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ARTICLE

Metallurgical characterization of the coins of the Sangama and Tuluva dynasties of Vijayanagara

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Abstract
Copper coins belonging to the Vijayanagara Empire, which ruled the Deccan Plateau region of South India, were excavated. Based on the inscriptions on both their obverse and reverse sides, the coins were identifiedwith the respective kings during whose time they were minted. Later, the coins were subjected to chemical and structural characterizations studies to understand their elemental composition and microstructure. X-ray diffraction studies, followed by inductively coupled plasma mass spectroscopic analysis, helped identify the alloying elements and their percentage concentrations. Scanning electron microscopic observation of the polished sections of the coins revealed the alloy microstructure. The results provide important insights into understanding the coin-minting technology of the historically well-known Vijayanagara Empire.

Keywords Sripra · Prata/pa · Srideva · *Tapakashna* · *Tapachyuta*

1 Introduction

Among the several kingdoms that have ruled Karnataka, the Vijayanagara empire was one of the most significant dynasties that contributed to the culture, history, and growth of the state. Having been established in 1336 CE, the empire flourished for almost two centuries, consolidating most of South India under a single imperial regime. The Vijayanagara architecture has garnered considerable attention, has been well-studied, documented, and preserved (Kamath, 1980, p. 183; Michell & Fritz, 2001). The coins and other artifacts of the empire have also been excavated and studied for their monetary value and historical background (Murthy, 1991). However, the metallurgical aspects of these coins are not very well known. A systematic study involving the identification of their composition and microstructure would provide important insights into the technology of coin minting in the ancient period.

The mining of copper had started very early in Karnataka, as revealed by the 14C date of more than 2070 years, derived from timber pieces collected from the old workings at Ingladalu in Chitradurga district. Other than at Ingladalu, ancient copper mining is also noticed at places such as 8–10 km west-south-west of Bellary, Thintini in Gulbarga district, Kalyadi in Hassan district, Hadabanatta in Mysore district, and Jambani in Shimoga district. Not only was the ore mined in all these places during this ancient period, but it was also smelted and the metal extracted.

The evergreen jungle near the village of Jambani in Shikaripur taluk, Shimoga district, contains heaps of slag resulting from the smelting of copper. The ore for the smelt was traced to the western slopes of the hill near the village of Jambani, where mining pits/shafts left behind by early miners were found, starting at about 30 m below the crest and extending up to the highest point of the hill. Kalyadi in the Arsikere district is another place that witnessed one of the largest old workings.

The open-cast mined area extends up to 1 km, with a width ranging from 20 to 30 m. At Ingladal, the presence of ores of antimony, arsenic, lead, copper, and zinc is noticed in a belt of schist extending for a length of 30 km on the eastern part of the Chitradurga schist belt. The copper mine over there reached a depth of 460 m below the ground level.

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A recent study indicates the occurrence of gold and silver with the sulfides. Gold occurs in native form as micron-sized inclusions in pyrite, pyrhotite, and arsenopyrite. Four types of mineralization have been recognized at Ingladal, viz., (a) stratiform massive sulphide, (b) bedded pyrite–pyrhotite rhythmite, (c) massive sulphide veins, and (d) fracture-controlled druzy-quartz veins carrying sulfides of Pb-Cu-As Jayaram et al. (1967).

The present work focuses on four copper-based coins of the Vijayanagara Empire: two coins of the Sangama dynasty, issued by Devaraya I and Devaraya II, and two coins of the Tuluva dynasty, issued by Krishnadevaraya and Achyutadevaraya. The studies involve unraveling the physical features of the coins that would help in associating them with their makers, identifying the trace elements present, and correlating this information with their chemical composition and microstructure.

2 Experimental

2.1 X-ray diffraction

The composition of the coins after grinding off one of the top surfaces was determined using the X-ray diffractometer, D8 Discover, Bruker AXS, (Madison, USA,) with Cu-K_α radiation ($\lambda = 0.15406$ nm).

