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ORIGINAL RESEARCH ARTICLE

Effort and Value: The Production Practices of Pre-Columbian Gold Objects of Costa Rica in Cultural and Technological Context

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Abstract

We investigated selected pre-Columbian Costa Rican metal objects by digital microscopy and portable XRF to reconstruct their manufacturing technique and technological choices. Lost-wax casting was confirmed as the production technique of the investigated (semi-)plastic objects. All decorations, of which some were produced with elaborate filigree, were worked into the wax model. Sheet metal objects were cast and/or cold-worked. Typically, no additions or changes were made after casting. Discs were often crudely pierced, sometimes even not respecting the decoration pattern. The different geometric shapes of the piercings match a set of investigated metal tools. Overall, a great deal of effort and skill was devoted to the manufacture of the wax model, while less attention was paid to casting and subsequent refinement steps. It is obvious that the various stages of production were treated separately. They were either the result of differences in specialised skills or of ritual or economic significance.

Keywords Goldsmithing · Lost-wax casting · Cold-working · Digital microscopy · pXRF

Introduction

Metal working technology in pre-Columbian Costa Rica is one aspect of our archaeological and archaeometallurgical research project [1]. It comprises field surveys of gold and copper mineralisations as potential sources for local metal extraction and studies of the gold and copper objects: their richness of form and stylistic evaluation, metal composition, provenance of the raw material as well as their production, use, distribution, and potential chronological classification. An overarching focus is on the significance and position of the metallurgical and metalworking tradition of Costa Rica as part of the larger Isthmo-Colombian region [2]. The diverse aspects are being interdisciplinary investigated by research in archaeology, metallogeny, mining archaeology, metallurgy, and archaeometry. Three campaigns have been carried out in Costa Rica from 2022 to 2024 to identify and survey gold and copper ore deposits and take samples for analytical characterisation. Furthermore, metal objects from museum collections were examined non-destructively to study manufacturing techniques and determine their main

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element composition. A crucial limitation in considering the objects as scientific indicators of historical practices is that most of them are without any archaeological context. More than 90 per cent of pre-Columbian metal artefacts from Costa Rica known today were dug up illegally and ended up in large, mostly private collections. Systematic pillaging of ancient cemeteries and large settlements began in the nineteenth century, when the construction of railway lines and then banana plantations led to the discovery of several archaeological sites with metal objects. The Línea Vieja and Diquís regions in the eastern and southern parts of Costa Rica, respectively, therefore were particularly affected by widespread looting. The exact dating, regional assignments, local and chronological development of metal production, integration into the larger regional context, or the metal supply are just some of the aspects that are limited by this lack of context. However, de-contextualised objects still offer valuable insights into the creative and technical practices of pre-Columbian societies. They hold symbolic significance as representations of a broader cultural heritage. This value persists, even if the object's original context is unknown. We considered them indispensable for our project, as otherwise too few contextualised objects could be examined in this depth.

Geological and Archaeological Setting

Gold and Copper Ore Deposits of Costa Rica

Costa Rica is located in southern Central America between Nicaragua in the north and Panama in the south. The country is rich in gold and copper ore formations (Fig. 1) [3–5]. These occur in the Cordillera Central as native copper mineralisation, which shares some similarities with Michigan-type ores [6], as hydrothermal copper veins in the Cordillera Central and the western Cordillera de Talamanca, in the form of porphyry copper deposits in the eastern Cordillera de Talamanca, and as volcanogenic massive sulphide (VMS) deposits of the Cyprus-type at the Nicoya Peninsula [5, 7]. Gold is present in the form of epithermal gold-silver veins in the Cordillera de Tilarán [8] and the Sarapiquí Volcanic Belt (Crucitas mineralisation) [9], and as (fossil) placer gold in the Osa and Burica peninsulas [10] in the south of Costa Rica. Today, some gold occurrences are still actively mined on an artisanal scale from partially heavily weathered outcrops or by following gold-rich layers in small underground mines, or by panning of gold-rich alluvial placers. Mining of base metals, including copper, has ceased completely.

Principal Metallurgical Techniques in Pre-Columbian Costa Rica

The metallurgical techniques identified in pre-Columbian objects from Costa Rica include ([11], pp. XX-XXIII):

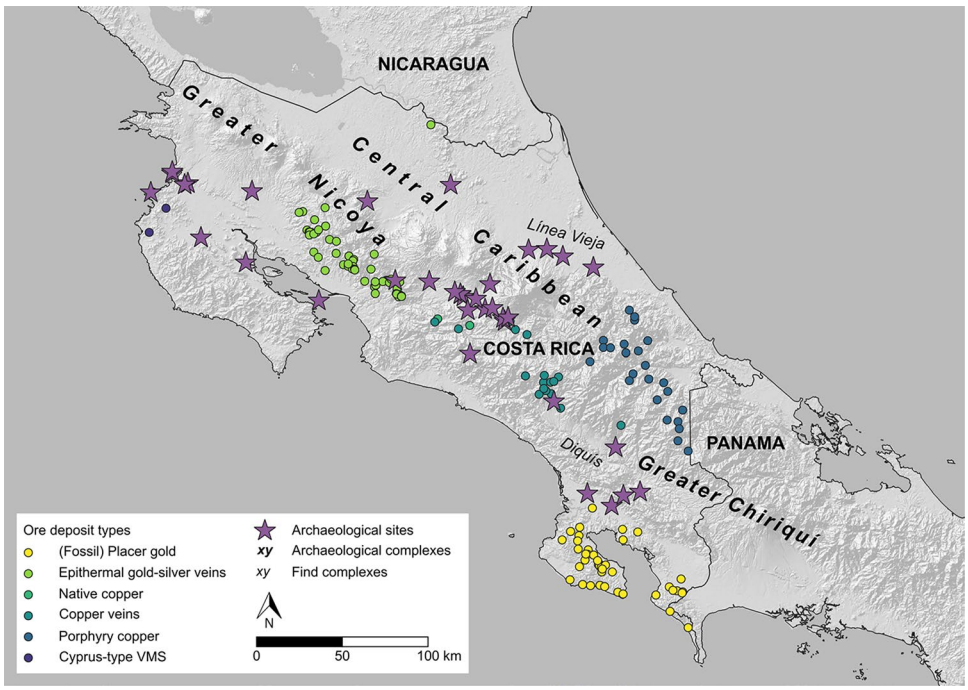


Fig. 1 Map of ore deposits, archaeological sites with metal finds, and archaeological regions in Costa Rica. The fill colour of the symbols representing ore deposits refers to their mineralisation style. Locations of ore deposits were compiled from USGS [5] and supplemented by own observations from fieldwork campaigns. Archaeological sites were derived from information on metal objects in the museum collections of the Museo Nacional de Costa Rica, Ethnologisches Museum Berlin and the Peabody Museum of Archaeology & Ethnology. Archaeological regions in Costa Rica are shown in [11]

