron-and-brass mail, which is usually thought to date from the 18th or 19th century. Interestingly, very similar patterned butted-link mail is a major component of the mid-16th century Archduke Ferdinand II's '*alla Romana*' Italian-made parade armour for man and horse, preserved in the Hofjagd- und Rüstkammer, Vienna (Waffensammlung inventory number A783). Some years ago the author of this paper carried out metallographic analysis of a broken and thus discarded ferrous link from this important armour, which was found to be made of a drawn wire consisting of ferrite and slag. More recent metallurgical examination of links from much later, but similarly patterned Asian mail (including the Wallace Collection's Indian mail shirt, OA1886) have produced virtually identical results.

Much European mail dating from the 15th and 16th century is ferritic in nature, but evidence has also been found of pearlitic structures and (albeit very rarely) martensite. In Asia, ferritic mail with high levels of slag seems to predominate, although better-quality mail can occasionally be found amongst the armour made for high-ranking warriors and the ruling classes. A link of mail from a *dastana* (arm-guard) once belonging to Shah Shuja and dated 1733-4 (Victoria & Albert museum inventory number 190-1904) was analysed some years ago at the Wallace Collection and found to be a pearlitic steel (although the pearlite was extremely coarse and mixed with much ferrite, giving a carbon content of 0.4% at the very most).

As yet, no Eastern (or indeed European) crucible-steel mail has been discovered, but crucible-steel blades (La Niece, Hook and Craddock, 2007) and Indo-Persian plate armour made from this material are well-known. Despite the uses to which we have been able to put our XRF scanner in recent years, it would nonetheless be fair to say that optical microscopy remains our principal analytical tool in the Armoury of the Wallace Collection, and it is this analytical technique that we have been using in our investigations into Indian armour made wholly or in part from crucible steel. Through optical microscopy (for which we are still chiefly reliant on a robustly-built vintage 1970s Vickers metallurgical microscope), we are currently pursuing a number of different research-strands, one of which is described below.

**Figure 1** Indo-Persian *char-aina* body-armour plate *c*.1850, mounted for metallography. Its outer surface is decorated overall with gold *koftgari* damascening, but the applied rim is only thus decorated at the corners and around the rivet-heads. (Wallace Collection inventory number OA2201)

For some time collectors, dealers, and museum curators have noticed that many items of 16th-19th century Asian and Middle-Eastern plate-armour appear to show evidence of a 'pieced' construction. To create a single plate of armour, a number of sections have been fixed together and then decorated on the outside to conceal visible evidence of the join. This feature has been observed in shields, helmets and in other parts of armour such as arm-guards (*dastana*). To corroborate this supposition, nearly one hundred 17th, 18th and 19th-century decorated Indo-Persian items of armour in the Wallace Collection were examined using a simple binocular microscope, and a majority of them did indeed appear to have been made in this way. We surmised that what we were seeing was a combination of 'watered' crucible steel and bloomery-iron, riveted and forge-welded together, with the ferritic material only being used for areas like the borders, which being damascened with gold (*koftgari* or *kuftgari*) were never therefore intended to reveal a 'watered' steel surface. Plain steel areas (usually the centres of the plates) often showed evidence of being made from a 'watered' crucible steel, glimpses of the 'watered' pattern often still being visible even on very worn and scoured (over-cleaned) objects.

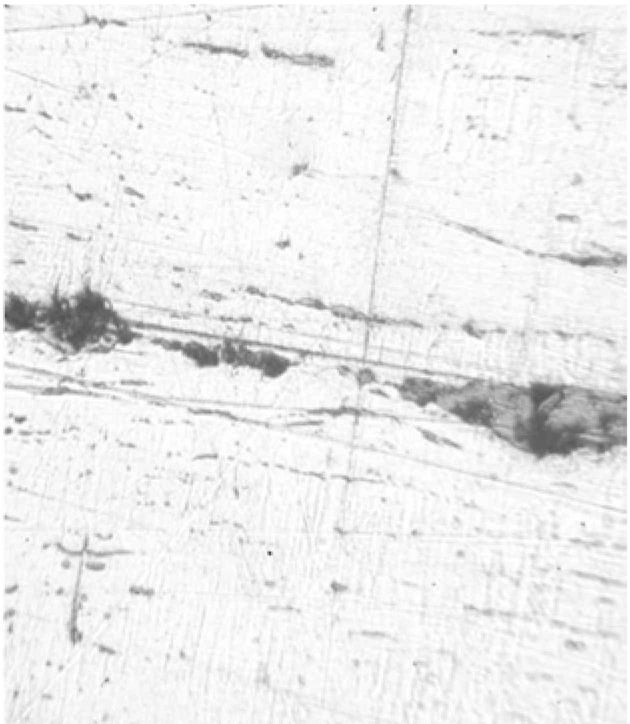

**Figure 2** Photomicrograph (*magnification approx. x160*) of the gold-damascened main plate of *char-aina* OA2201, revealing it to be made not of crucible steel but of fairly low-quality ferrite. Note the presence of slag inclusions; by comparison, the metal of the applied rim is almost slag-free

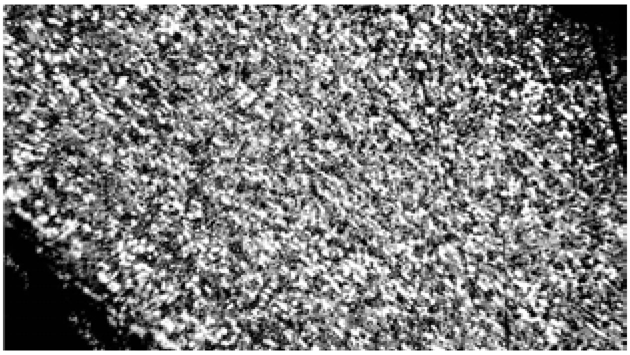

**Figure 3** Photomicrograph (*magnification approx. x160*) of the applied rim on *char-aina* plate OA2201, revealing the rim (only) to be made from a hypereutectoid crucible steel

Although curatorial policy at the Wallace Collection frowns upon taking samples or sectioning works of art for analysis, where an item possesses a cut edge it is sometimes possible to mount the entire artifact for microscopy, only polishing and etching a corner or section of the edge for metallography, and thus avoiding any need to physically detach a sample. This was undertaken, with curatorial sanction, for a richly-decorated Wallace Collection *char-aina* plate of body armour, its outer surface damascened overall with gold *koftgari* (Wallace Collection inventory number OA2201). The back of this armour plate would originally have been covered by a textile lining but this was now missing, so it was therefore possible to ascertain that the armour was made from one single rectangular plate with no evidence of any joins or a more complex 'pieced' construction. However, it was also furnished with an applied rim consisting of a more sparsely-decorated strip of ferrous metal running around the outside, riveted in place with small ferrous rivets; the corner edge prepared for metallography therefore consisted of both the main plate and the separately-applied rim [Fig. 1]. Interestingly, metallography revealed that the main plate of the armour consisted of ferrite and slag [Fig. 2] whereas the applied rim was made from a hypereutectoid crucible steel [Fig. 3]. A photomicrograph of the latter taken at higher magnification clearly shows the cementite particles of the rim segregated into bands [Fig. 4], which would create the famous 'watered' appearance of the crucible steel. Since the rim was only sparsely decorated, the distinctive appearance of the crucible steel would have been visible, perhaps deliberately (but dishonestly) giving the impression that the entire plate was made of this material.

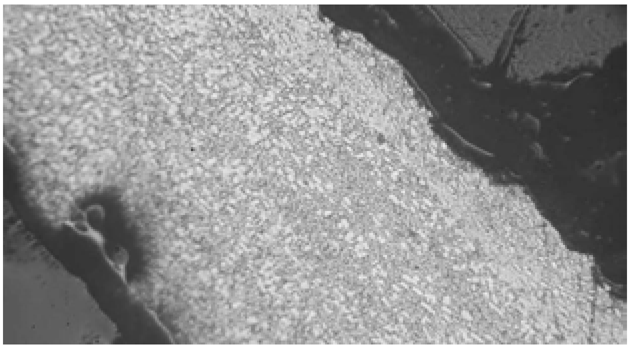

**Figure 4** Photomicrograph (*magnification approx. x800*) of the applied rim on *char-aina* plate OA2201, clearly showing that the cementite particles are partly segregated into bands which will generate a pattern when they intersect the surface, thereby creating the famous 'watered steel' effect so highly valued in arms and armour

Wallace Collection museum curatorial policy, however, means that works of art in the Collection are not permitted to be analysed 'destructively', so it was not possible to take a sample from the centre-back of the OA2201 plate, to corroborate the results obtained from the edge. It was accordingly decided to widen our investigations to include similar items in other collections. For comparison, therefore, a private collector (TP13) was persuaded to lend a second *char-aina* plate of Indian armour for analysis, this probably dating from the late 18th or very early 19th century [Fig. 5]. Unlike the Wallace Collection example, the outer face of which had been completely covered with gold-damascened (*koftgari*) decoration, this plate was decorated with gold only around the edges to a width of 4 or 5 cms, the central part of the plate being left plain steel. From the inside, the evidence of a 'pieced' construction was clear. This plate, too, had been edged with a thin beading of ferrous metal, applied like the first plate by means of a series of small rivets or nails... however, close examination indicated that it had probably been entirely gilded with no ferrous metal being left visible. By mounting and examining one corner of the plate we were able to ascertain the metallurgical composition of both the border of the main plate and its applied rim. In contrast to the Wallace Collection plate, analysis revealed that both the main plate-border and the applied rim of the TP13 *char-aina* plate consisted of ferrite and slag [Fig. 6].

**Figure 5** Indian *char-aina* body-armour plate *c*.1800, mounted for metallography. Its outer surface is decorated with a border of gold *koftgari* damascening, but the central area of the plate (now showing signs of corrosion) has been left undecorated. (Private Collection inventory number TP13).

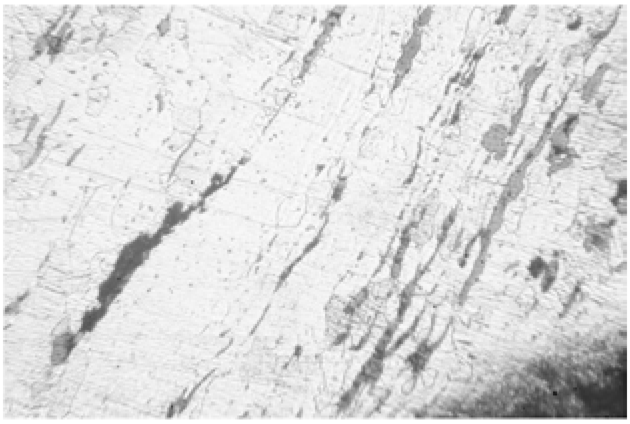

**Figure 6** Photomicrograph (*magnification approx. x160*) of the gold-damascened border of *char-aina* TP13, showing it to consist of ferrite and slag. Despite its rich decoration, the metal is of poor quality, with even greater levels of slag than that seen on OA2201. This *char-aina* is also furnished with an applied rim, but the metal of the latter is ferrite and slag too, virtually identical to that of the main border

Visual examination of the back of the plate, however, had indicated that it was made not of one single sheet of metal but of a central rectangular portion surrounded on all four sides by strips of ferrous material partly forge-welded and partly riveted to the central portion. From the outside it was difficult (though not impossible) to follow the line of the joint, the applied strips being decorated over their exterior with gold *koftgari* up to the very line where they were joined to the un-decorated central rectangle of metal. With the owner's permission, samples were taken from the back of the central area to see whether it was made of the same material as the outer border strips. A fine engraver's chisel was used to remove two small curls of metal barely 2mm long; these specimens were duly mounted in polyester, polished, etched, and subjected to optical microscopy, which revealed that the central panel of the *char-aina* plate was in fact made from a hypereutectoid crucible steel, albeit one that probably did not have a marked pattern [Fig. 7].

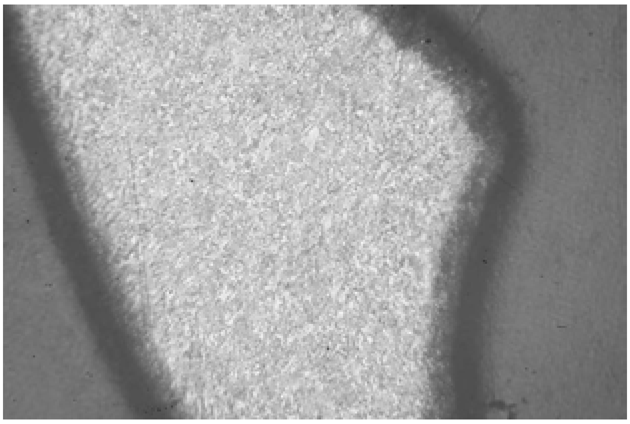

**Figure 7** Photomicrograph (*magnification approx. x160*) of one of a number of samples removed from the reverse of the central (undecorated) area of *char-aina* TP13, revealing it to be made from an (approximate) eutectoid crucible steel. The photomicrographs taken of these samples mostly reveal the presence of divorced pearlite, but once again there is very little visible evidence of any slag inclusions

To further corroborate these results, it was decided to examine a completely different category of Indian armour, a helmet [Fig. 8]. Again from a private collection (JB1), but similar in all respects to a large number in the Wallace Collection, this late-18th century Indian helmet demonstrated the same characteristics of construction as the two *char-aina* plates examined thus far. Again there were problems taking samples, but this time the problem was a practical one; although it was possible to mount and examine the edge without causing visible damage (other than polishing a small section of the rim), the only effective way to examine the material of the upper central dome of the helmet was to physically remove a sample of the metal for analysis, and the helmet's owner naturally required any such sampling to be invisible to the naked eye. Attempts to remove metal from inside the helmet-skull failed, but careful examination revealed that the helmet's central plume-holder, surmounting the dome of the skull, was only secured with three small brass rivets which were easily released, enabling a small sample of metal to be removed with a jeweller's saw from underneath. This sampling was then completely invisible from the outside once the plume-holder had been re-riveted back into position.

**Figure 8** Indian helmet dating from the late 18th-century. By detaching the plume-holder, a sample could be removed for metallography from the very top of the helmet skull underneath it. Once the plume-holder had been re-attached, no evidence of this sampling was visible from the outside. (Private Collection inventory number JB1)

The results of the helmet analysis corroborated those of the two *char-aina*. The helmet was constructed from two sheets of metal, the lower section running around the rim to a depth of 5 or 6 cms being composed of ferrite and slag [Fig. 9], and the upper area of the skull being a crucible steel [Fig. 10]. As with the two *char-aina*, the ferritic lower band of the helmet was covered on its exterior with gold *koftgari* damascened decoration, whereas the crucible steel upper helmet-bowl had been left undecorated. The join between the two materials appeared in this instance to be more the result of skilful forge-welding rather than riveting [Fig. 11], although the presence of ferrous rivets, disguised on the inside by heavy working and on the exterior by the over-lying gold *koftgari* decoration, cannot be entirely ruled out.