2.2 Inductively coupled plasma mass spectrometry (ICP-MS)

Metal determination was carried out by using ICPMS Perkin-Elmer ELAN DRCe Instrument. The instrument is equipped with a nebulizer and a Scott spray chamber and is coupled with an AS-90 series autosampler, controlled by PE ELAN 3 software. In this work, the concentrations of biogeochemically important elements (Ca, Mn, Fe, Ni, Zn, Mg, Pb, Cr, V, Cd, Cu, and Al) were measured in the digests using ICPMS.ICPMS calibration was carried out using standard solutions in the concentrations range 10 ng ml^{-1} to 1 mg ml^{-1}, prepared from a multi-element standard solution with 17 elements of 100 ng ml^{-1} in 5% nitric acid. For analyte concentrations outside the calibration range (10–1000 ng ml^{-1}), dilution in 5% nitric acid was used. The inter-element correction software provided with the PerkinElmer ELAN 3 was used to compensate for any interference encountered during the analysis of different metals.

2.3 Instrumental operating parameters for Perkin-Elmer ELAN DRCe

Rf power (W) 1350
Nebuliser flow (l min^{-1}) 0.8
Auxiliary flow (l min^{-1}) 15
Plasma flow (l min^{-1}) 0.5
Sample flow (l min^{-1}) 1.8
Read delay (s) 40
Rinse delay (s) 40
Number of replicates 3

2.4 Reagents/flasks

All reagents were provided by Merck and were of the following grades: Supra pure (HCl, HNO_3) and Pro Analysis ISO (HF). Prior to single use, the sample flasks were soaked for a few days in 65% HNO_3 diluted to 10%. The flasks were then washed with ultra-pure water (Millipore Corporation) and oven-dried.

2.5 Microwave-assisted digestion

An Anton Paar multiwave microwave sample preparation system with rotor 8MF100 was used for the decomposition of samples. Samples were placed in fluoroplastic vessels (MF100 TFM), which were mounted in ceramic supporting vessels. TMF is a chemically modified PTFE with strongly improved dimensional stability. The vessels support an operating pressure of 20 bar, a maximum operating pressure of 75 bar, and a maximum bottom temperature of 220 °C. The vessels are resistant to HF. The reaction vessels are cleaned before each digestion using 5 ml of HNO_3 (65% sub-boiled) heated for 30 min at 1000W. The various combinations of acids were used to determine the most accurate and efficient method of extraction of several metals.

2.6 Sample preparation

Different weights of samples have been used in the literature for the microwave digestion. A 50 mg of the sample was chosen and accurately weighed directly into the reaction vessels, and the decomposition reagents were added. Three replicates were taken for each sample, the tops of the reaction vessel were screwed on and hand-tightened. The pressure vessels were positioned in the rotor, which was then placed in the multiwave, and the safety door shut. A built-in control computer was used to specify the decomposition program, control the multiwave, and hold a library of sample/methods. An infrared sensor measured the temperature and pressure at the bottom of the reaction vessels. A cooling air flow between the reaction vessel and the bomb jacket prevented the components from overheating during the decomposition process. Upon completion of the reaction, the vessels were cooled as quickly as possible with a maximum of cooling air. When digestion was complete, the sample was transferred to a volumetric flask. The reaction vessels were washed out with Milli-Q water,

and the flask volume was made up to the mark. For each digestion, reagent blanks were obtained. For analysis by ICPMS, the samples were dilutedin 2% nitric acid.

2.7 Acid combinations used

The digestion study on microwave-assisted digestion of solid samples, concentrated HNO_3-HCl combined with HF acids were mainly used. In the present study, the acids selected for use in sample digestion were 65% HNO_3, 30% HCl and 40% HF. These acids were chosen since each helps in the decomposition of a specific part of the solid or sediment matrix. HCl is a strong acid and is used for the decomposition of organic samples in combination with HNO_3. Various combinations and different volumes of these acids were used to determine the best digestion conditions for each sample. After digestion, the samples were diluted, and the selected metals were analyzed using ICP-MS.

