New Appraisals of Angkorian Copper-Based Metallurgy (Ninth to Fourteenth Century): Mines, Foundries, and Cast Products

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ABSTRACT The result of almost thirty years of analytical campaigns performed on Khmer bronzes by the Centre de Recherche et de Restauration des Musées de France (C2RMF, Paris; 1996–2024), in collaboration with various Cambodian and foreign heritage institutions, the present paper aims to make available for scholarly research a unique, large, and representative analytical dataset, documenting, in particular, Angkorian copper-based metallurgy (ninth to fourteenth century). A total of 280 manufactured items (religious images, ritual paraphernalia, vehicle fittings, furniture parts, statue attributes, and architectural adornments) was selected and characterized by elemental analysis, before being studied in comparison with newly recovered (or rediscovered) metallurgical cast artifacts. The latter came, respectively, from a mining and metallurgical complex, Chhaep, in the margins of the Khmer kingdom; from a royal foundry in the heart of its capital, Yashodarapura (Angkor); and from major royal foundations within the same urban territory (West Baray, Royal Palace). Three major achievements have been made since the last reporting on this analytical research program in 2012. First, the characterization and understanding of the evolution of alloying practices throughout the Angkorian period were refined, showing the almost exclusive production of tin bronzes with isolated cases of either high-tin bronzes or leaded bronzes during very specific periods. Second, concurrent with these trends, a steadiness in the impurity patterns and, beyond, in the copper ores in circulation and use within the Khmer kingdom, was revealed. For the first time, what is potentially the major copper source for the whole Angkorian period may have been located within modern-day Cambodia. Third, the hypothesis of a succession of or coexistence of centralized and peripheral bronze-casting workshops has been raised, relating to the political history of the Angkorian kingdom during its peak period of the eleventh to thirteenth century.

Introduction

Initiated in the 1990s, a series of analytical campaigns performed by C2RMF in Paris (elemental analysis by direct-current plasma atomic emission spectrometry [DCP-AES], inductively coupled plasma atomic emission spectrometry [ICP-AES], inductively coupled plasma mass spectrometry [ICP-MS], and particle-induced x-ray emission [PIXE]) has focused on the technical study of Khmer bronzes, the most symbolically valued and technically elaborate metalcraft production of ancient Cambodia (e.g., Cort and Jett 2010; Bunker and Latchford 2011; Vincent 2012). This research program, continuing into 2024 and involving the collaboration of various museums and research and academic institutions in Cambodia and abroad, has resulted in the creation of a large and representative analytical dataset (Bourgarit et al. 2003; Vincent et al. 2012; Vincent 2012, 2014a, 2014b; Polkinghorne et al. 2014; CAST:ING 2018; Baptiste et al. 2025; see also Bourgarit and Vincent 2025a). This dataset is now used as a powerful research tool by the LANGAU research program (*langau* means copper in Old Khmer), which, since 2016, has undertaken a multidisciplinary and collaborative study of copper-based metallurgy in Angkorian Cambodia directed by Brice Vincent, École française d'Extrême-Orient (EFEO). While the Angkorian period conventionally spans the ninth to the fifteenth century, and while the present corpus has attempted to cover the whole period (at least six centuries between the ninth and fourteenth centuries), the study's focus has been on the eleventh to thirteenth century, when the Khmer influence on mainland Southeast Asia was at its peak and the Angkorian kingdom, centered around its capital of Yashodarapura, modern Angkor, was gradually characterized, both politically and economically, by an "imperial moment" (Bourdonneau 2014, 2025).

The Forbes symposia and their proceedings have played a key role in the dissemination of the results produced by this research program. Some twenty years ago, a first global synthesis on Khmer copper-based metallurgy was published in the first volume of proceedings, *Scientific Research in the Field of Asian Art*, which covered almost a millennium of production, from the seventh or eighth century to the sixteenth century, and presented the results of pioneering analytical approaches applied to 75 items from museum

Figure 1. Angkorian copper-based artifacts from the newly selected corpus: (a) Bull of Śiva, 12th–13th c., west of Angkor Wat temple, Angkor, Siem Reap province, h. 31 cm (statue), l.67 cm (base). NMC, Ga.5739; (b) garuda-*shaped boat finial, late 12th to early 13th century, unknown provenance (Phnom Sandak temple, Preah Vihear province, Cambodia?), h. 93.5 cm. NMC, Ga.7319; (c)* dvarapala *(element of bas-relief), unknown provenance (Cambodia or neighboring countries), h. 61 cm. NMC, NMC.2691, (d) rear view of same. © Thierry Ollivier.*

collections (Bourgarit et al. 2003). For the second synthesis, this time specifically dedicated to Angkorian copper-based metallurgy and published in the fifth Forbes volume, *Scientific Research on Ancient Asian Metallurgy*, 129 items were selected and analyzed, all attributed to the late eleventh to the early thirteenth century (Vincent et al. 2012).

While continuing the 2003 and 2012 syntheses, this paper can now take advantage of a much more consistent corpus of 377 items, which comprises additional types of artifacts from newly discovered metallurgical sites and embraces a larger chronological frame—that is, the entire eleventh to thirteenth century, plus some earlier and later production periods. The aim here is both to propose a revised global synthesis inclusive of all the analytical data accumulated thus far and to open the way to totally new insights into the study of Angkorian copper-based metallurgy.

Corpus of Study

Three Decades of Analysis: An Increasing Corpus of Angkorian Copper-Based Artifacts

To cover the eleventh to thirteenth century, and more largely the Angkorian period, the corpus under study first took into account all the copper-based artifacts selected for the 2012 synthesis (129 items, dated to the late eleventh to the early thirteenth century). Additional artifacts, first selected for the 2003 synthesis, were also included (19 items, dated either before the late eleventh century or after the early thirteenth century). The main input, however, came from the selection of 145 new Angkorian copper-based artifacts that had been studied, sampled, and analyzed since the 2012 publication; that is, between 2011 and 2024. Finally, in order to further expand the corpus, 24 artifacts from American and European museum collections that were analyzed by laboratories other than C2RMF were incorporated into the study. Most of the artifacts come from the following museum collections:

- Cambodia: National Museum of Cambodia (NMC), Phnom Penh; Angkor National Museum (ANM), Siem Reap; and Angkor Conservation Office (ACO), Siem Reap.
- Laos: Wat Phu Museum, Champasak.
- Thailand: Bangkok National Museum (BNM).
- France: Musée National des Arts Asiatiques—Guimet (MNAAG), Paris; and Musée des Arts Asiatiques (MAA), Nice.
- Germany: Museum für Indische Kunst (MIK), Berlin.
- United States: Walters Art Museum (WAM), Baltimore; Museum of Fine Arts (MFA), Boston; Art Institute of Chicago (AIC); Cleveland Museum of Art (CMA); Asia Society (AS), Brooklyn Museum of Art (BMA), and Metropolitan Museum of Art (MMA), all in New York; Asian Art Museum (AAM), San Francisco; and National Museum of Asian Art (NMAA), Smithsonian Institution, Washington, D.C. (table S1).[1]

Other research institutions based in Cambodia have also been solicited:

- APSARA National Authority, EFEO, the World Monuments Fund (WMF), and the Archaeology and Development Foundation—Phnom Kulen Program (ADF), all in Siem Reap.

Cast Products

The selected artifacts are representative of nearly all types of product cast by Angkorian founders: they include a majority of religious images of Hindu and Buddhist deities, of various sizes and uses, together with a wide range of prestige objects, such as ritual paraphernalia, vehicle fittings, and furniture parts, as well as statue attributes and architectural adornments (fig. 1).

Similarly to the 2012 synthesis, the items were chosen to satisfy one or several of the following requirements to reduce methodological bias.

First, on iconographic and stylistic grounds, all selected artifacts were identified as "Angkorian," which means produced between the ninth and fifteenth centuries within the former territory of the Angkorian kingdom, including modern-day Cambodia, south and central Vietnam, south Laos, and northeast and central Thailand. Ten groups of artifacts were distinguished, in an attempt to follow the classical divisions or "styles" of Khmer art history (e.g., Polkinghorne 2007; Baptiste and Zéphir 2008; Roche 2023), and broadly dated: Kulen (ca. 820–870 CE), Bakheng (ca. 890–920 CE), Koh Ker (ca. 920–940 CE), Pre Rup / Banteay Srei / Khleang (ca. 940–1000 CE), Baphuon (ca. 1000–1080 CE), Angkor Wat (ca. 1080–1150 CE), Beng Mealea (ca. 1150–1180 CE), Bayon (ca. 1180–1220 CE), Post-Bayon (ca. 1220–1300 CE), and Late Angkor (ca. 1300–1400 CE). Because of specific iconographic and stylistic features, however, some transitional items could not be attributed to any of these stylistic groups. These groups could have been further refined, but the resulting groups would have been too small to permit statistical treatment.