Hammering of nuggets or cast metal ingots: The metal is beaten with stone hammers to stretch it. Reheating at high temperatures prevents cracking, resulting in a sheet that could be cut with metal or stone chisels to shape it. With metal, bone, wooden or stone tools (see, for example, finds from Sitio Conté/Panama shown in ([12], pp. 87 ff.)), objects could be beaten, imprinted, chiselled, engraved, and perforated or otherwise decorated.

Lost-wax casting: The desired object is first modelled from beeswax, which is then covered with clay to create a mould with an added pouring sprue. When the mould is fired, the wax is poured out, leaving space to pour in the molten metal. Afterwards, the mould is broken, and the object is extracted.

Depletion gilding: Metals such as copper were removed from the surface of metal objects by bathing them in acids extracted from Oxalis spp. plants, which selectively oxidise copper and other metals with a less noble character than gold. The oxidised metal is eliminated by polishing the surface, resulting in a homogeneous gold layer [13, 14].

The Material

The presented study material comprises gold, copper, gold-copper alloy (*guanín*, also called *tumbaga*) and gold-plated pre-Columbian objects as examined in the Ethnologisches Museum, part of the Staatliche Museen zu Berlin Preußischer Kulturbesitz, and in the Museo Nacional de Costa Rica (MNCR) in San José, Costa Rica (Supplementary Material 1). The investigations in both museums were preceded by a detailed approval procedure. The objects selected were intended to be as representative as possible of the great variety of iconography, styles, shapes, and metallurgical techniques. Although all objects originally derived from Costa Rican locations, the study objects may also comprise ancient imports. Included in the study are all contextualised objects hosted by the collection of the MNCR. Some finds from neighbouring countries (Nicaragua, Honduras, Panama, Colombia) were also examined in Berlin, but are not discussed here. It should be mentioned that only material from the museum archives was accessible to us. Objects in the exhibition, which usually represent the most beautiful and perfect of their collection, are statistically missing. Therefore, a statement about the overall quality of production must fall short of a true representation. There were generally no signs of impairment from previous conservation treatments except stabilising measures.

Ethnologisches Museum Berlin

The investigated metal objects from the Ethnologisches Museum Berlin are part of its Mesoamerica collection, which comprises c. 50,000 objects from the modern-day countries of Mexico, Guatemala, Honduras, Belize, El Salvador, Nicaragua, Costa Rica, and Panama. The collection includes 107 metal artefacts from Costa Rica, which mostly were acquired in the early twentieth century. The largest share was collected by the archaeologist Walter Lehmann [15] during a research journey from Panama to Mexico carried out between 1907 and 1909 on behalf of the Ethnologisches Museum Berlin (then Königliches Museum für Völkerkunde Berlin). While for many objects a finding or purchasing location is recorded, all of them are without any known archaeological context. Information on the objects, including possibly performed conservational treatment and tests of metal fineness, was recorded in handwritten notes, which were available to us.

Museo Nacional de Costa Rica

The archaeological collection of the National Museum of Costa Rica began with the Troyo legacy items, which entered the museum seven months after its foundation in May 1887 [16, 17]. In its early stages, the museum focused, among other things, on collecting and exhibiting the country's ancient objects. Activities related to the archaeological past were understood as the search for unique and valuable objects, carried out by empirical researchers, *huaqueros* (looters), and foreign naturalists [18, 19]. This form of collecting continued until the mid-1970s, when archaeologists became part of the museum staff and began to develop research projects aimed at understanding the chronology and forms of sociopolitical organisation of the past. The 1982 Law 6703, known as the National Archaeological Heritage Law, reinforced the national character of the goods, prohibiting their trade and looting practices. Additionally, it established that the National Museum of Costa Rica is the entity responsible for the custody and protection of both archaeological sites and objects. Archaeological research must be conducted by professional archaeologists, whether public or private, who must obtain permission from the National Archaeological Commission. Once the research is completed, the archaeological material must be delivered to the museum with the corresponding inventories [20], entering the collections with context. Objects without context have arrived at the museum through various means, such as purchases (when their sale was legal) and donations. After the enactment of Law 6703, these objects have arrived at the institution through voluntary deliveries, seizures by the Public Ministry, and repatriations.

The museum's archaeological collections include among their notable objects metal artefacts made of gold, copper, or *guanín*. Contextualised objects are organised according to their geographical location and the archaeological site from which they originate, along with other special materials such as jade and obsidian. Most of the contextualised metal artefacts derive from the central and north-eastern parts of the country. The objects in the collection without context are classified by types: circular pendants (discs), avian-shaped, zoomorphic, and anthropomorphic pendants. Decorative objects such as necklaces, beads, ear ornaments, nose rings, and bells are also included, as well as tools like needles, pins, and chisels. According to the information from the collection databases, the quantity and diversity of objects in the collection without context are considerably greater than those obtained through scientific research. This is largely because metal objects were highly sought after by looters and collectors. According to delivery data, most of them come from the central and southern parts of the country, although more than half of these items lack this type of information due to being subject to seizures and repatriations.

Methods of Investigation

The features of Costa Rican gold, *guanín*, and copper objects were presented by, e.g. [13, 21, 22]. An extensive study of West Mexican metalwork by Hosler [23] included the comparison of bells concerning their material and chronology of appearance with the lower Central American, Ecuadorian, and Colombian metallurgy. Hosler made several technological considerations based on metallographic analysis, which enabled an objective distinction between casting and cold- and hot-forming by microstructural analysis. Although this method is considered essential for this type of study to, for example, distinguish whether sheet objects were made by casting or by (cold) working, sampling for metallographic preparation could not be performed here. We therefore decided on digital microscopy and portable X-ray fluorescence spectrometry (pXRF) as non-destructive analyses.