2.8 Microscopy

The coins were polished to a mirror finish using a series of emery sheets, starting from 320 to 1800 grit size, and then polished with alumina powder. Finally, they were finished using diamond paste of 0.1 µm size. The coins were subsequently etched with saturated CrO_3 solution until the grain boundaries were revealed. These were observed with a Leitz Laborlux 12 ME (Germany) optical microscope prior to scanning electron microscope (SEM) imaging. The microstructure of the etched coins, both in the secondary electron mode and backscattering mode, was subsequently studied using FEI Quanta 200 (USA) SEM fitted with lithium doped silicon energy dispersive X-ray spectrometer (EDS) of AMETEK Process and Analytical Instruments.

3 Results and discussion

3.1 Physical description of the coins

Coin 1: The coin weighs 3 g andis15 mm in diameter (Fig. 1). The obverse side features a bull to the right (Fig. 1a), and the reverse side displays inscriptions in three lines of Kannada characters, reading "*sri de va*". It also has a dagger between the conch followed by *raya* inscription (Fig. 1b). This type is similar to coin 59 listed by K. Ganesh(2009). The coin is attributed to Devararya I (1406–1422 CE, Sangamadynasty).

Coin 2: The coin is 16 mm in diameter weighing 3.4 g (Fig. 2). The obverse side has an elephant to the right (Fig. 2a), and the reverse side has a three line Kannada legend *pra ta/pa de va/raya* (Fig. 2b). This type is similar to coin 80 listed by Ganesh(2009). The coin is attributed to Devararya II (1424–1446 CE, Sangamadynasty).

Coin 3: The coin weighs 10.5 g and has a diameter of 18 mm (Fig. 3). A*Garuda* (a mythical bird-like creature) can be observed to the left in *virāsana* posture in the obverse side (Fig. 3a), and the reverse side has three linesof Nagari legend *sripra*/*ta pa kashna*/*raya* (Fig. 3b).This type is similar

Fig. 2 The obverse and reverse sides of the coin of Devaraya II

Fig. 1 The obverse and reverse sides of the coin of Devaraya I

Fig. 3 The obverse and reverse sides of the coin of Krishnadevaraya

to coin 129 listed by Ganesh(2009). The coin is attributed to Krishnadevaraya (1509–1529 CE, Tuluvadynasty).

Coin 4: The copper coin weighs 12.7 m with a diameter of 18 mm (Fig. 4) and has the back view of Gandabherunda (a two-headed mythological bird) flying upwards on the obverse side (Fig. 4a) and the bird is carrying in each of its two beaks and two claws a full-grown elephant. The reverse side features a three-line Nagari legend: sripra/ta pa chyu ta/raya (Fig. 4b). This type is similar to coin 147, listed by Ganesh(2009). The coin is attributed to Achyutaraya (1529–1542 CE, Tuluva dynasty).

The find spot of coin 1 is Karur (Tamil Nadu, India, 10.95° N 78.08° E), coin 2 is Madurai (Tamil Nadu, India, 9.919662° N 78.119393° E), and the other two coins were found near Hampi (Karnataka, India, 15.335° N 76.462° E).

3.2 Chemical and microstructural analysis

The X-ray diffractograms of the coins are shown in Fig. 5. The coins only show the presence of copper as the base element. However, the concentration of each alloying element in the coins, expressed as a percentage, is provided in Table 1 via inductively coupled plasma mass spectroscopy. Copper is the key element present in the coins, making up nearly 70% of the total composition. The second major element present in the coins is lead, which makes up between 4 and 7%. The presence of Ag, Zn, and Fe, which account for up to 3%, appears to be the other major alloying elements of the coins. The presence of eight different elements in trace quantities (< 1%) suggestsimpurities in the metal. The diffraction intensities of the copper peaks appear to be different from those provided for Cu in JCPDS. While the highest intensity peak for the plane (111) should ideally fall at around 43°, the (220) planes are the higher-intensity ones, occurring at around 75° for the coins. Additionally, a shift of approximately 1 degree is observed for all three characteristic peaks of copper, which may be due to the presence of other trace elements in the system.