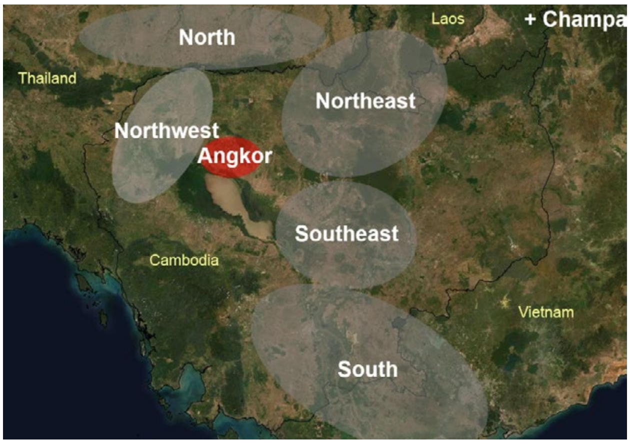

Figure 2. *Map of Cambodia showing the regional subgroups during the Angkorian period.*

Second, most of the selected artifacts were associated with an identified, or at least presumed, recovery context. A wide variety of archaeological and curatorial documentation was used to identify or confirm their place of discovery in Cambodia and neighboring countries. A regional grouping has also been attempted based on their provenance, thus leading to two main groups: artifacts from the Angkor region and artifacts from other regions of the Khmer kingdom, with six regional subgroups: North, Northeast, Northwest, South, Southeast, and Champa (fig. 2).[2] These regional subgroups do not necessarily refer to production places.

Third, some of the selected artifacts were classified as "major" productions according to several specific criteria, including their recovery context (Royal Palace, royal foundations, holy sites), size (medium and large statues), technical complexity (assembly, gilding, inlay), or uniqueness. Such a characterization may help in understanding the evolution of metallurgical practices as related to the status of the commission and the type of patronage and craftsmanship involved—in the case of these "major" productions, high to very high-level patronage (king, entourage, and dignitaries) and highly skilled artisans.

Mines and Foundries

In addition to statues and objects from museum collections, three further new types of artifact entered the present corpus.

First, in Angkor, there was a unique assemblage of metallurgical waste from a royal foundry site without any equivalent in the region, which was found in 2012 (Polkinghorne et al. 2014) and has been continuously excavated and studied since 2016 as part of the LANGAU—Casting for the King project (EFEO and APSARA National Authority; Vincent 2020, 2024). This site will be discussed more thoroughly below.

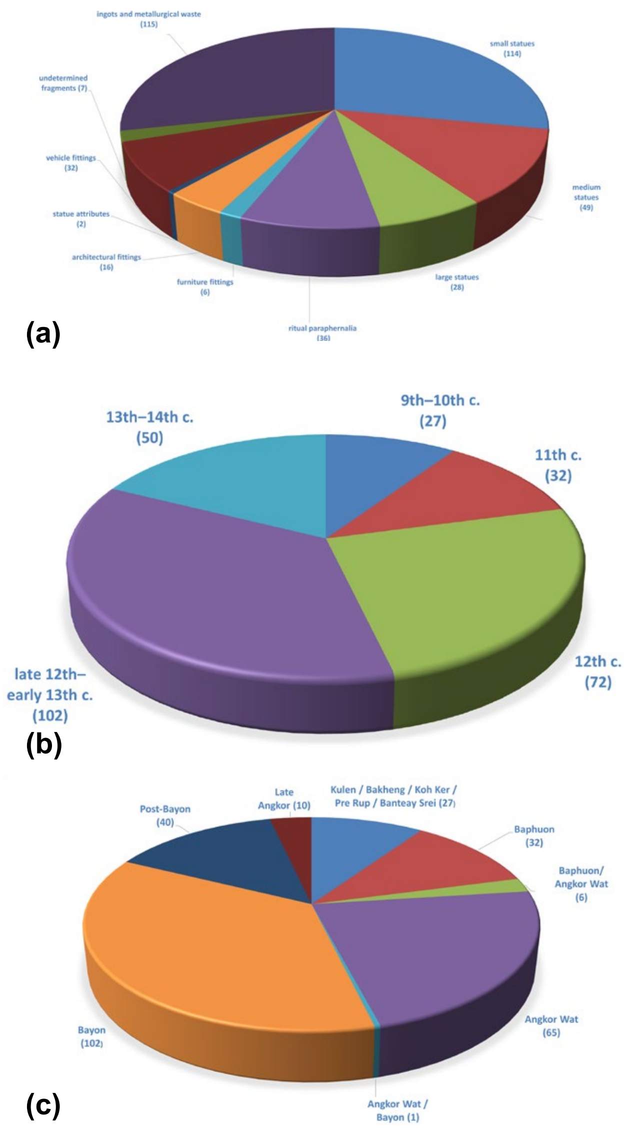

Figure 3. *Number of items in the corpus under study according to: (a) typology, (b) chronology (expressed in centuries), and (c) stylistic group. Charts (b) and (c) show a total of 283 analyses and statues, representing 278 ensembles. Chart (a) shows these, with the addition of 114 ingots and items of metallurgical waste.*

Second, outside Angkor, there was another unique assemblage of metallurgical waste, this time from a primary copper-production site, part of the Chhaep mining and metallurgical complex in Preah Vihear province, north Cambodia. This is the first such site identified within Cambodia, in 2021 as part of the LANGAU—The Sources of Angkorian Copper project (EFEO and Ministry of Culture and Fine Arts of Cambodia; Vincent 2024). This complex will also be discussed more thoroughly below.

Third, two sets of copper ingots from the Angkor region were selected for analysis. Five copper bar ingots were sampled from 163 similar items found in the 1920s in a cache in the northern dike of the West Baray artificial lake, whose construction is dated to the second quarter of the eleventh century.[3] A further five plano-convex copper ingots were sampled from 25 similar items found in the 1950s at the Royal Palace in Angkor Thom, within archaeological layers dated to the late twelfth to the early thirteenth century and related to another possible royal foundry (Vincent 2014b).

Building a Frame of Reference

The first aim of this study was to set up a robust reference database for Angkorian copper-based metallurgy. A number of items were discarded from the initial statistical treatment: those of unclear attribution, copper ingots, and the metallurgical assemblages from the Chhaep complex and the royal foundry site at Angkor. The discarded items were reintroduced afterward for comparative purposes. As for the 2012 synthesis, all ensembles were reduced to one composition,[4] except for the two Buddhist deities from CMA (1985.92.1 and 1985.92.2).

All items made of assembled parts were also represented by a single composition, with the following exceptions: one artifact already reported in the 2012 synthesis (WAM: 54.2715 [pedestal and two statues]; the Basak male deity (NMC: Ga.3485 [head] and Ga.6321 [body]); and the Srah Srang *naga*-enthroned Buddha (NMC: Ga.2425 [*naga*] and Ga.5989 [Buddha]). For these three ensembles, two very different alloys were evidenced, and thus two compositions were kept. Repairs, including secondary castings, were not taken into account.

Ultimately, the reference database builds on a total of 283 analyses, which correspond to 278 ensembles (table S2). As mentioned above, statuary is much more represented than other types of artifact, making up two-thirds of the present corpus. Similarly, some production periods, namely the late eleventh to the third quarter of the twelfth century (Angkor Wat and Beng Mealea groups) and the late twelfth to the early thirteenth century (Bayon group), are overrepresented (fig. 3).

Operating Conditions

Elemental Analysis

Analytical procedures were the same as those presented in the 2012 synthesis. However, ICP-MS, a recently introduced technique, was added to the existing capabilities provided by DCP-AES and ICP-AES (and PIXE in rare instances). The artifacts analyzed at C2RMF, as part of twenty-two analytical campaigns, were all sampled by drilling and prepared following similar protocols prior to analysis (Bourgarit and Mille 2003; Vincent et al. 2012), except for PIXE analysis (Bourgarit and Thomas 2012). The consistency of results throughout the four different analytical techniques used was systematically checked by analyzing a set of twelve solid copper-alloy reference materials. Additionally, a comparison with results obtained at the Laboratory of Biomedical and Environmental Sciences, University of California at Los Angeles, on Khmer bronzes from WAM was performed in 2014 on one item (WAM 54.2726; Woodward 1997), and proved successful (table S3). In the 2003 synthesis, the discrepancy of composition within the different parts of a given ensemble could not be related to any criterion, including the status of the commission. This conclusion is still valid.

Statistical Treatment

In an attempt to build a frame of reference, statistical treatment was performed on the selected 283 analyses following a protocol that proved successful for several archaeometallurgical provenance studies (Disser et al. 2016; Mille and Artioli 2017; Costa 2023). First, principal component analysis (PCA) was carried out on silver, arsenic, cobalt, iron, nickel, and zinc content normalized to 100% copper, assuming all six impurities were contributed by the copper ore alone, as shown by the absence of any correlation with either of the two potential alloying elements, tin and lead. Bismuth and antimony showing a strong correlation with lead (see below), their content has been normalized with respect to lead and added to the PCA processing. Although tracked since 1999, a number of other elements were not included since they were often below detection limits or not analyzed by the other laboratories. The eight selected elements still suffer from missing data, thus imposing standardization using a classical method (Baxter and Freestone 2006) rather than with a log-ratio method (Costa 2023). The six first factors generated by PCA were then treated by ascendant clustering, bringing to light eight composition groups.