Digital Microscopy

At the Ethnologisches Museum in Berlin, the objects were photographed using a digital microscope (Keyence VHX-2000D). The digital microscope enables high-resolution visualisation in real time by taking individual images layer by layer and merging them to achieve a significantly improved field depth, thus allowing even microscopically small details of production, processing, additions, subsequent changes, etc., of the objects to be precisely identified and documented. The digital recording of the device allows for long-term processing of the images. Image processing software offers additional tools for image analysis, such as measurements, markings, and labelling.

A Proscope HR portable digital microscope was used for the investigations in San José, Costa Rica. The portable microscope is more difficult to operate than a Keyence microscope, as the focal plane relies on subjective assessment. This is even more difficult if the examination area is located on a curved or recessed surface. Image processing is limited, e.g. the annotation of the scale. Despite these limitations, we decided on this device for San José due to its low weight, small size, and stability of components during transportation by plane.

Elemental Analysis

The selected objects were analysed with a portable ED-XRF (Niton Xl3t GOLDD, Thermo Fisher Scientific) hosted at the Materialkundliches Labor of the Deutsches Bergbau-Museum Bochum. Portable XRF analysis determines characteristic secondary X-rays that are emitted from a material excited by high-energy radiation, enabling the measurement of the elemental composition of materials quickly and non-destructively. Thanks to the compactness of the device and its mobility, pXRF can be used directly in the museum, which constituted a particular advantage for this project. The objects were placed on a lead plate covered with transparent film to protect the operator from X-ray exposition and the objects from lead contamination. The operator additionally wore a lead apron for personal protection.

Since the penetration depths of the X-ray beam generally are in the µm range for gold, copper, and their alloys [24, 25] and the analyses were carried out at the surface of the objects, the data reflect a mixture of their interior and surface composition. In case the surface is chemically altered due to post-depositional corrosion or depletion gilding, the determined composition consequently is not representative of the heart metal. While pXRF therefore is an analytically restrictive method and cannot replace detailed laboratory analyses of samples, it should be considered as a compromise between limited institutional accessibility of objects and information gain.

A pre-set measurement programme, which is adjusted to the elemental quantification of archaeological gold alloys, was used for the analysis. All specimens were measured for a maximum duration of 120 s and with a spot size of 8 mm. If the object size was sufficiently large, measurements were performed at a minimum of two different spots to test for depletion gilding or other effects influencing the composition as determined by pXRF. Objects with a visibly heterogeneous alloy colour were analysed for up to four times. Very small or narrow artefacts could only be measured once.

Results

Observations on the Fabrication of the Objects

It can be already macroscopically identified that the majority of the objects are castings, predominantly made of *guanín*, to a smaller degree of gold and, rarely, of copper (cf. the section on pXRF results). The pendants with their highly variable stylistic features and design attributes consist mainly of semi-plastic forms, combining thicker walled bulbed but hollow body parts (e.g. torsos, heads) with very complex filigree attributes and attached flattened parts (e.g. extremities, head decoration). They also have suspension loops. Pendants were made in various designs (anthropomorphic, zoomorphic, and avian-shaped). The casting quality is highly variable. Plastic figurines mostly possess a visible clay core, in which the final details of the objects are already integrated. The observations made particularly on the plastic figurines match the pre-Columbian Mesoamerican and Central American lost-wax practices as described in the sixteenth-century Mexican Florentine Codex [23]. Bells are products of casting and have different levels of decoration, ranging from rather plain to highly decorated, e.g. formed like a human face or in animal style. In some cases, earthy material was visible in the interior of the bells. Whether the material is a remnant of their production by casting or is soil introduced during burial could not be analysed within the scope of this study. The clappers are little spheres, which were made of metal, stone or clay-like material. Metal clappers were either cast simultaneously with the bells, which can be concluded from narrow, elongated, and parallel slits or were inserted afterwards by compressing the slit. Concerning the pitch of the bells, Hosler [23] discusses correlations of bell size, shape resonator cavity, slit width, and metal or alloy used. In the present study, the sound of the investigated bells has been recorded with good results for gold or *guanín* specimens. However, corrosion (especially of copper bells) and remaining earthy material are major obstacles to determining the individual pitches. Sheet metal objects, i.e. discs, were made of seemingly unalloyed gold with a variable extent of decoration. Their thickness ranges continuously from 0.06 to 1.5 mm for microscopically examined objects. The vast majority of sheet objects are well-polished and highly lustrous. The thinnest sheets (with a thickness of < 1 mm) are preserved as crumpled foils.

Particularly for the discs, microstructural analysis by metallography would have been helpful to clearly distinguish between casting and cold-working techniques and help in deciding whether they were made from one gold nugget or by hammering several alluvial gold grains together or were produced from a previously cast metal ingot. Digital microscopy nevertheless revealed some indicative evidence of pre-Columbian manufacturing practices in Costa Rica. The following phenomena can be observed:

Characteristics of the Preparatory Step/Wax Forming

(1) In rare cases, the pouring sprue, degasification channels, and bypasses are preserved. Sometimes, pouring sprues and bypasses were even camouflaged as decorative elements, e.g. as armrests (Fig. 2a, b). (2) Suspension loops, usually placed at the back of the pendants, were part of the wax model right from the start (Fig. 2c). No evidence can be found that they were attached separately. (3) Filigree decorative details, including even the tiniest threads, (twisted) wires, or braided ribbons, were formed in wax in great detail (Fig. 2d). They were fixed to the basic wax parts carefully. A slight smashing of the details at the very ends of some ribbons suggests that they were formed and then pressed firmly onto the surface. (4) On flattened areas, such as paddle-like lower extremities, work traces of parallel or cross-parallel scratch marks on surfaces of the front and back of the objects are visible (Fig. 2e, f). They are preserved in the finished objects. Since they were observed in several objects as being undistorted by casting effects (e.g. adhering glassy patches), they must already have been made by tools (rolls) to produce flat wax parts. (5) The front surface of the objects is mostly polished, except for bulbous and thus difficult-to-reach parts (e.g. globules, bellies, eyes, throats or heads) (Fig. 2g). Unpolished areas between smoothed flats and the base of bulged slopes are several millimetres wide. (6) Details, which were not firmly adhered were instantly repaired in the wax model (Fig. 2h). (7) Individual objects are of gold poured over the clay form by a special (lost-wax) casting procedure (Fig. 2i). To draw a parallel to Hosler's description for the production of bells, a prepared clay mixture, here possibly fired clay, into which the final shape and decorative details were carved, must first have been moulded and then coated with a thin layer of gold by casting ([23], p. 53).