Fig. 4 The obverse and reverse sides of the coin of Achyutaraya

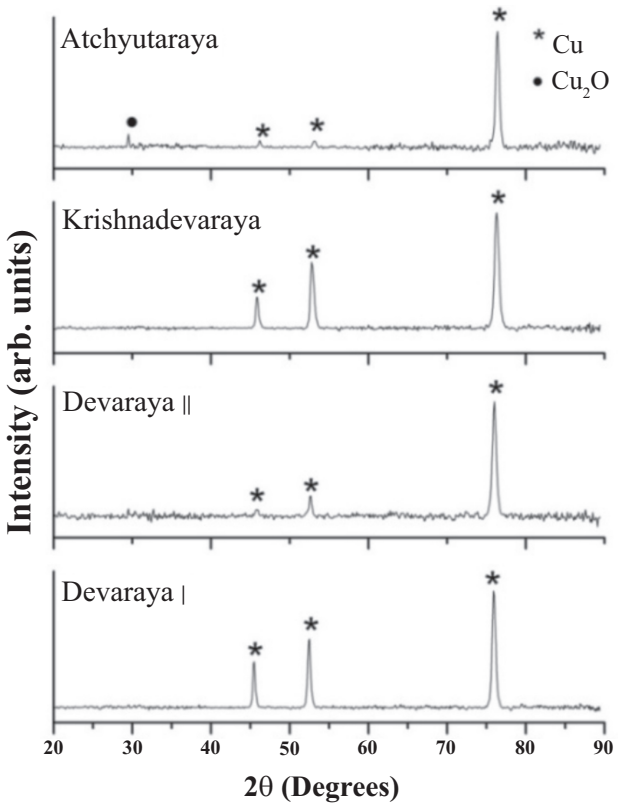


Fig. 5 X-ray diffractograms and ICPMS suggesting the different chemical elements present in each coin

The study by the Indian Bureau of Mines in the Chitradurga schist belt revealed pyrite- pyrhotite-chalcopyrite-sphalerite-galena in the Chitradurga schist belt (Radhakrishna, 1996). Nickel is also present in the Chitradurga

Table 1 Concentration results of the coin of Devaraya I, Devaraya II, Krishnadevaraya and Atchyutaraya

S.No	Analyte	Coin 1 concentration %	Coin 2 concentration %	Coin 3 concentration %	Coin 4 concentration %
1	Mn	0.729	0.884	0.264	0.382
2	Fe	2.422	1.659	2.345	2.124
3	Ni	0.617	0.451	0.061	0.245
4	Co	0.044	0.036	0.036	0.084
5	Cu	68.923	70.151	72.708	71.625
6	Zn	3.052	2.653	1.265	1.442
7	Se	0.455	0.261	0.357	0.081
8	Rb	0.089	0.059	0.014	0.033
9	Sr	0.453	0.241	0.124	0.156
10	Ag	2.042	1.583	1.831	2.242
11	Cd	0.027	0.016	0.034	0.041
12	Pb	7.064	5.421	6.457	4.523
13	Bi	0.450	0.389	0.171	0.368