Alloying Elements: Domination of Unleaded and Leaded Tin Bronzes

Tin Bronzes

During the whole period covered by the corpus under study, that is, between the ninth and fourteenth centuries, copper-based alloys in the Khmer region are exclusively tin bronzes. Angkorian copper-based alloys thus prove to be very specific with respect to the surrounding area and more distant regions. In contrast, in statuary traditions from north India and the Himalayan region (i.e., Rajasthan-Gujarat, Kashmir, Swat, Ladakh, Tibet, and Nepal) brass is largely prevalent with unalloyed copper being used only for fire-gilded images (e.g., Craddock 2015). South Indian and Sri Lankan statuary appears to be made either of copper or, more frequently, leaded bronze, with a variable but overall quite low tin content (Craddock 2015; see also Craddock and Hook 2007).

In the present corpus, regarding the tin content distribution (fig. 4), the authors considered the limit between unalloyed copper and tin bronze to be at 3 wt% tin. This limit is indicative: for example, the NMC door decorations (Ga.5615, 5616, 5618, 5619, 5622, and 5623) are clearly unalloyed copper but bear 2–3.7 wt% tin.

The variations in tin-bronze composition previously observed for the late eleventh to the early thirteenth century (Vincent et al. 2012) are not only confirmed, but extended to other periods.

First, high-tin bronzes with 13 wt% tin and more are revealed during the early Angkorian period, namely between the late ninth and the first half of the tenth century (table S4, see fig. 4). These high-tin bronzes echo the so-called Blai Pat II bronze-casting tradition of Buriram province, northeast Thailand, dated between the seventh and ninth centuries (Becker et al. 2014; Murphy et al. 2025). Further back in time, they also echo a series of high-tin bronze statues and objects found in the Oc Eo region, An Giang and Kien Giang provinces, south Vietnam; that is, within the former Khmer kingdom of Funan (first–sixth century) (Malleret 1960). Tin-surface enrichment (National Museum of Vietnamese History, Ho-Chi-Minh City [BTLS]: Vishnu, BTLS 1585) and tin-based alloys (NMC: Avalokiteshvara, Ga.5330; Bourgarit et al. 2003) were mastered by Khmer founders as well, at least from the seventh or eighth century. Additionally, a recent study has revealed Indonesian high-tin bronzes dated to approximately the same period and, more broadly, a Southeast Asian tradition of high-tin bronze statues (Mechling et al. 2018). The particularly high content of silver (2.4 wt%) in the high-tin decorative plate from Phnom Bakheng temple should be mentioned (WMF: Bakheng 12; see table S4). It is discussed later in the section titled "Architectural Adornments: From Decorative Ornaments to Golden Temples."

Second, in the later periods, each subsequent production seems to exhibit specific tin compositions (see fig. 4).

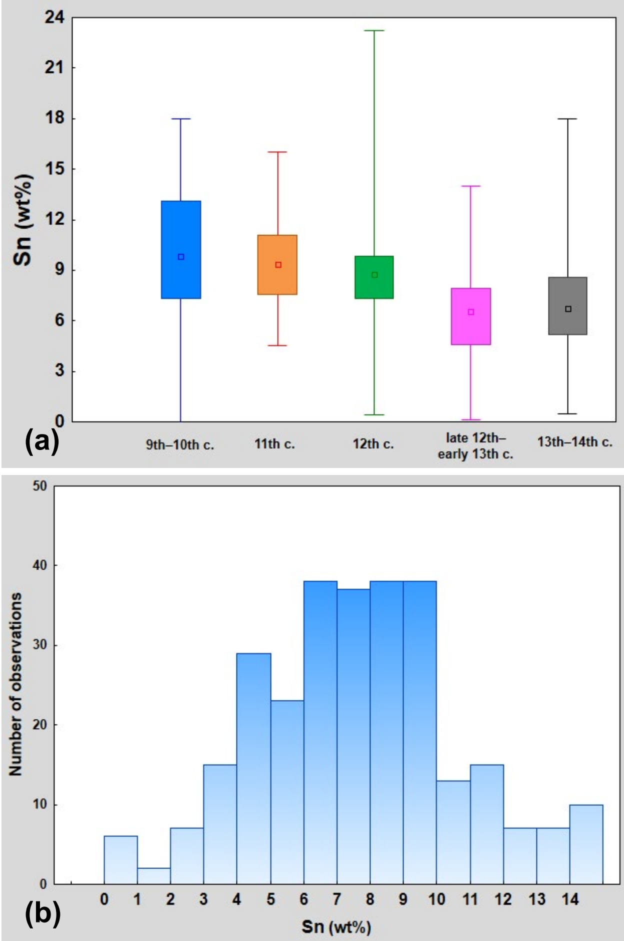

Figure 4. *Distribution of tin content (wt%) among the 283 selected artifacts. (a) The box and whisker plots are organized chronologically and show variations of tin content over time. (Two objects were discarded because of unclear dating.) For each time period, the small square represents the median value, the lower edge of the box represents the first quartile, and the upper edge the third quartile. The whiskers report the extreme values. (b) The histogram shows the general distribution of tin content.*

Note that all periods are not equally represented (see fig. 3b), thus possibly generating an analytical bias. However, the lower tin content during the late twelfth to the early thirteenth century, when compared with the late eleventh to the third quarter of the twelfth century—already pointed out in the 2012 synthesis—is fully supported by a larger statistical population. This relatively low-tin content during the late twelfth to the early thirteenth century is magnified by the fact that, among the eight unalloyed coppers from the present corpus, six are dated to this period (ANM: Ga.3000, 3545.2, 3785, 4256; MNAAG: MG 18888; NMC: Ga.5410; table S5). Also of note is the piece of finial from Phnom Bayang temple dated to the late twelfth to the early thirteenth century (ANM: Ga.4256), although it is marked by a relatively high silver content (2 wt%).

So far, no technical reason can explain the variations of tin content. Neither the typology (statues versus objects) nor the status of the commission ("major" versus "minor" productions) can be put forward. A single counterexample is a fragment of high-tin bronze mirror (18 wt% tin) found at the Terrace of the Elephants in Angkor and dated to the thirteenth century (ACO: CA1); in that specific case, tin was deliberately added to obtain a silver-colored metal that takes a fine polish and gives a highly reflective surface (Meeks 1993). Additionally, very frequent gilding of Angkorian statues and objects made it irrelevant to control the color of the bronze through tin content. That said, the variations in tin are too small to allow any visible color variations.

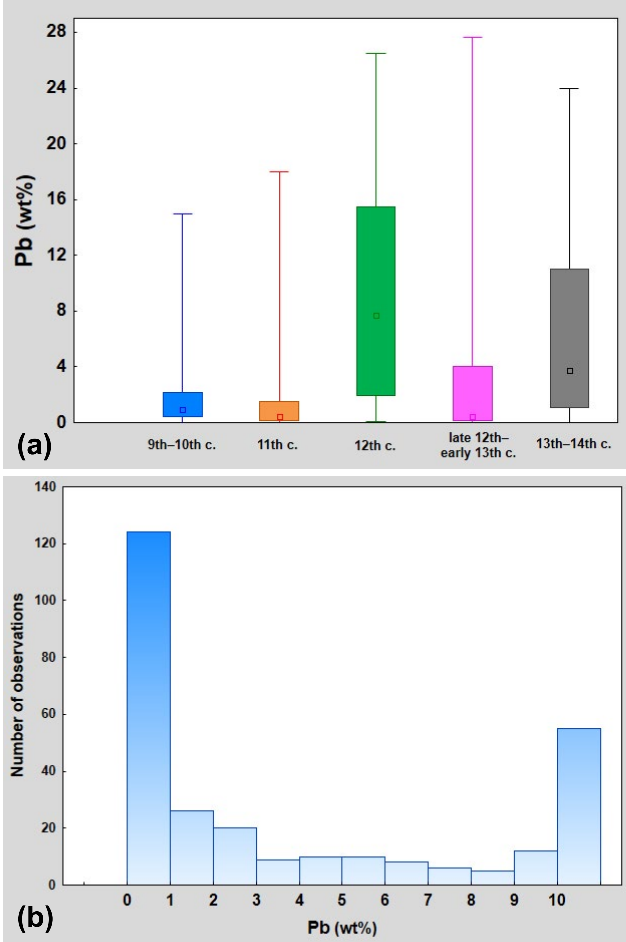

Figure 5. *Distribution of lead content (wt%) among the 283 selected artifacts. (a) The box and whisker plots are organized chronologically. (b) The histogram shows the general distribution of lead content and particularly the gap after 1%.*

Leaded Bronzes and Gilding

Echoing these trends in tin content, Angkorian bronzes appear to be leaded during very specific periods, namely during the late eleventh to the third quarter of the twelfth century, and the thirteenth and fourteenth centuries (fig. 5a). This chronological distribution led the authors to consider, in the present corpus, the limit between unleaded and leaded bronze to be at 4 wt% lead. Although in the present paper this 4% limit is retained, note that the global distribution of lead content tends to lower this limit to 1 wt% (fig. 5b). This is further supported by the five copper bar ingots from West Baray (table S6). Because of their very low tin content (less than 0.008 wt%) and the domination of tin bronzes during the Angkorian period, it is unlikely they were made of recycled metal but more probably of "fresh metal." Consequently, the circa 1 wt% lead all these ingots bear was very probably added intentionally. Although the hypothesis of lead stemming from fresh copper cannot be fully discarded (lead-bearing copper ore or by-product of silver extraction from silver-bearing copper ore), the absence of lead in the other "fresh metal" occurrences (Royal Palace ingots, copper from Chhaep; see below) makes this unlikely.