The Casting Step

(1) The often ill-fired broken parts of clay moulds from lost-wax casting rarely survive in the archaeological record. Thus, the find of almost half a clay mould for casting a frog pendant at the Ruiz site in the Greater Nicoya archaeological area (see Fig. 1) was especially fortunate (Fig. 1 in [26]). (2) A miscasting of a frog pendant from the Reventazón region (Central Caribbean archaeological area) derives from the collection of the MNCR (Fig. 3b in [27]). It gives only a rudimentary impression of the originally intended shape. Adhering to the head of the figure, the original pouring sprue is still preserved as it is filled with metal. (3) Occasionally, suspension loops are incomplete, rendering originally intended wearing use

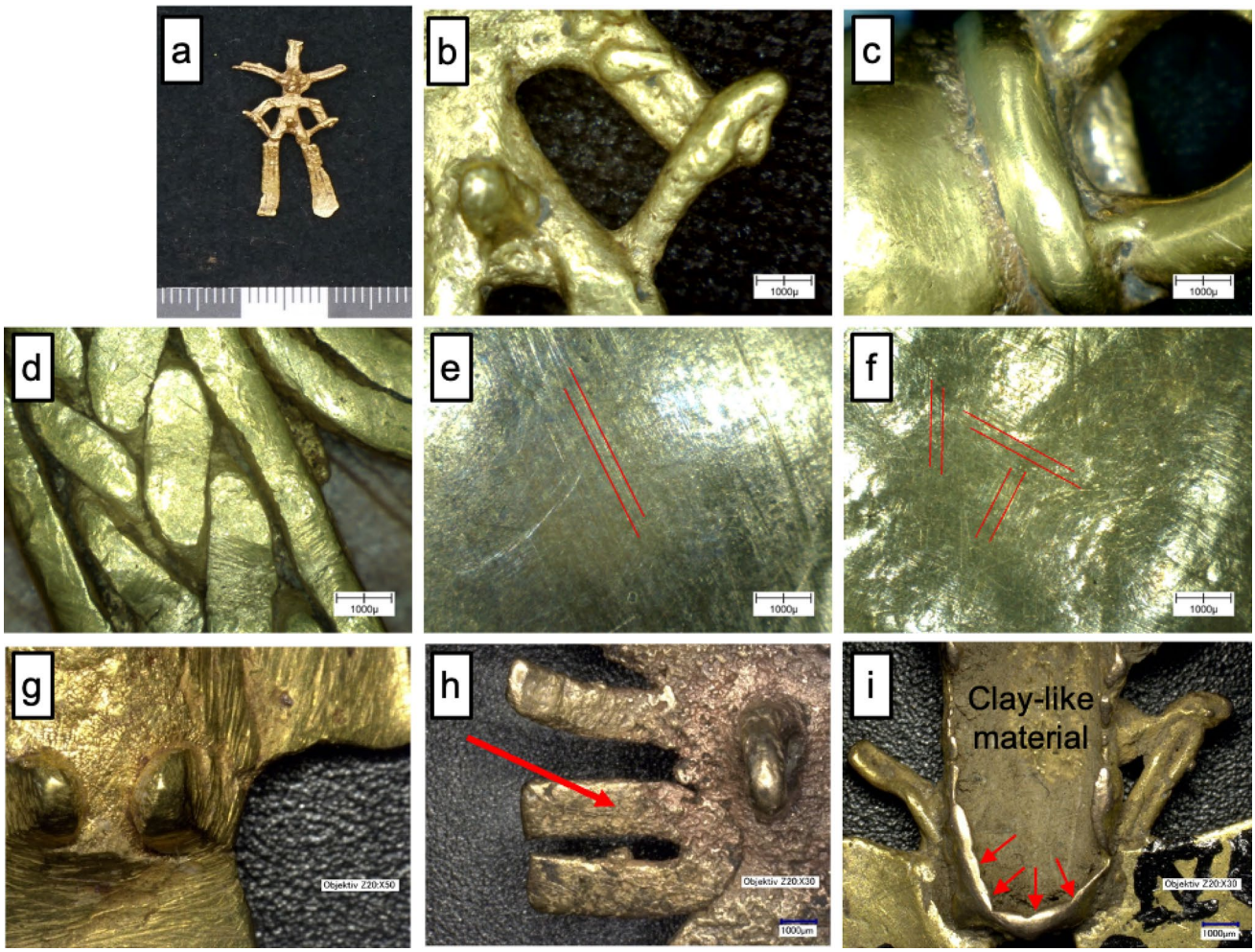


Fig. 2 Wax-forming step **a** MNCR 22943/anthropomorphic: Degasification channels and pouring sprue camouflaged as decorative elements, e.g. as armrests. Three head decoration details are visibly different. The left was incompletely cast, and the centre was cut and presumably the pouring sprue. The legs were hammered flat either already in the wax model or more presumably, after the casting since some details (stripes) initially worked in the wax form are compressed. **b** MNCR 22943. Close-up of the left half of the torso. Degasification channels connect the arm and the leg. **c** MNCR H-26 CN/zoomorphic: The suspension ring was an integral part of the wax model. **d** MNCR 22895 K41/monkey: Detail of a braided ribbon. The braiding is created by individual wax pieces positioned crosswise. **e** and **f** MNCR 27037 + MNCR 27577/discs: Parallel and cross-parallel tool marks (scratches) by working the wax using a rolling tool. **g** EMB IV Ca 34187/zoomorphic: Parallel rolling marks on flat parts. The raised breast part is not smoothed and as cast. The cast microstructure in the form of dendrites has been preserved. **h** EMB IV Ca 34234/anthropomorphic: Back view. A curved attachment was fixed to the wax form, presumably an in situ repair of the wax detail. In the front view, the addition is invisible. **i** i EMB IV Ca 34273/frog: Back view. The wax was modelled as a thin layer over a clay figurine. Additional attachments were attached in wax. [MNCR = Museo Nacional de Costa Rica; EMB = Ethnologisches Museum Berlin]

impossible. (4) Finer decorative metal wires have occasionally slipped out of their intended position, indicating that they were integrated into the wax form, but that the wax wire was not sufficiently fixed onto the wax model and slipped off during the subsequent processing step. Occasionally, complete figures have been squashed, presumably during the mould-forming or the casting process (Fig. 3a). (5) Extremities or other protruding parts are often miscast. They are either missing completely on one side of the figure and are not of identical length compared with the mirror-symmetrical counterpart or taper at the very end of extremities (Fig. 3b, c). (6) Vastly applicable for the pendants, metal burrs adhere mostly circumferentially (Fig. 3d). These burrs are remnants of metal that have run in the liquid state into shrinkage fissures or gaps within the moulds. Surprisingly, the protruding metal was not removed after casting, which could be expected in metal workshops to perfect the objects and save metal for further use. (7) Dendritic metal structures were often observed, e.g. on the surface of the bulged parts of the pendants (Fig. 3e). Since they are comparably large, they are indicative of a slow cooling process supporting the use of rather

