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Beyond the aesthetics of Tang and Liao dynasties artifacts in the British Museum's collection

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This study investigates fourteen silver vessels from the Tang (618–907 CE) and Liao dynasties (916–1125 CE) in the British Museum to examine their production techniques, compositions and decorations. Part of the museum's permanent exhibition, these objects reflect rich cultural exchanges along the Silk Road, blending local craftsmanship with foreign influences. Acquired at different times from varied sources, the vessels are museum-held rather than excavated, presenting challenges in determining authenticity and chronology. To address these issues, the study adopts a multifaceted approach combining provenance research and scientific analysis to reconstruct objects' "life history." Techniques including XRF, SEM-EDX, microscopy, and radiography revealed diverse manufacturing and decorative methods and consistent silver-copper alloys, with compositional shifts linked to historical changes following the An Lushan Rebellion (755–763 CE). Also, increased gold content in post-rebellion vessels likely reflects the use of different ore sources and trade conditions. This research contributes new data and directions for future study.

The Tang dynasty (618–907 CE) is renowned for its exceptional achievements in Chinese silverware, representing a zenith in both scale and sophistication of production. This period saw a significant shift in artistic influences and a remarkable expansion in the creation of silver and gold vessels, characterised by diverse forms and elaborate decorations. During the late 7th and early 8th centuries, silver vessels became a new trend in China, marking a departure from previous centuries when silver and gold were used sparingly. In this period, while pottery, bronze, and iron wares were widely accessible across various social strata, silver objects, particularly those of intricate design, were typically restricted to the elite, serving as symbols of wealth, prestige, and elevated social status[1]. This cultural shift was largely influenced by increased contact with Central Asia and Iran, especially after China regained control over the Tarim Basin in the early Tang period[2,3]. By the late 500s, China had already established regular contact with the Sasanian Empire, known for its advanced traditions in metalwork, glassmaking, and textiles. After the empire's collapse, many members of the Sasanian court, along with skilled artisans, sought refuge in China[4]. These artisans introduced new forms and decorative elements, as well as silversmithing technologies and techniques, which Chinese craftspeople adapted to local tastes and traditions[5–8].

Although silver was highly valued in the Mediterranean and Iran as a symbol of wealth and luxury, China did not initially develop a strong native silverworking tradition despite its appreciation of the metal. Instead, the Chinese court's evolving taste for Western luxury led to the importation of silver vessels from these regions. This introduction of imported silverware marked the beginning of China's rapid adoption of Western fashion in luxury goods during this time. However, as the demand for silver vessels among the Chinese elite grew and eventually exceeded the supply of imported items, local artisans began to produce their own silver cups, bowls, and platters[9]. Known for their tendency to "sinicise" foreign influences, Chinese silversmiths replicated vessel shapes originating from Western regions, Central Asia, Iran, and as far as the Mediterranean, adapting these forms to reflect indigenous artistic tastes and cultural aesthetics[10]. Such advancements were facilitated by the abundant mineral resources available in Tang China, which supported extensive production capabilities[8,11].

Some of the objects investigated in this article may also belong to the Liao Dynasty (916–1125 CE), which succeeded the Tang in northern China and parts of Inner Asia. While one piece can be attributed only to the Liao dynasty based on its inscription, all the others span the broader timeframe of the Tang and Liao dynasties, with their dating based mainly on visual

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stylistic characteristics and biographies (see Introduction). The Liao dynasty is known for its unique synthesis of Chinese and steppe traditions, including its production of silverware. Liao silver objects often feature distinct stylistic and technical characteristics that reflect their cultural milieu, blending influences from the Tang dynasty and neighbouring regions. Although the forms and decorative elements of these vessels have been subject to previous studies[1–3,12–14], there remains a gap in understanding their production techniques and material compositions.

This study seeks to reduce this gap by providing a thorough examination of fourteen silver vessels from the Museum's collection. It is worth highlighting that these vessels became part of the collection from different sources and at different times (see Introduction) and are part of a museum context rather than excavated assemblages. Given the distinct nature of museum collections compared to excavated assemblages, their investigation as museum-held objects involves interpretative challenges, especially regarding authenticity, chronology, and function.

In this sense, the current study operates within the landscape of museum collections — requiring a more nuanced, multifaceted approach. Accordingly, this study adopts a comprehensive strategy that goes beyond visual assessment, integrating provenance documentation, typological comparison, and scientific analysis to reconstruct the "life history" of each object and to support a more rigorous investigation.

Based on this premise, the samples selected for this study were chosen to represent the most typical styles of silver vessels from the Tang and Liao periods, as displayed in the museum's permanent collection (Gallery 33). This approach ensures that the analysed objects are representative of the broader artistic and cultural trends of the time, while also addressing the current gap in the scientific study of gold and silver artefacts from this period. Although there are museum collections and excavated objects from these periods that have undergone scientific analysis[1,11,12,14,15], such studies remain limited in scope. This research not only contributes new analytical data that enhances our understanding of Tang and Liao silver metalwork but also introduces hypotheses that might guide future scientific investigations in the field.

This project was initiated to support and enrich the narrative of the Silk Roads exhibition held at the British Museum from 26 September 2024 to 23 February 2025. The exhibition featured one of the images included in this study (Fig. 5a), and the project itself is referenced in the accompanying book on p. 59, fn. 228[16]. The findings presented here build on the exhibition's themes and invite further exploration and scientific analysis of Tang and Liao period silver metalwork, contributing to a deeper understanding of cultural and artistic exchanges along the Silk Roads.

The objects investigated from the British Museum's collection comprise fourteen vessels, currently on display as part of the museum's permanent exhibition in Gallery 33 (Fig. 1 and Table 1). They include a silver bowl shaped like a lotus flower (BM reg. no. 1968,0422.11), two silver diamond-shaped foliated dishes (1926,0319.8 and 1926,0319.10)[3,17], a silver lobed bowl (1926,0319.9)[17], four silver oblong and polylobate cups (1926,0319.6; 1926,0319.4; 1926,0319.7; 1926,0319.11)[17], three small silver bowls (1938,0524.705; 1938,0524.704[12]; 2022,3034.22), two silver stemwares/goblets (1968,0422.10[3]; 1937,0416.212), and a silver circular cup with a semicircular handle (1938,0524.706). Seven vessels were purchased in 1926 from the Japanese dealer Yamanaka & Company. Initially based in Osaka, Japan, Yamanaka & Company was a prolific art dealer that sold Asian art to collectors and institutions in Europe and the United States during the late nineteenth and early twentieth centuries[18]. Over time, it established branches in many cities, including London, where the group of silver vessels was featured in an exhibition held in 1925. The catalogue dated the collection to the Tang dynasty (618–907 CE) and gave its provenance – 'found in a tomb at Pei Huang Shan in Hsi-an Fu, the capital of Shensi Province'[19]. Hsi-an Fu refers to Xi'an (西安) prefecture in Shaanxi (陕西) province, the capital of Tang China. However, the location of 'Pei Huang Shan' is uncertain. Qi notes that, prior to the development of field archaeology in China, Tang gold and silverware, many of which ended up in overseas museums, primarily came from tombs located in areas around Xi'an and along railway lines constructed in the late Qing (1644–1911/2) and early Republican periods (1912–1949) that passed through Beimang (北邙) (also known as Mangshan 邙山) in Luoyang (洛陽), Henan (河南) province[8]. The silver vessels in the British Museum were covered in surface incrustation when they were shown at the 1925 Yamanaka & Company exhibition. Hobson thought the similar appearance of the incrustations confirmed that the vessels belonged to one single burial[17]. By the time of Hobson's publication in May 1926, the surface incrustations had been removed[17]. Traditionally, this group of vessels has been dated to the Tang dynasty. Notably one of the pieces, an oblong lobed cup (1926,0319.11), has an incised inscription on its foot that reads 乾符四年王大夫置造, "Made to the order of the grand master Wang in the fourth year of the Qianfu reign". The fourth year of the Qianfu reign is equivalent to 877 CE. However, more recent discoveries from Khitan, Liao dynasty (907–1125 CE) tombs have revealed pieces similar in appearance to those from the Tang dynasty. Shen[20] presents a number of such examples; for instance, a gilded-silver lobed plate excavated in 2003 from the Tuerjishan (吐爾基山) tomb in Inner Mongolia has a similar shape to 1926,0319.10 (see[20] pp. 64-65, fig. 40). The dating of each individual piece in the British Museum will require further research. The other vessels included in this study were purchased from George Eumorfopoulos from 1936 to 1938, bequeathed by Mrs Walter Sedgwick in 1968 and Sir Joseph Hotung in 2022. Unfortunately, the findspot of these pieces are not known. They have been attributed to northern China and dated to the Tang and Liao dynasties based on their stylistic features and similarities to excavated examples. The vessel bequeathed by Sir Joseph Hotung (2022,3034.22) also carries an inscription 太平乙丑進奉文忠王府祭器, "Sacrificial vessel presented to Prince Wenzhong's mansion in the *yichou* year of the Taiping reign". Prince Wenzhong (文忠) of the Liao dynasty was the posthumous title of the official Han Derang (韓德讓) (Khitan name Yelü Longyun 耶律隆運; 941–1011 CE). If genuine, the inscription dates the vessel to around 1025 CE.

The assemblage encompasses the typical forms and decorative motifs prevalent during the Tang dynasty period. According to Deydier and Wei[5], the polylobed stemware/goblet with the rim slightly folded towards outside (1937.0416.212) recalls the shape of lotus petals as they were used in the early Tang Dynasty (7th to mid-8th century). The oblong deep-set stemware/goblet with 4 lobes and supported by a small foot (1926,0319.7) is deemed a Tang "adaptation of the earcup of the Warring States (c.475–221 BC) period"[5]. The lotus flower-shaped bowl (1968,0422.11) is typical of the late Tang dynasty (9th–10th century)[5].

However, while the stemwares/goblets closely resemble those used in the Mediterranean area, their decoration is distinctly Chinese (e.g., 1968,0422.10), according to Rawson[3], who suggests that this shape was introduced to China based on earlier Sasanian or Sogdian items from Central Asia and lands further west. Similarly, the circular lobed bowl (1926, 0319.9), was typical of the Sogdian world. Its shape potentially arrived in China through Sogdian merchants whose homeland was what is now Tajikistan and Uzbekistan, and who gained prominence in the Silk Road trade from the 4th into the 8th century CE[21]. Additionally, the influx of goldsmiths to China following the Muslim conquest of Persia around 636 CE and the fall of the Sasanian Empire in 651 CE likely played a significant role in spreading techniques and styles[5].

As for the decorative motifs, a diverse array adorns these artefacts. Although five (1926,0319.6; 1926,0319.7; 1938,0524.705; 1928,1022.85; 1938,0524.706) lack any decoration, the remaining ten exhibit elaborate floral, human and animal representations typical of Tang aesthetics. Lotus flowers, smooth petals and leaves intertwine with intricate plant scrolls with palmette-like flowers and depiction of animals engaged in fishing and hunting scenes (including fishermen, archers on horses, and boars, hares, dogs/foxes). Michaelson and Portal[22] note that such motifs draw inspiration from Chinese paintings, lacquer designs, and tomb murals, offering glimpses into Tang dynasty daily life. The mounted archer chasing a deer is also often found on different Tang dynasty artefacts, such as woven and printed silks from

Fig. 1 | Photographs of all objects examined in this study. Details of each object are provided in Table 1 and in the Supplementary Materials. All images © The Trustees of the British Museum.

the Turpan region in northwest China. Notably, while these plant scrolls with palmette-like flowers distinctly evoke Tang aesthetics, as observed on 1968,0422.10 and 1936,1118.130, their origins can be traced back further West, underscoring the transcultural contact and transmission of artistic traditions across regions[2,9,10].