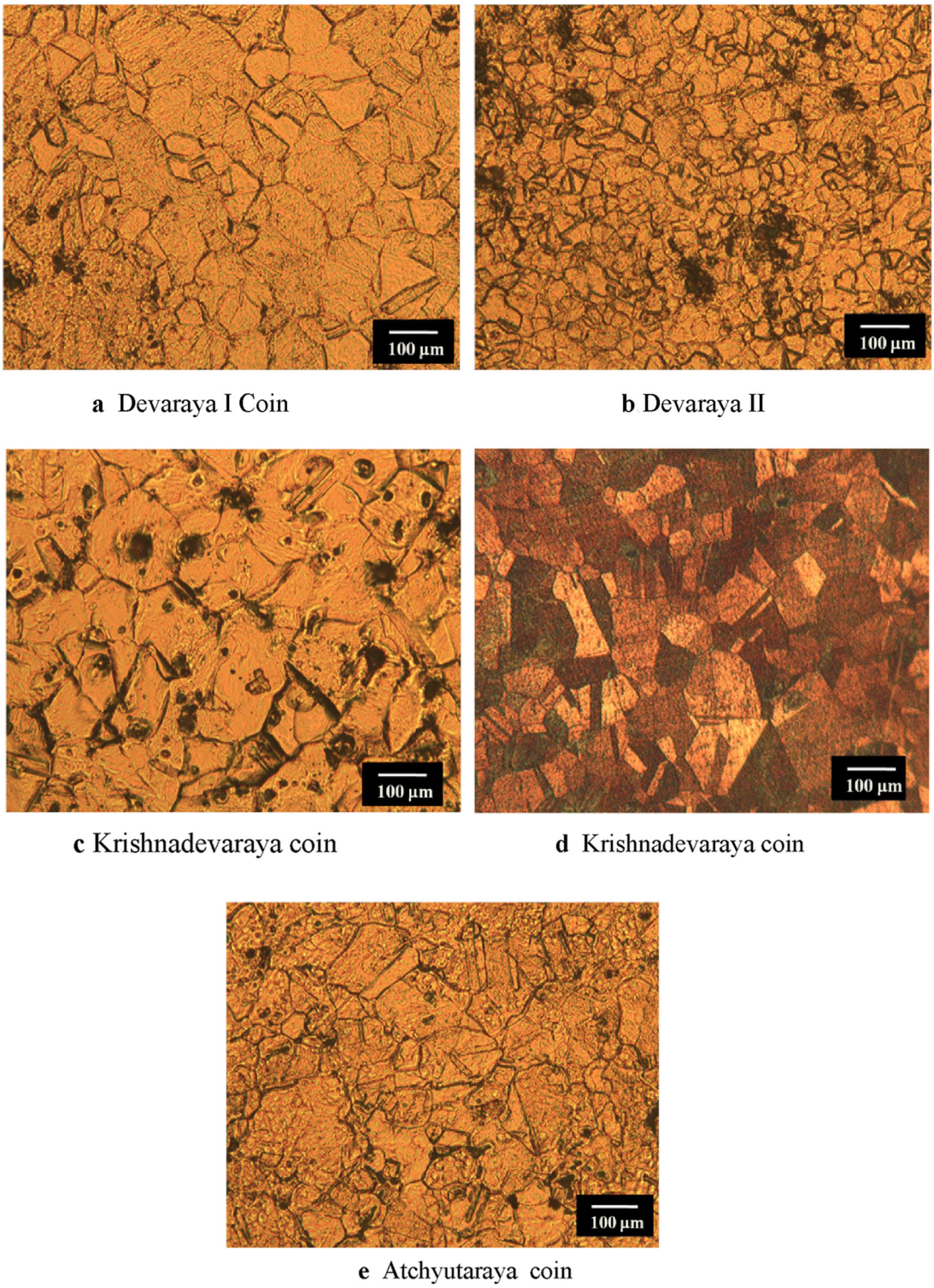


Fig. 6 **a**–**e** A representative optical micrograph of the microstructure of the coins after etching

schist belt. Bismuth is present in all the analyzed coins, and its occurrence points to the presence of arsenic and gold in the ore. The presence of arsenic, gold, and bismuth in Vijayanagar coins indicates that the Chitradurga schist could be the probable source, as the mines at Ingladal and Kalyadi show ancient workings (Foote, 1888). The Vijayanagar dynasty likely exploited the copper mines in the Chitradurga district to produce copper alloy coins. Similarly,rubidium's

occurrence indicates the presence of lead in the ore, and lead could have probably originated from the mines under their control in the state of Andhra Pradesh, India.