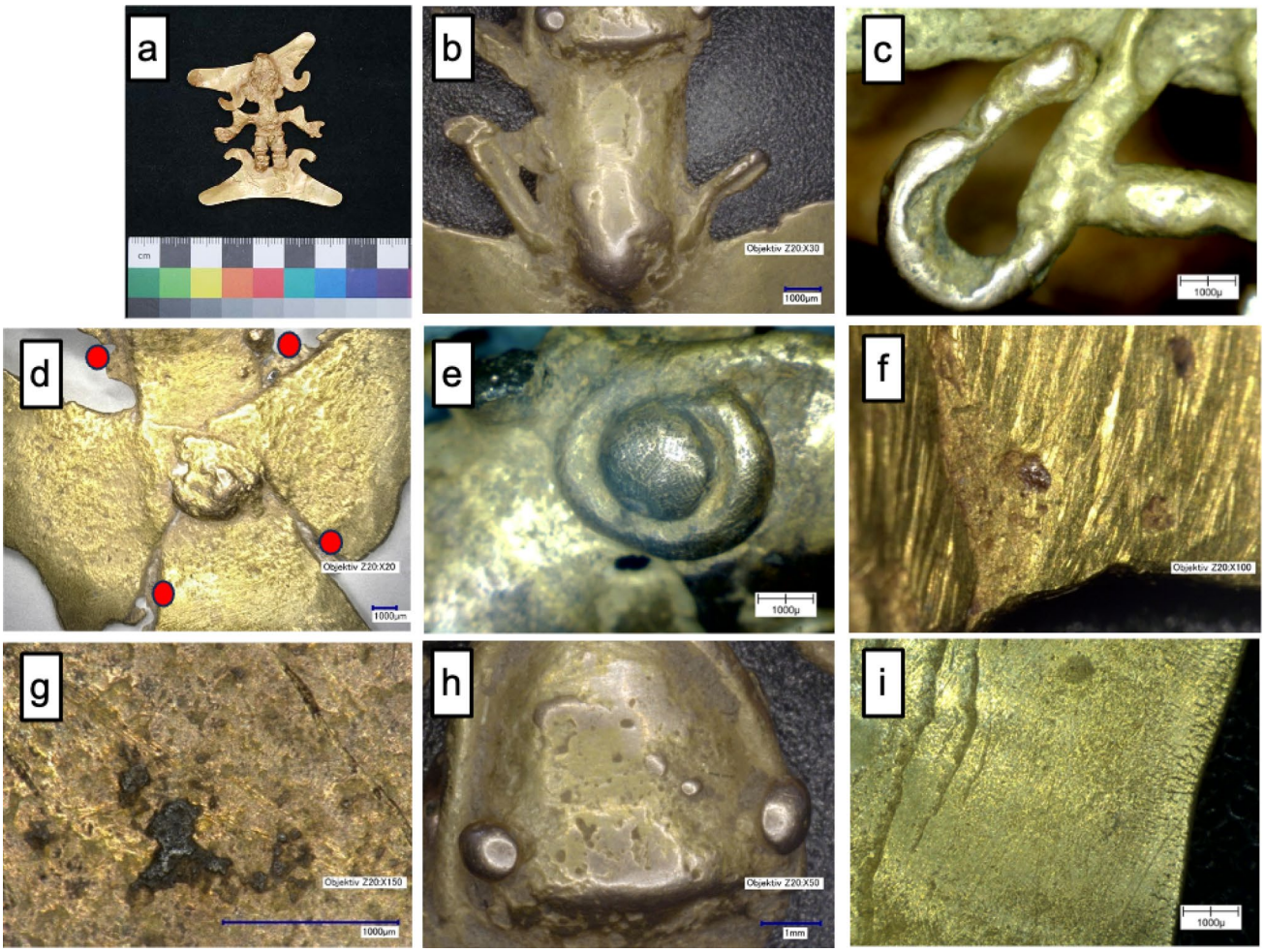


Fig. 3 Casting step **a** MNCR 31966/anthropomorphic: Deformed figure. **b** EMB IV Ca 34273/zoomorphic: The failed casting of a frog. View on the head with two knob-shaped eyes, torso, legs, and lower extremity paddles. The right part of the figure was unsuccessfully cast. The right leg and upper attachment are only half-long or missing. Burrs or casting connections (left side) were not removed. **c** MNCR 21716/fish: Failed casting of a detail. **d** EMB IV Ca 34342/zoomorphic: Circumferential burrs left as cast. **e** MNCR A-36 CS_26/avimorphic: Detail of a left eye with as-cast dendritic structure. **f** EMB IV Ca 34187/eagle: Grainy red-brown and semi-transparent inclusions. The inclusions are harder than the metal, causing protruding grains and negative imprints in the surface metal. **g** EMB IV Ca 34234: Dark grey patchy material, concentrated in indentations of the surface metal. Surrounding scratches are not disturbed, presuming that the scratches rather result from the wax forming (rolling?) than from the finishing (polishing) step. **h** EMB IV Ca 34273/frog: Metal patches adhering to the surface. Presumably, small rounded wax residues that have stuck to the surfaces when modelling wax details. **i** MNCR 25628/jewellery: Brittleness of the metal. The fine cracks result from omitting the annealing step in the cold hammering procedure. [MNCR = Museo Nacional de Costa Rica; EMB = Ethnologisches Museum Berlin]

thick-walled moulds and/or the absence of quenching. (8) Stabilising of bulged parts was achieved by either preparing nuclei of hardened clay-like material or by stuffing them with earthy matter. Hosler ([23], p. 53) describes the use of a kneaded and dried mixture of clay with ground charcoal. (9) Grainy inclusions are visible on the surface of some objects (Fig. 3f). They possess a brownish, black, grey, or silvery colour and have a hypidiomorphic to idiomorphic shape. Particularly the black and silvery grains appear rather hard in comparison with the metal since they protrude from the surfaces. (10) Patches of glassy material adhere to the surface of some of the objects (Fig. 3g). It can be supposed that they are remains of the moulding material, which had partly melted during the casting process. (11) Casting pores and shrink holes may show up in all parts of a cast (Fig. 3h). Also, some bulged bellies are incompletely filled with metal and hence show prominently located holes. (12) Individual discs reveal brittleness of the metal composition, especially close to their rims (Fig. 3i). (13) Attachments of sprues and degasification channels were often not removed and were either left as cast or formed as a deliberate detail (see again Fig. 2a, b). Nevertheless, their position in the figure reveals their true function.