Methods

The objects underwent macroscopic and microscopic examinations. Initially, they were visually inspected to assess their general features, such as colour, texture, shape, and size. Subsequently, examinations were conducted using a binocular microscope (Leica MZ APO) at low to moderate

Table 1 | Objects analysed in this study

	Reg. No.	Object	Period	Production date	Date on display (G33)	Dimensions				Findspot	Acquisition		
						Ø	L	W	H		Method	From	Year
1	1938,0524.706	Circular cup with handle	TD, LD	618–907	650–700	5			5.1	North China	p	G. E.	1938
2	1968,0422.11	Lotus-shaped bowl	TD, LD	618–907	680–750	18			5.5	probably Xi'an, Shaanxi province	b	W. S.	1968
3	1968,0422.10	Stemware/goblet/cup	TD, LD	618–907	700–750	7.7			9.8	probably Shaanxi province	b	W. S.	1968
4	1937,0416.212	Stemware/goblet/cup	TD, LD	618–907	700–750	6.8			4.3	North-central China	p	G. E.	1937
5	1938,0524.705	Small bowl	TD, LD	618–907	700–750	8.6			4.5	North China	p	G. E.	1938
6	1938,0524.704	Small bowl	TD, LD	618–907	700–750	10.9			4	North China	p	G. E.	1938
7	1926,0319.9	Lobed bowl	TD, LD	9th–10th	800–900	18			12	Pei huang shan, Shaanxi province (?)	p	Y & Co.	1926
8	1926,0319.10	Foliated dish	TD, LD	10th	800–900		22.5			Pei huang shan, Shaanxi province (?)	p	Y & Co.	1926
9	1926,0319.8	Foliated dish	TD, LD	10th	800–900		21.5			Pei huang shan, Shaanxi province (?)	p	Y & Co.	1926
10	1926,0319.6	Oblong and polylobate cup	TD, LD	c.9th–10th	800–900		12	7	5	Pei huang shan, Shaanxi province (?)	p	Y & Co.	1926
11	1926,0319.4	Oblong and polylobate cup	TD, LD	c.9th–10th	800–900		12	7	5	Pei huang shan, Shaanxi province (?)	p	Y & Co.	1926
12	1926,0319.7	Oblong and polylobate cup	TD, LD	c.9th–10th	800–900		13.2	7.8	5.1	Pei huang shan, Shaanxi province (?)	p	Y & Co.	1926
13	1926,0319.11	Oblong and polylobate cup	TD, LD	c.9th–10th	800–900		12	7	4	Pei huang shan, Shaanxi province (?)	p	Y & Co.	1926
14	2022,3034.22	Small bowl	LD	–	1025	11			2	North-East China	b	J. H.	2022

Reg. No. Registration Number. Period, *TD* Tang Dynasty, *LD* Liao Dynasty, Dimensions: *Ø*, diameter, *L* length, *W* width, *H* height. Acquisition—Method: *p* purchased, *b* bequeathed, *G.E.* George Eumorfopoulos, *W.S.* Walter Sedgwick, *Y & Co* Yamanaka & Co, *J.H.* Joseph Hotung.

magnifications ranging from x5 to x20. This allowed for a detailed investigation of the morphology of the artefacts, including surface features and ornamental techniques. Following the stereoscopic examination, further microscopic visual analyses were performed using a Digital microscope (Keyence VHX 5000) with magnifications ranging from x20 to x200. The primary objective was to identify and document evidence of the manufacturing and decorative techniques employed on the objects. Additionally, this method enabled the observation of fine structures, intricate surface textures, and characteristics not discernible to the naked eye. To minimise reflective light from metallic surfaces, an anti-glare lens was consistently employed. High-resolution images were captured at 600 dpi. Furthermore, when necessary, 3D reconstructions of specific details were generated. This technique consists in acquiring a series of images at different focal heights by vertically adjusting the lens toward the target. Variations in focus across the image stack were used to determine the relative height of surface features, enabling 3D reconstruction even in areas without perfect focus. Subsequently, Scanning Electron Microscopy (SEM) was used to examine finer details such as tool marks and surface textures, primarily through the acquisition of backscattered electron (BSE) images. X-radiographs of several artefacts were also acquired to clarify and better identify their manufacturing technique(s). Radiographs were acquired with a Euroteck 225 X-ray cabinet, at a tube voltage of 175 kV and a current of 5 mA, using a focal spot setting of 0.4 mm. Each exposure lasted 180 seconds. A 14 × 17 in cassette with copper filtration was used to hold the radiographic plate. The primary X-ray beam was filtered using a 3 mm thick copper filter, and a lead shield was positioned behind the vessel under study (the unit is lead lined). The source-to-object distance was set at 1626 mm. Quantitative compositional analyses were conducted using two instruments: a Bruker Artax X-ray fluorescence (XRF) micro-spectrometer and a Hitachi Variable Pressure Scanning Electron Microscope S-3700N equipped with Energy Dispersive X-ray Spectroscopy (SEM-EDX). XRF measurements were performed at 50 kV and 300 μA, using a 0.65 mm beam collimator with a counting time of 200 s. SEM-EDX analyses were carried out at an accelerating voltage of 20 kV, with a chamber pressure of 40 Pa, a working distance of 10 mm, and a live time of 90 seconds (corresponding to 30% dead time), using both spot and area scanning modes. Quantitative results were optimised against a cobalt standard. Data acquisition was performed using an Oxford Instruments INCA EDX microanalysis system, featuring an INCAx-act silicon drift detector and Aztec 5.1 software. Both techniques primarily provide surface-level elemental data, and due to their limited penetration depth, results may be influenced by surface alterations such as corrosion or patination. To mitigate this issue and access the uncontaminated core alloy composition, surface areas of 1 mm^2 were carefully abraded before analysis. These areas were deliberately chosen to ensure optimal analytical conditions while minimising visual impact on the objects. This precaution was necessary to eliminate potential surface effects, as the artefacts—with their shiny metal surfaces—had likely been cleaned, although the specific cleaning methods are undocumented. Selecting these abrasion points helped avoid contamination products and soil element markers such as silica (Si), magnesium (Mg), calcium (Ca), aluminium (Al), and iron (Fe), which are commonly found in archaeological silver artefacts due to their interaction with corrosion products while buried[23,24]. Abrasion also minimised the potential for surface depletion of copper (Cu) and silver (Ag), which often occurs as a result of preferential surface corrosion during burial, resulting in an artificial increase in the proportion of Au on the artefact's surface by decreasing Cu and Ag contents. This occurs because depletion of Cu and Ag levels leads to a relative increase in gold (Au) concentration, even if the absolute amount of Au remains unchanged. The objective was to identify and compare the elemental composition of the objects' surfaces.

Results

In this section, the findings of the investigation are presented after investigation, categorised into three main subsections: manufacturing techniques, decorative techniques, and compositional analyses. Each part provides insights into different aspects of the studied artefacts, shedding

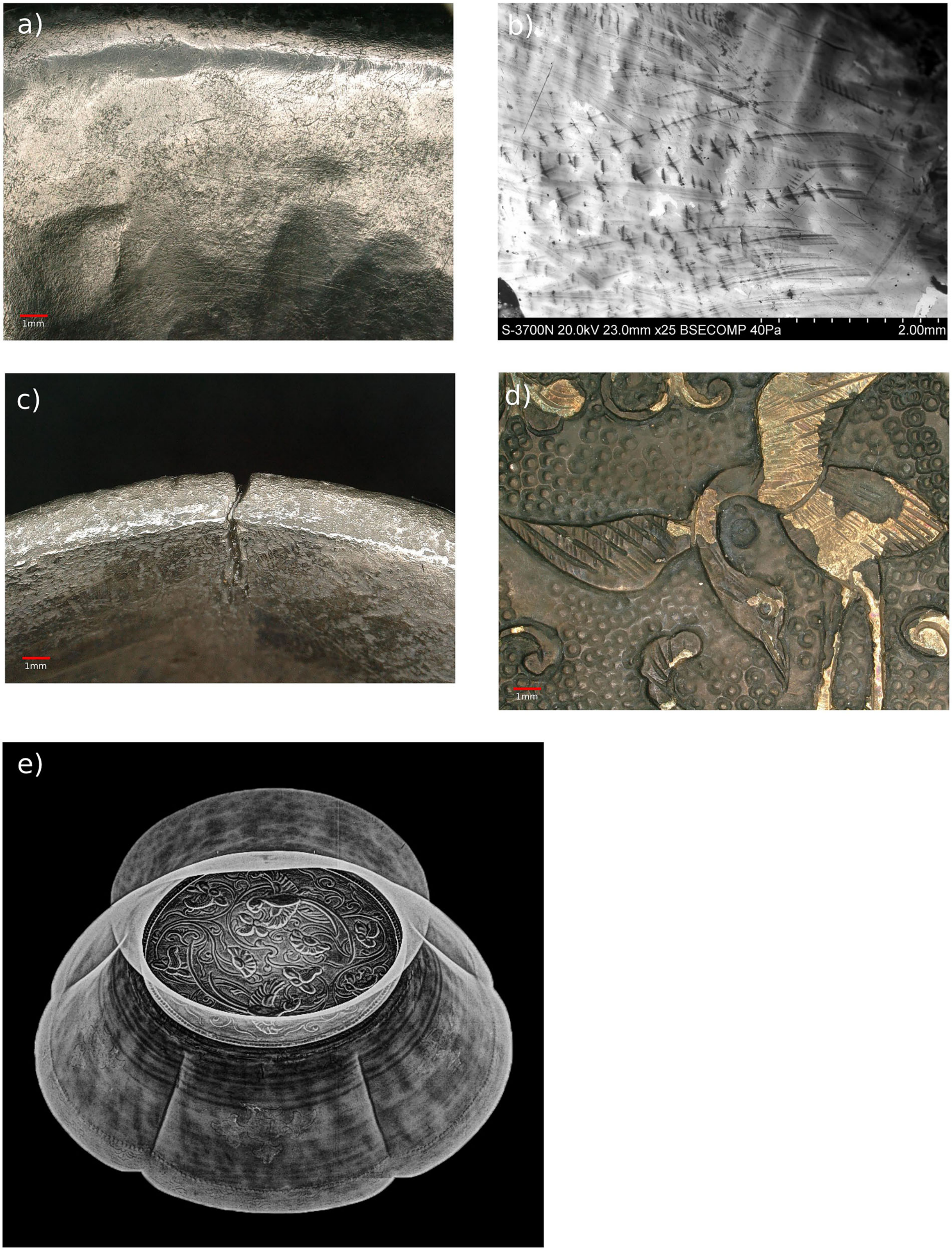


Fig. 2 | Evidence of hammering and tool marks. **a** Detail of the hammering marks on the inner rim of the oblong and polylobate cup 1926,0319.6 (magnification ×20). **b** Cross-shaped punched toolmarks on the bottom of the foot of the cup 1937,0416.212 (BSE image, magnification ×25). "Modern" scratches can also be seen. **c** A crack on the lobe of the oblong and polylobate cup 1926,0319.7, indicating the excessive hammering during the shaping process (magnification ×20). **d** The lathe pinpoint identified on the bowl 1968,0422.11 (magnification ×20). **e** X-radiograph of the gilded lobed bowl 1926,0319.9 upside down, showcasing the unmistakable lathe turning bands on the bowl and the discernible hammer blows present on both the foot and the bowl (max diameter of the bowl 18 cm).

Fig. 3 | Details of the primary decorative techniques identified. Front (**a**) and back (**b**) of a lotus flower, detail of the decorative design of the lobed bowl 1926,0319.9, shaped by repousse' and outlined on the front by chasing and decorated by punching (magnification ×20).

light on their production processes, decorative elements, and material compositions.

Manufacturing techniques

The investigation of the artefacts led to the identification of technical attributes, such as casting, hammering, lathe turning and soldering. Traditionally, the fabrication of silverware adhered to a sequential procedure: initial casting of a silver disc or sheet, subsequent shaping through hammering, followed by lathe turning as necessary. Additional components, such as a foot or a handle, could be incorporated through soldering (see Compositional Analyses sub-section). These techniques epitomise the distinctive technical characteristics associated with Tang dynasty silverwork[5].

All the objects examined exhibits clear evidence of hammering, as shown by the slight unevenness of the surface and variations in radiographic texture (further discussed below), which were caused by the individual hammer blows (Fig. 2a, e). Hammering was particularly prominent in shaping hollow shapes such as bowls and stemwares.

It involves two separate processes known as raising and sinking. The first usually means working on the outside with a suitably shaped stake inside, gradually stretching and shaping the metal outward, whereas the second involves deforming the metal inward over a form or mould to create depth and curvature. Toolmarks visible on the bottom underside of the stemware 1937,0416.212 were created using a cross-end punch, which was hammered vertically towards the top of the stem, resulting in the formation of parallel lines (Fig. 2b). The purpose of this process seems to have been to push the bottom of the stem outward, thereby enlarging its base. Cracks on the rim were identified, suggesting that hammering was performed with low or no annealing during the shaping process (Fig. 2c). This likely introduced localised stress concentrations, ultimately leading to structural weakness and eventual cracking of the rim, which may have occurred during burial. Annealing involves heating the metal or alloy above its recrystallisation temperature and cooling it slowly to relieve internal stresses, increase ductility, and reduce brittleness, making the metal more resistant to cracking when subjected to additional deformation[25]. Silver is usually quenched into a picking solution to retain softness (probably to prevent grain growth and therefore introduce brittleness)[25].