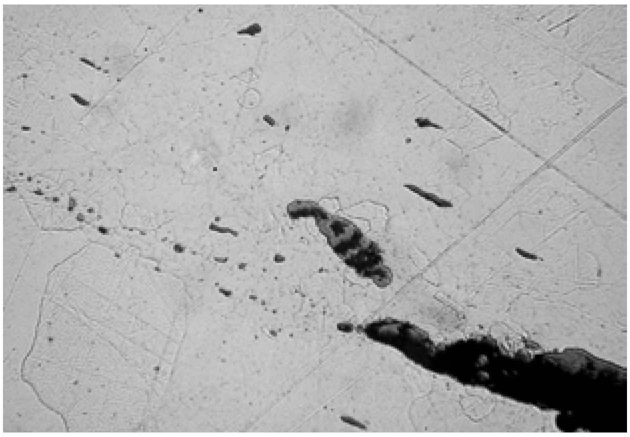

**Figure 9** Photomicrograph (*magnification approx. x160*) of the rim of the gold-damascened border around the base of helmet JB1, showing it to have been made of plain iron rather than steel. As with the other items of Indian armour examined, this ferritic area was high in slag, in complete contrast to the central undecorated area made from crucible steel

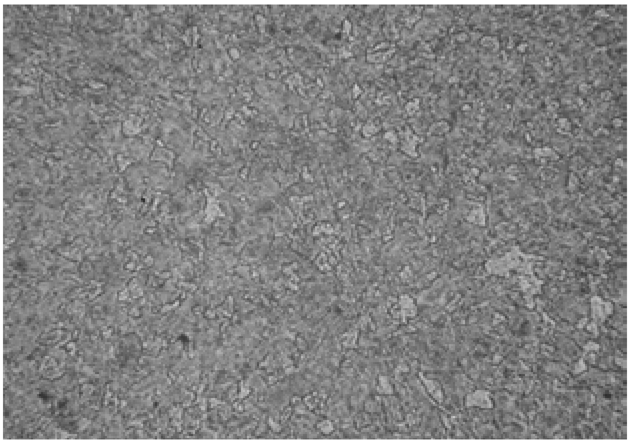

**Figure 10** Unlike its lower border, the upper (undecorated) bowl of helmet JB1 is made from a hypereutectoid crucible steel. This photomicrograph (*magnification approx. x160*) shows a random mix of pearlite and cementite; the latter is not ordered in any way, so it is unlikely that any 'watered' pattern would have been visible on the armour's surface when new

**Figure 11** This view of the interior of helmet JB1 shows the two-piece construction of the skull, and the lap-welded joint between the ferrite of its lower border and the crucible steel of the upper helmet-bowl. There is little visible evidence of this seam being reinforced by rivets (only one potential rivet can be seen, right of center); the four bright spots on the left are copper-alloy rivets securing a plume-holder applied to the outside

In conclusion, it seems that on Indian armour of this type iron was only used for areas like the borders, damascened with gold and not therefore intended to reveal a metallic ferrous-metal surface, while the areas made from crucible steel were usually left undecorated so as to reveal the nature (be it the distinctive patterning, or the colour) of the steel. This 'pieced' construction has been noted on many occasions by scholars, but as far as we are aware, this is the first time that metallographic analysis has been carried out on such armour to confirm this construction technique and the reasoning behind its employment. The above results seemed to bear out our hypothesis that crucible steel was often used sparingly, and was valued for its appearance as much as for its hardness and strength. It is also apparent that the difficulties of forge-welding this material to ferritic iron seem to have been overcome by craftsmen in India (and probably also in the Middle East). The use of crucible steel seems relatively widespread in the East from an early date; its centres of manufacture (Craddock, 1995), and the network of trade-routes whereby it was distributed far and wide (Bronson, 1986), have long been studied and discussed. In contrast, European metal-smiths do not seem to have mastered the necessary skills and knowledge to work crucible steel itself, still less combine it with other ferrous metals, and crucible steel remained an extreme rarity in medieval as well as post-medieval Europe. Only relatively recently has evidence emerged that this raw material might well have been traded up into north-western Europe as early as the ninth century AD, albeit probably on a relatively small scale (Williams, 2009) and only to those very few smiths capable of working such a specialised material.

It is well known that the physical working and shaping of crucible steel is extremely difficult and in blacksmithing terms, counter-intuitive, in that the metal must be worked at a low-red heat rather than following the normal practice with wrought iron which is to work it at as high a heat as possible (cherry red to white-hot). At such high temperatures, obtaining a good forge-weld between two pieces of wrought iron is quite easy, but the welding of crucible steel to iron requires very much more skill and practice. This skill the Indian metal-smiths seem to have developed to an extremely competent degree; both the composite structures of the *char-aina* plate and the helmet described here showing evidence of an extremely close-knit and regular weld-line, although of the two the helmet (JB1) was the most competently constructed. Not all surviving examples of armour constructed in this way are as neatly made, however. Visible flaws, cracks and join-lines occur in very many instances, and it is commonplace for craftsmen to disguise' such flaws by decorating over them. This can be seen even on items of otherwise high-quality workmanship and rich decoration... for example, a shield in the Wallace Collection (inventory number OA2188). One of the finest in the Collection, it is likely to have been made in Lahore for a nobleman at the court of Ranjit Singh, founder of the Sikh dynasty in the Punjab, in about 1840. Gold *koftgari* animals, foliage and figures, progressing in an unbroken band around the outer border, conceal flaws in the welded join between it and the centre. Occasionally, the irregular line of a flaw is simply covered with gold, to produce a random, asymmetrical 'squiggle'. This seems to be perfectly acceptable practice in terms of the design and marketability of such objects, and similar examples of armour thus decorated can be found in virtually every significant collection of historic Asian armour across the world.


**Figure 12** The skill of Indian metal-smiths in working crucible steel can be deduced from this forge-welded joint in an Indian *tulwar* sword-blade, made in about 1800. The joint, formed as a chevron, can be faintly seen between the 220mm and 235mm points of the measure. Traces of the original 'watered' crucible steel pattern can still be seen in the surface of the blade. (Author's collection).

The fact that Indian crucible steel can be welded at all is evident from the examination of Indian sword blades, some of which seem to have made from more than one ingot or billet of crucible steel, the two lengths of metal being joined with a lap-weld, sometimes taking the form of a chevron. The crucible-steel blade of an Indian *tulwar* in the author's possession shows evidence of just such a construction [Fig. 12]. In 2007, a number of museum colleagues accompanied the author on a research trip to India (Edge and Kitto, 2007). During a visit to the Alwar Palace Armoury in Rajastan we discovered a number of swords having crucible-steel blades clearly welded together from two, and occasionally three, equal-sized pieces… suggestive of a manufacturing technique, surely, rather than 'repairs' carried out to make broken blades whole. Intrigued and inspired, upon our return a swift search amongst the fine collection of Indo-Persian edged weapons on display in the Wallace Collection quickly revealed the hitherto unknown presence of at least one blade with the self-same feature, exactly like those in Alwar. Whether this was a method of construction or a common mode of repair, of course, is not absolutely certain, but sword blades made in this way are sufficiently numerous that the skill of the Indian metal-smiths who made or worked on them cannot be in doubt.

The excavation of crucible-steel production sites (Feuerbach, Merkel and Griffiths, 1997) has indicated that ingot sizes generally seem to be quite small, potentially limiting the size of artefacts that could be made from them; however, the ability of Indian smiths to weld ingots or billets together in such a way as to avoid destroying any 'watered' pattern in the steel might radically alter that picture. Even if one were not concerned to retain its 'watered' characteristics (and we must remember that not all crucible steels necessarily *have* a pattern) the working of crucible steels in general was and still is very much in the hands of specially-skilled craftsmen. There is still much traditional knowledge lying untapped in remote corners of the world, and perhaps the only way to access it is to physically go there... it is certainly intended that we at the Wallace Collection should continue to maintain and develop closer links with India, and attempt to tap into the enormous potential of 'living' knowledge held by craftsmen who still practice the traditions of their forefathers (Edge, 2007).

Despite the overall success of our current research programmes, as described in this paper, one of the principal problems with the further analysis of Indian arms and armour in the Wallace Collection remains the (perfectly understandable) curatorial concern about the 'destructive' nature of metallography. We are always keenly interested, therefore, in any analytical techniques that profess to be entirely non-destructive. One such technique is neutron diffraction. Accordingly, in March of this year a team from the Wallace Collection visited INES (the Italian Neutron Experimental Station) at ISIS, the pulsed neutron source of the Rutherford Appleton Laboratory in Didcot, just outside London, to investigate whether neutron diffraction might be used as a non-invasive method for estimating the carbon content of the high-carbon steels so often encountered in Indian swords and armour. We compared the results of metallurgical analyses already undertaken in the Wallace Collection's Conservation Department laboratory on broken and damaged Indian sword and dagger blades from Hyderabad (Williams and Edge, 2007), with results obtained on the same sword fragments at INES. Unfortunately, the results showed some discrepancies; this is certainly a promising technique, but more work needs to be done to calibrate it… work which is on-going, with the support of our colleagues in Europe.

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# Section VI - Ethnoarchaeology and Metals

Chola Nataraja, Kankoduvanithavam, Tanjavur District, Government Museum, Chennai, with 8% tin and 9% lead showing details in high relief suggesting that not much post-cast tooling was done

*Sharada Srinivasan*

# Bronze image casting in Tanjavur District, Tamil Nadu: ethnoarchaeological and archaeometallurgical insights

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*ABSTRACT* The profusion of metal images made in the Tanjavur region, going back to the early medieval Chola bronzes of the 9th-13th century ranks amongst the finest of Indian artistic expressions. Clusters of artistic and artisanal activities have thrived over generations in the Tanjavur district including metalworking workshops for bronze and bell metal casting of images and ritual objects especially around Swamimalai and Kumbakonam. Ethnometallurgical and archaeometallurgical insights on the making of icons at Swamimalai are highlighted from observations made over the past couple of decades, especially in relation to making comparisons with historical practices of bronze casting going back to Chola times. Since the processes are rapidly undergoing change, to get a better sense of the trajectory of past practices, this paper particularly aims to highlight unpublished observations made by the author going back to her first visits in 1990-1, as background to her doctoral work (Srinivasan 1996) and in relation to observations reported by other scholars going back to the early landmark efforts of Reeves (1962). These observations were particularly made by the author at the workshop of late master craftsman Devasena Sthapathy, in his time the most renowned of Swamimalai Sthapathis. His son Radhakrishna Sthapathy has now inherited this mantle. While Levy et al (2008) give a more recent account of image casting at the workshop of Radhakrishna Sthapathy, this paper attempts to also contextualise the previous trajectory that has not been covered much therein. Since their workshop now goes under the name of Sri Jayam Industries, for the sake of convenience it will be referred here by the same name.

## Sthapatis of Swamimalai and social history

In medieval south Indian temple worship, following Hindu *agamic* traditions, metal images were made as *the utsava murti*, i.e. images that were exclusively intended to be used in processional worship. While the Imperial Chola who ruled from the 9th to 13th centuries were predominantly worshippers of the Hindu god Shiva, they also patronised Buddhism, Jainism and temples to the Hindu god Visnu and hence a diverse range of images are found from this period. In the lost wax process or investment casting process, the image is cast by first making a model in wax, and then investing it with moulding material to form a mould, which is then heated to expel the wax. Finally the molten metal is poured into the hollow to solidify into the metal icon. The Sankrit phrase *'madhuchchehistavidhanam'* refers to the lost wax process and is described in the artistic treatise of the Manasara of the 4th-5th century (Reeves 1962: 29-31).

The Tanjavur district of Tamil Nadu, the former Chola heartland, still has traditional families of *Sthapatis* or icon manufacturers of the status of *silpacari* (or art teachers), who make lost wax images. In the 60's, in her comprehensive work, Ruth Reeves observed over a hundred families engaged in making lost wax images in Tamil Nadu, and as many as fifty of these in the Tanjavur district (Reeves 1962: 101). Today there are far fewer families, mainly clustered around the village of Swamimalai, on the banks of the Kaveri river,and close to Tanjavur (30 km away). Traditionally speaking, South Indian bronzes were most often solid casts whereby the model was made of a single piece of wax with no clay core. This preference, despite the greater amount of metal required compared to hollow cast images, seems to have been based on ritualistic reasons. The process of casting images by the Sthapatis at Swamimalai also generally follows the solid lost wax process, although the hollow casting process is also now more widely in vogue to cast larger images. An early Chola inscription (Sivaramamurti 1963:14) describes the gift of an image of a deity which was *ghanamaga* or dense and heavy and of a *chcheyda rishabha* or hollowed bull. In a fine metaphoric poem, Tamil women poet-saint Andal (*c.* 800) compares rain clouds to the mould holding wax to be expelled (Dehejia 2002:13) : this demonstrates that the process was widely known.

## Alloys past and present

In recent times the alloying compositions used by the master craftsmen in Swamimalai seem to be more akin to brass, going back to the 60's and 70's. Reeves (1962: 108) observed that alloys of 75 wt. % copper, 15 wt. % brass, and 5 wt. % tin were used by South Indian icon manufacturers. In another comprehensive study, Krishnan (1976:17) found that an alloy of twenty parts copper, four parts brass and one part lead was used at Swamimalai. During the researcher's field visits to the workshop of Sri Jayam Industries in 1990, the late master craftsman Devasenapathy Sthapathy indicated to her that they used an admixture of industrial ingots labelled as '15% brass, 82% copper and 3% lead' for image casting (Fig. 1 ). Presumably, here brass referred to an alloy of copper and zinc. A small image of Ganesa was cast by him for the researcher in 1990 (Fig. 2). A sample collected by micro-drilling with a 1mm drill bit was analysed by her by Atomic Absorption Spectroscopy at Institute of Archaeology, London in 1992-3 and was found to contain 84 wt. % Cu, 7 wt. % Zn, 5 wt. % Pb and 0.4 wt. % tin. Craddock (2007) reported that during his visits to the Sthapatis of Swamimalai, they claimed to use an alloy that contained zinc, tin and lead, whereas in fact an alloy procured from them was found to have 10% zinc, 4% lead and 1% tin. Although the date of these communications and procurement is not clearly indicated, it also reinforces the idea that in recent times leaded brassy alloys appear to be used.