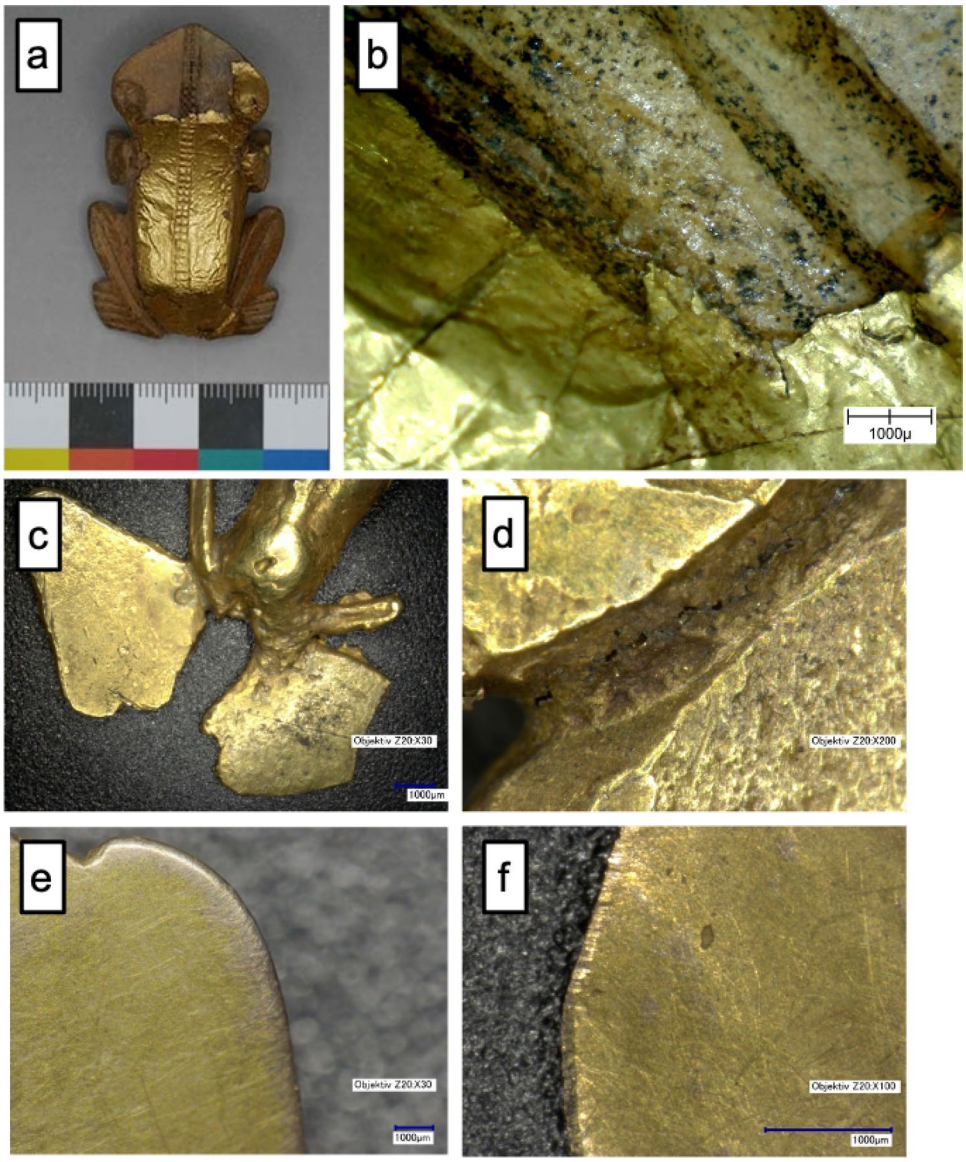


Fig. 4 Gold plating, repairs and later inventions. **a** MNCR 25525/frog: Elaborated clay with carved details wrapped on the front side with gold foil. **b** MNCR 21716: Close-up of a gold foil wrapped around a clay figurine. **c** EMB IV Ca 34142/frog: Repair/replacement of the left paddle by a substitute with the wrong shape (a triangular paddle is typically rather used as bird's tail). Incomplete casting of the right leg and the right paddle.. **d** Joint of the repair in close-up (back view). **e** EMB IV Ca 34273/frog: Gold plating on the surface of one of the paddles, which has worn off at the edges. Underneath, the reddish-yellow colour of the core metal *(guanín)* is visible. **f** EMB IV A 34273: Paddle-like extremity with cutting tool marks. [MNCR = Museo Nacional de Costa Rica; EMB = Ethnologisches Museum Berlin]

Gold Plating, Repairs, and Later Inventions

Almost all objects have shining and highly polished surfaces on the front side, while the back side was often left as cast and then is comparably rough. (1) Some objects are made of clay wrapped with gold foil (Fig. 4a, b). (2) Only very occasionally individual extremities were attached deliberately, presumably for repair, as the example of a frog-shaped pendant in the Berlin collection with two differently shaped paddle-like extremities (Fig. 4c, d) shows. The object is from the site of Bugaba/Panama in the Greater Chiriquí archaeological province, which extends from Panama to southern Costa Rica. (3) Many intensively corroded *guanín* pendants have relics of gold surface layers, often preserved in depressions only. Gold surface layers are also observable on rims, where the gold layer was worn down (Fig. 4e). (4) Individual extremities have been removed, with the separation line sometimes appearing as having been broken off, cut with a blunt blade, or, in other examples, with a very sharp cut instead (Fig. 4f). This might have been done in modern times, e.g. to sell parts of the objects for their material value or to test the objects for their metal fineness. (5) Small patches of metal can be very rarely observed on surfaces. They have been presumably pressed into the surface of the objects after casting to, e.g. close a casting defect.