Seven artefacts display evidence of lathe turning. The parallel lines scored on the metal surface indicate that a lathe, with a cutting tool, had been used likely to remove uneven surface layers. This technique typically refers to the process of shaping and detailing the vessel on a lathe while keeping the part securely positioned throughout the machining. Negative traces of lathe pinpoints (i.e., where the artefact was secured, while turning was carried out) were identified on three vessels. These negative traces were often integrated into decorative motifs (Fig. 2d) or found as circular or spiral, reflecting the motion of the tool across the material's surface. X-radiographs of the foot and bowl of the lobed bowl (1926,0319.9) confirm the combined use of hammering and lathe-turning techniques (Fig. 2e). The foot displays typical hammer marks, visible as darker areas where the metal was thinned by repeated hammering, alternating with lighter zones of slightly thicker metal in regions left unstruck. Evidence for lathe use is provided by parallel narrow bands of light and dark tones, particularly concentrated towards the base. These bands gradually transition into more pronounced hammer marks towards the outer edge, indicating a shift in technique to hand hammering during the forming process.

The results of the analyses of the soldered joins are reported in the Compositional Analyses section.

Decorative techniques

Out of the 14 artefacts examined, 9 feature surface decorations predominantly consisting of relief and plane motifs typical of Tang dynasty art[1,5,13,26]. The remaining pieces (1926,0319.6; 1926,0319.7; 1938,0524.705; 1926,0319.11; 1938,0524.706) lack decorative elements. While this absence may suggest that these objects were left unfinished, it cannot be determined with certainty.

Two primary decorative techniques were identified and are usually found in combination:

- Repoussé: this technique involves shaping the metal by hammering it from the reverse side to create patterns in relief on the front surface[27,28]. It was skillfully applied on several silver vessels to craft intricate floral and animal designs. The picture on the left (Fig. 3a) captures the side of a lotus flower in relief, showing its three dimensionality. In contrast, the picture on the right (Fig. 3b) shows the sunken side of the same lotus flower, where the metal has been carefully pushed and shaped to create the corresponding recessed areas on the underside of the vessel.

- Chasing/engraving: this technique involves gently hammering a blunt-edged tool into the metal surface to create furrows or grooves by pushing the metal aside, without piercing or cutting through the sheet[27]. For useful definitions (and illustrations) of this technique refers to Lowery et al.[29]. In contrast, engraving is a process that uses a sharp-edged tool to cut into the metal surface, removing a small sliver of metal to form a design.

These techniques were applied using tools such as punches, chasers, hammers, and chisels. It is important to note that a single tool could have produced different marks. For example, a blunt-edged chisel could have served both as a chaser and a punch, depending on the angle and force applied. The marks identified vary in size and shape, including sharp-ended liner punches (e.g., for horse and bird details in Fig. 4a–c) and blunt-ended liner punches (e.g., for intricate flower details, Fig. 4d, and horse details, Fig. 4a), each contributing to the unique decorative effects (see also ref. 11).

As an example, part of the decoration of the foliated dish (1926,0319.10) was created using a punch or chisel with a square cross-section, held at an angle. Additionally, a star-shaped punch was employed on the inner wall, while a small punch with a triangular tip was used for the leaves. The figures were outlined with jagged chased lines, consisting of a series of wedge shapes, applied with varying pressure. Moreover, plane motifs were predominantly executed using punching and chasing techniques (see Supplementary Materials, hereafter SM). For a comprehensive understanding of these techniques, refer to Destrée[30].

Fig. 4 | Examples of punched details produced with different tools. Punched details of **a** the horse's finer hair on the inner surface of the foliated dish (1926,0319.10), **b** a bird's wing's feathers on the external surface of the foliated dish (1926,0319.8), **c** a bird's head, chest and wing's feathers on the bottom of the bowl (1926,0319.9); and **d** the shallower and thinner lines on a flower on the inner surface of the bowl (1968,0422.11). (Magnification ×20 for all).

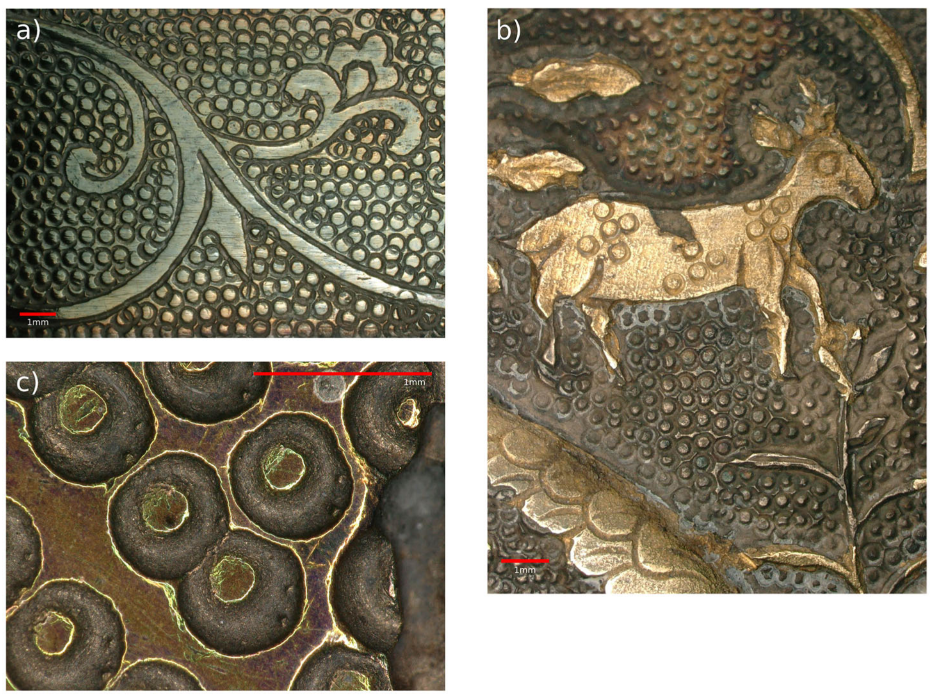


Fig. 5 | Ring punching and matting techniques. **a** Ring matting over the upper band of cup 1968,0422.10, showing minor imperfections where rings overlap with the flower decoration, a result of inevitable manual errors, emphasising the handmade nature of the artefacts (magnification ×30). **b** Rings used to define the wool of a sheep on the exterior surface of a lotus flower bowl, in addition to ring matting for the background created with the same tool (1968,0422.11), (magnification ×20). **c** Two small, raised points observed on each ring of a lobed bowl (1926,0319.9), indicating repeated punches made with a single ring-end tool (magnification 150x).

Besides the two main techniques, ring punching and matting consistently appeared as a decorative background motif on all decorated artefacts examined.

- This technique involves creating rings on a metal surface by hammering a hollow circular punch onto the metal to imprint the design[30]. These rings cover the entire background surface of certain objects, such as the lobed bowl 1926,0319.9. In this piece, two small, raised points within each punched ring were observed, showing the presence of minor imperfections in the punch itself. The consistent repetition of these features indicates the repeated use of the same specific punch (Fig. 5c). The arrangement of the rings varies, with some arranged spirally, others in parallel lines, and still others outlining details of animal figures (Fig. 5b) or forming overlapping patterns. Upon further examination, notable inconsistencies in the dimensions of the rings were observed, both within individual artefacts and across the assemblage. For instance, the foliated dish 1926,0319.10 shows significant variation in ring diameters. Three different sizes of ring punch were used with rings measuring approximately 1mm on the rim and on the internal wall, and about 0.7mm on the flat bottom. Evidence also suggests that punches were applied at different angles: inclined punches

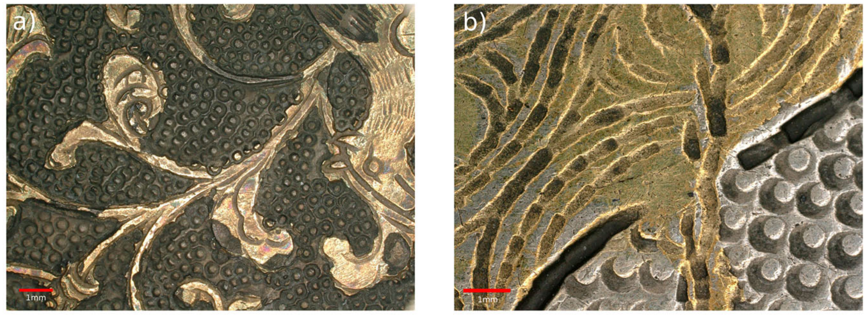


Fig. 6 | Gilding techniques observed. a Possible use of the leaf gilding technique on the lotus flower bowl (1968,0422.11), applied before ring matting of the background. **b** illustrates the likely application of fire gilding applied to a foliated dish (1926,0319.10), after ring matting and chasing.

produced half-moon shapes, while orthogonal punches resulted in clean, circular impressions. Furthermore, some sections feature deeply etched rings that create pronounced indentations, whereas others exhibit only subtle impressions, barely visible upon close inspection (Fig. 2d). In several pieces, the overlaying details helped to define and illustrate the sequence of creating patterns and decorations. Ring matting of the background has been applied both before and after other decorative elements, indicating a lack of a strict sequence in their creation. Furthermore, the identification of minor imperfections throughout the assemblage (e.g., Fig. 5a) highlights the handmade nature of these artefacts, suggesting that the ring-matted backgrounds were created through a single-punching technique, without the presence of a matrix or modular tool.

The surfaces of four artefacts (1968,0422.11; 1926,0319.9, 1926,0319.10; 1926,0319.4) showed the use of gilding as a decorative technique.

- This method consists of applying a thin layer of gold to solid metal surfaces, giving them a shiny golden hue[31]. Before the discovery of electrolysis in the early 19th century, a process used industrially from the 1830s that deposits a thin layer of gold onto metal surfaces by passing an electric current through a solution containing gold ions[32], gilding was achieved only through two distinct techniques, leaf gilding and fire gilding. Leaf Gilding: this technique involves the meticulous application of an extremely thin gold (Au) layer, often in the form of leaf, foil, or sheet. The gold adheres to the silver surface through pressure alone. It is typically laid on the surface and then pressed down with a burnisher (a smooth-faced tool made of agate, steel, or sometimes even glass), resulting in a pure gold appearance (Fig. 6a). In some cases, before applying the gold layer, the surface is coated with mercury (Hg), a step known as *quickening*[28,33]. Another method involves applying a gold-mercury amalgam to the surface, followed by heating. Fire Gilding: gold is ground finely into mercury (Hg) to create an amalgam paste, which is then brushed onto a metal surface, sometimes leaving distinct brush strokes, and subsequently heated to make a firmly bonded gilding layer (Fig. 6b). Aesthetic nuances given by the structure and colour of the amalgam arise in fire gilding due to varying mercury contents (Au/Hg ratio ranging approximately from c.8 wt% to c.25 wt%) and the change of temperature adopted during the heating process[28,34].

Elemental analyses by XRF and SEM-EDX confirmed the presence of Au and Hg on all the analysed gilded surfaces. However, it is important to understand that the mercury (Hg) percentages detected by elemental analysis do not represent the total amount of mercury originally used in the gilding process. This is because mercury vaporises when heated during gilding, leaving only relatively small traces trapped in the gilding layer. Although often visually difficult to distinguish, leaf gilding was tentatively identified on the lotus flower-shaped bowl 1968,0422.11 by the presence of thin, uneven parts of gold foil located in raised or ornamented areas of the surface (Fig. 6a and SM). These parts, sometimes partially detached or lifted, are consistent with the manual placement of gold leaf rather than the application of a fluid amalgam. Furthermore, the absence of clear brush strokes supports the interpretation of a pressure-based technique. Conversely, fire gilding was tentatively identified on the lobed bowl, on the foliated dish and on the oblong and polylobate cup (1926,0319.9, 1926,0319.10, 1926,0319.4) by the presence of visible brush strokes and absence of raised or uneven parts (Fig. 6b and SM). However, both identifications remain provisional pending further detailed analysis.