**Figure 1** Industrial ingots at workshop of late Devasena Sthapathy of Swamimalai (1990) which they said was used for making icons, with ingots labeled as 82% copper. 15% brass and lead 3%

**Figure 2** Image of crawling baby Ganesa (the elephant-headed god), 8cm, cast as a *panchaloha* icon for Srinivasan by late Devasena Sthapathy of Swamimalai in 1990 found to have 84 wt. % Cu, 7 wt. % Zn, 5 wt. % Pb by AAS

On the other hand, investigations by the author- as previously reported in Srinivasan (1996, 2004, 2012)- indicated that a majority of the South Indian medieval bronzes were of leaded tin bronze. These investigations were undertaken on micro-drillings extracted from the bronzes using drill bits of 1-1.5 mm of tungsten carbide or HSS and which underwent dissolution for ICP-OES analysis. Analyses by such methods are usually regarded as being more representative of bulk analyses than other methods techniques like XRF. About 80% of 130 south Indian images analysed by the author (Srinivasan 1999, 2004) from the early historic to late medieval period were leaded bronzes with tin contents not exceeding 15% and keeping within the limit of solid solubility of tin in copper. Beyond this limit as-cast bronzes become increasingly brittle due to the increasing presence of delta phase. The average tin content in icons of the Chola period (*c.* 850-1070 CE) was the highest at around 7% for about 31 images, while a decline in tin to an average of 3.5 wt. % for 11 images is seen by the Later Nayaka period (*c* 1565-1800 CE) (Srinivasan 2004). In a few pieces, the maximum lead content went up to 25%. Of the total number of images only 15% were leaded brass images. In these brass images, the maximum zinc content went up to 25% zinc and images from the post-Chola period had higher levels of zinc. However, the use of zinc-brass was found also in early artefacts (Srinivasan 2007) such an analysed 5$^{th}$ century votive bowl in the Victoria and Albert Museum (acc no. IM-9-1924) recovered from an early Andhra Deccan Buddhist site, excavated from the Krishna delta with 14% zinc and 10% tin. The lead isotope ratios of this octagonal brass bowl closely matched those of a zinc ingot with a Deccan Brāhmī inscription dated to about the 4th century, clearly suggesting the use of metal from the same source, although it is not as yet identified (Srinivasan 1998, 2007).

One may surmise that in medieval south Indian cast images, the use of low-tin leaded bronze, over bronzes with a higher tin content (Sn >20 wt. %), was deliberate rather than incidental, since increasing amounts of tin embrittles the as-cast alloy. For example, an as-cast Maitreya image from Chaiyabhum Province of Thailand, 7th–8th century, in the Philadelphia Museum of Art, found to have a composition of 20% tin, 88% cu, Pb 2% (Woodward 1997: 57–8), has a right arm broken off. In fact, a traditional *Kammalar* or metalworker from Tanjavur district, Tamil Nadu, from the region of Nacharkoil, who made bells, interviewed in 1991, mentioned to the author that alloys with too much *velliam* (i.e. tin) were not used for images, as it renders them breakable (Srinivasan 1997). However, a notable and longstanding trend in the selective and specialised use of high tin bronze alloys in ancient South India has been demonstrated from metallurgical investigations, one by the researcher on the making of wrought and quenched high tin bronze vessels from the Iron Age or megalithic period, such as the bowls from Adichanallur and Nilgiris in Tamil Nadu, the Vidarbha megaliths of Maharashtra and Gandharan Grave Culture of Taxila and continuing into recent times, as first observed in the 1990's (Srinivasan 1994, 1997, 2010). The micro-structure and analysis of a vessel from the workshop confirmed it to be wrought and quenched beta bronze of about 23% tin. Indeed, the deliberate use of bronzes of a higher tin content to make wrought and quenched high tin bronzes of about 23-24% tin is seen in the Chola period from the analysis of a platter (Fig. 3) from Government Museum, Chennai. Thus it appears that the functional aspects of working with different types of copper alloys of high and low tin bronze were appreciated in such cases in the past (Srinivasan and Glover 1995).

**Figure 3** Micro-structure of 11th Chola platter, Government Museum Chennai with a two-phase structure of wrought and quenched high-tin bronze alloy analysed to have 24% tin (200X)

Athough South Indian bronzes are generally described as *'panchaloha'* or five-metalled icons they are not really found to markedly have five different major alloying constituents. However, as Devasenasthapati explained in 1990 to the author, this was more a ritual prescription where gold and silver were added in very small amounts on the request of the interested client, as he did for the leaded brass Ganesa image cast for her (since the alloy they used already had, in his opinion, three constituents of copper, brass and lead), and as discussed in more detail later. Such accounts vary even across craftspeople. For example, Mukherjee (1978:127) reported that a mastercraftsman from Nagercoil described *panchaloha* as 'an alloy of copper, lead, silver, gold and iron dust'.

## Making of the wax model

The modelling of the wax images in southern India generally followed the artistic conventions of the treatises of the Silpasastras. The use of a traditional measuring system was used as explained by Radhakrishnasthapaty in 2006 (Fig 4) to the author whereby, in the preparation of the wax model the use of the *odiolai* or the palm frond is made with 124 divisions for the modelling of the male figure and 120 for the female figure.

Reeves (1962: 63) mentioned that the wax used for the models consisted of equal parts beeswax, powdered dammar resin with a little ground nut oil or gingelly (or sesame) oil. In Tamil Nadu and Kerala *Kunkuliyam* generally refers to dammar resin. Krishnan (1976: 10) mentioned that the wax model was made of twenty parts beeswax, twenty parts dammar resin and five parts groundnut oil; these accounts were mostly based on the practice of craftsmen in the Bangalore area. The use of groundnut oil was also noted during the author's interview of 1990 at Sri Jayam Industries. Furthermore, as told to her in 2014, harder paraffin wax has been used as an additive at their workshop for the past sixty years, as beeswax tends to get soft and loses shape more easily, given that the Tanjavur area can be quite hot with temperatures going up to 40 degrees in summer. As first observed by the author in 1989, for making the wax model, two different grades of wax were used: a softer grade richer in beeswax, used for finer details like ornaments, and a harder grade richer in paraffin for the main body parts of the images. The grade of beeswax is generally known as *tein meluhu* or 'honey wax'. Levy et al (2008: 56) also mention the use of equal parts of paraffin wax with resin, employed at this workshop for making the harder grade of wax. Nevertheless, the use of the more traditional harder dammar resin or *Kunkuliyam* was also observed by the author in the making of models for bells in the Nacharkoil region of Tanjavur in 1991 (Srinivasan 1997). It is believed that this mixture renders the wax easier to melt out since it is has a lower melting point.

**Figure 4** Radhakrishna Sthapathy demonstrating the use of the *odiolai* for modelling the wax in 2008

The making of the wax model proceeded as follows: a rough model of the torso was made and then progressively built up and refined by warming the parts to be modelled with a heated steel spatula, to make it pliable before working it. The different parts of limbs, attributes and head were separately modelled and several of these were seen stored in buckets of cold water to keep them solid. (Fig. 5) shows wax copies of the well known Rishabhavahana image from Tanjavur Art Gallery being made in Devasena Sthapathy's workshop in 1990. Then these various solid pieces of moulded wax were heated along the edge over the brazier and attached to the main torso and the contours merged and smoothed over with melted wax. Then the ornaments and other details were added by pressing fine wax threads in place. The finished details of features and decorative details were left for tooling after the casting was completed. The ornaments were made from the softer grade richer in beeswax and darker in colour. The sprue cup and the riser were also made of the harder wax of cylindrical or conical shapes.

**Figure 5** Wax models at Devasenapathy Sthapaty's in 1990 showing a wax copy being made of the well known 11th century Chola bronze of Vrshabhavahanadeva in Tanjavur Art Gallery with some pieces of wax left in water to keep them solidified

As observed by the author at the workshop of Devasena Sthapati in Swamimalai in 1990, the mould was built up on the wax model, using successive layers of clay and leaving it to dry after each coat. The first coat was of very fine alluvial silt (*kaliman*) from the River Kaveri, very carefully and evenly smoothed down with no coarse inclusions and then left to dry (Srinivasan 1996: 108). The quality of this clay is such that the craftmen say that even a finger-print can be visible on it, indicating a great ability to pick up details. The next layer was of slightly coarser clay from the river known as *vandal mann*. Finally, it appeared that a coat of *kaliman* mixed with *mannal,* (i.e. coarser siliceous sand) was applied. (Fig. 6) shows the successive layers of moulding clay being packed on the wax model placed on a linen cloth.

**Figure 6** Application of the layers of moulding clay on the wax model with wax runners

Accounts of different scholars suggest various practices at different times and places in the Tanjavur area. For example, while Craddock et al (2007) mention the observance in 1986 of the use of cowdung as being added to moulding clay, tallying with the account of Krishnan (1976: 14), this was not observed by the author at Devasenasthapaty's nor by Raj et al (2000) and Levy et al (2008); and it might be that it was an earlier practice. In the author's experience however, the use of cowdung as an admixture especially in the final layer of clay was certainly noticed in other workshops such as at Irinjilakuda in Kerala in 1991, where bells were being made (Srinivasan 1997). This in fact makes a lot of scientific sense, since it would have helped to give a charred carbonaceous inner layer adjacent to the molten metal, which could better absorb the gases to give a better casting, as the prevalence of gases can result in a spongy casting. Both Raj et al (2000: 51), and Levy et al (2008: 56-8, 64) recorded the use of coarser clay from the paddy fields known as *padimunn* for the moulds. However, in a communication in 2014, Mr Shiva at Sri Jayam Industries, Swamimalai clarified that in recent times, and only when they wanted to make larger moulds, they used such coarser clays which were also bound with iron bands. During the visits in the early 90s the researcher did not observe the making of such large moulds at the workshop of Sri Jayam Industries, while the workshop itself and its activities seem to have expanded very greatly in the years since then.

## De-waxing of the mould, risering and runners

The term 'de-waxing' is invoked in this paper to describe the process whereby the wax model, once it is encased within the clay mould, is then melted out to create a hollow cavity into which finally the molten metal would be poured. As practised in recent times, at the workshop of Radhakrishna Sthapaty, (as seen in 2006, 2008 and more recently in 2014), it was noted that a special hearth dug into the ground at a slight incline was designated for this activity. The hearth in which the mould is heated is generally known as *ulai*. Here, the mould was propped up over four inverted large graphite crucibles, laying it down and along a gradual incline, so that the end with the sprue for pouring was slightly lower than the other part of the mould, to ensure that the wax could flow out smoothly and steadily. The mould was heated from below using coconut husks as a combustible material and it was also packed on top with cowdung cakes (known as *raati*), as a fuel to ensure overall uniform heating of the mould so that the wax would drain out completely. A long tray below the mouth of the crucible was kept to collect the melting wax, with a bucket placed below it so that the wax could be collected for re-use as observed in 1990 (Fig. 7). As pointed out in Chandramouli (2004 :94) the hollowed mould is described as *'karuvu'*. This term also refers to the foetus or embryo so that there is almost a birthing connotation to the lost wax process. Metallurgy, ritual aspects and aesthetics were finely melded together in these traditional arts and crafts (Srinivasan and Ranganathan 2006).

Some finer details were however noted by the researcher during field visits made in 1990 concerning the de-waxing process at the workshop of Devasenasthapati. After the wax had run out from the heated mould, the artisan further waited until the ground nut oil (which had been deliberately added to the prepared wax and which stained the mouth of the mould), had also been burnt off. He could tell this from the gases emanating from it and until the stain had disappeared. The purpose was to ensure that no wax residues remained which could cause problems during casting, and to ensure that the mould was as dry as possible since trapped gases could result in faulty and spongy castings.

**Figure 7** Mould just having been dewaxed (1990) in Devasenathapati's workshop

## Risering and pouring practice and comparison with medieval bronzes

The moulds used at Swamimalai usually have two openings, one is the sprue through which the metal is poured in, and the other is called the riser, which is the channel through which the gases escape from the mould during casting and without which the trapped gases could result a spongy casting. Standard graphite crucibles of various sizes are used these days to melt the metals in a hearth provided with a blower. The moulds are often packed in rows into mud with only the mouth being exposed before pouring is undertaken (Fig. 8).In this way, should the mould burst and hot metal ooze out, the associated hazards are minimized. While the metal is poured the impurities or oxidized matter is pushed aside to allow a steady flow. A lighted wick is held at the mouth which made sense to prevent oxidation losses. Interestingly, the 12$^{th}$ century Chalukyan text of the *Manasollasa* which described the lost wax casting process (Saraswati 1936) also prescribes that before pouring metal into the mould, 'one should place a burning wick in the mouth of the tube of the heated mould'. The mould is allowed to cool for several hours before breaking it open. In 1990 a casting of a small Ganesa image was done for the author at the workshop of Devasenasthapaty's as a *panchaloha* icon. For this she and her husband Digvijay Mallah were asked to purchase a small amount of gold and silver of 100mg and 200 mg respectively. This was then heated in a ladle and then the Sthapati held Mr Digvijay's hand to pour the mixture into the crucible for melting the metal for casting the image (Fig. 9).

**Figure 8** Pouring of molten metal into moulds packed in mud at Radhakrishna Sthapathy's workshop at Swamimalai in 2006

**Figure 9** Pouring of small amounts of gold and silver in a ladle into crucible for casting of panchaloha icon at Devasena Sthapathy's workshop in 1990

As mentioned by the late Devasenasthapati to the author in 1990 at Sri Jayam Industries, in the past the pouring practices differed, and more than one pouring sprue cups were used along the length of the rear of the image (Srinivasan 1996: 113). Indeed, a damaged and unfinished Vishnu which the author examined in 1989 from the Chhatrapati Shivaji Maharaj Vastu Sangrahalaya (CSMVS) Museum, Mumbai, (then Prince of Wales Museum of Western India), also indicated a similar gating design, of feeding the mould through sprues along the rear of the horizontally inclined mould. A long protruding irregular patch of metal at the rear of the torso indicated the use of a main sprue cup in this central region of the image (Fig. 10). Another sprue seems to have been at the back of the head. In addition, as still seen in images being made today, runners connected the attributes held in the arms to the main body which in most images are cut off after casting. The aim of this method appears to have been to achieve adequate risering, and more directional solidification. Furthermore, by pouring with the mould lying horizontal, the problems of the metallostatic pressure of a great weight of the metal used for the solid casting, which might break a vertical mould, would have also been avoided. Studies by Johnson (1972:45-53) on an unfinished 12th century Krishna image suggested a similar pouring practice. The *in-situ* metallograph undertaken in 1989 with the author's collaboration with Dr S. Gorakshekar, then Director, Prince of Wales Museum / CSVMS Museum, Mumbai and BARC on the unfinished Vishnu from the same museum showed the heavy impregnation of mould material into the metal fireskin of this damaged image (Fig. 11). In fact late Devasenasthapathy in 1990 mentioned to the researcher that for the *panchaloha* images, the small additives of gold and silver would have been done through the runner at the back of the head, as it was thought to give lustre to the face of the image.

**Figure 10** Unfinished/damaged casting of Vishnu, 13th century, Prince of Wales Museum / CSVMS Museum, Mumbai showing sprue at the rear of the torso

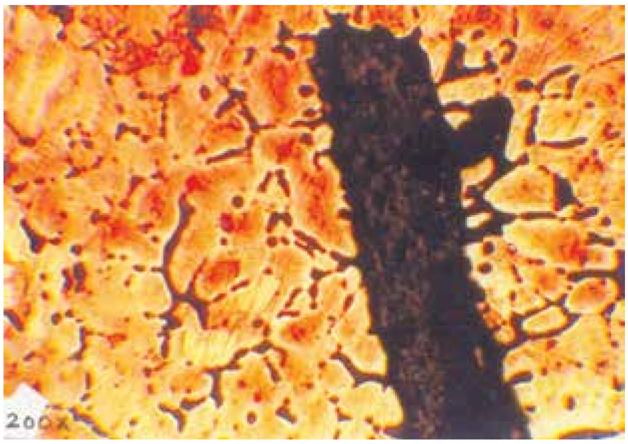


**Figure 11** Surface *in situ* metallograph of the unfinished and damaged Vishnu, Prince of Wales Museum / CSVMS Museum, Mumbai showing impregnation of mould material into metallic areas

## Final finishing

A hammer is used to break open the mould and to remove the debris to retrieve the image. After breaking open the mould the present day *stapathis* finish the cast images by chasing and polishing the image and all the finer detailing nowadays is done by chiselling after casting (Fig. 12). This is possible because of the more brassy alloy they use these days. In more recent times, as observed by the author during a trip in 2014 to the workshop of Radhakrishna Sthapathy in Swamimalai, the use of dilute nitric acid was also seen for removing the thick fire-skin formed on the casting.