The optical (Fig. 6a–e) and scanning electron microscopic (Fig. 7) images of the coins etched with saturated CrO_3 solution for 11–14 min reveal their microstructure. On closer observation, the twinned grain structure of Cu with localized segregation of Pb is visible throughout for each coin. Upon lowering the magnification, the segregation of Pb into an interconnecting network structure, similar to the fingers of dendrite arms (typical of as-cast alloys),can be observed, especially in the BSE mode (Fig. 8). This network structure is not identical for all the four coins although coin 1 and 2 share similar microstructure with large network structures of 0.2 to 0.8 mm in length (Fig. 8a and b). The structure is relatively ajar for coin 3 (Fig. 8c) and is less than 250 µm for coin 4 (Fig. 8d). It is known that lead and copper which mix well above the melting temperature exhibit liquid miscibility gap at the liquidussurfaceand a monotecticreaction resulting in lead-enriched liquid and copper is obtained on cooling the liquid phase (Hong-bao et al., 2006; Kamio et al., 1991). As the metals are cooled further, copper solidifies first in the form of dendrites, and the liquid lead is forced towards the boundaries of the dendrite. Upon further cooling,Pbsolidifies across the interface of the dendrite arms and becomes trapped there unless secondary processing iscarried out (Dong & Wei, 1996).The magnified view of the dendritic armssuggests that several grains exist within, with Pb segregation along their boundaries (Fig. 9). The grains are almost of the same size, but those in the vicinity