Low accuracy and minor flaws were observed on the gilded surfaces of the artefacts. For instance, on the lotus flower-shaped bowl 1968,0422.11, the gold layer does not perfectly align with the shape of the flowery decoration (Fig. 6a). Similarly, the foliated dish 1926,0319.10 shows that the amalgam was brushed by the artisan without staying within the boundaries of the designs (Fig. 6b). Additionally, it is worth noting that the sequence of decorative steps appears flexible, with gilding occurring both before and after other elements of the design. Gilding techniques can be further explored in the following literature[27,35–38].

The *jinyin pingtuo* (金銀平脱) technique is evident on the bowl 1938,0524.704[12,39]. Developed during the Tang dynasty (618–907 CE), this decorative method was used for producing luxury wares adorned with silver and/or gold inlays, typically featuring Tang lotus floral motifs, set into lacquered surfaces. The process involved cutting sheets of gold and/or silver into decorative shapes, which were then applied onto a prepared surface, often with a textile base, coated in layers of lacquer. These layers were built up until the metal elements were fully covered. Once dried, the surface was finely burnished to reveal the metallic inlays, which were leveled with the surrounding lacquer to create a smooth, integrated finish. Evidence of the same decorative technique was found in the Hejiacun (何家村) hoard and in a number of Tang tombs[8]. For a detailed description of the technique, see the following references:[12,39–41].

Compositional analyses

The analytical results reveal considerable variability in the elemental composition of the vessels, with silver (Ag) content ranging from 71.2 wt% to 99.3 wt% and copper (Cu) content ranging from 0.5 wt% to 26.4 wt%. The scatterplot of Ag/Cu ratios illustrates this variation across the assemblage (Fig. 7). Most of the data points cluster above 90.0 wt% Ag, and below 7.2 wt % Cu. Except for two vessels (1938,0524.704 and 1926,0319.8) - which were manufactured as single pieces, all the others comprise two components: a foot and a body or in the case of item 1938,0524.706 a ring handle and a body. In these cases, each part was examined individually, producing a dataset of 25 components, plotted in Fig. 7. Compositional similarity between the foot and body is observed in 11 vessels, indicating uniform alloying practices. In contrast, three vessels exhibit significant differences between their components. The body (cup) of 1926,0319.4 contains 11.4 wt % Cu, compared to 4.3 wt% in the foot. The foot of the lobed bowl (1926,0319.9) contains 24.6 wt% Cu, markedly higher than its body (6.9 wt %). Similarly, the body of the foliated dish (1926,0319.10) shows 26.4 wt% Cu, compared to 5.0 wt% in its foot. These component-specific

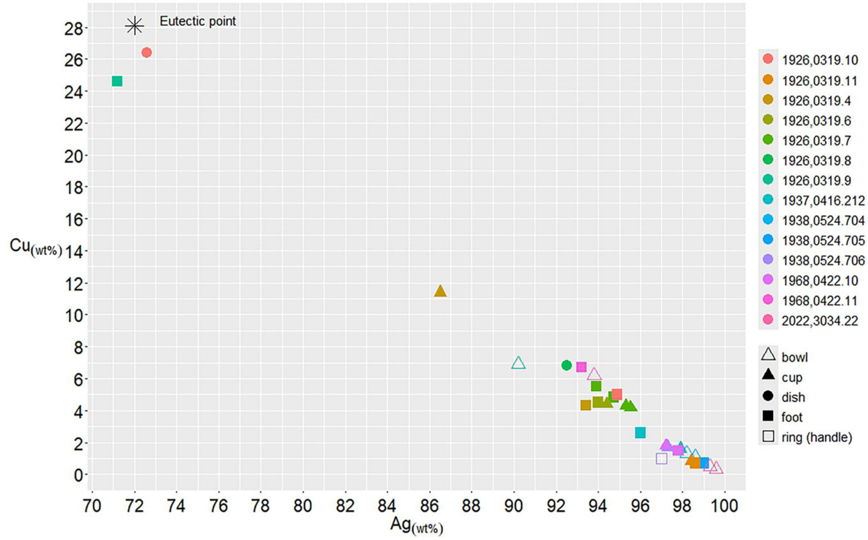


Fig. 7 | Scatterplot of Ag/Cu ratios showing the variability in copper content among the silver alloys for each part analysed. The eutectic point of the Ag-Cu alloy is provided (≈28 wt% Cu / 72 wt% Ag), (see Discussion and conclusions section). All the analyses were carried out on abraded spots. Analyses are shown in wt% normalised to 100%.

compositions not only diverge sharply from their counterparts but also from the rest of the assemblage.

When the two previously mentioned outliers with near-eutectic compositions are excluded - due to their distinct alloy characteristics—two main groups can be identified based on copper (Cu) content: one characterised by more than 4.0 wt% Cu and the other by less than 3.0 wt% Cu. The first group (HC) includes 7 vessels (1968,0422.11; 1926,0319.7; 1926,0319.4; 1926,0319.6; 1926,0319.9; 1926,0319.10; 1926,0319.8), which have copper content ranging from 4.3 wt% to 11.4 wt% and silver content ranging from 86.5 wt% to 95.3 wt%. The second group (LC) includes the remaining 7 vessels (1938,0524.706; 1937,0416.212; 1968,0422.10; 1938,0524.705; 1938,0524.704; 1926,0319.11; 2022,3034.22), which are characterised by lower copper content ranging from 0.5 wt% to 2.6 wt% and higher silver content ranging from 96.0 wt% to 99.3 wt%.

Minor amounts of gold (Au) and lead (Pb) were detected in most of the vessels (Table 2 and Fig. 8). Gold concentrations ranged from below the detection limit up to c. 2.2 wt% in the foot of 1926,0319.4 and the bowl 1926,0319.9. Traces of Hg were identified in the cup of 1938,0524.706, in the cup of 1968.0422.10 and in the bowl 1926,0319.9. It should be noted that the presence of Hg may indicate an overestimation of Au content, as these objects likely retain remnants of gilding. Lead showed a similar range peaking in the foot of 1926,0319.4 and in the handle of cup 1938,0524.706. No gold was detected in bowl 1968,0422.11, bowl 1938,0524.705, bowl 1938,0524.704, both components of 1926,0319.7, and bowl 2022,3034.22. Overall, Pb contents were similar across vessels from both groups. In contrast, although vessel 1968,0422.11, the foot of dish 1926,0319.10, and both components of 1926,0319.7 showed no gold, overall higher Au concentrations were generally observed in the high-copper (HC) group.

Soldering. The soldering process involves melting a filler metal or alloy, known as solder, which has a lower melting point than the metals to be joined. When molten, the solder flows into the gaps between the parts by capillary action, creating a strong mechanical bond as it cools and solidifies. Soldering techniques are generally classified into two main categories, based on the melting temperature of the solder used[27,28]. Soft soldering typically uses alloys with melting points below 450 °C. With silver the most common soft solder is tin (Sn)-based, often alloyed with lead (Sn–Pb) for ease of flow, or with small amounts of silver (Sn–Ag) to improve strength and corrosion resistance without raising the melting point significantly.

These solders allow for effective joining while minimising the risk of damaging the base metals that typically have much higher melting points. They also provide adequate strength for low-load applications. Hard soldering, on the other hand, involves solders with higher melting points, generally above 450°C, that are typically made from various combinations of tin, copper, zinc, and silver. These variants can offer improved mechanical properties, better flow, and enhanced thermal or corrosion resistance, depending on the application. (see Brepohl[28] and Untracht[27] for more details on soldering techniques).

Soldered areas were visually identified on all the vessels, composed of two parts (12). However, due to accessibility constraints, detailed analyses using SEM-EDX were conducted on only three of these vessels (1926,0319.4; 1926,0319.6; 1938,0524.706). In these cases, the feet had temporarily become detached, likely due to the degradation of old conservation adhesive rather than active disassembly. This condition, already present prior to the study, provided direct access to the joint surfaces between the foot and upper parts at several points, allowing for more accurate analyses.

The other artefacts had joins in narrow or inaccessible positions, preventing thorough analysis. Additionally, recent conservation treatment using glue to reattach parts of the objects hindered a proper visual investigation of the soldered areas. It is important to note that these results should not be considered quantitative, as they were obtained from not-abraded surface analyses and from areas potentially affected by glue residues, which may have compromised accurate element detection and quantification. Nonetheless, all three vessels showed an increased presence of copper and tin in variable amounts in correspondence with the soldered areas (Fig. 9 and SM). This indicates that silver-based alloy such as Sn/Cu/Ag was used to solder (see Discussion and conclusions section).

Additionally, minor amounts of elements such as Si, S, Cl, Br, Au and Pb were identified (see SM for details). While lead and gold are part of the main alloy of the vessels, the other elements may be associated with conservation treatments and/or the application of adhesives or cleaning agents (e.g., S, Cl), soil residues (e.g., Si), or corrosion products (e.g., Cl, Br, S). In burial environments—particularly marine or coastal—bromide ions present in the soil or groundwater can react with silver artefacts, resulting in the formation of silver bromide (AgBr) on the surface, often in conjunction with silver chloride (AgCl) and silver sulphide (Ag_2S)[42].

The 6-lobed bowl (2022,3034.22) features a beaded rim decoration (Fig. 11a) composed of uniformly sized small spheres, likely shaped using a hollow die. This die, with a concave cavity and raised edge, allowed a silver sheet to be inserted and hammered onto the negative shape, forming a series of individual hollow spheres[27]. Unfortunately, a detailed examination could not be performed as all recesses between the beads/spheres are covered with a slightly sparkling grey-greenish material Nevertheless, SEM-EDX analyses conducted on various not-abraded areas of the main body of the object (see Table 3), revealed notable compositional changes at the joins between the beads and between these and the main body. Specifically, higher concentrations of Cu were detected at these various joins (Fig. 10, spectra 6-8),

Table 2 | All the analyses were carried out on abraded spots except when noted as n.a

Reg. no.	Description	Date	Findspot	Part analysed	Cu	Ag	Au	Pb	Other elements	Technique
1938,0524.706	Handled circular cup	650–700	North China	cup	1.7	97.3	0.4	0.6	Hg	SEM-EDX
				ring (handle)	1.0	97.0	b.d.l.	2.0		SEM-EDX
1968,0422.11	Lotus-shaped bowl	680–750	Probably Xi'An	bowl	6.2	93.8	b.d.l.	b.d.l.		XRF
				foot	6.7	93.2	0.1	b.d.l.		XRF
1937,0416.212	Goblet/cup	700–750	North-central China	cup	1.6	97.9	0.1	0.5		XRF
				foot	2.6	96.0	1.0	0.4		XRF
1968,0422.10	Goblet/cup	700–750	Shaanxi	foot	1.5	97.8	0.4	0.3		XRF
				cup (n.a.)	1.8	97.2	0.8	0.2	Hg	XRF
1938,0524.705	Bowl	700–750	North China	foot	0.7	99.0	0.1	0.2		SEM-EDX
				bowl	1.1	98.6	b.d.l.	0.2		SEM-EDX
1938,0524.704	Pingtuo bowl	700–750	North China	bowl	1.3	98.2	b.d.l.	0.5		SEM-EDX
1926,0319.7	Oblong and polylobate cup	800–900	Pei huang shan, Shaanxi province (?)	foot	5.5	93.9	b.d.l.	0.6		SEM-EDX
				cup	4.3	95.3	b.d.l.	0.4		SEM-EDX
1926,0319.4	Oblong and polylobate cup	800–900	Pei huang shan, Shaanxi province (?)	cup	11.4	86.5	1.5	0.6		SEM-EDX
				foot	4.3	93.4	1.4	0.8		SEM-EDX
1926,0319.6	Oblong and polylobate cup	800–900	Pei huang shan, Shaanxi province (?)	cup	4.4	94.4	0.8	0.4		SEM-EDX
				foot	4.5	94.0	0.7	0.8		SEM-EDX
1926,0319.11	Oblong and polylobate cup	800–900	Pei huang shan, Shaanxi province (?)	cup	0.8	98.4	0.5	0.2		XRF
				foot	0.7	98.6	0.5	0.2		XRF
1926,0319.9	Lobed bowl	800–900	Pei huang shan, Shaanxi province (?)	foot	24.6	71.2	2.2	2.0		XRF
				bowl	6.9	90.2	2.2	0.7	Hg	XRF
1926,0319.10	Foliated dish	800–900	Pei huang shan, Shaanxi province (?)	foot	5.0	94.9	tr.	0.1		XRF
				dish	26.4	72.6	0.6	0.4	Bi, Zn	XRF
1926,0319.8	Foliated dish	800–900	Pei huang shan, Shaanxi province (?)	dish	6.8	92.5	0.6	0.2		XRF
2022,3034.22	Beaded rim bowl	1025	North-East China	bowl	0.5	99.3	b.d.l.	0.2		SEM-EDX
C2 – secondary standard	Nominal Values				1.7	97.5	0.3	0.7		
	Measured values				1.6	97.3	0.3	0.7		XRF
	Measured values				1.4	97.6	0.3	0.7		SEM-EDX

Analyses are shown in wt% normalised to 100%; 'b.d.l.': below detection limit; 'tr.': means that a peak has been recognised but is too close to the detection limit of the instrument for the analyte to be reliably quantified. The values should have a precision (a measure of reproducibility) of c. ±1–2% relative to copper, c. ±5–10% to the major alloying elements and c. ±10–30% to the remaining minor/trace elements [61]. A secondary standard (C2) was used to test for the accuracy and precision of the instruments.