**Figure 12** Final finishing of cast image with intact runners by craftsman late Vadivelu at workshop of Devasena Sthapathy in 1990

**Figure 13** Pallava Somaskanda image, Government Museum, Chennai, 7$^{th}$ century, with runners still intact, copper alloy with 3 wt. % lead and 0.7 wt. % tin

Most early medieval bronzes (8$^{th}$-10$^{th}$ century) seem to show much less apparent evidence of post-cast tooling or working after casting. The miniature Pallava Somaskanda from Tiruvelangadu, in Government Museum, Madras (Fig 13) perhaps illustrates this point. That this bronze was probably not subjected to any post-cast tooling is indicated by the fact that two runners are still intact on the shoulders of the Siva image, connected to the weapons, while Siva's figure also shows a bit of metal drip at the base. These would have been trimmed off, if it had been finished. Moreover although intricately executed, the detailing of the ornaments and attire has a certain fluidity, smoothened contours and gentle relief, which suggest that they were executed in the wax rather than cut with files on metal. This image is a copper alloy with 3 wt. % lead and 0.7 wt. % tin. Another example, a superb 11$^{th}$ century Nataraja image from Kankoduvanithavam in Government Museum, Chennai, (the analyses carried out by the author showed it to contain 8% tin and 9% lead) has decorative features that stand up smoothly in high relief (Fig 14) in a way that suggests that minimal post-cast tooling was undertaken and the details were more or less as-cast.

**Figure 14** Chola Nataraja, Kankoduvanithavam, Tanjavur District, Government Museum, Chennai, with 8% tin and 9% lead showing details in high relief suggesting that not much post-cast tooling was done

## Conclusions

The above ethnometallurgical account provides insights into links between the past and present in the long and enduring tradition of image casting in the Tanjavur district, while also throwing some light on the points of departure with changing times. This paper also tries to more comprehensively string together observations of different scholars than it was previously attempted and to gain more insights into the recent trajectory of this metal craft tradition in the Tanjavur district and in relation to other surviving craft traditions. Finally the aim of this paper was to place it better within the context of the archaeometallurgical studies of medieval bronzes.

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# Documenting copper mining and smelting technology

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*ABSTRACT* This article presents research on contemporary copper mining and smelting of copper in Western Nepal, by describing the technological process and its social setting through an ethnoarchaeological study. Not much is known about copper mining and smelting in general, beyond a few historical sources from India and Africa. The article describes in detail how the mining was performed as well as rituals and taboos connected to this. After this a description is given for the three-stage copper smelting, and lastly placing the practise into a large culture-historical framework.

## Introduction

The objective of this paper is to present a research on copper mining and smelting in Western Nepal (Anfinset 1996). Part of this has been published in the past (Anfinset 1999, 2000), and a full and detailed publication has now been published (Anfinset 2011). The main aim here is to present the technological process of copper mining and smelting, and briefly relate it to the social setting through an ethnoarchaeological study. Furthermore, in addition to the documentation, a basic premise is that this information may potentially offer explanations and information to archaeologists.

*Earlier researches*

Few archaeological and anthropological surveys on copper metallurgy in the Indian sub-continent have been carried out up to now. However, there are at least three sources that shed some light on the process. They include a 1831 source (E. 1831), Percy (1861) and Ball (1881), all describing copper smelting in northern India. Except from the mentioned texts, not much is known and therefore comparative ethnographic material from Africa (see Herbert 1984, with references) has been used, to some extent, as a frame to facilitate the understanding of the processes.

Andras Höfer's study (Höfer 1976) is the only one giving some background information on a «Kami» (Nepalese for smith) settlement in a village just outside of the Kathmandu Valley. However, this is mainly a technical study, and Höfer does not consider any social aspects connected with these activities. On the other hand he gives very good technical information on the procedures and technology used to produce different kinds of tools made of both copper and iron. There is also a brief description of copper mining and smelting by Gajurel and Vaidya (1984:12-17), however they mention the use of crucibles for smelting, and the method seems to be slightly different. Anne de Sales (1993) has briefly touched the identity of the miners in her article on the miners in the Dhaulagiri region. However, her article is only concerned with the Chantel ethnic group that - in earlier times - was exclusively delegated to mining.

This study is specifically limited to Nepal, and on the mining and smelting of copper in the village of Okharbot in Western Nepal. The Kami is a specialised occupation of a low caste in the Parbate (Nepalese) caste hierarchy. In a wider cultural frame Nepal must be seen as part of the Indian sub-continent.

## The Setting of the Study

The population of Nepal consists of more than 50 different ethnic groups, distributed all over the country. According to the 1987 census, 89,5 % of the Nepalese population are Hindus (Shresthra, 1989). In Hindu cosmology, the repertoire of gods and myths is immense. Shiva and Vishnu are two of the most important deities.

Lesser deities of the Hindu pantheon can combine both good and evil spirits (Kinsley 1982). Here mountains, hills and streams may all be sacred places (see Khattri 1998). Cows and their secondary products are also sacred. The products include milk, curd, butter, urine and dung, often used as purifying agents in ritual contexts. The main agricultural crop is rice, which is grown wherever possible. However, maize, wheat, millet and potatoes are also cultivated.

With the exception of the Kathmandu Valley, there is not much we know of the history and archaeology of the regions of Nepal. There is some information about places like Lumbini, the birth place of Buddha, but in general there are extremely few sources. From the medieval period onwards, Nepal - and especially the Kathmandu Valley - was strongly influenced by India. Until the middle of the 20th century, Nepal remained minimally influenced by colonialism, European technology and the industrial revolution, but this does not mean that Nepal was an isolated country. For centuries ideas and influences have travelled along the many trade routes through the Nepalese Himalayas to and from India, Tibet and China. Nepal is now going through a rapid change in the political system, and in culture and economy. Traditional living, adaptation to the environment and old technologies are now being forgotten or abandoned. This study represents therefore a documentation of vanishing technologies and knowledge.

## Methodological Considerations

Ethnography and social anthropology are both, in different ways, associated with the study of how people organise themselves and interact with each other in contemporary societies. Archaeology, on the other hand, uses the material remains from past actions to infer something about prehistoric societies. The combination of archaeology and these disciplines is often called ethnoarchaeology (e.g. Kramer 1979 & 1982; Gould 1980; Hodder 1982 a & b; Haaland 1988; Spaulding 1988; David & Kramer 2001). The lack of focus on material culture in social anthropology makes it necessary to use ethnoarchaeology as a method to achieve a better understanding of material culture and how materials were produced. By using information and data collected from a contemporary society it is possible to obtain new dimensions and interpretations of the archaeological record. This information is not necessarily based on a strict correspondence in space or time, but it gives meaning to the archaeological record both in a specific and general cultural sense. By using ethnoarchaeology it is possible to illuminate and achieve a better understanding of archaeological remains and the behaviour of the people who produced them. The problem in the study of the past is that it is impossible to observe or question people who produced the archaeological finds. Haaland (1977, 1) pointed out that the aim of archaeology is to understand the relationships between the artefacts and the cultural environment in which they were produced. This link is not observable by archaeologists, and ethnoarchaeology may in some cases be useful. In this way it is sometimes possible to link the social environment, and the places in which the artefacts were produced, to the artefact itself (Haaland 1977).

The basic premise for this method is that there is a relationship between society, material culture, and, as in this case, the technological process. With regards to this study, the aim is not to link the observations directly to a specific past, but parts or elements of this study may be of importance in order to interpret metallurgical aspects of the past and to understand the people who performed these activities.

**Figure 1** Scene from Okharbot village, the mines are just behind the houses

In March 1995 I visited for the first time the Okharbot village (see fig. 1) in Western Nepal to study the technology and the social aspects of the mining and smelting of copper. Later in the same year, in October and November 1995, I returned to this location to find out more about the copper smelting technology and its related aspects. As these occupations were still pursued, it was easy to come in contact with the right persons. This approach gave to the field-situation the great advantage and the quality of being immediate, and not reconstructed. As there were many new details to understand, I frequently found myself either participating or more passively observing. However, participant observation also means living with people, sharing food and drink, and sleeping under the same roof. In this way the observer is part of the household, shares their moods, and takes part in festivals. I participated in all the main activities and collected information through observation and by interviewing the informed persons, both inside and outside the households. By this method it is possible to understand people's knowledge and social life (Hammersley & Atkinson 1987), although all social interaction is coloured by the context.

## Mining and Smelting of Copper in Western Nepal

*The background and organisation of mining and smelting*

Nepal is relatively rich in copper resources, but they are often found in areas that are difficult to reach. The ore deposits are not regularly distributed, due to many faults in the Himalayan region. The mines of Nepal are generally situated in the Hill Region, and Western Nepal is especially well known for its copper resources. After heavy rain or land slides it is possible to see areas where the earth turns greenish, because of the presence of copper salts. Sometimes ores are discovered by the patterns of vegetation, which may function as indicators of mineralization.

All mineral resources of Nepal belong to the state (Regmi, 1984: 29), also minerals on private land. In recent periods copper mining has been regarded as a state affair, although it was usually handed over to contractors who organised the actual mining and smelting. A system of contractors was in use during the Rana-period. Mining was never transferred to individuals (Regmi, 1984: 17-20), but the contractor acted as governmental agent in the area. The mined copper was divided between the miners, the head of village (contractor) and the government.

In the hillsides of the Myagdi River, many villages were engaged in the mining and smelting of copper. However, most of the mines were closed down 50 to 100 years ago, and nowadays people do not know much about the technology previously used. The suffix «khani» (Nepalese for mine) can be found in many village names, and indicates that in the area there had been a mine. This also is the case of Okharbot («Okharbot Bir Khani»). The outcrops of the main ore in Okharbot follows a southwest-northeast direction, and at the widest it is about 13 centimetres thick. There are generally layers of rock between the copper ore. The people involved in the mining (Nepalese «agri») could be of any kind, but often this occupation was assigned to low status castes, and groups such as Chantel, Magar, Gurung, Siris and Poon (Hamilton, 1990 [1819]: 77; Regmi, 1984: 85; Regmi, 1988: 134; Macfarlane, 1989: 183). Gajurel and Vaidya (1984:14) also use the name "khaniwalas" for miners. The Chantel were exclusively engaged in copper mining until the 1930s when the government closed down a large number of mines all over Nepal (de Sales 1993). These groups were mainly landless, and were bound to this kind of work. Mining was organised as rotation work, and each team (Nepalese «maiyabhai») worked for a turn of four hours. During the mining season they often worked both during the night and the day, while from June to September no mining was possible, as it was too wet to both mine and smelt (Hamilton 1990; Regmi, 1988). In this period especially the charcoal is too damp to produce sufficient heat for the smelting process. Nowadays, during the wet season, the smiths are engaged in agriculture and animal husbandry.

The smith had earlier a patron-client relationship with the clean castes, but the recent economic and social changes have broken down these ties. Smiths live in almost all villages, and their houses are often located at the village border. Their workshops are mainly situated outside the main village or in areas that is not used for agriculture, but this is not a rule. Only the smiths could carry out the smelting, while other ethnic groups were only allowed to work along in the mines. The smiths belong to the Untouchables in the caste hierarchy, and this, to a large extent, frames their interaction with other groups and castes. The knowledge of mining and smelting is passed from father to son (the eldest son is preferred), and the society categorises the whole family on the basis of the occupation and caste of the man in the household. The god Biswakarma is regarded as their ancestor, and it is believed that the clan originates from him. Biswakarma is regarded as the creator of all handicrafts and arts, and he is one of the many manifestations of Shiva.

## The mining of copper

Both Hamilton (1990) and Regmi (1984) described the copper mines of Nepal as quite superficial where only open air ores could be mined, because of the lack of more advanced technology. However, in Okharbot some of the trenches are several hundred meters deep. In this district other mines have also been documented to be very deep. Mining has been described as rather time and labour consuming, and difficult during the rainy season. The soft rock made it possible to mine long narrow trenches with relatively simple tools. The width and height of the mines varies in size, but in some places the galleries were so low that the miners had to crawl. Often the trenches open into galleries and new narrow tunnels, in order to follow the ore veins at different levels or to provide ventilation. Strong wooden beams were used to support the rock, and to prevent rocks from falling down. This was the usual method for mining known in antiquity, known as overhand stoping. Explosives and fire were not employed, because the rock is easily fragmented, and it would have been extremely dangerous to use such methods. Besides, it was not possible to provide the equipment needed. The only tools employed were an iron hammer with a wooden handle (Nep. «ghan»), a chisel (Nep. «tanga») and a wooden stick (Nep. «miro») to keep the chisel in place. No analysis has been done, but the ore is yellow and brassy in colour. It could therefore be chalcopyrite with some oxidation.

*Rituals and taboos connected to mining*

Although mining was a commercial activity, there was a need for spiritual guidance and security. Offering and sacrifices played an important role for successful mining and smelting.

During the more intensive mining in Okharbot, offerings and sacrifices were performed by the miners twice a month: on the first day of the new moon, and on the day of full moon. Such sacrifice could also be performed for exceptional reasons, for example if there was not much copper in the mine, if stranger had to enter the mine or to avoid accidents inside the mine. During the rituals, sacred threads were offered for all persons that had lost their lives in the mine, one pair for each person, in order to pay respect to dead people and ancestors. In addition a cock would be sacrificed and incense burned outside of the mine entrance. There is  a credence, that if the offering and sacrifice are not performed, Shiva would drink the copper. The offering is also necessary to keep ghosts and spirits away from the mine. In a larger comparative perspective, rituals and taboos connected to the mining are well known from other continents such as Europe, Africa and south America, but this will not be further discussed in this paper.

## The smelting of copper

During two fieldtrips to the village, seven separate operations connected to the smelting copper have been observed.

*Making charcoal*

Charcoal is usually made of pine or rhododendron, as they are both hard wood and preferable for making charcoal. The wood employed to make charcoal in Okharbot comes from the tree «Bung Salla» (Nepalese). These trees are usually found at an altitude of 2000-3000 m above sea level. There are mainly two ways to produce charcoal. One is the pit method in which` the wood is put in a pit in the ground and covered with soil in order to slow down the process, and to avoid a complete burning. This usually takes 3 or 4 days. This method is common in South India and in large parts of Africa. The stack method is faster, but the wood is more burnt and the produced charcoal burns up relatively fast, in about 3-5 hours. This latter was the method used in Okharbot (see fig. 2).