Cold-Working

(1) Some discoid objects were created by hammering smaller grains of gold together. The individual grains are still recognisable from the surface structure (Fig. 5a–c). (2) Beads and tubular objects are produced from hammered gold

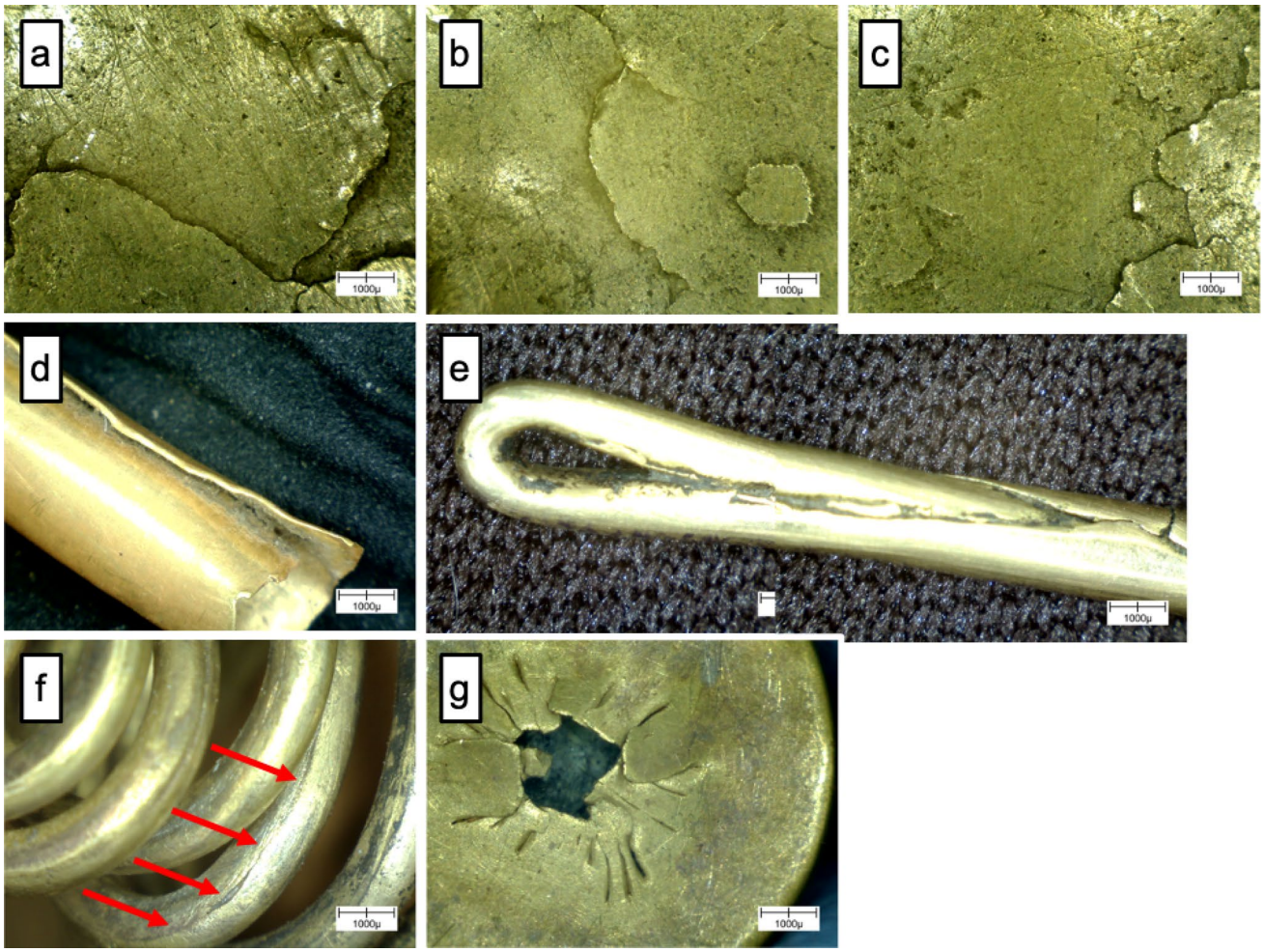


Fig. 5 Cold-working. **a**–**c** MNCR 20462: Individual gold grains are jointly hammered to produce sheet metal. **d** MNCR C-343 TR/bead:Cylindrical gold sheath made by a hammered and rolled metal sheet. **e** MNCR 23169/needle: The needle was formed from a sheet of hammered gold, then rolled to form a tube and bent at the end to form the eye. The loop was finished by inserting the very end into the needle's shaft. **f** MNCR 25628/jewellery: A coil is made of hammered and rolled sheet metal. **g** MNCR 25518.1 and 25518.2/two pieces of cylindrical sheet metal. One of the tubes is open at both ends, while the other one is formed as a cap. Presumably, the metal has been pressed over a mould since it is made from one piece without a seam. Final hammering to close the cap. [MNCR = Museo Nacional de Costa Rica; EMB = Ethnologisches Museum Berlin]

sheets, which have visible seams from rolling and cylindrical shaping (Fig. 5d–f). (3) One of two small cylinders without a seam was left open at both ends, while the other was moulded as a lid. Presumably, the metal was pressed over a mould to form an open cylinder. The final hammering resulted in a nearly closed cap (Fig. 5g).

Discs, Piercings, and Reuse

Discs are products of casting and cold-working (e.g. by hammering, repoussé, embossing, chasing, or punching), as well as possibly annealing. (1) Experimenting with a set of metal tools from the collection of the National Museum in San José revealed that such tools could have been used for piercings of discs since they produce comparable geometric shapes (Fig. 6a, b). The piercings of the discs are round, triangular, or pentagonal. Contrary to the carefully executed piercings, others appear to be of rather hasty and crude workmanship. The protruding metal resulting from the piercing procedure often left crowns on the backside of the pierces. These have been partly hammered flat, but not as consistently as could be expected (Fig. 6c–f). The piercings are almost always paired. They are typically closer to the edge than to the centre and often, even if roughly executed, in consideration of the decoration or even integrated into decorative elements (Fig. 6g–i).