As for tin, no technical reason can explain the presence or absence of lead as an alloying element. As pointed out in the 2012 synthesis (see also La Niece and Robcis 2025), it is well known that fire-gilding is not compatible with lead-bearing alloys. Although a comprehensive characterization of the gilding techniques employed by Angkorian founders could not be carried out on the present corpus, this assertion is largely confirmed by the analytical data (table S7): thirty-three out of forty fire-gilded items—securely identified by surface analysis (portable x-ray fluorescence spectrometry [p-XRF]), visual, or microscopic examination—are attributed to periods where unleaded bronzes were dominating, especially the eleventh century (eight items) and the late twelfth to the early thirteenth century (twenty-five items) (see also Bunker 2008; Gerschheimer and Vincent 2010; Vincent 2012). That said, the question arises as to whether the presence of lead during several periods prevented the use of fire-gilding or, conversely, whether gilding techniques were adapted to the alloys available. Political and economic factors are more likely to have constrained the alloying strategies.

Brasses

In this landscape dominated by tin and sometimes lead, zinc-bearing alloys have to wait for the late Angkorian period to enter the play, especially from the thirteenth century, as can be seen with eleven items of the present corpus that clearly demonstrate the use of brasses and red

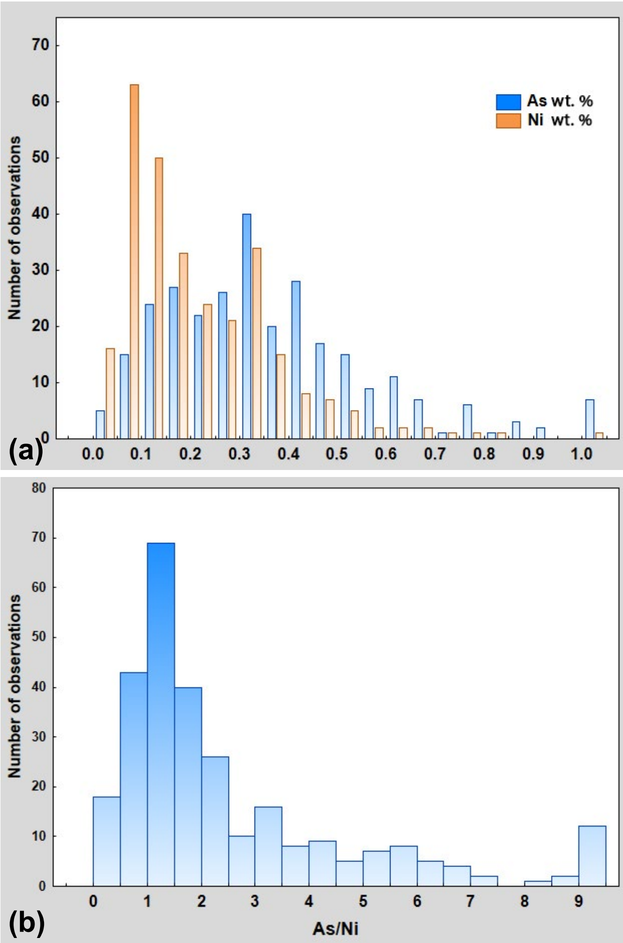

Figure 6. *Distribution of (a) arsenic (As) and nickel (Ni) content (wt%), and (b) arsenic-to-nickel ratio among the 283 selected artifacts. The contents have been normalized to 100% copper to avoid the diluting effect of possible alloying elements, namely tin and/or lead and/or zinc.*

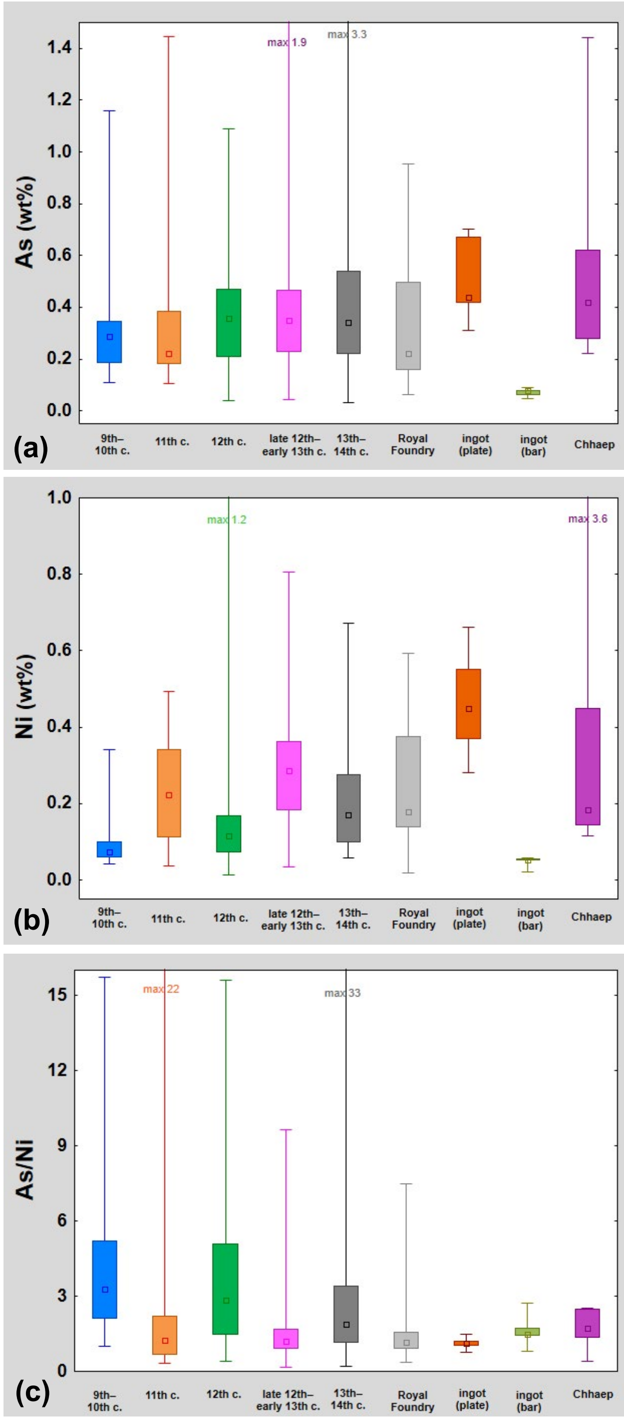

Figure 7. *Distribution of (a) arsenic (As) content (wt%), (b) nickel (Ni) content (wt%), and (c) arsenic-to-nickel ratio among the 283 selected artifacts according to chronology. In addition, the composition distributions of the 6 items of copper waste from the Chhaep complex, the 2 sets of 5 copper ingots each (the bar ingots from West Baray and the plate ingots from the Royal Palace), and the 68 items of cast metallurgical waste from the royal foundry are plotted on each chart. The contents have been normalized to 100% copper to avoid the diluting effect of possible alloying elements, namely tin and/or lead and/or zinc.*

brasses (with or without lead) during this period, due to their zinc content ranging between 8 and 19 wt% (table S8). These items are both statues—either Hindu (MNAAG: MA 1829, MA 2592; NMC: Ga.2772; WAM: 54.3017) or Buddhist (MNAAG: MG 9807; NMC: Ga.5985)—and objects (ANA: PKD.10.9001.1; MMA: 1995.570.1; NMC: Ga.5681; ACO: CA2). However, brasses might have circulated in very small quantities during the Angkorian period, as discussed below.

Copper Impurities: Toward a Characterization of "Angkorian Copper"

Domination of Nickel and Arsenic

The main copper impurities are nickel and arsenic within a quite narrow range of contents during the whole Angkorian period (fig. 6). Of course, other impurities are present in the metal, but the statistical treatment of the analytical data revealed a quite homogeneous set of compositions. This results in one major group of artifacts altered only by some thirty atypical patterns. The latter are mainly marked by high contents in one or several of the following elements: silver, arsenic, cobalt, bismuth, zinc, tin. These will be discussed later. Therefore, one main type of copper can be considered to dominate the Angkorian production. For simplicity, this copper will here be referred to as "Angkorian copper."

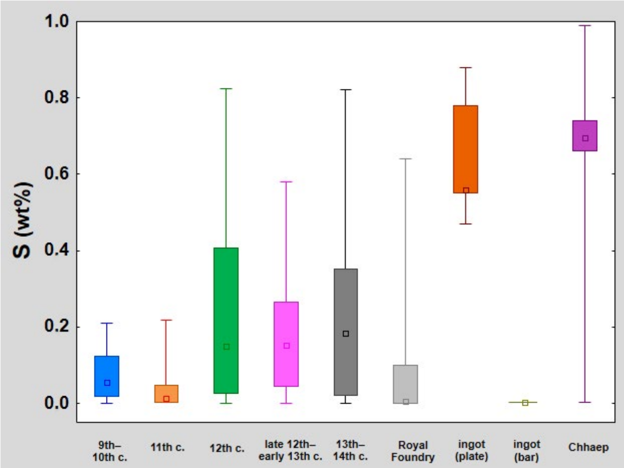

Figure 8. *Distribution of sulfur (S) content (wt%) among the 245 selected artifacts according to chronology (for 38 items, sulfur was not measured and these were discarded). In addition, the composition distributions of the 6 items of copper waste from the Chhaep complex, the 2 sets of 5 copper ingots each (the bar ingots from West Baray and the plate ingots from the Royal Palace), and the 68 items of cast metallurgical waste from the royal foundry are plotted. The contents have been normalized to 100% copper to avoid the diluting effect of possible alloying elements, namely tin and/or lead and/or zinc.*

A detailed observation reveals, however, a clear bipolar distribution for nickel (centered around approximately 0.1 and 0.3 wt%) (see fig. 6). These two poles refer to specific time periods in an alternating pattern. Hence, the eleventh century and the late twelfth to the early thirteenth century are marked by relatively high nickel content, whereas the late eleventh to the third quarter of the twelfth century (and possibly the ninth and tenth centuries, although they are not well represented in the present corpus) exhibit lower nickel content. The thirteenth and fourteenth centuries reveal an intermediate behavior (fig. 7). Although the arsenic-to-nickel ratio exhibits a dominating distribution pole, between 0.5 and 2.0 wt% (see fig. 6), slight variations with time may be observed (see fig. 7). No extreme values of nickel were observed.