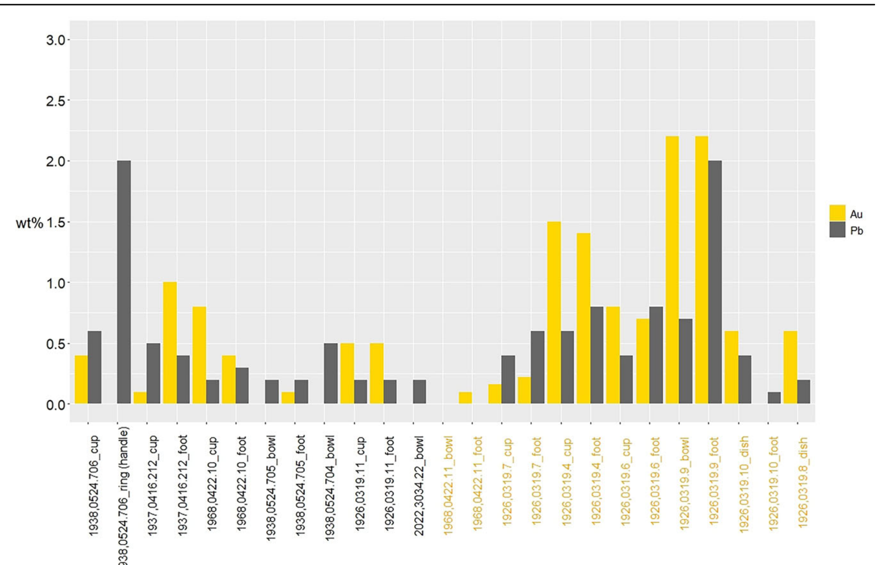


Fig. 8 | Histogram showing the concentrations of Au and Pb in each analysed component. Vessels belonging to the high-copper (HC) group are shown in orange. All the analyses were carried out on abraded spots. Analyses are shown in wt% normalised to 100%.

Fig. 9 | SEM micrograph and elemental maps of the main elements (Ag, Cu, Sn) identified in a soldered join area between the foot and cup of vessel 1926,0319.6. Detailed analyses are reported in the SM.

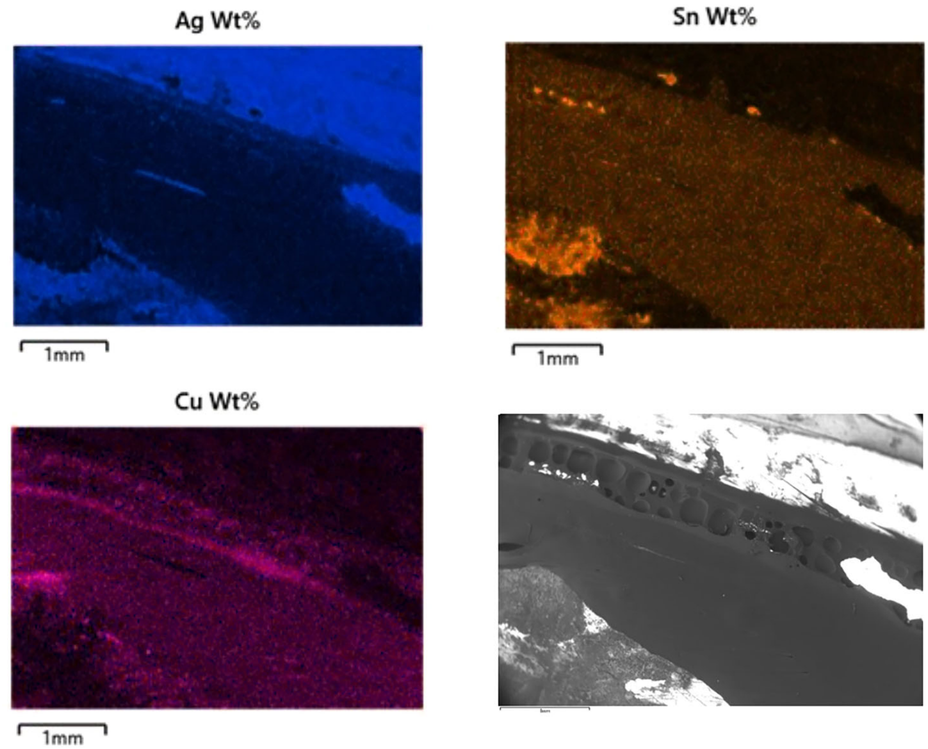
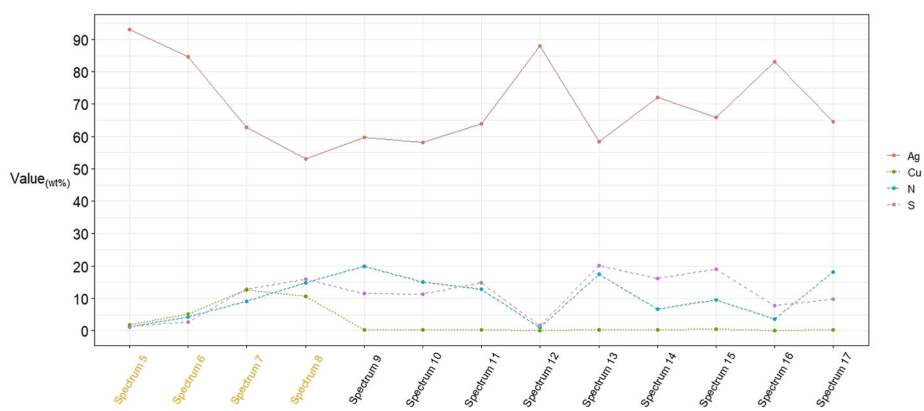


Fig. 10 | Line chart illustrating the distribution of Ag, Cu, N, and S values reported in Table 3. Copper (Cu) is only detected in significant quantities at the beaded rim's joins (spectra 6-8). Additionally, it shows a correlated increase in nitrogen (N) and sulphur (S) with a decrease in Ag values. Analyses conducted on the rim are highlighted in orange, while those on other areas of the object are represented in black.



suggesting the use of an Ag/Cu solder. Additionally, an increase in nitrogen (N) and sulphur (S), corresponding with a decrease in silver (Ag) was observed moving from the beads towards the centre of the joins (spectra 5–8, see Fig. 11b) and across the entire surface of the object—except on the cleaned or abraded spheres of the beaded rim (see line-chart in Fig. 10 and values in Table 3), suggesting the presence of ammonium sulphide ($(NH_4)_2S$)[43,44].

Its presence is further supported by the vessel's darkened appearance and by the typical crystallised whiskers identified on the surface[45] (see SM). These structures form when silver is exposed to sulphur-containing gases, leading to discolouration and eventual darkening due to the formation of a silver sulphide (Ag_2S) tarnish layer. However, the exact timing of this treatment remains uncertain. Heat damages were noted in some beads at the join with the rim, appearing slightly melted, likely from excessive heat during soldering (Fig. 11c). However, it cannot be excluded that the observed melting could have resulted from heat exposure during a later period of use or due to environmental factors affecting the object.

Discussion

The investigation of Tang and Liao dynasty silverware reveals the use of different manufacturing and decorative techniques, reflecting a highly skilled and systematic approach to metalwork. Manufacturing techniques identified include casting, hammering, lathe turning, and soldering. Decorative techniques observed on 9 vessels comprise repoussé, chasing, punching, ring-matting, leaf- and fire-gilding, and *jinyin pingtuo*, demonstrating technical and artistic versatility. These techniques were commonly used in the Tang and Liao periods. Often used in combination, they are consistent with practices observed in comparable silver vessels from sites such as the Wei (韋) family cemetery[13], and Xiaolizhuang (小李莊) site in northern China[1] and the pagoda crypt of Famen Monastery (法門寺), made in southern China[11]. However, according to Dydier and Wei[5], the chasing technique observed on several artefacts does not appear to have been traditionally associated with Chinese decorative practices, but rather aligns more closely with techniques commonly employed by Western silversmiths. This observation may suggest the possibility of

Table 3 | displays SEM-EDX analyses from various not abraded areas of the vessel 2022,3034.22, highlighting significant compositional variations at the joins between beads and between beads and flattened rim

Spectrum	Area	N	Na	Si	S	Cl	Ca	Cu	Br	Ag	Au	Pb	Total
5	Rim	1.1	b.d.l.	0.3	1.5	0.8	0.2	1.9	0.3	93.0	0.6	0.2	99.8
6		4.2	0.7	0.4	2.6	1.4	0.2	5.1	0.3	84.8	b.d.l.	0.2	99.9
7		9.0	b.d.l.	0.6	13.0	0.6	0.4	12.7	0.2	62.7	b.d.l.	0.8	100.0
8		14.9	b.d.l.	1.3	16.0	0.6	2.6	10.7	0.2	53.0	b.d.l.	0.6	99.9
9	Main body	19.9	b.d.l.	2.1	11.5	2.1	2.3	0.3	0.3	59.6	0.3	0.5	98.9
10		15.1	b.d.l.	7.7	11.3	2.0	2.3	0.3	0.7	59.1	0.4	1.0	99.8
11		13.0	b.d.l.	1.4	14.8	1.1	3.6	0.4	0.4	63.9	0.3	0.8	99.6
12		0.9	0.3	0.2	1.5	8.0	0.1	b.d.l.	b.d.l.	87.9	b.d.l.	0.4	99.4
13		17.6	b.d.l.	0.4	20.2	0.8	0.4	0.2	b.d.l.	58.5	0.2	0.8	99
14		6.6	b.d.l.	0.6	16.1	0.8	1.6	0.2	0.2	72.0	b.d.l.	1.0	99.2
15		9.5	b.d.l.	0.6	19.1	0.8	1.1	0.4	0.2	65.8	b.d.l.	1.4	98.9
16		3.5	b.d.l.	0.3	7.7	5.1	b.d.l.	b.d.l.	0.2	83.1	0.2	b.d.l.	100
17		18.2	b.d.l.	1.5	9.9	2.4	2.0	0.2	0.4	64.7	0.2	0.4	99.8

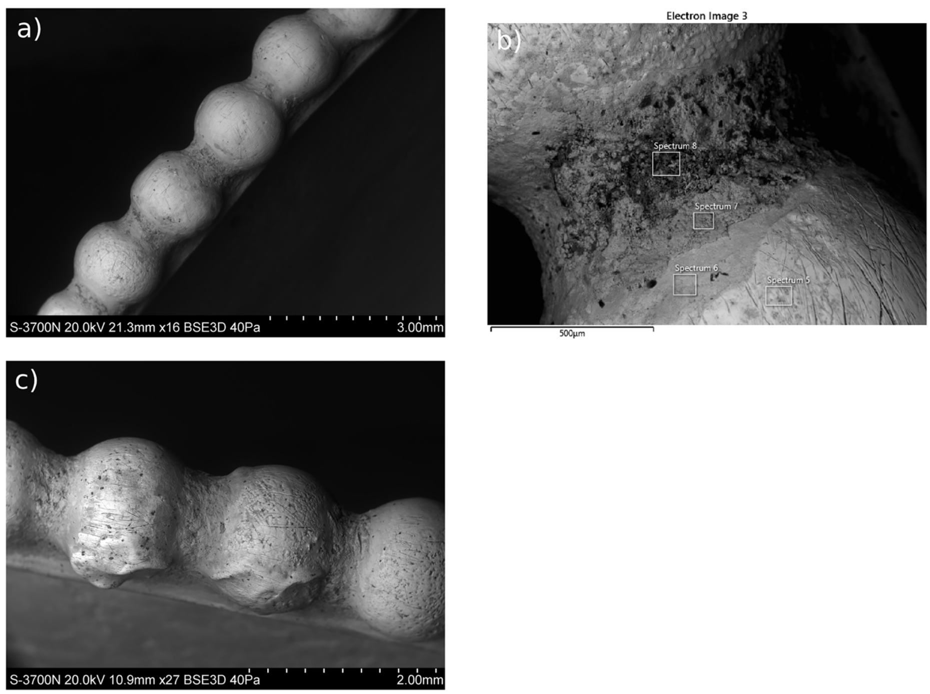


Fig. 11 | SEM BSE images. a Beaded rim decoration on the 6-lobed bowl (2022,3034.22). **b** Areas of SEM-EDX analysis showing gradual increase in nitrogen (N) and sulphur (S) from the beads towards the join (from spectrum 5 to spectrum 8). **c** Heat damage on some beads at the join, appearing slightly melted, likely due to excessive heat during soldering.