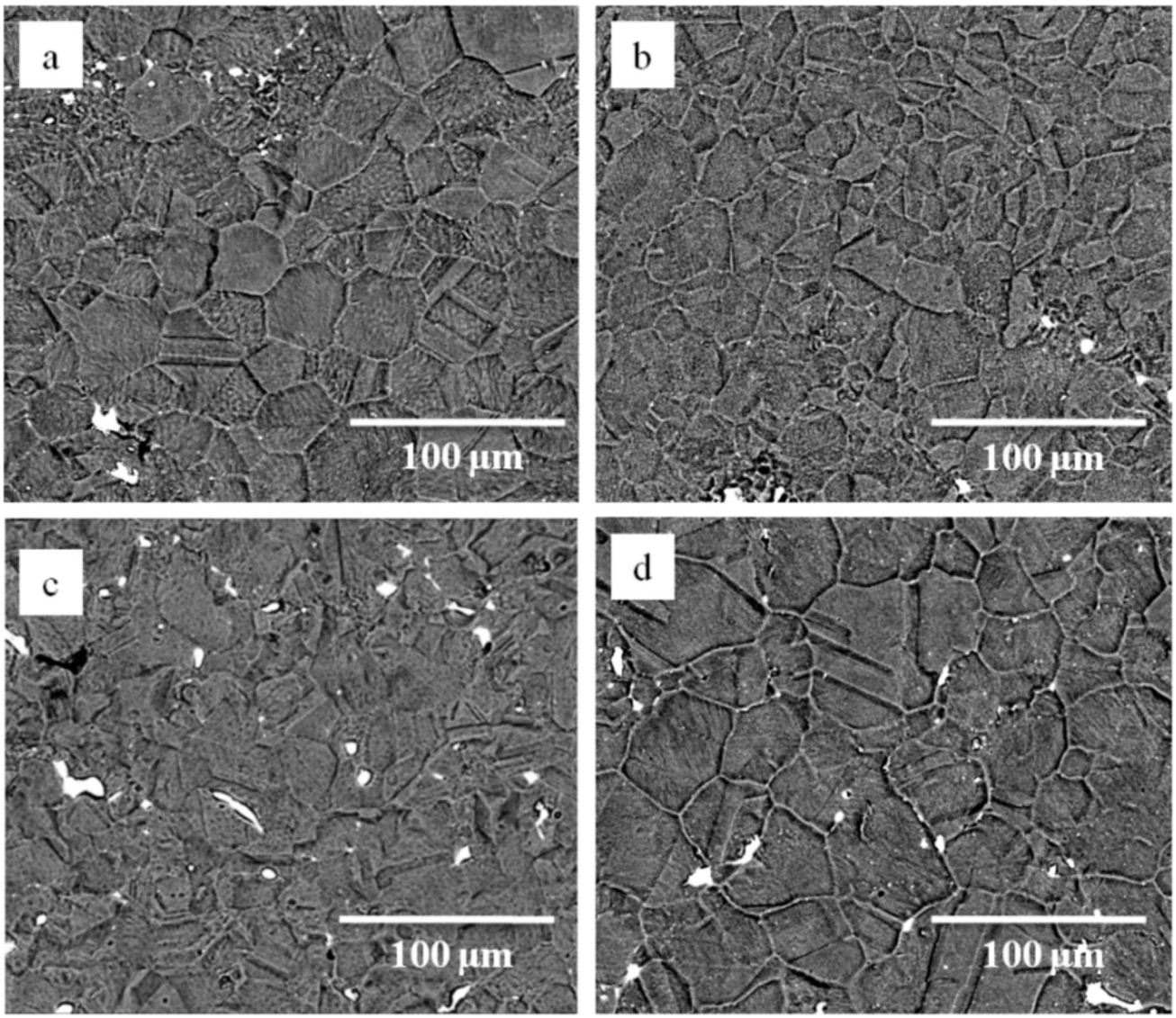


Fig. 7 The microstructure of the coins in BSE mode, indicating the twinned grain structure of Cu matrix and Pb inclusions (brighter phase) in the chronological order of their synthesis