The arsenic content does not evolve much with time. However, a few atypical high-arsenic items (more than 0.75 wt%, normalized content), with various arsenic-to-nickel ratios, were observed (table S9, see fig. 6a). Among these, four high-level-commissioned statues, with very high arsenic-to-nickel ratios (see fig. 6b), are dated to the middle of the tenth to the early eleventh century, and certainly produced in present-day Cambodia (NMC: 1992.336 [MMA], NMC.2855; MNAAG: MA 2239, MA 12276); whereas four Buddhist statues with high arsenic-to-nickel ratios are dated to the middle of the eleventh and early twelfth centuries, and certainly produced in northeast Thailand (ANM: Ga.4427; CMA: 1985.92.2; NMC: Ga.5325; WAM: 54.2715 [pedestal]). As anticipated in the 2012 synthesis, the question arises of a deliberate selection of a high-arsenic-bearing copper ore for specific bronze productions and periods; if that was the case, these periods are prior to and after the main activity of the royal foundry installed in the heart of the Angkorian capital (see below). The only other atypical compositions are related to cobalt and silver, as discussed below.

Evolution of Sulfur Content with Time

The Angkorian period may be divided into two subperiods according to the sulfur content of copper (fig. 8): before the twelfth century, the content is quite low (mean and median values less than 0.1 wt%), whereas during and after the twelfth century, the content proves to be significatively higher (around 0.2 wt% and more). Note that sulfur has not been measured for forty items of the present corpus (those analyzed by DCP-AES and PIXE at C2RMF and by ICP-AES in the other laboratories), most of which are dated between the twelfth and thirteenth centuries. The iron content does not follow the same trend, as discussed below.

Sources of Raw Metals

The Chhaep Mining and Metallurgical Complex

The 2012 synthesis stated that: “the possibility of a ‘local’ copper supply may not be completely rejected for the Angkorian period” (Vincent et al. 2012, 140). This is confirmed by the recent identification of the Chhaep complex. Its study was part of a PhD research project on the copper sources of Angkorian Cambodia and copper extractive metallurgy, conducted by Sébastien Clouet at Sorbonne University (Clouet 2025; see also Clouet et al. 2025). The complex is characterized by the primary production of both copper and iron. There, the site of Phnom Chroap Phdau is a uniquely preserved copper mine—surveyed since November 2022—retaining its original extraction pits as well as additional mining evidence, such as soil heaps and a water drainage system. This copper-ore extraction site proved to be active before and during the Angkorian period. One kilometer east of the copper mine and directly connected to it, the site of Trapeang Choan Sanlong—surveyed since November 2021 and excavated in April and May 2023—includes around 100 slag mounds organized around two natural ponds. Evidence of copper smelting, copper refining, copper ingot casting, and iron smelting are attested, at least from the late fourth or early sixth century until the early fourteenth century (with two possible onset dates due to C14 calibration uncertainties).

Analysis was performed on six copper waste items recovered from Trapeang Choan Sanlong. Their arsenic-to-nickel ratio echoes the dominant impurity patterns of Angkorian statues and objects (see fig. 7c and table S10). Many more samples are needed to fully characterize the copper from this mining and metallurgical complex. However, in first approximation it is possible to propose that the Chhaep region was a major source of “Angkorian copper.”Note that the existence of a unique copper source was proposed in the 2003 synthesis, before being contradicted in the 2012 synthesis.

How then to explain the alternating chronological evolution of nickel content in the items of the present corpus? Three hypotheses are presented for examination.

Hypothesis One: Variation of Pyrometallurgical Operating Conditions over Time

Perhaps the variations of Angkorian copper over time, especially the nickel content, were generated by variations in metallurgical operating conditions. Depending on these conditions, significant losses of the volatile elements (iron, sulfur, antimony, and arsenic) in Angkorian copper may occur during any of the pyrometallurgical operations (roasting, smelting, refining, alloying, and casting; see Slater and Charles 1970; McKerrell and Tylecote 1972; Tylecote et al. 1977; Burger et al. 2010). Two points contradict this hypothesis. First, despite the fact that nickel content varies greatly over the course of time, it is not a volatile element under the usual pyrometallurgical conditions (Pollard et al. 1991). Second, no clear variation of either iron or arsenic content, which are known to be affected by the operating conditions, has been observed in the present corpus. Of note, however, is that thermodynamic calculations show that loss of arsenic is drastically decreased when arsenic is associated with nickel, as in the items under study (Sabatini 2015).

That said, some metallurgical processes might have evolved during the twelfth century, as shown by the bipartition of sulfur content (see fig. 8). If refining was responsible for the low content of sulfur, then the iron content would also be low, as observed in one copper waste find from the Chhaep complex and in the bar ingots from West Baray. This is, however, not the case for the statues and objects. To process sulfidic ores such as chalcopyrite, a preliminary oxidation of the ores in an open fire may be used. This step is called "roasting." Such a process, if any, might have played a role in the resulting "Angkorian copper" compositions. Some experimental simulations have suggested indeed that the quantity of sulfur remaining in the ore after roasting, and consequently in the metallic copper, varies greatly—independently of iron—depending on the operating conditions of the roasting process (Doonan 1994; Burger et al. 2010). At the Chhaep complex, a smelting process without roasting has been revealed (Clouet 2025). However, the associated two-step process, including a matte conversion phase, may have generated variations of the sulfur content in the final product (i.e., copper) over time. More archaeological data are needed to test this hypothesis further.

Finally, it has been observed that "major" productions have substantially lower mean and especially median values of iron and sulfur content when compared with the other artifacts of the corpus (fig. 9). This probably pertains to a more systematic use of carefully refined copper for these productions.

Hypothesis Two: Different Minining Zones within the Same Mining and Metallurgical Complex

Different mining zones might have been exploited over time within the same mining and metallurgical complex. It is well known that most ore deposits are spatially zoned, each zone having distinct mineralogical assemblages leading to specific geochemical characteristics (Ixer 1999). This possibly holds for the Chhaep complex, although its mineralization has not been fully characterized yet. The discrepancy between arsenic and nickel content in the six items of copper waste from the same smelting area, sector 1 of Trapeang Choan Sanlong (see table S10 and fig. 7)—disregarding other impurities such as cobalt, tin, and bismuth—constitutes at least one piece of evidence.

The Royal Palace copper ingots constitute further evidence of "fresh copper" that may indicate that different mineralogical assemblages enclosing the same arsenic- and nickel-bearing ore, but in different proportions (for example, more chalcopyrite or another ore not bearing arsenic and nickel), might have been smelted over time in the Chhaep region (see table S6, see fig. 7). In these ingots, the content of tin is very low (less than 0.007 wt%), showing, as for the West Baray copper ingots, that they are very probably all made of fresh, not recycled, metal. Moreover, unlike the West Baray copper ingots, the metal has surely not been refined. This is attested by the significantly higher amounts of volatile elements, namely iron, sulfur, antimony, and arsenic, than in the other items of the present corpus. Whereas the arsenic-to-nickel ratio (between 0.8 and 1.5) is consistent with that of Angkorian copper, the actual content of arsenic and nickel (0.3–0.7% for both elements) is significantly higher (see table S6 and fig. 7).