**Figure 2** Making charcoal

*The bellows*

The production of goatskin bellows can be rarely observed, because they last for a long time. The smiths argue that ox-skin is better for smelting iron, because of its size, and its toughness and durability. For the smelting of copper the goat skin bellows have the shape of bags with  one end tightened to the tuyere, while the other is open where the smith is holding it.

*Tuyeres*

The tuyeres are a crucial element in the copper production, as they blast air forcefully into the furnace. It is important that the tuyere reaches deep enough into the furnace in order to produce as high a temperature as possible. The tuyeres are made of red or yellow clay found close to the smelting hut. The tuyeres break quite frequently, and immediate repair is then needed (see fig. 3).

**Figure 3** Repairing a broken tuyer

**Figure 4** The smelting hut

*The smelting hut*

The smelting hut is placed in an area not used for agriculture. It is partially built of stones and wood, with the roof and walls of bamboo and grass (see fig. 4). The construction is relatively simple, but offers a good ventilation during the smelting process. The bench on which the workers sit while working the bellows, is made of stones and covered with earth on top. The furnace is placed in the middle of the hut, and on the lower right hand side there is a wooden water tank (Nepalese «dotho»). The area in front of the water tank is paved with stones. A grinder (Nepalese «janto») and three wooden poles are placed on the right side of the paved area. The other half of the hut is used mainly for the roasting of the copper. In this area there can be several pits in use at the same time.

*The furnace*

**Figure 5** The copper smelting furnace

The furnace is placed in the middle of the smelting hut and is a permanent structure (see fig. 5). It is built with stones and clay on the upper part and as a lining in its interior. This construction has the advantage of ensuring minimum loss of heat and to allow CO-gasses to circulate properly. The furnace is slightly narrower at the top than at the bottom, but the exact size is difficult to measure as the furnace is filled with crushed charcoal. Only the upper 30 cm of the furnace are used for smelting. For a more detailed description of the furnace see Anfinset (forthcoming).

*Washing copper*

The area in which the copper ore is assembled after extraction from the mine, is called «tabil» (Nepalese). Here the beneficiation is carried out, and the copper ore is washed (see fig. 6). Good copper ore is kept and low-grade copper ore is discarded.

**Figure 6** Basin for washing copper

**The smelting**

The only preparations needed for smelting are the production of charcoal and collection of the copper ore. The process consists of three separate stages excluding the preparations: first smelting, roasting, and finally a second smelting to obtain the maximum quantity of pure copper. This is a matte process used basically for low-grade ores. Craddock (1995, forthcoming) considers this process to be of great antiquity, and in terms of the chemical process he points out that it reduces iron, sulphur and silicon prior to the copper reduction. This happens during the first smelt. More sulphur is removed during the roasting, and this leaves copper and iron oxides with some silica and sulphides for the second smelting. In the second smelting process the copper oxides are reduced to copper metal. No samples were analysed, but from the details of the process it seems that the ores are rather low-grade copper ores with some iron and sulphur.

*1) First smelting*

The furnace is already two-thirds full with crushed charcoal from previous smelts, and therefore only the upper third of the furnace is used for smelting. First of all, the charcoal in the bottom of the furnace is crushed thoroughly (Nepalese «aafar») with a wooden hammer (Nepalese «mungro»). The charcoal powder prevents the copper from sinking down between the pieces of charcoal. After the charcoal has been crushed, larger pieces of charcoal are added, and set on fire by using a few embers from the hearth in the house. The air blasts from the goat-skin bellows are immediately started, and the bellows are worked continuously by two persons, one on each side of the furnace. When the charcoal catches fire, more is added. Höfer (1976) mentions in his article on a Kami village outside the Kathmandu Valley, that lime powder is used in the furnace to prevent the molten metal from sticking to the furnace walls. However the smiths of Okharbot do not use lime powder, nor have they ever heard about this. The tuyeres lie loose on the furnace rim and channel air from the bellows into the centre of the furnace. When adequate heat is reached, the large pieces of charcoal turn red with heat. At this point the copper ore is added, and the furnace is then filled to the rim with charcoal (see fig. 7). Slag fragments from previous smelts (Nepalese «pata») are regularly added to accelerate the process. Two different types of slag are used, but the last layer of slag taken out from a previous smelt is considered necessary for a successful smelting. After a few minutes, the smell of sulphur becomes noticeable, as gasses are released in the furnace. The bellows are worked continuously during most of the smelting, with only short breaks to change the workers, rest or eliminate slag. It is important to keep an adequate and constant heat. When the charcoal starts to fall down inside the furnace and the colour of the flame turns reddish, the slag has separated from the molten metal. After approximately 45 minutes, the smith takes a wooden stick and stirs roughly in the furnace to further separate the slag and the molten metal, while the bellows are still in function. A few minutes later the charcoal is pulled out in front of the furnace. The bellows are then stopped and the slag is left to cool down for a couple of minutes. When the bellows stop, the slag becomes viscous and hardens fast. It is therefore easy to lift out cakes of slag from the furnace (see fig. 8). First the charcoal is removed from the still glowing slag, and then water is poured on top, so that the slag cools down quicker and is easier to lift out. Several layers of slag are usually removed using wooden sticks, until only matte is left at the bottom of the furnace. The matte is left in the furnace to cool down and then put into a water tank (Nepalese «dotho») for 3-4 minutes to cool completely. If there is more ore to be smelted, the process is repeated by adding more charcoal and copper ore.

**Figure 7** Copper ore added to the furnace

**Figure 8** Taking out slag from the furnace

*2) Roasting*

When the matte has cooled down sufficiently it is crushed into small pieces with a stone (Nepalese «lohoro»). These pieces are then ground with a stone grinder (Nepalese «jantro»). The grinder is of the same type of the ones used by women for grinding rice or flour. The matte is placed in the middle of the grinder and ground to fine powder. The powder is ground twice to make sure that all pieces are crushed properly (see fig. 9).

**Figure 9** Grinding after the first smelt

When the grinding is finished, the powder is mixed and kneaded well with cow dung on the stone floor just next to the grinder. It is important to mix cow dung and powder properly.

**Figure 10** Roasting the copper over natural draught using bark

In the other half of the smelting hut there is an area used for roasting. A shallow pit, usually 10-20 cm deep is prepared. The diameter of the roasting pit varies between 40-100 cm, depending on the amount of roasted dung and powder buns. Several layers of bark are placed in the bottom of the pit, then the buns of copper and cow dung are placed on top of the bark with the flat side down, and are thoroughly covered with more bark. Dry grass is added at the bottom in order to have the bark catching fire more easily. The fire burns for 10-12 hours, or usually overnight (see fig. 10).

**Figure 11** Ghe roasted balls of cow dung and matte are re-smelted

*3) Second smelt*

When the roasting of the matte is finished, it is necessary to repeat the smelting, to retrieve as pure copper as possible. When the charcoal has reached an adequate temperature (controlled by looking at the colour of the flame) the buns of copper and cow dung are laid side by side on top, and covered with charcoal (see fig. 11). From time to time the smith stirs in the furnace with a wooden stick, and more charcoal and buns are added. The stirring speeds up the separation of the slag from the molten metal. After approximately 45 minutes the first layer of slag is taken out of the furnace with two wooden sticks, in the same way as in the previous smelting. The last slag (Nepalese «pata») taken out from the furnace contains a relatively high amount of copper, and is reused in the next smelting, to speed up the process. When the copper is lifted out of the furnace it is placed first in the water tank, and afterwards on the charcoal in front of the furnace.

*The scale of production*

In October 1995 three separate smelts were documented, and the following measurements were recorded:

| | SMELT 1 | SMELT 2* | SMELT 3 |
|---|---|---|---|
| | Kilograms | Kilograms | Kilograms |
| **1st. smelting:** | | | |
| Crushed charcoal | 0.4 | 0.5 | 0.4 |
| Charcoal | 11.5 | 3.2 | 3 |
| Copper ore | 15.3 | 6.2 | 5.5 |
| Slag added («pata») | 5.5 | 1.6 | 1.8 |
| Slag after 1st. smelt («batho») | 15.8 | 5.2 | 5.9 |
| Impure copper | 3.5 | 1.5 | 1.3 |
| | | | |
| **Roasting:** | | | |
| Cow dung* | 6 | 3 | 2.6 |
| Bark | 18.2 | 8.6 | 8.7 |
| | | | |
| **2nd. smelting:** | | | |
| Crushed charcoal | 0.5 | 0.5 | 0.5 |
| Charcoal | 4.5 | 3.2 | 2.5 |
| Slag added («kit») | 1.6 | 0.9 | 1 |
| Slag after 2nd. Smelt («pata») | 3.2 | 1.9 | 1.7 |
| Slag with copper | 0.3 | -- | 0.1 |
| Pure copper | 1.4 | 0.7 | 0.5 |

* During smelt number 2 cow dung was not available and buffalo dung was used.

**Figure 12** Measurements recorded during three different smelts.

It is worth noting that the copper ore gives approximately 10% of its weight of pure copper. In order to produce 1 kg of pure copper approximately 10 kg of ore, and around 13 kg of charcoal and 17 kg of bark are needed.

## Some Cultural-Historical Implications of Metal Working

This study has mainly focused on the technological process itself and, more briefly, on the related social setting. The information collected has implications on two levels for the understanding and the interpretation of archaeological material: firstly the technological and social context with reference to the specific cultural context and the region. Secondly, it is important on a general level in order to point out the variability of social contexts.

*Technological aspects of metal-working*

The mining technology in Okharbot has been described as a relatively simple process without the use of fire or explosives, and has many similarities to the processes described by Ball regarding the exploitation of the Buxa mines in Darjeeling-Sikkim in Eastern India more than a century ago; «The tools used are an iron hammer, a gad or chisel held in a split bamboo, and a pick. The light is afforded by thin slips of bamboo, the smoke from which in the confined passages is not so irritating to the eyes as that from other kinds of wood. The ore is carried out in narrow baskets, and picked, crushed and finally pounded with a stone hammer or pounder fixed in a forked stick» (Ball 1881: 276). In the archaeological record all this would leave very few traces, except for the ores and trenches themselves.

In Rajasthan and Bihar in India there is evidence of mining probably from an early date (Agrawal 1971, 1982; Shrivastva 1999). The mining and smelting on the Indian sub-continent goes back to the third millennium BC (Allchin & Allchin 1993). There were probably influences from the West, either by diffusion or by migrating people that introduced metallurgy to the Indian sub-continent. Hegde and Ericson (1985: 62) have dated the mines in Rajasthan to ca. 3120 +/- 120 BP. They were up to 120 meters deep with regular ventilation shafts and timber supports. According to Chakrabati (1988) especially Baluchistan, Bihar, Andhar, Gujarat, Madhya Pradesh and Rajasthan have rich copper resources. Further deposits are found in Uttar Pradesh and in Nepal, but they are not suited for intensive mining.

A problem with the study of mining sites is that they are often destroyed by more recent activities. It is therefore important to document the mining technology that can give us information that can be useful for understanding prehistoric technologies and traditions, and examine possible smelting sites in an area. As we have seen from Okharbot the ore was sorted out just outside the mine and the smelting was performed a short distance from the mine. It would be inconvenient to carry copper ore over a large distance in order to smelt elsewhere. The archaeological remains would be relatively few with regards to the mining activity itself (see fig. 13).

**Figure 13** A copper smelting site in Okharbot abandoned ca. 15 years ago

*Copper smelting*

The technological process of smelting copper in the Okharbot village is itself special, as there was no slag tapping. Slags were lifted out of the furnace with two wooden sticks, but the process of smelting copper itself will also vary, depending on the nature of the ore.

Based on the information collected from Okharbot postholes, building remains, grinder, crushing stones and other tools, fragments of tuyers, slag and debris heaps, remains of the furnace or furnace walls etc. it is possible to recognize such activities in the archaeological material. The copper smelting in Okharbot left circular «cakes» of slag, another indication of metallurgical activity, and, for the archaeologist, the most important evidence of metal production (Haaland, 1985: 64). The major problems in the process of mining and smelting, besides the know-how itself, are obviously the availability of copper ore, and the access to hardwood to make charcoal.

Hegde and Ericson (1985) excavated copper smelting sites in the Aravalli Hills in Rajasthan. The furnace was of a type different from that used in Okharbot, and had slag-tapping holes. After the smelting the furnace was destroyed in order to take out the metal ingot, and the crucible also had a slag-tapping hole (Hegde & Ericson, 1985: 65). Because of its nature, this ore had to be also roasted. A further site of copper smelting in the same hills, the Ahar site was dated to ca. 1800 BC (Allchin & Allchin, 1993: 262). In addition, Ball (1881: 276-277) gave a good description of the smelting of copper from the Buxa mines in Darjeeling-Sikkim, and described almost exactly the same process as in Okharbot.

Agrawal (1971: 115) argues that metallurgy came to India late, but possibly reached Harappa and Sind ca. 2300 BC. According to Gordon (1950) and Lamberg-Karlovsky (1967), and based on the data on the introduction of painted pottery, the technology spread towards India from Iran and Afghanistan. The scarcity of descriptions, and of archaeological finds of copper smelting furnaces make it difficult at the present stage to compare various types of furnaces on the Indian sub-continent. However, a comprehensive synthesis of South Asian mining and metallurgy is now on its way (Craddock, forthcoming).

The copper smelting process in Okharbot has parallels in Europe, for example from an archaeological context mentioned by Jacques Happ (1995), in which the Bronze Age mines of Mitterberg, Austria, have been investigated. The smelting furnaces and roasting areas near the mines have been documented, and give information on the smelting methods (Happ 1995: 8). On the basis of the archaeological remains, experiments have been also carried out. The remains testify that the smelting stages were similar to those in the Okharbot village, without slag tapping, and with the reduction of a sulphidic ore that had to be roasted and re-smelted. However, one should bear in mind that the technology may also change within a small area, depending on the nature of the ore.

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# Traditional jewellery of South India

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*ABSTRACT* Early archaeology and literature describe jewellery for adornment and for providing property to daughters. Gold was a precious metal, but silver was also used. Jewellery was worn by men and women, gods and goddesses. The designs were derived from nature – plants, birds, animals, mountains and temples. South Indian jewellery was made of gold on a wax base, raised and rounded, with stones fitted in, creating a relief effect, and decorated with uncut stones. Each part of a woman's body was adorned by a jewel with a specific name and design. There are few traditional *achari* (goldsmith) families who still make traditional designs. Many items have disappeared with time and the passing away of rich traditional clients.

## Introduction

The use of jewellery goes back to the very dawn of civilization, when primitive men and women, taking inspiration from the flora and fauna around them, decorated themselves with reeds, flowers, feathers, and beads carved out of wood, stone and bone. Shells, berries, wings of butterflies and beetles were all used with great ingenuity. With the advance of civilization, the materials changed to copper, ivory, agate and semi-precious stones, and later to silver, gold and precious stones. Nowhere in the world has jewellery formed such an important part of adornment as in India, continuously through its history. The love of jewellery is an expression of the aesthetic impulse of the people and their joy in the creation of beauty.