cultural exchange or influence between Western and Chinese artisans, pointing to a potential blending of artistic traditions. Such interactions could have contributed to the introduction of new tools and techniques, thereby expanding the artistic repertoire accessible to Chinese craftspeople during the Tang dynasty. One example of this cross-cultural interaction is the ring-matting technique, which appears on all nine of the examined decorated artefacts—indicating its importance as a decorative convention. As already noted by Michaelson and Portal[22] the ring-matted background highlights the decoration, difficult to discern without textural contrast, making the designs stand out from a plain background (Fig. 5a). This technique not only serves an aesthetic purpose but also was adopted as a device/tool to achieve a visually striking effect. The deliberate variation in punch angles and impression depths may indicate an artistic intention to introduce a sense of three-dimensionality and visual complexity into the designs. Such manipulation of surface texture could have been employed deliberately to enhance light reflection or to "animate" the background beneath figural or ornamental elements. However, the observed inconsistencies in ring sizes and the presence of imperfections across different artefacts could reflect a lack of uniformity in execution, possibly due to variations in the skill levels of the craftspeople involved. Alternatively, it is possible that these imperfections were considered unimportant, especially if the objects were intended to be viewed from a distance, where such minor surface irregularities would have gone largely unnoticed. According to Marshak[21] this ornamental motif was commonly adopted in Sogdian silver from the sixth through the early ninth century likely influencing the Chinese aesthetics. This cross-cultural influence might have introduced the ring-matting technique into Chinese metalworking practices, demonstrating the adaptability and exchange of artistic methods across regions. The adoption of this technique on Chinese artefacts amongst more traditionally local ones is exhibited by a combination of styles on objects, possibly reflecting broader socio-cultural exchanges between the Sogdian and Chinese societies during this period.

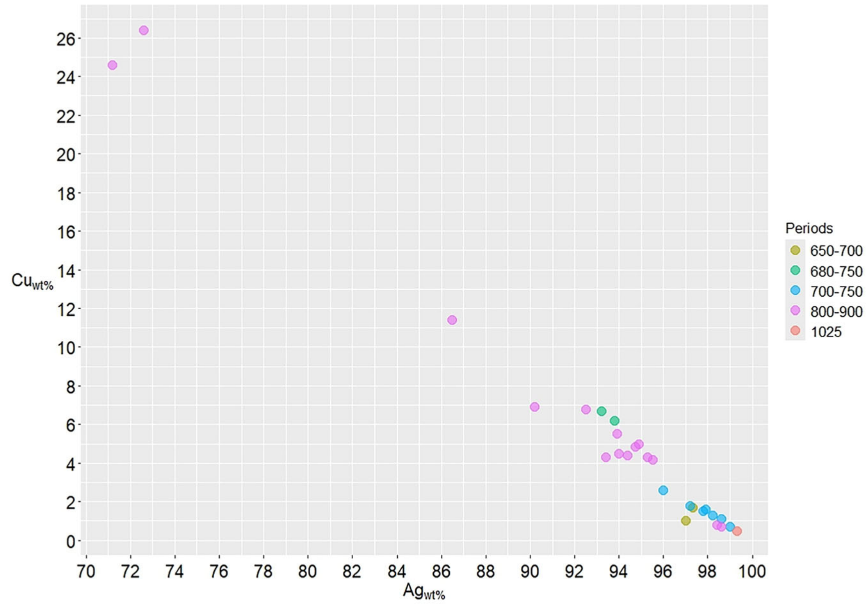


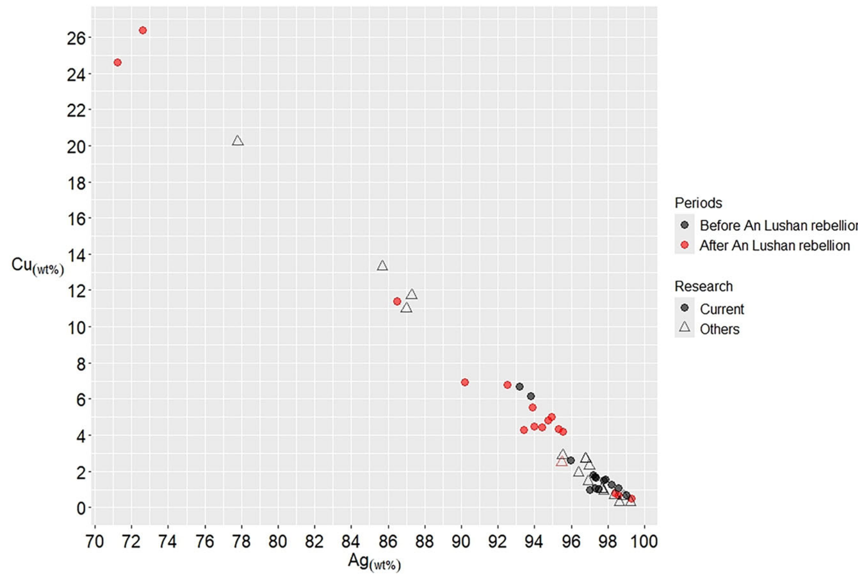
Fig. 12 | Scatterplot of Ag/Cu ratios for the objects categorised by period. All the analyses were carried out on abraded spots. Analyses are shown in wt% normalised to 100%.

The variations observed in ring arrangements and intensity suggest a level of artistic and technical creativity and experimentation.

The *jinyin pingtuo* technique, identified in the bowl 1938,0524.704, exemplifies the luxury and opulence characteristic of Tang Dynasty art. The fact that it was banned after the An Lushan 安祿山rebellion (755-763 CE) due to its extravagance[5] underscores its significance in reflecting the period's aesthetic and socio-political context. Additionally, the parallels between this bowl and other pieces from the Hejiacun hoard and Tang tombs[12,39], reinforce the technique's widespread use and its importance in Tang Dynasty metalwork. This technique's continued presence in multiple locations and contexts indicates its broad acceptance and popularity during the Tang period.

The compositional analyses of all the 25 components revealed that, except for two cases—the foot of the lobed bowl (1926,0319.9) and the body of the foliated dish (1926,0319.10)—all other components display a high silver content (>85 wt%), consistent with other Tang dynasty silver artefacts from the same cultural region (see SM in reference 11). The two aforementioned components lie very close to the Ag–Cu eutectic point (≈28 wt% Cu/72 wt% Ag), (see Fig. 7). Alloys at or near this eutectic composition, even if they are not exactly at the eutectic, solidify into a fine, interwoven microstructure (α–β) that maximises fluidity during casting and enhances hardness and wear resistance upon cooling[25,46]. Such properties would be especially advantageous for load bearing or abrasion-prone parts (e.g., feet), while conserving silver by partially substituting with less expensive copper. Overall, except for the above-mentioned items and cup 1926,0319.4, compositional similarity between the parts of the same vessel is observed, indicating uniform alloying practices. The presence of copper in all the vessels indicates that they were made from silver deliberately alloyed with copper[25]. An exception may be the bowl 2022,3034.22, where the copper content is extremely low at 0.5 wt% in the bowl, suggesting that copper in this case may be a natural impurity from the ore rather than a deliberate addition. All the other vessels were grouped into two groups, a Low-Copper Group (LC) and a High-Copper Group (HC), based on a tentative threshold of 3.0 wt% copper, proposed to distinguish between high-purity silver (<3 wt% Cu) and low-purity silver (>3 wt% Cu). This variability in copper content among the vessels was explored in relation to their relative chronology (see Introduction). Overall, a correlation between the compositional groups identified (LC, HC) and the relative chronological periods was observed. Objects from the 800-900 CE period consistently show copper contents higher than 4.2 wt%, while those dated to the earlier 650-700 CE and 700-750 CE periods exhibit purer silver alloys with copper content below 2.6 wt%. The hypothesis tested was that there was a decline in the control over alloy composition following the mid-eighth century CE. This period coincides with the An Lushan Rebellion (755–763 CE), a time of profound political and economic instability that may have disrupted access to refined materials and altered metallurgical practices. Before the Rebellion the Tang dynasty had a well-established, resource-rich, and partially decentralised silver production system, supported by abundant mineral resources and permissive state policies[8,11,47,48]. The government's decision to allow private mining under a regulated tax-revenue framework enabled the operation of over 58 documented silver mines across the empire. This decentralised yet state-benefiting structure ensured a steady supply of silver, which was not only critical for maintaining governmental fiscal needs but also played a central role in sustaining elite consumption, court rituals, and the production of high-status artefacts for the imperial family[8,11,48]. The rebellion marked a significant shift in the Tang Empire's political and economic landscape, with the economic centre moving from the North to the South, and a new geopolitical axis emerging from the northwest to the southeast. During this period, there was a loss of state control over property and subjects, alongside increased commercialisation and urbanisation[8]. When the copper contents are categorised by the relative chronology, a clear pattern emerges (Fig. 12). Notable exceptions include the beaded rim bowl (2022,3034.22), dated to 1025, with a composition of 99.3 wt% silver, and the lotus-shaped bowl (1968,0422.11), dated to 680-750 CE, with a composition of *c.* 6 wt% copper. Nevertheless, this pattern allows for the following considerations. The increased copper content may reflect a decline in control over silver purity, potentially resulting from diminished refining capabilities, disruptions in supply chains, or limited access to high-quality ore—factors that, according to historical sources, emerged in the aftermath of the major socio-political upheavals following the An Lushan Rebellion. As a result, craftsmen in later periods may have adapted to the reduced quality of available materials by deliberately alloying silver with copper or recycling high-copper silver alloys, whether to improve workability, compensate for resource constraints, or meet increased demand. From this perspective, what might be interpreted as a deliberate metallurgical choice could in fact stem from broader structural limitations within the silver production system. This pattern appears to be further supported when the analysis is extended to additional artefacts from the same cultural area. As shown in Fig. 13, most silverware dated to before the An Lushan Rebellion clusters in the region with less than 3 wt% copper, consistent with the trend previously observed, possibly reflecting a shift in metallurgical practices following the rebellion, particularly in the alloying of copper with silver.

Fig. 13 | Scatterplot of Ag/Cu ratios for objects analysed in the current (circles) and past (triangles) research (see text fordetails) in the same cultural area, categorised by period. Analyses are shown in wt% normalised to 100%.



Some exceptions to this trend are noted (Table 2 in the SM), such as the front and foot of a gilded silver dish (nos. 9, 13), the body and ring foot of a gilded silver ewer (nos. 16, 19), though the latter has a counterpart with approximately 5.0 wt% Cu.

These outliers, however, do not significantly disrupt the overall pattern. These data were then integrated with existing literature (Fig. 13). Specifically, they were sourced from[11] and filtered to ensure comparability with the vessels analysed in the present study. Only plates, dishes, ewers, cups, boxes, and foils (18 components in total) were included, while ornaments, hairpins, belts, wires, and rivets were excluded. Where multiple measurements existed for a single component, average values were used. Objects with chlorine (Cl) concentrations between 19.3 and 25.0 wt%—indicative of advanced surface corrosion—were also omitted to ensure data reliability. In addition, items dated broadly to the entire Tang Dynasty (618–907 CE) were excluded to maintain chronological precision. This trend should nonetheless be interpreted with caution, as relatively few analyses exist for silver objects from the post-rebellion period, making definitive conclusions premature.