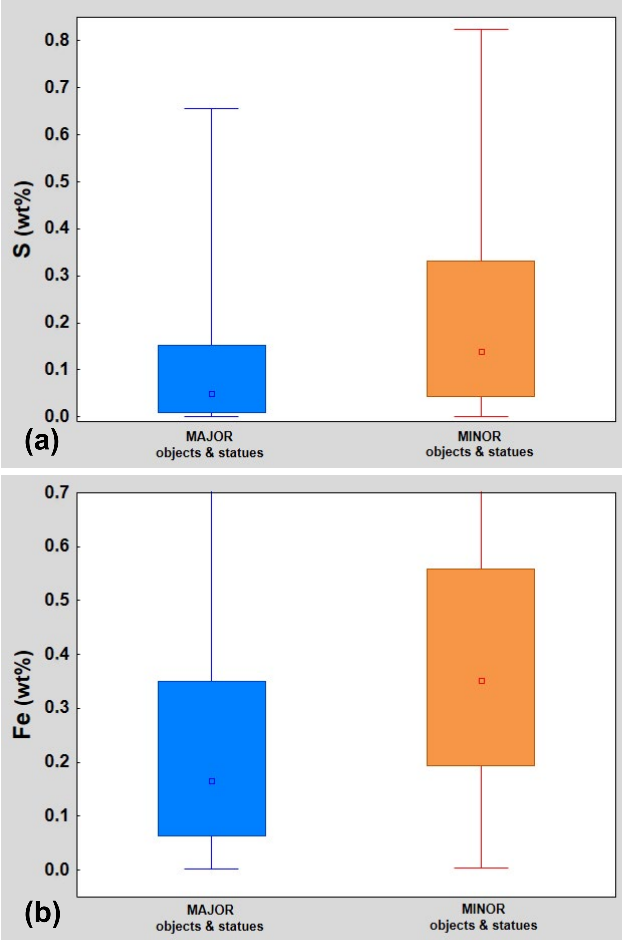

Figure 9. Distribution of (a) sulfur (S, 245 artifacts; the items where sulfur was not measured were discarded) and (b) iron (Fe, 283 artifacts) content (wt%) according to the status of the production. In the corpus under study, 104 out of the total 283 items were considered to be "major" productions. The contents have been normalized to 100% copper to avoid the diluting effect of possible alloying elements, namely tin and/or lead and/or zinc.

The chronological variations of sulfur content might also originate from a change in mineralogical assemblages. Before the twelfth century, mining might have focused on the upper supergenic zones and the associated altered copper ores poor in sulfide. As mining proceeded, the primary sulfides might have been reached. Again, this hypothesis needs further investigation, keeping in mind that the assumption of "oxidic ores first" does not always apply (Bourgarit 2019), and that at the Chhaep complex, the supergenic zones seem to have been exploited and exhausted long before the Angkorian period (Clouet 2025).

Hypothesis Three: Recycling

It is possible that variations of composition are due to variations over time of the relative quantities of recycled metal and fresh metal entering the melt. More specifically, the lowering of nickel content during the twelfth century may attest to more intensive recycling at that time than in other periods. Unfortunately, at no period is any decrease of arsenic observed that might prove and help quantify recycling—considered here as remelting (Bray et al. 2015). However, as mentioned above, small quantities of nickel as observed in our artifacts have been shown to severely hinder the loss of arsenic by volatilization during remelting (Sabatini 2015). Thus, the lowering of nickel during the twelfth century might have been induced by recycling, by dilution of the Angkorian copper by a metal without nickel, such as lead.

Considering the inclusion of lead as an alloying element, specifically during this period, might support this hypothesis. Lead was probably mainly used to dilute copper, in the case of a copper supply shortage. However, the lead addition (rarely more than 15 wt%; see fig. 5) could hardly have divided by two the nickel content, as observed during the twelfth century (see fig. 7b).

Another metal without nickel might have been included in the recycling process. Pure copper may be a good candidate. However, so far, pure coppers prove to be very rare, even for copper devoted to hammering (Meas, forthcoming). At this point, one cannot fully discard the possibility of other copper sources than the Chhaep complex, at least during specific periods. The recent discovery of copper mining at Wat Phu (Champasak province, south Laos) and Khvav (Siem Reap province, 60 km east of Angkor), two areas very well connected through the royal road system to the Angkorian capital, deserves some attention in this regard (Clouet 2025).

Whereas a large majority of items contain less than 0.1 wt% zinc, twenty-one artifacts made of bronze-type alloys show zinc content between 0.6 and 1.8 wt%, in addition to the eleven brass-type alloys mentioned above (see table S8). Given that all other impurities match the dominant impurity patterns, zinc pollution might be the origin of these high-zinc impurities. Remelting of the few brasses circulating within the Angkorian kingdom (imported religious images or possibly Chinese coins) may be an explanation, as first proposed in the 2003 and 2012 syntheses. This is exemplified at the eleventh-century royal foundry of Angkor (discussed below). There, two items of foundry waste revealed brass and red-brass compositions (TRL12_cat#171 and TRL16_cat#55; table S11). These rare zinc-bearing alloys exhibit the dominant impurity patterns, as do the brass items of the late Angkorian period (see table S8). This would appear to indicate that both brass and bronze items of the period were alloyed with "Angkorian copper" as the base metal.

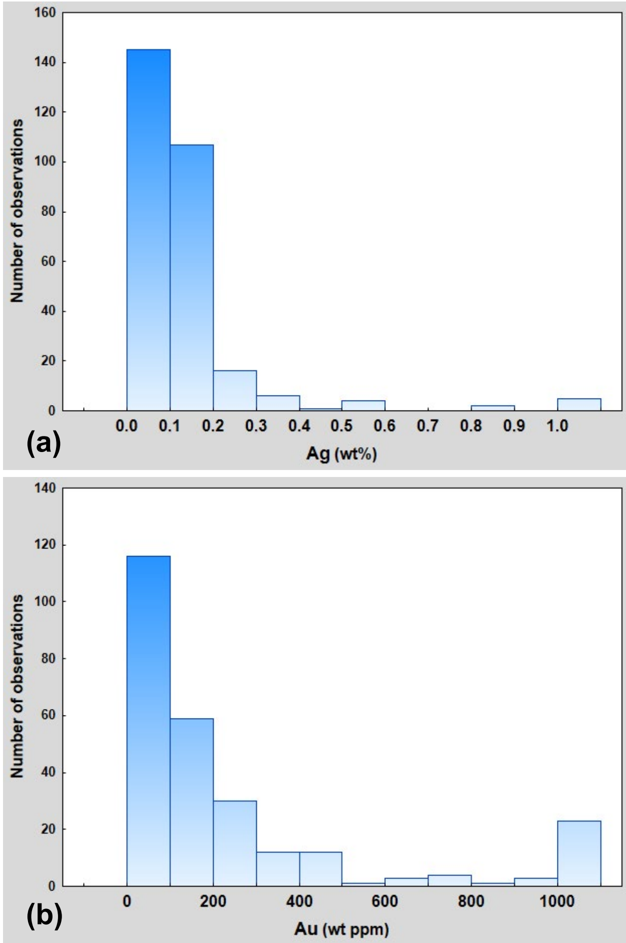

Figure 10. *Distribution of (a) silver (Ag) and (b) gold (Au) content among the 283 selected artifacts. The contents have been normalized to 100% copper to avoid the diluting effect of possible alloying elements, namely tin and/or lead and/or zinc.*

Gold and Silver

The presence of numerous high-gold-containing artifacts has been confirmed: more than half of the present corpus shows more than 100 parts per million (ppm) of gold (fig. 10b). In the 2012 synthesis (see also Bourgarit et al. 2003), besides referring to the traditionally gold-rich modern *saṃrit*, the origin of this gold was questioned: does it come from the copper ore or from gold-containing offerings added to the melt? The copper ore from the Chhaep complex, so far, does not contain significant gold, which would confirm the supposition of ritual offerings, or at least the deliberate addition of pure gold, maybe in powder form (Clouet 2021). Note that eleven items of metallurgical waste from the royal foundry of Angkor show high gold content, up to 2000 ppm, confirming, if needed, the importance of recycling.

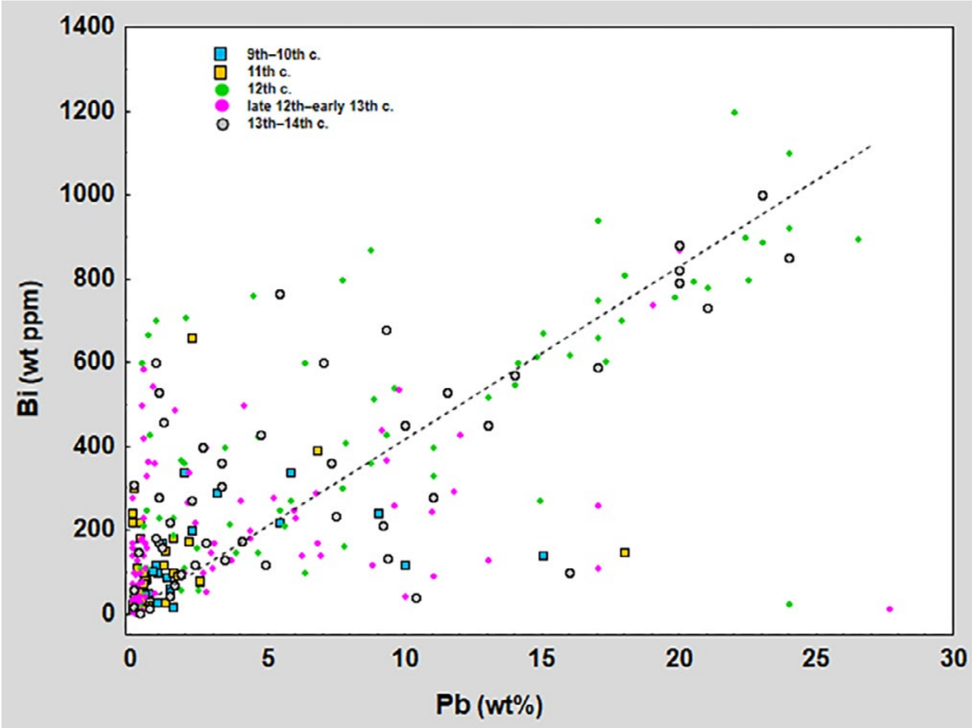

Figure 11. *Lead (Pb) and bismuth (Bi) content in the 283 selected artifacts, showing a clear linear correlation for a majority of items. The items escaping this correlation, either because of relatively low bismuth when compared to lead (below the dotted line), or conversely because of high bismuth with respect to lead (above the line), are further detailed in table S13.*

Seven artifacts also exhibit unusually high silver content (more than 0.8 wt%; table S12, fig. 10a), while all other impurities match the dominant impurity patterns. The same supposition, this time of silver-containing offerings or the deliberate addition of pure silver, may be proposed. Two statues are also atypical, both made of a silver-tin-copper alloy: a female deity dated to the middle of the tenth century (MNAAG: MA 2239; 19 wt% silver, 5 wt% tin; see table S12) and a Hevajra dated to the late twelfth to early thirteenth century (NMC: Ga.2494 [central statue of a Hevajramandala]; 17 wt% silver, 15 wt% tin).[5] Both are fire-gilded, indicating a use of silver not for any polychromatic effect, but rather related to religious and symbolic beliefs.