Jewellery was also a form of savings and providing property to daughters. Gold was regarded as the purest of materials, although some items were made of silver, regarded as a lesser metal. The value of precious and semi-precious stones was known very early and formed an important part of decoration. Jewellery was regarded as *streedhana*, a woman's wealth, from as early as the Vedic period, and was a gift from her father and her husband, since it was the only form of investment that could be used in an emergency. A married women was – and still is - expected to wear a minimum amount of gold jewellery – necklace, ear-rings, bangles – and silver anklets, to proclaim her status as a *sumangali* ("very auspicious"), as opposed to a widow.

Today, India possesses the world's largest private collection of jewellery, especially gold. Balaji, Lord of Tirumala (Tirupati), owns the single largest private collection of gold and diamonds in the world. The importance of jewellery in India can be seen from the sculptures and carvings in temples, a veritable cornucopia of the jeweller's art.

## Early jewellery

As early as the Indus-Sarasvati culture, which flourished over 5000 years ago, jewellery was made of gold, silver, copper, bronze, shell and semi-precious stones. The ornaments included ear-rings, nose-studs, finger-rings, pendants, bangles, bracelets, armlets, hair pins, fillets and necklaces (Pal 1978, 82). An eight-petalled flower inlaid with lapis lazuli and red stones and necklaces of beads with a single pendant made of silver, gold or faience are among the many pieces of jewellery found in that period (Nandagopal & Iyengar 1997, 3-4). *Ṛig Veda* (I.166.9; VII.56.13) mentions the seven *ratna* or treasures: the *kurīra* or head ornament, *nyochani*, a bride's ornament, *khādi* or armlet / anklet, *rukma*, an ornament worn on the breast, *vajra* or diamond, gold ear-rings, necklaces and bracelets. The wearing of gold is indicated in the prayer "May all the divinities secure to us a life rich with gold ear-rings and jewelled necklaces" (*Ṛig Veda*, I.122.14). Thus by 3000 BCE, gold jewellery had become the norm in India.

In the epic period, moulded jewellery had become very popular and is frequently mentioned in the *Rāmāyana* and *Mahābhārata*. Men - including monks – wore ear rings / drops, necklaces, girdles, bangles, bracelets and rings. Women wore moulded ornaments, ear rings, nose rings, necklaces, bracelets, golden anklets and golden bells on their toes. The *Rāmāyana* mentions a variety of jewellery worn by Sita (Pal 1978, 88). When abducted by Ravana, Sita drops her jewellery to show Rama the way and these are picked up by the forest-dwelling Vanaras. Hanuman takes Rama's engraved ring to identify himself to Sita, while Sita sends back a *chūdāmani* (a jewel worn on the head). Karna, the anti-hero of the *Mahābhārata*, was born with golden ear-rings (*kundala*). While several ancient texts abound with descriptions of ornaments, the *Bṛihatsamhitā* of Varahamihira is one of the most abundant and authentic (Pal 1978, 91).

**Figure 1** Didarganj Yakshi, Chauri Bearer, Maurya, 3rd century BCE

A good example of early Indian jewellery is to be seen on the Mauryan stone sculpture of the female *chauri* (fan) bearer from Didarganj. She wears a short *kantha* at her throat, usually made of gold and inlaid with precious stones. She also wears a long string of beads with a pendant or amulet at the end; a *mekhala* or girdle made of multi-stringed beads; heavy anklets; a jewel on her forehead and so on (Fig. 1). The only remnant example of Mauryan jewellery is a single ear-ring resembling Greco-Roman and Etruscan jewellery found in Taxila and datable to 200 BCE (Alkazi 1983, 23). Kautilya's *Arthaśāstra* ($3^{rd}$ century BCE) says that jewellery was made of gold; he discusses the mining and trading of gems (Nandagopal & Iyengar 1997, 5). Indian jewellery has not changed much over millennia. The jewellery worn by the Didarganj *chauri* bearer (known as the Didarganj *yakshī*, although she is no *yakshī*) is still worn in North India and in different forms all over India.

Ancient Tamil literature abounds in references to jewellery. The *Silappadikāram* ('Epic of the Anklet') is based around the anklet of Kannagi, wife of Kovalan. Puhar, where they lived, is described as a city of wealth, abounding in jewels of gold, pearls and precious stones (*Puhar kāndam*, 5.2). Jewellers were held in such high regard that the main street of Puhar was occupied by them. The jewels of the courtesan Madhavi are described in great detail. The same jewellery is worn by dancers and brides today.

It is obvious that even as far back as the Sangam era, South Indian jewellery traditions had reached the height of excellence and refinement, and that today's traditional ornaments, of stone-set gold jewellery, are practically the same as those worn two millennia ago. The Tamils, having been great seafarers and traders from the very dawn of history, were familiar with gems imported from beyond the seas, and the Sanskrit *kuruvindam*, derived from the Tamil *kurundam* (English corundum) was probably brought from Burma.

**Figure 2** Ajanta Paintings, Vakataka, 6th century CE

The best examples of South Indian jewellery are to be seen in the paintings of Ajanta (Fig. 2), Panamalai, Thanjavur, Vijayanagara (Fig. 3) and Nayaka temples and the Mattancheri Palace (Fig. 4); and the Pallava, Chola (Fig. 5), Hoysala, Vijayanagara and Nayaka sculptures in stone and bronze. Both bridal and popular jewellery are visible here. The jewellery of Tamilnadu, Karnataka, Kerala and Andhra Pradesh may be solid or hollow, but most are common to all parts of South India, although there are individual pieces unique to each region that have different names. It is interesting to note that even while there is variety in jewellery patterns and designs all over India, the forms of jewellery are similar, probably derived from early goldsmiths who spread out all over the sub-continent with their craft.

**Figure 3** Varadaraja Perumal Temple painting, Vijayanagara, 14th century CE

**Figure 4** Mattancherry Palace, Kochi, 17th century CE

**Figure 5** Shiva and Parvati, Chola Bronze, 10th century CE

Marco Polo and Manucci, medieval travellers to India, were amazed at the wealth of male ornamentation. Marco Polo, visiting India in the 13th century, says that the kings of the Coromandel country wore golden bracelets set with rich pearls, necklaces of rubies, emeralds and sapphires, anklets, gold rings on the toes and a rosary of 104 large rubies and pearls. Much later, Abbe Dubois recorded that men wore gold ear ornaments and ascetics (*sanyasis)* also wore them for health reasons, but in copper to show their non-attachment. However, the best pieces were gifted to the temple deities.

## Jewellery classes

There are four types of jewellery: Temple jewellery – worn by the gods; Spiritual / religious jewellery – with special qualities; Bridal jewellery; Popular jewellery worn by men, women and children.

Temple jewellery is employed in the practice of offering the best jewellery to Gods and Goddesses in temples. Ornaments were made of gold, diamonds, silver, gems, etc., with designs similar to those seen in temple sculptures. Temple jewellery is generally well preserved, since the South did not face many foreign invasions. The art of jewellery making reached its sophistication during the Chola period and its zenith under the Vijayanagara Empire. However, most existing jewellery in South Indian temples belongs to the Nayaka period. Nature was the inspiration, with designs of mango, lotus, leaves, peacock, swan and other birds and animals. Vadasery near Nagercoil, in Kanyakumari district of southern Tamilnadu, is the only place in India where temple jewellery has been made continuously since the last few centuries (Santhanam 2012).

Spiritualism and beauty are interconnected, a belief prevalent in the efficacy of the *navaratna* or nine sacred gems in controlling the nine planets, which influence all life on earth. These nine gems are considered so powerful that they are worn to this day to enhance the powers of a beneficial planet or to minimize the ill-effects of a malefic planet. The nine stones usually associated with the planets are the ruby (Sun), pearl (Moon), coral (Mars), topaz (Jupiter), diamond (Venus), sapphire (Saturn), zircon (Rahu- the ascending node of the moon) and cat's eye (Ketu- the descending node of the moon). The seeds of the *rudrāksham* ("eyes of Shiva") (*Elaeocarpus ganitrus)* tree, the most sacred of Indian plants, often decorated with gold clasps, are used even today as a rosary during worship. They are believed to be beneficial in controlling blood pressure.

Gold worn on the body was believed to have medicinal properties. Gold worn on pierced nostrils was believed to cure sinus infection and head colds. Gold was so highly regarded that it was never worn on the feet, where it could be soiled. Only the Gods were permitted to wear gold anklets and toe-rings, which were later adopted by royalty.

Fig. 6, depicting Krishna and his mother Yashoda, contains most of South Indian jewellery.

**Figure 6** Tanjore Glass Painting, 19th century CE

Starting with jewellery worn on the head, the elaborate *talaisāmān* is a bridal decoration. Since the *devadāsī* or temple dancer was considered to be the bride of the temple deity, she wore a bride's jewels while dancing. This tradition still continues and has resulted in South Indian bridal jewellery being mistakenly called dance jewellery. The *talaisāmān* consists of heavy stone-set jewellery, with rubies or red stones predominating, but interspersed with emeralds and uncut diamonds. One piece of this jewel is worn on the centre parting and another tied along the hair-line on the forehead. Decorative pieces shaped like the sun and the moon are worn on either side of the head to invoke the blessings of these celestial beings, the sun for good health, brilliance and power, the moon for romance and a life of peace and calm. On the back of the head is worn the *nāgar*, a five-headed snake in gold or a *rākkodi,* a circular piece, stone-encrusted with a swan in the centre. When a *jadanāgam* (literally meaning hair-serpent) is worn, the *rākkodi* is followed by a stone-set crescent moon and a third piece shaped like the fragrant *thālampoo* (screw pine) flower. Then commences the actual *jadanāgam,* the most elaborate jewel found anywhere in India for hair decoration. Worn on braided hair, it is now practically extinct. It commences with a ruby and diamond studded many-headed cobra, the divine Ananta, with rows of coils which serve as the couch of Lord Vishnu. This is followed by a hair-piece of diminishing thickness consisting of flowers and buds cleverly interlaced, so that the jewel is soft and supple and appears to be a part of the braided hair. At the narrow lower end burst out three tassels (*kunjalam* or *jadaguchchu),*topped by gold-encrusted bells. The whole effect of this jewel is extremely dramatic (Fig. 7).

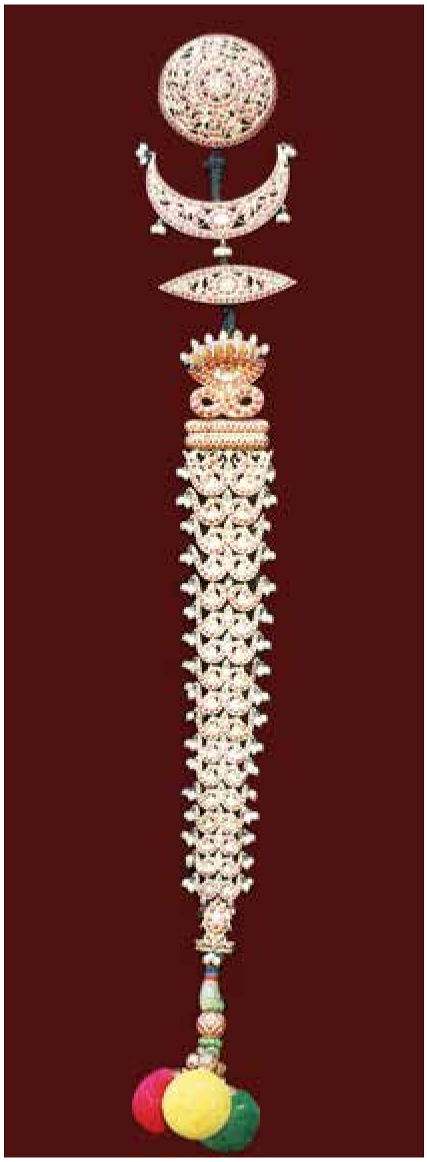

**Figure 7** From top: Rākodi; Chandraprabha (crescent moon); Screw pine; Jadanāgam; Kunjalam

Another unusual ancient hair ornament is the *sevarikottai*, a golden buckle used to attach an artificial switch of hair to the chignon. For plaited hair not decorated with a *jadanāgam*, a circular *thirugusāmanthi poo,* also called a *thirugupoo* is worn in the middle of the braid. It is made either of diamonds, red stones or plain gold, depending on the wearer's wealth.

Jewellery is literally worn from the cradle. The *uchchippootīkka* is a small lotus-shaped ornament worn by little boys and girls on top of the head, on the right side. Believed to be a copy of the jewel worn by the child Krishna, this is another piece that is practically extinct now.

There are several kinds of jewellery to adorn the ear. In the southern districts of Tamilnndu, older women enlarge the hole in the ear lobe by wearing rolled palm leaves which are made larger and larger, increasing the size of the hole to nearly three centimetres in diameter. A *pāmbadam,* a jewel of six gold earrings of different shapes, is then worn, dragging the ear lobe half-way down to the shoulder (Fig. 8). The normal ear jewel of women consists of ear-studs made of gold diamonds, called the *kammal* or *thodu* / *thoda*.Below this hangs the *jimikki,* a bell-shaped ear-drop, either in gold or studded with stones. Sometimes another ear-drop may be worn, a *lolākku,* which can be of any design. Jewellery worn on the outer and inner ear had gone out of fashion but is coming back today. They are the *kattiribāvali, kuruttubāvali, jilpabāvali,* and *koppu.* The *māttal* of gold or pearls holds the *kammal* to the hair above the ear. Its purpose is to support the weight of the ornaments. Men in rural areas wear ear-studs of single stones called *kadukkan*.

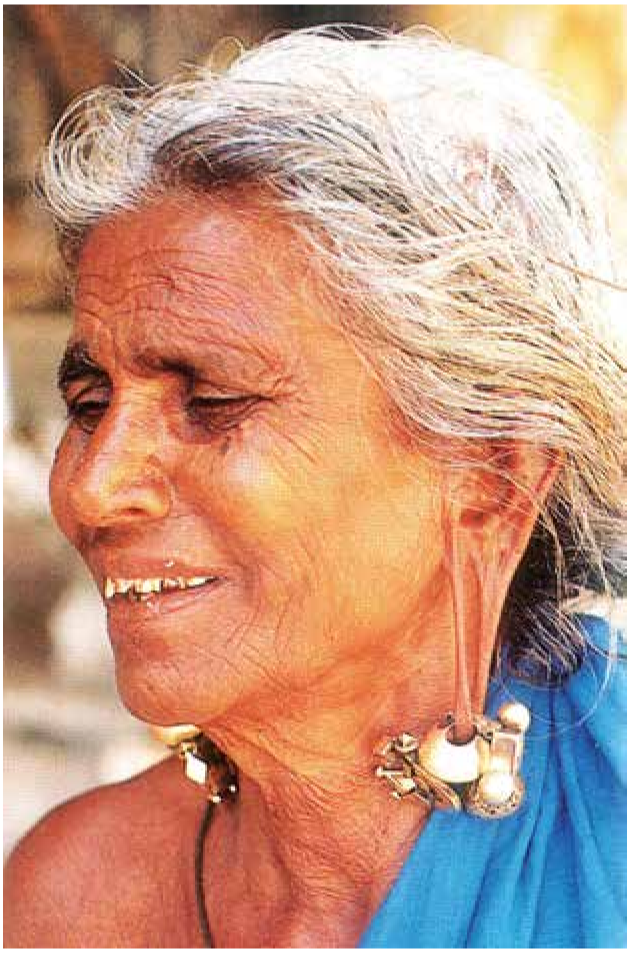

**Figure 8** Paambadam

The jewel most commonly worn on the nose, on the left or right nostril, is the single stone *mookkupottu*. The *besari* (of eight diamonds) worn on the left side of the nose is balanced by the *muthu* (consisting of a large diamond with three diamonds hanging loosely below it) on the right side. The *nathu*, a stone-studded ring pierced through the left nostril, is very popular in Andhra Pradesh. Another nose jewel which appeared in the south for the first time around the 17th century is the *bullākku*. This diamond-studded jewel is suspended from the pierced central membrane of the nose and falls on the centre of the upper lip ending in a single pearl (Fig. 9).