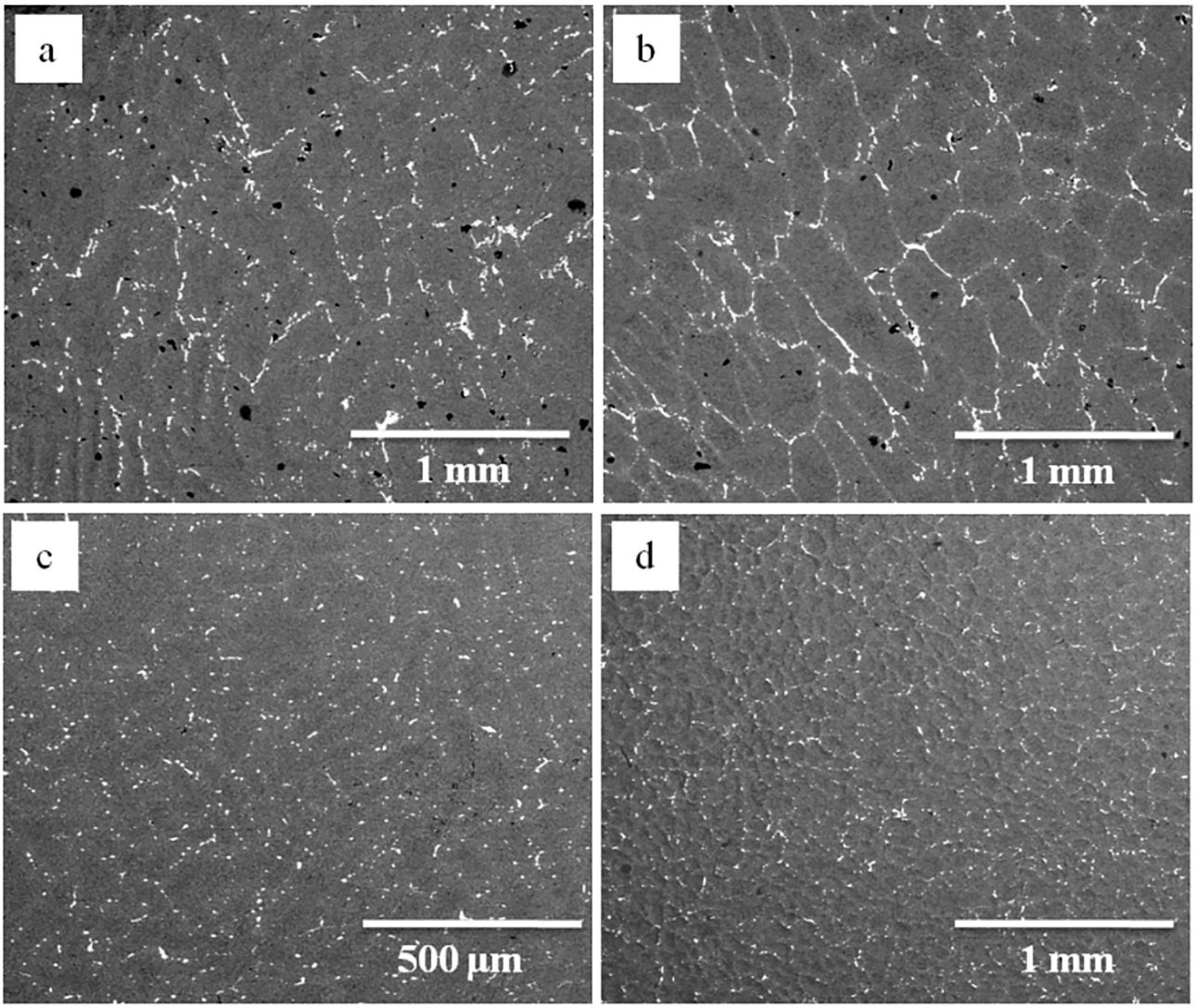


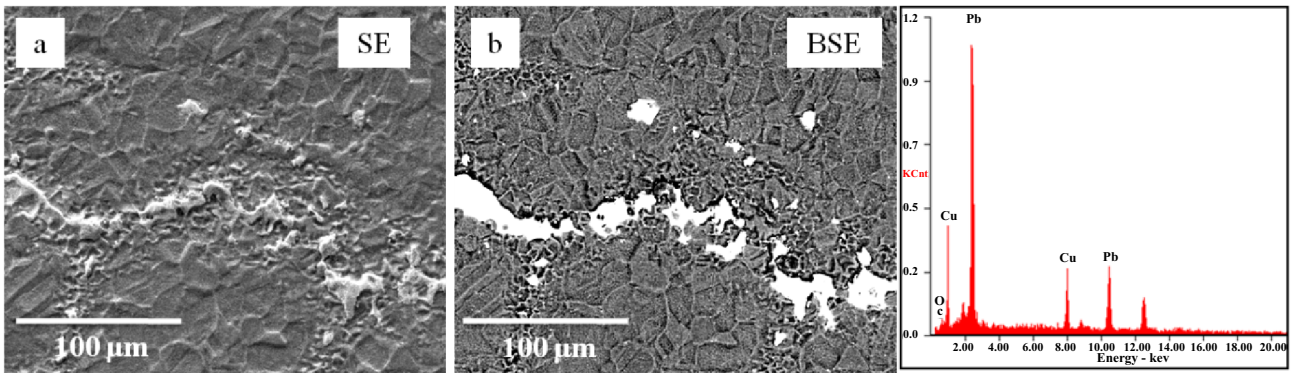
Fig. 8 Lower magnification BSE images representing the dendrite arms with Pb segregation at the interface in the chronological order of their manufacturing

of the boundary are severely distorted and corrugated. Since the arms are not disturbed, the implication points towards the absence of any post-processing of these coins. Thus, the metallographic examination of these coins suggests that they were cast to produce blanks andthen hot-forged to imprint their face value.

While most copper-based historical artifacts are either Sn-based or Zn-based, the coins of Vijayanagara show absolutely no content of Sn, suggesting that the coins are mostly leaded brass, although Zn is present in lower quantities. No variation in the Zn distribution was observed, suggesting that there was no dezincification of these coins. The concentration of trace elements appears to be similar across different coins, suggesting that the technology of coin minting was transferred through the lineage from the time of Devaraya I to Achyutaraya (from 1406 to 1542 CE).

4 Conclusions

Based on our investigations of the four different coins, it can be inferred that the coins were made of copper as the major element, with other alloying elements including lead, silver, zinc, and iron. The concentration analysis of different elements suggests that the composition of these coins is similar. The finger-like pattern of segregation of Pb suggests the dendritic solidification of the alloy synthesized by casting.The presence of twins indicates that the coins were hot-forged on both surfaces.



Element	Wt%
CK	05.29
OK	02.73
CuK	13.28
PbL	78.71
Matrix	Correction

Fig. 9 A magnified view of Pb segregation at the interface of the dendrite arms in both **a** SE and **b** BSE modes. Note that the matrix is not continuous but have similar grain size. A localized EDS measurement confirming the segregation to be Pb is also provided

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