In addition to the main alloying elements, minor amounts of other elements such as lead (Pb), ranging from below detection limits to 0.4 wt%, and gold (Au), ranging from below detection limits to 1.6 wt%, were consistently detected in the vessels. These elements are likely residual impurities originating from the silver ore itself, rather than deliberate addition. It is worth noting that gilding may influence the detected gold content, potentially impairing accurate assessment of its original concentration in the alloy. Nonetheless, the overall consistent presence of lead (Pb) and gold (Au) points to the use of argentiferous lead ores as the source material for silver[49–52], a common source in ancient metallurgy and especially prominent in Tang China[47].

Because ancient refining technologies lacked the precision of modern methods, complete removal of such impurities was rarely possible. One of the primary refining techniques used in antiquity and in Tang China[11,47] was cupellation—a high-temperature process designed to separate precious metals like silver and gold from base metals such as lead, copper, and tin. This was achieved by heating the metal under oxidising conditions in a porous vessel known as a cupel. During the process, the base metals oxidised and were absorbed into the cupel, while the purified noble metals remained[27]. For instance, research by Yi identified silver slag containing more than 80 wt% lead, a clear by-product of this refining method and a key indicator of its use in ancient silver production[39].

Higher concentrations of gold (Au) were unexpectedly observed in vessels with higher copper (Cu) content in the alloy. To better understand this unusual correlation, since gold as a trace element is typically associated with silver (Ag) rather than copper (Cu), the dataset was expanded to include additional artefacts from[11] and investigated in relation to their chronological context. When grouped before and after the An Lushan Rebellion (755–763 CE), the data show an increase in gold content in the post-rebellion group (Fig. 14). This difference could suggest that the silver used in artefact production after the rebellion may have originated from different ore sources than those used before. This change might be a result of the shift in mining and trade practices following the rebellion, potentially linked to the movement of the economic centre from the north to the south of China. Southern regions were known to have rich mineral deposits, and, during this period, mining policies became more flexible and trade was less restricted, which likely facilitated access to different ore sources. Differently, although variations in lead concentrations were observed among the objects, no consistent trend could be identified.

Two different types of solder were identified in the assemblage. One characterised by an alloy of Ag/Sn/Cu (1926,0319.4, 1926,0319.6, and 1938,0524.706), the other by an alloy of Ag/Cu (2022,3034.22). Evidence from both historical texts and scientific studies concerning the soldering agents used in silver artefacts from the Tang Dynasty and earlier remains limited. The only fluxes recorded for facilitating silver soldering are *Hutonglei* (胡桐淚)—a resinous gum from *Populus diversifolia*—and *Lusha* (鹵砂) (NH_4Cl)[53,54]. Interestingly, a recent work by Tan et al.[11] identified a solder made of an alloy of Ag/Cu/Zn on a 9th century silver box from Famen Monastery, Shaanxi province. However, Tan et al. dismissed the presence of zinc as a metallic element in the solder, claiming that (a) the artificial alloying of zinc with Ag–Cu alloy would not have improved the alloy in terms of temperature, making the alloying not worth it[55] and (b) the Chinese traditional zinc smelting originated during the Ming dynasty (1368–1644 CE)[56]. Similar solders have been also recorded for copper objects in the literature of Qing dynasty (1644–1912 CE)[57,58] and also used to bond silver objects in modern metallurgy[59]. Instead, they interpreted zinc as an impurity associated with silver and copper and that the Ag–Cu alloy should have been employed as solder.

Differently, the high amount of tin detected at several points on the three above-mentioned vessels, cannot be dismissed as a residual element in the solder. Instead, its consistent presence across multiple soldering areas strongly suggests a deliberate inclusion of tin in the alloy. This points toward an intentional technological choice, rather than accidental contamination or unintentional presence. However, the use of Ag/Sn/Cu alloys has not been previously identified in silver artefacts from the Tang or earlier periods. Its

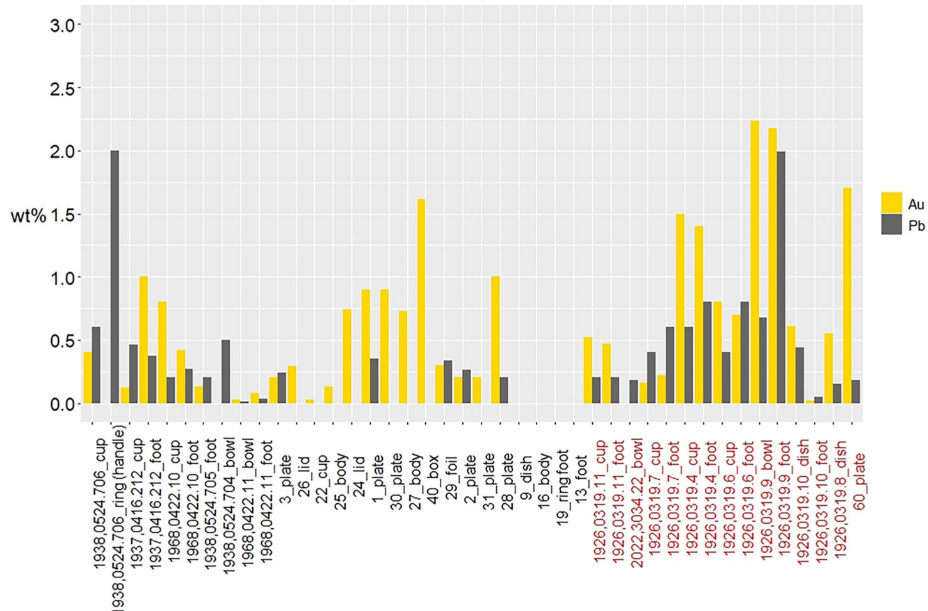


Fig. 14 | Histogram showing the concentrations of Au and Pb in each analysed component from this research, along with additional artefacts from Tan et al.[11]. Vessels dated to the period before the An Lushan Rebellion are labelled in black, while those from after the rebellion are labelled in red. All analyses were conducted on abraded spots and are presented in wt%, normalised to 100%.

detection in these artefacts therefore extends our current understanding of the range of metallurgical techniques employed during the Tang dynasty. The deliberate use of a ternary alloy including tin may have served practical purposes, such as lowering the melting point, improving the flow characteristics of the solder, or enhancing bond strength, underscoring the technical sophistication of Tang metalworkers. Nevertheless, the possibility that this Ag/Sn/Cu solder represents a modern intervention, such as conservation or undocumented restoration, cannot be entirely ruled out. Tin-containing solders are widely used in modern repair practices, and their presence in archaeological material must be carefully interpreted. To address this ambiguity, further analysis of a larger number of comparable and securely dated artefacts is essential. An expanding dataset will improve the available comparative framework and help clarify whether the use of this alloy reflects historical practice or later modification.

The other type of solder—an alloy of Ag/Cu—was identified in vessel 2022,3034.22. According to its inscription, this piece is dated to the Liao dynasty (see Introduction), a period for which more extensive documentation exists concerning the soldering of silver objects. The presence of Ag–Cu solder in this context is consistent with practices observed in other Liao-period silver artefacts. Similar Ag–Cu alloy solder has been detected at the joining areas of a securely attributed Liao dynasty vessel[60], suggesting that this technique was not an isolated occurrence but possibly part of a broader and more standardised metallurgical tradition. However, it is worth noting that lead (Pb) and gold (Au) analyses of vessel 2022,3034.22 are respectively at 0.2 wt% and below detection limits (b.d.l.), alongside an unusually high overall silver content of 99.3 wt%, which contrasts with ancient silver artefacts that typically exhibit a broader range of alloying elements and trace impurities due to less refined metallurgical techniques[50]. This composition suggests patterns commonly associated with modern refining processes designed to produce high-purity silver, calling for careful consideration of the object's authenticity. Additionally, it cannot be completely excluded that the presence of the dark tarnish identified on the object (see Results section and SM), may be artificial, possibly applied to sumulate surface aging and create the illusion of antiquity.

One notable aspect of the study is the variation in coloration observed among the silverware. These colour differences, which can be quite significant, appear to stem from several factors, including prolonged exposure to fire, acidic corrosion from liquids, and post-depositional transformations due to burial/soil conditions. Such surface alterations often lead to the formation of patinas that obscure the original appearance and composition of the objects. The presence of these patinas underscores the necessity of thorough surface preparation, such as abrasion, to ensure accurate compositional data of core alloys. A ternary plot diagram of the Ag-Cu-Au system was employed to assess the coloration characteristics for the range of compositions observed in the presented assemblage (Fig. 15). The data points clustered within a specific area of the diagram, corresponding to the white region. This clustering supports the historical reference of silver as "baiyin," (白銀) or "white silver," in ancient China, as recorded in China's earliest-known dictionary *Erya* (爾雅) dated to the 3rd century BCE[5]. It could be hypothesised that, even in a context where copper may have been added or varying sources of raw material exploited, possibly reflecting a less centralised system of control, there was still sufficient technical knowledge to achieve the desired white-silver coloration.

Overall, this study demonstrates the high level of technical skill and artistic quality achieved by silversmiths during the Tang and Liao dynasties. Beyond their technical complexity, the artefacts also reflect strong cross-cultural influences that shaped early medieval Chinese metalwork. Forms like lobed bowls and stemmed goblets can be traced to Sasanian and Sogdian prototypes, while many decorative motifs and techniques originated in Western and Central Asia. These elements were reinterpreted by Chinese artisans and integrated into local traditions, illustrating the fluid cultural exchanges along the Silk Roads. In the Liao period, this synthesis continued, blending Tang Chinese and steppe traditions into a distinctive cosmopolitan style. Compositional analyses showed a consistently high silver content in earlier artefacts, with increasing copper levels in later examples. This trend likely indicates declining control over silver resources following the An Lushan Rebellion (755–763 CE), although some degree of quality control, particularly in terms of maintaining desired coloration, may still have been exercised. Such shifts suggest that geopolitical and economic changes had a direct impact on material choices and artistic production.

Trace elements, including lead and gold, point to the use of argentiferous lead ores and traditional refining methods like cupellation. Notably, higher gold levels in post-rebellion artefacts may reflect changes in ore sources, possibly driven by shifting economic centres and more flexible mining policies in southern China. These compositional changes offer further insight into how political and economic transformations affected silver production during and after the rebellion.

Two distinct solders—Ag/Sn/Cu and Ag/Cu—were identified. The former represents a previously undocumented alloy in Tang silverwork, while the latter, found on the Liao-period vessel, has been previously

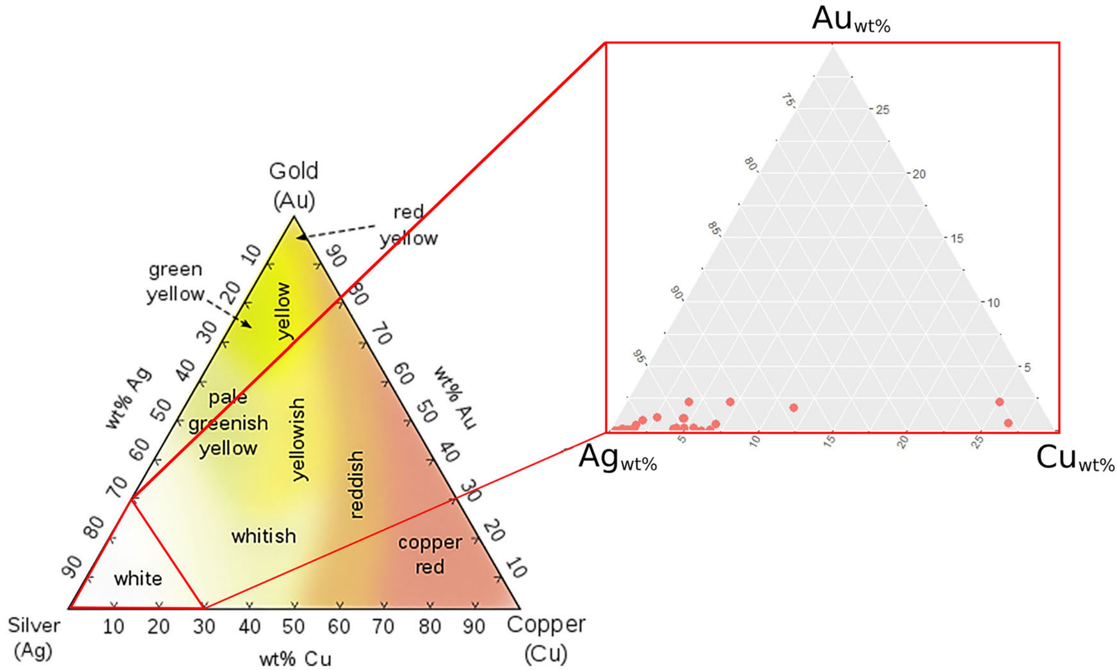


Fig. 15 | Ternary diagram plotting the elemental composition of the artefacts and the corresponding colour of their alloys. Analyses are shown in wt% normalised to 100%.

documented as a soldering material from that period. However, without further comparative analysis, the possibility of modern restoration for this latter object cannot be excluded.