**Figure 9** Nose jewellery of Telugu Chetty woman

Neck jewellery is a world, apart, and the variety is endless. The basic jewel for a married woman is the *thāli* or *mangalasutra*, the marriage talisman. The important part of the old *mangalasutra* is the pendant, whose design is determined by the community to which the woman belongs.

The *Rāmāyana* says that Sita wore a *nishka* necklace, made of gold coins (Dhamajia 1970, 57). The *kāsumālai,* a necklace typical of South India, is made of gold coins, the size and weight depending on the wealth of the wearer. However, the traditional *adigai* is a necklace of large cabochon rubies or diamonds set in ascending order ending in a lotus-shaped pendant. The *māngāmālai* consists of stone-studded gold mangoes strung together with a huge pendant. Strings of pearls with large stone-studded pendants have been popular from time immemorial, as pearls are found in the seas off Tuticorin and pearl-diving was once a lucrative trade. It was believed that flawless pearls prevented misfortune. Equally strong was the belief in the power of a tiger's claw to prevent ill-luck. It was set in gold, framed with stones and made into a pendant. *Salangai* are gold beads strung together, while the gold *kanthi*, seen in early sculpture, is worn at the neck. The *asili* is a stiff stone-set necklace which is believed to be a protection for the wearer's collar-bone.

Of the jewels worn on the upper arm, *vanki*, with its inverted V design, may be made of gold or inlaid with stones. An effect of coiled snakes, or an inverted V achieved by two parrots or two peacocks carved on either side slips over the arm. The *nāgavattu*, the name derived from its appearance of a serpent encircling the arm, is an armlet of gold with a stone-studded crest in the centre. The *kadayam* is an armlet worn by young girls.

There is a wide range of bangles or *valai* and *kankanam* either of gold or set with stones. *Gettikkāppu* are plain gold bracelets worn tight around the wrist, and the *pātil* is a bracelet with a stone-set crest.

Matching the *vanki* is the inverted v-shaped ring called the *nali,* unique to South India, presented to a bride by her maternal aunt.

Another jewel unique to the south is the waist belt, the *oddiyānam,* worn tight around the waist. Plain silver or gold belts used to be worn all the time by women as they kept the waist slim and accentuated the hips, this being a sign of beauty.

On the feet are worn *golusu* or silver anklets. *Puduchcheri* (*Pondicherry) golusu* has a chain design; *gajja* (elephant) *golusu* are heavy anklets with bells that tinkle; *thandai* are stiff anklets with bells inside which also tinkle; *kaal kaappu* protects the ankle of the wearer and was believed to be necessary for children to wear (Fig. 10).

**Figure 10** Silver Golusu (anklets)

On the toes, again, only silver is worn. On the second toe are worn the heavy silver *metti*, two on each foot, which produce a musical sound as they strike the floor. To keep the *metti* in place is the *siththu,* made of two rows of silver wires and worn tight on the toe. The *peeli* is designed like a crest and is worn on the third eye.

Jewellery in Tamilnadu has always had closed settings, with stones deeply embedded in gold. Open-setting work was virtually unknown. A three-dimensional effect was achieved with the use of wax, which formed the base over which the design was fashioned in gold and the stones encrusted. Thus the jewellery appears heavier than it actually is. The traditional jewellery of South India is made of hand-worked gold. Pearls were used to give a tinkling edge to the heavy pieces, almost like a lace edging. When the Tamils fled Burma, they converted their wealth into rubies, which were easy to take along. Hence the predominance of rubies in South Indian jewellery.

## Goldsmiths and techniques

In India, goldsmiths are usually men and are referred to by a variety of names depending on the region - *swarnakāra*, *panchālar*, *thattān*. Goldsmiths have had a higher standing than other artisans, because they work with gold, a precious metal. They belong to the Vishvakarma caste and wear the sacred thread (like Brahmins). The craft of the goldsmith was highly regarded. Historical records show that Indian jewellers mastered quite early the various skills required to make fine jewellery - mixing alloys, moulding, drawing fine wires, setting stones, inlay work, relief, drawing gold and silver into thin wires, plating and gilding. In most places, the goldsmith may perform all the processes involved in producing a finished piece. In cities, the different operations may be undertaken by different people.

Pure gold is rarely used because of its softness. It may be alloyed with silver or copper or silver and copper. The metal is melted in a crude clay crucible in an earthenware furnace. The goldsmith also blows air through a blowpipe on the heated gold, which is so soft that it is semi-molten, with the consistency of butter, and spreads out in the process. His tools include the anvil, hammer, tongs, pincers, files and small chisels or engravers which give the finishing touches. Gold wire is made by drawing thin strips of gold through a steel plate with holes of different sizes. Gold is beaten into shape by hammering or by the use of dies (Mehta 1960, 21).

There are four primary forms of workmanship:

1. *Nagās*. This is the oldest workmanship, with frontal *repoussée* work where the design is punched and hammered from the back. The design in gold is then joined to a flat gold plate at the back by heating cadmium powder, which solders the two sheets

together, sometimes leaving a beading at the side. It is polished in front, producing a 3-dimensional bas-relief surface. However, the whole piece – generally a pendant or ear-ring – is hollow (Fig. 11).

**Figure 11** Nagās pendant with tiger claws and embedded kuruvindum rubies

2. *Javai* or *kundan*. *Javai* (filigree work) design is made on a 24 carat gold plate. This is the front. Wax moulds of equal size are attached to the back and covered with 24 carat gold plate heated on a fire stove (*kumti*) using paddy husk and charcoal. Stones are placed within the design and heated. The gold plates are joined with heated cadmium powder. A three-dimensional effect is achieved with the use of wax, which forms the base over which the design is fashioned in gold and the stones encrusted. Thus the jewellery appears heavier than it actually is. Kundan was probably influenced by Mughal jewellery (Fig. 12).

**Figure 12** Javai or filigree work

3. Mass production from dyes. This is much cheaper and therefore very popular today.
4. Moulded jewellery. Anthill mud (*puttu mannu*) is made into a *patti* (paste) and placed on a gold plate, an alloy of 22 carat gold and copper. Another gold plate is designed like filigree (*javai*), placed on the *patti* and heated together with cadmium powder. Stones are fixed within filigree design on the upper gold plate. The upper and lower gold sheets are joined by heating cadmium powder, which solders the two sheets together. A heated wax stick placed at the rear plate holds the stones to the *patti*. The stones are deeply embedded in the gold filigree. Open-setting work was virtually unknown.

Another form of moulding ornaments is to make a resin mould which, once hardened, is enclosed in a mixture of clay and cow dung. A vent is made to reach the resin model and sealed with clay. It is placed on fire and molten metal, generally gold or silver, is poured in till it reaches the resin model, which melts and destroys itself, and the molten metal takes its place. This is a form of the lost wax or *cire perdue* process which was perfected in bronze crafting and used for making jewellery too (Brijbhushan 1979, 34).

Gold leaf (covering) work makes it possible for the common man to possess rich designs at a fraction of the cost of pure gold. The ornament may be made out of silver, brass, bronze or any base metal. Gold is beaten to a thin layer, after which the ornament is covered with mercury and then placed on the gold leaf. Heat is applied and the leaf is finished over (Brijbhushan 1979, 35).

The art of making jewellery is as old as the Indian civilisation and will probably last forever, given the Indian passion for gold and precious stones. Today there is greater mechanization and less hand-craft, as newer and faster methods of production are introduced from other countries. However, none of this has diminished the Indian passion for traditional jewellery. What is more worrying is whether traditional craftsmanship will survive in this age of mass production, as hand-crafted jewellery costs become higher. Demand is growing exponentially as incomes grow and purchasing power increases, making machinery-produced jewellery more affordable and faster to produce. While the growing demand is a cause for celebration, the loss of the traditional craft of jewellery-making would be a tragedy.

## Acknowledgements

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information about the different types of workmanship of traditional South Indian jewellery.

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# Caste, community and rituals in wootz making centres of Telangana - a cultural continuity in wootz making tradition

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*ABSTRACT* A detailed survey of iron and wootz steel production sites in four districts of northern Telangana has revealed valuable material and archaeological evidences, related to the manufacture of iron and use of wootz steel. Some attention-grabbing rituals and smith community participation are presented. Wootz manufacturers belonged to the *Kammari* or blacksmith community. In particular, five groups represent the so-called *panchannam varu,* which include blacksmiths, goldsmiths, bronze-smiths, carpenters and sculptors (idol makers). Iron smelters are different from wootz makers. The community involved in iron extraction was called *muddakammarulu* or *muddakolimi kammarulu*, who are also referred to as *bayatikammari* or *advikammari.*

In most of the wootz production villages we find a temple devoted to the Goddess *Mammayee*. She is considered the Goddess of Metalwork. *Mammayee* is the Goddess of iron, the Goddess of smith families. She is being offered prayers by the smith communities in all the villages even to this day. Most of the temples are now in a totally dilapidated condition. Only one temple at Kalvala village in Karimnagar district is still intact and focusing on the age old tradition. There are two temples of *Mammayee* and there is also a street called Mammayee Wada at Konasamudram village.

The careful study of the culture and traditional life of the blacksmiths of this region will be highlighted. Finally, the results of field survey and investigation on existing culture and tradition of the wootz steel manufacturers of this region are presented.

## Introduction

The unique wonderful wootz is a legendary metal of the Orient has been the subject of several books (Jaikishan 2009, Juleff et al. 2011, Srinivasan and Ranganathan 2014). The Telangana region (Fig. 1 and Fig. 2) is justly famous as a major centre for Wootz steel. A detailed survey of Iron and Wootz steel production sites in about 3000 villages in four districts of the northern Telangana region revealed valuable archaeometallurgical debris and archaeological evidences. 2000 villages are iron manufacturing sites and more than 600 villages contain wootz steel manufacturing sites. The dating tests are yet to prove this fact, but this region has unique uninterrupted wootz usage tradition, continuing from times immemorial.

Secondly, the ethnographic interviews and other conversations in the field, were recorded in the field notebook. The interviews were then carefully studied and subject checklist was prepared based on the themes discussed and the interviews sorted out under different

**Figure 1** Telangana in India

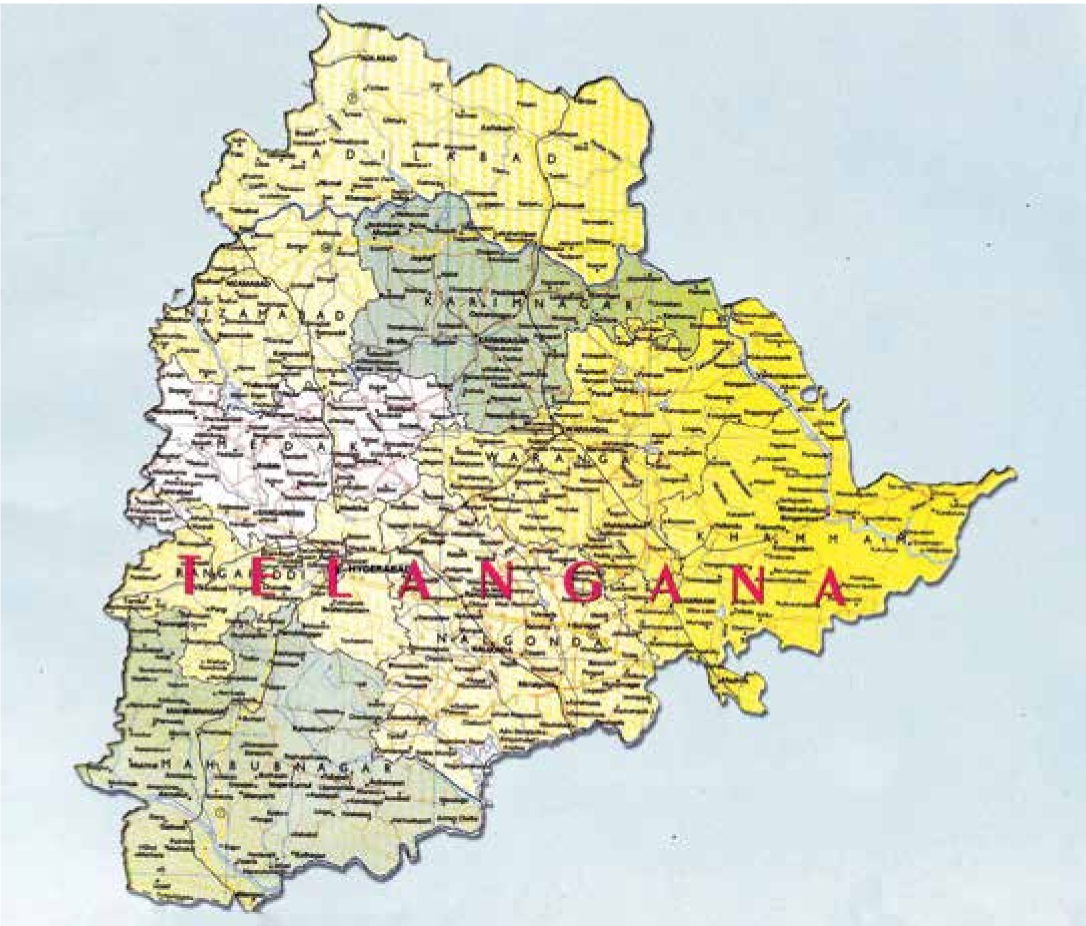


**Figure 2** Telangana districts

heads as raw material source. The collected tools, furnace remains from the manufactured sites were classified. The final ethnographic archive consists of five principal datasets-Interview, photo and video records, collected artifacts of iron tools, festival record data was archived.

An attempt has been made in this paper to focus on the caste, community and their rituals in wootz making centres of Telangana, and their cultural continuity in wootz making and using tradition, based upon empirical knowledge of rituals, enquired with the living smith community. It enlarges on two earlier reports Jaikishan (2007) and Neogi and Jaikishan (2011). The families belonging to the community have traditionally participated in wootz production, and still retain a few memoirs and the tools and implements that were used by them, besides monumental secondary sources.