Lead, Bismuth, and Tin

Regardless of the time period, the lead used for alloying is marked by bismuth, as shown by the strong correlation between the two elements for a majority of items (fig. 11). This presence of bismuth—and the clear correlation of bismuth-antimony and, to a lesser extent, lead-antimony—clearly shows that lead was not a by-product of silver production by cupellation. In this process, where the lead is oxidized preferentially in order to separate it from the silver, it has been shown experimentally that the bismuth does not follow the lead (L'Héritier et al. 2015). Although this observation is far from being sufficient to claim that a unique source of lead was used during the whole Angkorian period, it is important to note that a minority of leaded bronzes do not follow this rule (table S13). This points to a specific supply of lead for these items: either a bismuth- and antimony-free lead ore or a lead coming from silver cupellation. A minority of items without lead show high levels of bismuth (see table S13, fig. 11), pointing to a specific copper marked by bismuth, although all other impurity levels are similar to those of Angkorian copper. However, these items could not be assigned any particular typology, chronology, or geographical provenance.

As far as tin is concerned, no clear provenance could be proposed, although the "Southeast Asian Tin Belt," running from central Burma down through the Malay Peninsula, appears an ideal candidate (Bronson 1992). The present study shows that, regardless of the time period, tin content always exhibits quite narrow distributions, which is an indication of the use of a well-controlled tin supply (see fig. 4a) (Pollard et al. 2018). This does not prove that only fresh tin, not recycled, was used for alloying. However, tin-bronze recycling, if any, or any other tin recycling source, should have been very well mastered.

Angkorian Foundries: From Center to Periphery

The Eleventh-Century Royal Foundry of Angkor

The ongoing archaeological and archaeometallurgical study of a royal foundry site at Angkor provides further important documentation to help establish the date and provenance of copper. This workshop was active during the eleventh

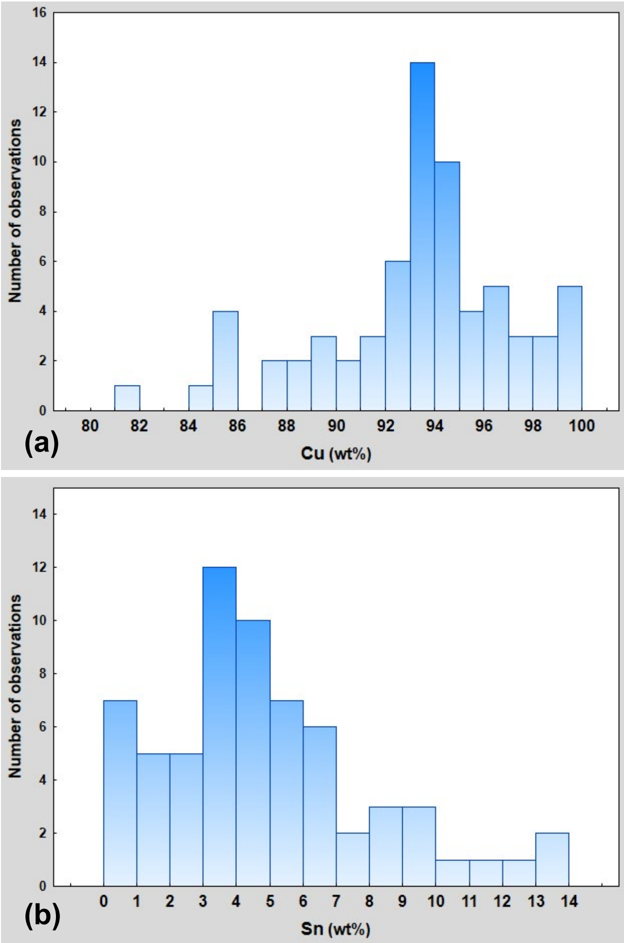

Figure 12. *Distribution of (a) copper (Cu) and (b) tin (Sn) weight percent among the 68 items of cast metallurgical waste from the royal foundry, showing the two main distribution poles corresponding to the two main alloys: unalloyed copper (ca. 99–100% Cu and 0–1% Sn) and tin bronze (ca. 94–97% Cu and 3–6% Sn).*

century and served as one of the major production centers of bronzes at the time (Vincent et al. 2025).

A unique assemblage of metallurgical structures and artifacts was unearthed, consisting notably of casting furnaces, foundry and hammering waste, copper slag, crucibles, investment molds, and other technical ceramics. The metal of sixty-eight of the artifacts associated with casting[6] (fifty-five foundry waste items, seven fragments of fireclay crucibles containing metal deposits, two pieces of copper slag with metal inclusion, two clay wall fragments of casting furnaces with metal inclusion, one precast ingot or half-product, and one fragment of clay investment mold or core with metal inclusion) has been analyzed, revealing two main alloy compositions: unalloyed copper and unleaded tin bronzes (fig. 12, see table S11). This shows that alloying (with tin) was carried out at the workshop, as confirmed by the variety of unearthed melting crucibles in association with furnaces and at least one precast ingot made of tin bronze (Vincent 2020). The impurity patterns very closely match the Angkorian copper (see fig. 7), particularly the eleventh-century version, due to its low sulfur content (see fig. 8). This eleventh-century bronze production—mainly represented in the corpus by large statuary—includes the monumental Vishnu Anantashayin from the West Mebon temple at Angkor, the largest cast cult image known in Angkorian Cambodia (NMC: Ga.5387 [torso], plus thirty-nine large fragments and forty-two pieces of debris recently identified, for an original length of more than 5 m) (CAST:ING 2018; see also Baptiste et al. 2025).

As mentioned above, together with casting waste, fragments of hammering waste were unearthed at the foundry. This shows that the workshop was quite multifunctional, and was producing more than just cast items—there is archaeological evidence of iron smithing on the site including half-product, furnaces, hearth bottom slag and other types of iron slag, hammer scale, and iron tools. The fragments of hammering waste, as with all hammered items analyzed so far, are made of unalloyed copper. Moreover, a large majority of the hammering waste fragments (eleven out of sixteen) shows the same impurity patterns as the cast items.

Finally, the set of plano-convex copper ingots unearthed at the Royal Palace in Angkor Thom might attest, with other archaeological evidence (lead or lead-tin alloy ingots, miscast statues, stone molds, iron tools and slag, plus possible clay ingot molds and crucibles), to another royal foundry—or at least another multifunctional metal workshop—producing bronzes from the core of the capital, during the late twelfth to the early thirteenth century, the reign of King Jayavarman VII (r. 1182/1183–ca. 1220 CE) (B. Groslier 2014; Vincent 2014b).

Buriram as a Potential Bronze Production Place

The authors strongly suggest that, during the eleventh century, the royal foundry of Angkor, although central and highly supported by the royal authority, was not the only bronze-casting workshop to provide the Khmer kingdom with religious images and other types of artifacts. Four bronze statues said to have been found in modern-day Buriram and Sisaket provinces, Thailand (AS: 1979.69; CMA: 1978.8, 1982.51; BNM: 1972.147 [MMA]), plus another from the northwest of Siem Reap province, Cambodia (NMC: Ga.2726-2731), exhibit particularly high cobalt content. Ranging from 0.1 to 0.9 wt%, such high cobalt content has also been measured in three statues attributed to the so-called Plai Bat II bronze-casting tradition, associated with Buriram province and northeast Thailand (MNAAG: MA 3321, MA 4985; NMC: Ga.2966). More analyses from this region, located on the royal road from Angkor to Vimāya, modern Phimai, would be useful to test the hypothesis of a local bronze production there and to understand its relationship with both ceramic production (Desbat 2023) and iron primary production (Venunan 2015).