As a final note, the current study focuses on museum-held objects rather than excavated artefacts, it also acknowledges the unique interpretative challenges posed by these collections. Museum pieces, often disconnected from their original archaeological contexts, require more nuanced methods of analysis. Unlike objects found in excavation sites, which provide contextual data, museum collections often lack direct associations that clarify their chronology, use and function. This absence calls for a more comprehensive strategy—one that goes beyond visual assessment and incorporates provenance documentation, typological comparison, and scientific analysis. Rather than dismissing these items, this challenge invites us to adopt and embrace a multifaceted approach to fully understand and appreciate them. By reconstructing the "life history" of each object, this study considers both historical and material aspects to support a more rigorous investigation into their origins, uses, and cultural significance.

Data availability

All data generated or analysed during this study are included in this published article and in the Supplementary Materials file.

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References

1. Yao, Z. & Gong, Y. Study on a silver box unearthed from the Tang Dynasty (AD 618–907) tomb at Xiaolizhuang Site, Henan Province, China. *Herit. Sci.* **7**, 1–11 (2019).
2. Rawson, J. *Chinese Ornament. The Lotus and the Dragon* (British Museum Publications, 1984).
3. Rawson, J. The lotus and the dragon: sources of Chinese ornament. *Orientations* **15**, 22–36 (1984).
4. National Gallery of Victoria. Council of Trustees. Tang Silver bowl. *Art J. Natl. Gallery Vic*. **49** (2010).
5. Deydier, C. & Wei, H. *Understanding Ancient Chinese Gold and Silver* (Privately Printed, 2021).
6. Hansen, V. Chapter 3. Midway between China and Iran. In *The Silk Road: a new history* (ed. Hansen, V.) 83–112 (Oxford University Press, New York, 2012).
7. Rawson, J. *The Ornament on Chinese Silver of the Tang Dynasty (AD 618–906)* (British Museum, 1982).
8. Qi, D. *Research on Tang Gold and Silver* (China Social Science Press, 1999).
9. Gyllensvard, B. *T'ang Gold and Silver* (Elanders Press, 1957).
10. Kelley, C. W. in *Chinese Gold & Silver in American Collections: Tang Dynasty, AD 618-907* (ed. Kelley, C. W.) 18–25 (Dayton Art Institute, 1984).
11. Tan, P., Yang, J. & Ren, X. Technical features of a ninth-century silver vessel of southern China uncovered from Famen Monastery, Shaanxi province. *Herit. Sci.* **9**, 55 (2021).
12. Wang, Chen, Q. & Tamburini, Y. D. Was Lacquer the Key Ingredient for Luxurious *Jinyin Pingtuo* Products in the Tang Dynasty of China (AD 618–907)?. *Archaeometry* **62**, 646–659 (2020).
13. Tan, P., Yang, J. & Li, X. Primary study on silver vessels from Wei family cemetery of the Tang dynasty in Xi'an Shaanxi province. *Res Qian Mausoleum Cult* 38-49 (in Chinese) (2014).
14. Ma, Q. & Scott, A. D. Metallographic study of gilded silver cup from Dachangling tomb of Tang dynasty in Sunanyugu autonomous county, Gansu province. In *Chinese Materials Research Society* 2104–2107 (in Chinese). (Metallurgical Industry Press, Beijing, 2003).
15. Armigliato, A., Yu-ping, L., Perucchetti, L., Ruiliang, L. & Lang, J. Exploring the Making of Tang Silverware from the British Museum Collection. *Orientations* **55**, 30–37 (2024).
16. Brunning, S., Yu-ping, L., O'Connell, E. R. & Williams, T. *Silk Roads* (British Museum Press, 2024).
17. Hobson, R. L. A T'ang Silver Hoard. *Br. Mus. Q.* **1**, 18–21 (1926).
18. Brady, C. Yamanaka and Company: Transforming the East Asian Art Market *Doctoral dissertation* (The University of Edinburgh, 2019).
19. Yamanaka & Co. *Illustrated Catalogue of Ancient Chinese Bronzes* (Yamanaka & Co. Ltd, 1925).

20. Shen, H. *Gilded Splendor: Treasures of China's Liao Empire (907-1125)* (Asia Society, 2006).
21. Marshak, B. I. A Sogdian silver bowl in the Freer Gallery of art. *Ars Orient*. **XXIX**, 101–110 (1999).
22. Michaelson, C. & Portal, J. *Chinese Art in Detail* Vol. 3 (British Museum Press, 2006).
23. Ashkenazi, D., Gitler, H., Stern, A. & Tal, O. Metallurgical investigation on fourth century BCE silver jewellery of two hoards from Samaria. *Sci. Rep.* **7**, 1–14 (2017).
24. Casaletto, M. P., Ingo, G. M., Riccucci, C. & Faraldi, F. Production of reference alloys for the conservation of archaeological silver-based artifacts. *Appl. Phys. A* **100**, 937–944 (2010).
25. Scott, D. A. & Schwab, R. *Metallography in Archaeology and Art* (Springer International Publishing, 2019).
26. Dongfang, Q. Gold and Silver Wares on the Belitung Shipwreck. In *Shipwrecked: Tang Treasures and Monsoon Winds* (eds. Krahl, R., Guy, J., Wilson, K. J. & Raby, J.) 221–227 (Arthur M. Sackler Gallery, National Heritage Board and Singapore Tourism Board, Washington DC and Singapore, 2010).
27. Untracht, O. *Jewellery Concepts and Technology* (Doubleday, 1982).
28. Brepohl, E. In *The Theory and Practice of Goldsmithing* Ch. 8 (ed. McCreight, T.) 293–330 (Brynmorgen Press, 2001).
29. Lowery, P. R., Savage, R. D. & Wilkins, R. L. Scriber, graver, scorper, tracer: notes on experiments in bronzeworking technique. In *Proceedings of the Prehistoric Society* Vol. **37**, 167–182 (Cambridge University Press, 1971).
30. Destrée, M. In *Gold Jewelry. Craft, Style and Meaning from Mycenae to Constantinopolis* (eds. Hackens, T. & Winkes, R.) Vol. 5 171–180 (Art et Archéologie Publications, 1983).
31. Singh, V. & Singh, S. Mercury-amalgam gilding in Nepal: a study of traditional material and technique. In *METAL 2016: Proceedings of the Interim Meeting of the ICOM-CC Metals Working Group 26–30 Sep*tember (eds. Raghu, M., Claudia, C. & Achal, P.) 47–52 (ICOM and IGNCA, 2019).
32. Raub, C. in *Metal Plating and Patination: Cultural, Technical and Historical Developments* (eds. La-Niece, S. & Craddock, P. T.) 284–290 (Butterworth-Heinemann, 1993).
33. Dandridge, P. A. in *Gilded Metals, History, Technology and Conservation, London* (ed. Drayman-Weisser, T.) 123–143 (Archetype Publication Ltd, 2000).
34. Margreiter, R. et al. Investigations on fire-gilding. *Archaeometry* **64**, 1465–1478 (2022).
35. Anheuser, K. The practice and characterization of historic fire gilding techniques. *JOM* **49**, 58–62 (1997).
36. Shao, Y., Jiang, F. & Yang, J. Process and technical characteristics of traditional gilding technology on silver: experimental replication and analysis of silver gilded products. *Archaeol. Anthropol. Sci.* **16**, 51 (2024).
37. Shao, Y. et al. Formation mechanism of copper-gilded coronet ornaments excavated from a Sui or early Tang tomb situated in Xi'an, Shaanxi. *Herit. Sci.* **11**, 162 (2023).
38. Shao, Y. et al. Technical characteristics and coating formation mechanism of gilded silver products unearthed from the Consort Tomb of Emperor Shengzong of the Liao dynasty. *Archaeol. Anthropol. Sci.* **15**, 28 (2023).
39. Fu, J. Lacquer wares by the jinyin pingtuo technique. *Forbid. City* **147**, 136–143 (2007).
40. Shen, Y. & Liu, Z. A brief study of the jinyin pingtuo technique of the Tang dynasty. *Zhongyuan Wenwu* **2**, 91–96 (2010).
41. Lu, R., Yoshida, T. & Miyakoshi, T. Oriental lacquer: A natural polymer. *Polym. Rev.* **53**, 153–191 (2013).
42. Hedges, R. E. M. On the occurence of bromine in the corroded silver. *Stud. Conserv* **21**, 44–46 (1976).
43. Selwyn, L. S. Historical silver: Storage, display, and tarnish removal. *J. Int. Inst. Conserv. -Can. Group* **15**, 12–22 (1990).
44. Lins, A. & McMahon, N. The inhibition of silver tarnishing. In *Current Problems in the Conservation of Metal Antiquities: Thirteenth International Symposium on the Conservation and Restoration of Cultural Property, 4-6 October 1989, Tokyo, Japan* 135–162 (Tokyo National Research Institute of Cultural Properties, 1993).
45. Selwyn, L. *Metals and Corrosion: A Handbook for the Conservation Professional* (Canadian Conservation Institute, 2004).
46. Scott, D. A. *Metallography and Microstructure of Ancient and Historic Metals* (Getty Trust, 1991).
47. Yi, B. The primary study of silver smelting in Tang dynasty. *Cult. Relics* **6**, 40–45 (1972).
48. Liu, S. Gold and silver production in imperial China: technological choices in their social-economic and environmental settings. *Doctoral dissertation* (University College London, 2015).
49. Gale, N. H. & Stos-Gale, Z. A. Cycladic lead and silver metallurgy. *Annu. Br. Sch. Athens* **76**, 169–224 (1981).
50. Craddock, P. T. *Early Metal Mining and Metal Production* (Edinburgh University Press, 1995).
51. Forbes, R. J. *Studies in Ancient Technology, Metallurgy in Antiquity* (E.J. Brill, 1971).
52. Liu, S. et al. Coal-fuelled crucible lead-silver smelting in 12th-13th century China: A technological innovation in the age of deforestation. *J. Archaeol. Sci.* **104**, 75–84 (2019).
53. Su, J. In *Xinxiu Bencao*. 127–146 (Anhui Science and Technology Press, 1981) (in Chinese).
54. Ban, G. Traditions of the Western Regions: Part 1. In Book of Han (ed. Ban, G.) 3871−3900 (in Chinese) (Zhonghua Book Company, Beijing, 1962).
55. Okamoto, H., Schlesinger, M. E. & Mueller, E. M. *Alloy Phase Diagrams* Vol. 3 (ASM International, 2016).
56. Kharakwal, J. S. & Gurjar, L. K. Zinc and brass in archaeological perspective. *Anc. Asia* **1**, 139–159 (2006).
57. Wang, S. In *Qingdaijiangzuozelihuibian* Vol. 1, 1181–1218 (Elephant Press, 2000) (in Chinese).
58. Zheng, F. Zuo Zhaojingjing. In *Jinginglingchiyizhu* (eds. Han, Y. & Xu, C.) Vol. 4, 276–296 (Shanghai Guji Press, 2015) (in Chinese).
59. Mongiatti, A., Suleman, F. & Meeks, N. Beauty and belief: the endangered tradition of Omani silver jewellery. *Br. Mus. Tech. Res. Bull.* **5**, 1–14 (2011).
60. Yang, X. *Fine Gold Artifacts and Their Techniques of China* (China Science Publishing & Media Ltd. (CSPM), 2008).
61. Cowell, M. In *Metallurgy in Numismatics* (eds. Oddy, W. A. & Cowell, M. R.) 448–460 (University of Oxford, 1998).

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Author contribution

L.P., R.L. and Y.P.L. conceived the research idea and designed the study. A.A. and L.P. collected and analysed the objects. A.A. interpreted the data and wrote the main manuscript. L.P. and J.L. assisted in data interpretation and in drafting the manuscript. R.L., Y.P.L. and J.L. contributed to data interpretation, revised the manuscript, and provided critical feedback. A.A. coordinated the revisions. All authors reviewed and approved the final version of the manuscript

Competing interests

The authors declare no competing interests.

Additional information

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