Wootz is very high-carbon steel, made in this region in small clay crucibles from unknown times (may be 300 BCE). 'Wootz' is a word derived from the Telugu word: *Wokku* or *Ukku* means melt. It is also caked *Urukku* in Tamil, and *Ukku* in Kannada. (Telugu Dictionary, Shabdaartha Ratnakaramu and Shabdhartha Chandrika)

**Figure 3** Chakreshwari a Jain Goddess

**Figure 4** Kurikyala trilingual inscription

Since the Kannada language in the early medieval period was very much prevalent in the Telangana region, several Kannada inscriptions are noticed in this region. The Rashtrakuta feudatories, known as Vemulavada Chalukyas, ruled from Vemulavada in Karimnagar, and they patronised Kannada as their court language. The first Kannada poet Pampa, the *Aadikavi* ( i.e "first poet" in Kannada Language) belongs to the Karimnagar district, where we find a gift inscription on a big boulder on the hillock called *Bommalamma gutta,* near the Kurikyala village, in the district Gangadhara Mandal. This inscription is a trilingual inscription in Sanskrit, Kannada and Telugu. It revealed that the Pampa received Dharmapuri *aghrahara* as village grant from the king Ari Kesari-II in 945 CE. (Fig. 3 and 4)

This fact proves that the Kannada language was very much prevalent under the Vemulavada Chalukyas. (Karimnagar Inscriptions 1974) The wootz is a well-known production, it was in usage in South India, and it is found in the South Indian languages. The material heritage of wootz is still continued in Northern Telangana to this day.

## Wootz Making

**Figure 5** Wootz crucible bottom

Pieces of iron were placed in refractory crucibles, and the flux added was a piece of wood, green leaves and borax (*Veligaram*), the crucibles were covered with cone-shaped lumps of clay, and kept for greening (Fig. 5 & 6). In this region, they were called *Konam pavulu* or *Wukku pavulu*. These crucibles were kept in a specially constructed circular furnace, and places in the bed of charcoal. They were blasted for 24 hours and left for 12 hours in the same furnace for annealing. The ingots were taken out by breaking the crucible. In this region we find broken crucibles heaps in a good number of villages. (Jaikishan 2007; Egerton, 1896/2001)

The thermo mechanical processing was the key to obtain from wootz steel ingots and objects. Wootz steel is used for all cutlery items (Fig.7) and the people in this region were making and using them since times unknown.

**Figure 6** Wootz ingots with bottoms

**Figure 7** Wootz Knifes with Pattern welding (Photo Courtesy R Balasubramanian)

## The community involved

In this region, Wootz producers were called the *Kammari* (Blacksmith) community. In particular, five artisan groups were represented in the so-called *'panchannam varu'*, that included blacksmiths, goldsmiths, bronze-smiths, carpenters and sculptors (idol makers). "These five communities believe that they all originated from God *Vishwakarma* (*Vishwa*-universe and *Karma*-action), whom they regarded as their divine God of Architecture and Engineering/ Technology/ Manufacturing in Hindu tradition. These communities are also called *Rathakara* communities. (Niranjana Shastry V, 1934) "They are the rural artisans having five major occupational groups, viz. Kamsali or Sarabu or Ausala (gold smith), Kanchari or Musari (brass smith), Vadrangi or Vadraor Vadla (carpenter), Kammari (black smith), Silpi or Kasi (sculptor and stone mason)" (Singh SK, 2003). Among these communities blacksmiths were particularly important, due to their close association with the ruling class as well as with the farmers and industrialists during the historical periods. Their technical expertise was much in demand from the state for making wootz steel and war equipment, such as arrow heads, swords, daggers and artillery pieces, and equally for the farmers for their agricultural implements. The very survival of the state depended on the workmanship of the blacksmith community.

The iron ore extraction and the iron making were carried out by the community called *Muddakammari* or *Muddakolimi Kammari.* Their name is derived from their traditional practice of erecting *kolimi* (over blown bellows) in open space. They prefer to call themselves *Are Kammara*. They are also referred to as *Bayatikmmari* or *Advikammara,* while others refer to them as *Baita Kammara*, *Byta Kammara, Kammari Vallu* or *Marathi Kammarollu*. In the Telangana region, they are known as Ghisadi; the name is derived from the Urdu word *Ghisana 'to rub'* (Thurston, vol-I, 1909). This community is involved only in iron smelting since they were residing in forest, away from the villages (From field notes, 2005). The other smelters were tribal communities like Asur, Kolami, Gond, and Agaria tribes living in central Deccan.

Some interesting observations were recorded in respect of the blacksmith community in the villages of Telangana. In most of the wootz producing villages we find a temple devoted to the Goddess *Mammayee.* She is considered the Goddess of Metalwork. Interestingly, the name *Mammayee* is derived from *Amma,* and means mother. Iron is called *ayee, ayah* or *aiyas* in the Prakrith and Sanskrit languages and *Ayo* or *aya* or *aye* in the Pali language. (Rhys David's, 2007). The root *aya* is found in a set of few metals forming an alloy, ayo- or *loha* means iron, copper is *tipu*, tin is *sisa,* and lead and silver are *sajjha*.

**Figure 8** Dilapidated Mammayee Temple Mammunur

**Figure 9** Mammayee Temple at Kalval Peddapalli Mandal

**Figure 10** Pedda Mammayee Temple at Konasamudram

*Mammayee* is the Goddess of iron or of metals, and the Goddess of the Viswakarma families. The five communities will offer prayers to this Goddess. Most of the wootz producing villages contain a temple dedicated to *Mammayee*, but most of the temples at present are neglected and a few are in dilapidated condition. (Fig.8) Only one large temple remains, in the Kalvala village, Peddapalli Mandal, in the Karimnagar district (Fig.9), to continue the *Mammayee* tradition, but there are also afew more *Mammayee* temples in this region in which traditional rituals continue. Two temples are in a legendary wootz steel manufacturing centre, and there is a street called *mammaye wada* in the Konasamudram village (Fig.10). Other temples are in Uppuloor in Kammariplli Mandal, and in Rautla Sirikonda Mandal in the Nizamabad district. A further temple dedicated to this Goddess is found at the Ibrahimpatnam Mandal headquarters, in the Karimnagar district. A few temples are in and around Hyderabad city. At Siddipet town in Medak district, there is a temple dated to the 15 th century CE, and one more temple is found in the region, in the Pembarthi village, Warangal district.

## Unique Customs

The blacksmiths of the Telangana region, like most of the blacksmith communities of south India, belong to the caste of *Viswakarma*, the Hindu god of arts and crafts. In the Telangana region five distinct craft communities belong to the *Viswakarma* caste. It is not completely clear whether marriages with other craft groups, such as for example stone masons and carpenters, are generally approved or not, however there are often cases of intermarriage among the three metal craft communities. Marriage outside the caste is not favourably seen. The members of the *Viswakarma* caste of this region, and therefore also the people within the blacksmith community, wear sacred threads like the Brahmins. We also noticed that there exists a strong inter-caste competition with the Brahmins, and this can be in particular observed in the traditions and taboos of the blacksmith community.

The community of the blacksmiths lives in close clusters often not very far from slag or a crucible heap. On observation their residences and work stations are situated closer to the residential cluster of the agricultural community, who are their primary clients. The community has a strict seniority order and stratification. At the head of each community in the villages there is a body of elder blacksmiths, consisting of mostly three or four senior smiths. Every new moon evening communal meetings are organized in the premises of the temple of their goddess *Mammayee.* The meetings are conducted by the elder blacksmiths and in this occasion all important decisions regarding community problems are taken. The topics include for example disputes in the villages, auspicious and inauspicious days and festivals. The decisions of the body of elder blacksmiths are considered in most cases final and not to be discussed. We have observed that the relations between castes, but also in the intra-community hierarchy, and in other inter or intra community relations, there is a fixed and typical ritualistic behaviour, and mechanisms of obligation and reciprocation.These could be observed in further detail during their annual rejuvenation festival. In this context it must be mentioned that the participation of women to any aspect of goldsmithing, but also to the cult of their goddess is severely forbidden.

The immediate clientele for the rural blacksmiths is represented by the farmers community. The two groups have a long standing tradition that directs their trading transactions and is characterized by oral contracts. In this business relationships the farmer and the blacksmith stipulate an oral contract, in which the basis of payment is normally rice or pulses, and the blacksmith agrees to provide or to repair as many agricultural tools as the farmer desires from him. The blacksmith receives his retribution in two installments i.e., after two harvest seasons. This tradition is apparently very well established and long standing in most of the villages of the region, and monetary transactions do not seem to be in use, except in some villages which are closer to the urban centers or highways. However one itinerant blacksmith was interviewed during the survey, and, because of his kind of wandering work, he preferred to be paid in cash. The blacksmiths belonging to the rural community produce tools exclusively to provide to the needs of the local farmers. Mass production of iron equipment and tools does not seem to be practiced, while the manufacture of objects and repairs are only carried out after specific request, probably because of the declining of the local production of tools at the face of industrialized products.

## *Mammayee* Festival

The annual festival event of the goddess *Mammayee* traditionally takes place in the temples and usually at the beginning of the Telugu New Years day (Ugadi). It continues for eleven days. The Telugu New Year day begins on *padyami,* the first day of the *Chaitra* month. On the first day they establish the *kalasha* or light the sacred oil lamp in the temple (Fig 11 and 12), and the entire community brings their one or two implements, used for daily work. They keep them at the sacred stand of the Goddess, in the early morning. In the evening a procession in honour of the goddess goes through the streets of village. Fig 13 shows the rituals in their houses. The community members do not work during these festive days. On the 11th day they start their normal routine work.

**Figure 11** Oil lamp in the Temple

**Figure 12** Implements placed on the goddess' stand

During our visit in 2010 the festival was however shortened to three days, because of serious economical problems of the blacksmiths of the region. In the course of the festival, we surveyed four villages. The final day of the ritual is also the Telugu New Year's Day, and in this occasion we could collect information and observe the rituals in the village of Ibrahimpatnam, where the cult of the goddess is still the strongest.

**Figure 13** Rituals in the home of blacksmiths

On the first day of the festival the blacksmiths do not work and carry some of their tools to the nearby temple of *Mammayee* for worship. The blacksmiths eat exclusively vegetarian food and it is imperative that this food is cooked within the temple premises. As women are not allowed to participate in the cult rituals, the blacksmiths must carry out all activities by themselves. Apparently the cult of *Mammayee* is exclusively followed by the blacksmith community, but also other craft groups belonging to this caste refrain to from working and worship the God *Viswakarma* inside their homes. A local saint Veera Brahmendra Swami is also worshipped together with the deity.

On the final day of the festival the blacksmiths gather in the temple before sunrise and prepare the food offerings consisting of five principal items such as pulses, rice, maize, coconut and jaggery. The senior blacksmiths then carry out the final worship, and the oldest among them acts as high priest by reciting mantras. It is quite interesting to note that the oldest blacksmith serving as high priest, in at least three villages, has also the function of goldsmith. At the end of the rituals, the assembled group of blacksmiths help each other and fasten to their wrists the sacred threads, dipped into fresh turmeric, in the temple courtyard. Finally they tie sacred threads on their working tools that, with all probability, are seen as extension of the blacksmith's body and are rejuvenated through infestation of divine power and blessings of the goddess. The inauguration of the smithy in individual houses follows the ritual in the temple. In this ceremony the eldest family member hits the anvil with five blows for three times and is then followed by all other family members in order of age. After this the eldest smith has to light the hearth and manufacture an agricultural tool, while the second eldest operates the fan bellow. Finally, the junior apprentices of the family carry the tools produced during the ritual to the houses of the farmers, and these are required to offer rice, pulses, turmeric and garlic in exchange. In this way the ancient relationship with the farming community is renewed through a ritual contract every year.

## Conclusions

In the region Telangana, the iron industry was greatly prevalent. At the same time the Wootz steel industry was predominant and its associated weapon industry expanded, due to high demand both in the country and from external traders. These occupational group customs and rituals are still continuing among these smith families, but in modern days most people do not know about the Goddess Mammayee and the traditional culture.

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BUMA-7 Inaugural function, NIAS

BUMA Standing Committee, NIAS

BUMA-7 Banquet, Ashoka Hotel


Group photograph of BUMA-7 participants, NIAS

BUMA-7 Cultural event of Bharata Natyam performance directed by Smt Padmini Ramachandran

Bob Maddin at photo-exhibition on 'Chola bronzes & art-science-dance explorations'

Mysore Palace with Dussehra lighting, BUMA 7 excursion

BUMA 7 excursion to 12th century Hoysala Somnathpura temple

## About this Book

The proceedings of BUMA VII, held in 2009 in Bangalore as part of the renowned international conference series on the 'Beginnings of the Use of Metals and Alloys', are published as an edited volume entitled "Metals and Civilisations". With twenty eight valuable peer-reviewed papers covering inter-disciplinary research, it widens our knowledge of the use of metals in antiquity and several aspects of the archaeology, archaeometallurgy, historical metallurgy, crafts practices and metallurgical heritage of many Asian and some non-Asian countries

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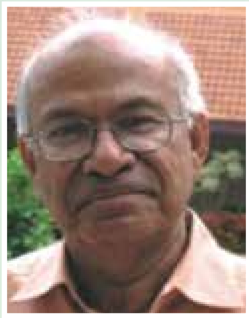
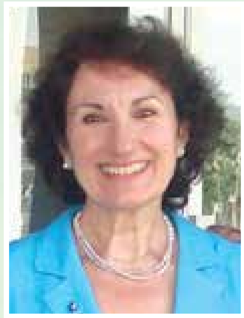


### Prof. Srinivasa Ranganathan

Prof. Srinivasa Ranganathan is Emeritus Professor at the Indian Institute of Science and Homi Bhabha Visiting Professor at the National Institute of Advanced Studies. His interests cover physical metallurgy, history of science and heritage science. He is a member of International Advisory Committee of the BUMA Conference series, INSA National Commission for the History of Science and the DST Programme Advisory Committee on Indian Digital Heritage – Hampi. He taught the inaugural course on Science and Civilization in India to IISc Undergraduates in August 2011 and a course on Materials Heritage and Conservation at the Tokyo University of the Arts, Japan in 2012. He is a Fellow of four Indian Academies of Science and Engineering and the World Academy of Sciences (TWAS) and recipient of Lifetime Achievement Awards from the Indian National Academy of Engineering (2014) and Indian Institute of Metals (2012).



### Dr. Alessandra Giumlia-Mair

Dr. Phil., M.Sc. Alessandra Giumlia-Mair was first lecturer and then Professor by contract (1992-2001) in Archaeometallurgy and Archaeometry at the Universities Salzburg (Austria), Trieste and Udine (Italy). In 2000 she founded AGM Archeoanalisi, a laboratory specialising in Archaeometallurgy. She worked on European and Asian finds from excavations and from the British Museum, Ägyptische- and Antiken Sammlung Munich, Royal Ontario Museum Toronto, Römisch-Germanisches Museum Cologne, National Museum of Transylvania, National Museum Budapest, National Museum Cyprus, Institute of Aegaean Studies Crete, and many museums in Italy. She is Member of the BUMA Standing Committee, Fellow of seven European Academic Societies, published around 200 books and papers on Archaeometallurgy, and edited 12 volumes of Proceedings of International Conferences on Ancient Metallurgy and Archaeometry.

Proceedings of the VII International Conference on
'The Beginnings of the Use of Metals and Alloys'

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