Chpār Ransī / Preah Khan of Kompong Svay

Located 100 km east of Angkor, on another major road of the Khmer kingdom, the site of Preah Khan of Kompong Svay, or Bakan, today in Preah Vihear province, might have been another production place. Now identified as the ancient sanctuary of the Buddha of Chpār Ransī known from inscriptions (Estève 2009; Estève and Vincent 2010; Lowman 2011; Roche 2023), it was the most venerated Buddhist holy site of the Angkorian kingdom and, for this reason, a major political and religious center. The present authors' hypothesis is that it might have specifically produced tantric-inspired Buddhist statuary and ritual paraphernalia, at least from the late eleventh century onward, the reign of King Jayavarman VI (r. 1080/1081–1107/1108 CE) and the beginning of the so-called Mahīdharapura dynasty. In the present corpus, twenty-five ensembles possibly produced at Preah Khan of Kompong Svay have been identified, based either on their recovery context or on iconographic and stylistic grounds. This group's compositions fit more or less within the impurity patterns of the late eleventh to the third quarter of the twelfth century. However, a large majority of items (seventeen) show an arsenic-to-nickel ratio higher (between 3 and 40) than that of the "Angkorian copper" (between 0.8 and 1.5; table S14), although the absolute content of nickel and arsenic are not anomalous, as those discussed above and reported in table S9. This raises questions regarding the uniform distribution of "Angkorian copper" throughout the Khmer kingdom. One may also wonder to what extent this casting workshop, still to be further documented, affected Angkorian bronze production as a whole during this period.

Architectural Adornments: From Decorative Ornaments to Golden Temples

Architectural decoration using copper-based alloys has been far less studied than statues and objects (e.g., Clouet 2019; Clouet and Meas 2025). Thus, the recent analysis of sixteen such fragments, representing various types of architectural adornment (plates for outer stucco decoration, outer and inner cladding for stone masonry, plates for wooden doors, bas-relief, finials, and miniature temples for statuary), may deserve particular attention. The small decorative plate from Phnom Bakheng temple dated to the late ninth to the early tenth century has already been mentioned for its high silver content (WMF: Bakheng 12). The NMC door decorations (Ga.5615, 5616, 5618, 5619, 5622, and 5623) dated to the twelfth to the thirteenth century are made of unalloyed copper with relatively high iron and sulfur content. Apart from these two sets of decorative plates, all other items are unleaded bronzes with particularly low sulfur and iron content (table S15). The absence of lead is not particularly noteworthy, since most items are dated to the late twelfth to the early thirteenth century, when unleaded bronzes were the rule. Two architectural fragments found in the central sanctuary of the Preah Khan of Kompong Svay temple are also made of unleaded bronze (NMC: Ga.2295, 2296). They were originally part of a metal cladding covering its inner and outer walls, whose commission has been recently attributed to King Tribhuvanādityavarman I (r. 1149/1150–ca. 1177) based on epigraphical material (Griffiths et al., forthcoming; see also Baptiste et al. 2025). This large-scale and technically elaborate architectural decoration, leading to the transformation of the original central stone sanctuary into a "golden temple"—as described in epigraphy and confirmed by the fragments themselves, both showing traces of gilding—can be considered one of the prototypes for the later monumental metal cladding decorating the royal foundations of King Jayavarman VII in the heart of Angkor (especially the Bayon, Preah Khan, and Ta Prohm temples).

Also of note are three items possibly found at the same Bayon temple: a fragmentary column originally part of a miniature temple (NMC: Ga.1062), and a forearm of statue and a head of ascetic from a figurative bas-relief (NMC: Ga.5288, 5424; G. Groslier 1931; see also Baptiste et al. 2025). The first two exhibit particularly high nickel content (circa 0.5 wt%) compared to the other architectural fragments. Moreover, all three may be distinguished by their unusual gilding technique: mechanical plating where the edges of the gold sheets are punched into grooves (Estève and Vincent 2010; see also La Niece and Robcis 2025).

Finally, the consistently very low iron and sulfur content in architectural decoration, regardless of the time period, should be stressed. However, this phenomenon is probably mainly linked to the specific status of most of the decoration analyzed, to be clearly considered "major" productions. As stated above, the latter are characterized by having lower iron and sulfur content than other artifacts of the corpus.

Conclusions

As far as is known, the corpus now at the authors' disposal to investigate Angkorian copper-based metallurgy has no equivalent in historical Southeast Asia. It consists, so far, of 283 analyses of well-documented statues and objects representing a variety of typologies and uses, mostly of the political and religious elite; one excavated royal foundry that has provided a large metallurgical assemblage (sixty-eight analyses); two sets of copper ingots (ten analyses); and one recently discovered mining and metallurgical complex including a primary copper-production site (six analyses).

This large corpus enabled the authors, for the first time, to locate in space and time one copper source in the Cambodian territory and to discuss recycling as a possible alternative for raw copper supply, specifically during the twelfth century. It also allowed discussion of the existence of a unique centralized foundry depending on the commissions of the Angkorian king and of his court and entourage. Other bronze-casting workshops, more peripheral, may have been active and coeval with the eleventh-century royal foundry at Angkor, as possibly in the Buriram region. From the late eleventh century onward, the site of Chpār Ransī / Preah Khan of Kompong Svay might have gained a more developed role in bronze production, especially for Buddhist statuary and ritual paraphernalia, whereas during the late twelfth to the early thirteenth century, a royal foundry would have regained its importance at Angkor, within the Royal Palace of Angkor Thom.

This still to-be-confirmed succession or coexistence of centralized and peripheral bronze-casting workshops clearly connects to the political history of the Angkorian kingdom between the eleventh and thirteenth centuries. Specialized artisans such as bronze founders were then of great significance for the successive dynasties, kings, and elites who employed their outputs to legitimatize royal power. In return, these wealthy patrons ordered commissions and supplied the raw materials needed, while affording decent living conditions to the workers.

Perspectives

In order to deal with both the long duration and the complexity of Angkorian and Khmer copper-based metallurgy, the corpus still needs to be extended—as recently initiated as part of the exhibition *Bronzes royaux d'Angkor: Un art du divin* at the Musée Guimet in Paris (Baptiste et al. 2025)—toward the early Angkorian productions (ninth to tenth century), but also, for comparison, toward the pre-Angkorian period (sixth to eighth century). The post-Angkorian period (fifteenth to nineteenth century) is already under investigation in collaboration with Martin Polkinghorne at Flinders University in Adelaide, Australia.

The authors will also take advantage of new analytical equipment, namely the ICP-MS triple quad recently acquired at C2RMF, which opens the way to the analysis of a much larger range of discriminant geochemical markers, including the platinum group and rare earth elements. Additionally, the newly acquired LA-ICP-MS also at C2RMF will enable the analysis with increased sensitivity of micrometric items, such as copper inclusions in slag and technical ceramics (crucibles, furnace walls, tuyeres, and other ventilation systems), thus opening the analytical dataset to new types of artifacts that prove crucial for establishing provenance.

In addition to elemental analysis, the study of manufacturing techniques may be very informative. Twenty years ago, some seventy-five Khmer bronze statues and objects were radiographed by x-ray and some of their manufacturing techniques discussed (Bourgarit et al. 2003; Vincent 2012). This deserves to be revisited and extended, in taking advantage of the expertise gained by this research team since then, notably through the CAST:ING project (Bourgarit et al. 2025) and the Vishnu project (Bourgarit and Vincent 2025b). A significant number of elemental analyses (182) were not taken into account in the present study since they were carried out on assembled parts and/or on repairs (64 ensembles are concerned): these should be included in future discussion on manufacturing techniques.

Acknowledgments

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Notes

1. Tables S1–S15 cited in the text provide more detailed information on artifacts and collections: they can be accessed at: https://doi.org/10.5479/10088/124228.
2. The group "Angkor" corresponds to artifacts discovered in the province of Siem Reap; the group "Northwest" to artifacts from the provinces of Banteay Meanchey, Battambang, Oddar Meanchey, and Siem Reap (Srei Snam district); the group "Southeast" to artifacts from the provinces of Kompong Cham, Kompong Chhnang, Kompong Thom, and Tbong Khmum; the group "North" to artifacts from the provinces of Buriram and Sisaket in Thailand; the group "Northeast" to artifacts from the provinces of Preah Vihear, Stung Treng, and Champasak in Laos; the group "South" to artifacts from the municipality of Phnom Penh and the provinces of Kandal, Kompong Speu, Prey Veng, Svay Rieng, Takeo, and Binh Duong and Can Tho in Vietnam; and the group "Champa" to artifacts from the province of Binh Dinh in Vietnam. Some artifacts without any provenance, especially from European and American museum collections, were kept in the selection because of their iconographic, stylistic, and technical features.
3. Because of their recovery context, these ingots have been tentatively dated to the eleventh century. However, as discussed, the impurity patterns of the five ingots more closely match the composition of the twelfth-century statues and objects of the present corpus.
4. The term "ensemble" is used to describe a single artifact or group of artifacts, namely pairs of finials, parts of a single assembled artifact (statues, triads, parts of statuary, finials, and furniture parts), and fragments of a single artifact (Vincent et al. 2012). This is notably the case for the six NMC door decorations analyzed (Ga.5615, 5616, 5618, 5619, 5622, and 5623) and for the forty-eight analyses carried out on the West Mebon Vishnu primary cast.
5. The metal of the central Hevajra figure was not analyzed the way the other items of the present corpus have been, but by scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS) on a cross-section (sampled on its pedestal; see Arc'Antique 1997). Consequently, it is not reported in tables S2 and S12.
6. Since the present paper deals exclusively with the composition of cast items, the artifacts from the royal foundry associated with hammering are not discussed in detail here. A number of fragments of cast objects were also recovered at the site and analyzed. However, since these items represent possible recycling material, and not objects produced by the royal foundry, the authors discarded them from the discussion.

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