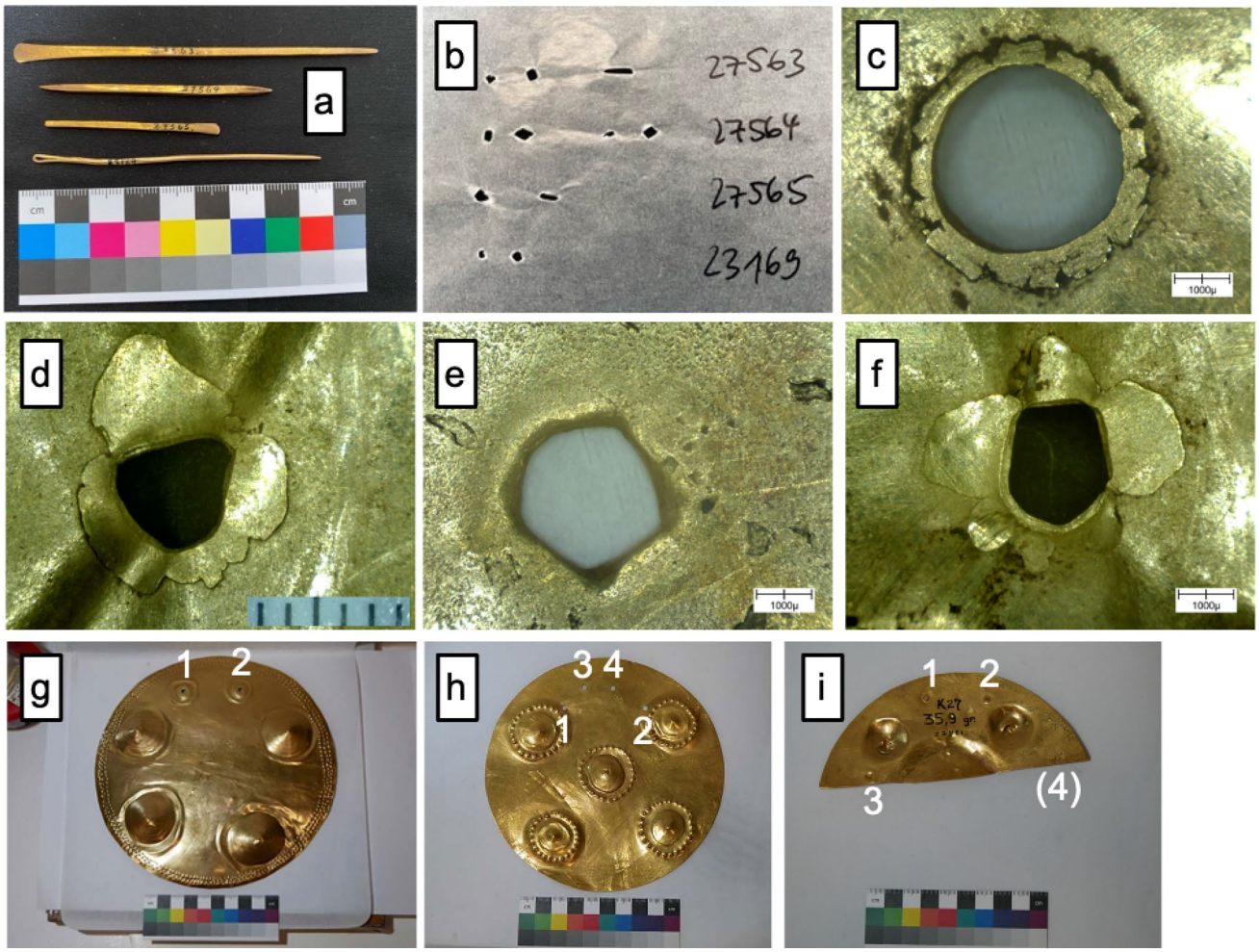


Fig. 6 Discs, piercings, and reuse. **a** MNCR 27563-65; 23169: Set of three tools and a needle. **b** Piercing tests: Test holes produced from the individual tools. The needles might have been used alternatively from both ends or were mounted one-sided, e.g. on a wooden stick. 27563: squares and elongated holes; 27564: diamonds, 27565: triangles or elongated holes 23169: rounded holes. **c** MNCR 27575/discoid: Back view of a perfectly rounded/circular piercing. The crown was subsequently hammered flat. **d** MNCR H-33 LR 24/disc: Triangular piercing. Reverse, the crown is subsequently flattened. **e** MNCR 20473/disc: Pentagonal piercing, front view. **f** MNCR H-33 LR 24/discoid: Pierce of pentagonal shape, back view. The crown is subsequently flattened. **g** MNCR 27037/discoid: Pair of pierces, perfectly positioned within decorative elements. **h** MNCR 27575/discoid: Two separate pairs of two spherical piercings each. Two (#1, #2) are positioned symmetrically and very close to the base of bulged decoration elements. The second pair is closer together (#3, #4) and asymmetrical to the decorative elements. **i** MNCR 22881/cut disc: Two pairs of pierces are visible. One pair of rounded pieces is placed in the curve. They were applied asymmetrically to the two bulbous protrusions. A second pair is located right and left along the cut flat side. Only the left one of the two is defined, and the other is lost in a crack. Presumably, the cut piece of the disc was re-shaped and later reused, e.g. as a pendant. [MNCR = Museo Nacional de Costa Rica; EMB = Ethnologisches Museum Berlin]

Main Element Composition

The results of the pXRF analyses (Supplementary Material; Fig. 7a) match the compositional variation of pre-Columbian metal objects from Costa Rica determined in previous studies [28–34]. For a more robust assessment of metallurgical practices, the complete data set including reference data is therefore used in the following description.

The main element composition of most investigated objects varies between argentiferous gold and argentiferous gold-copper alloy, which can possess Cu contents of up to 57.4 wt% (Fig. 7a). The Ag abundances overall show a narrow variation among the investigated artefacts with a median value of 4.50 wt% and a corresponding median percentual Ag/(Ag + Au) ratio of 5.32. Since silver metallurgy is absent from the Isthmo-Colombian region (e.g. [35]), the Ag content of metal artefacts directly relates to their ore source. The low to non-detectable Ag abundances in copper objects (with one exception from [30] ≤ 0.10 wt%) indicate that silver was mainly introduced by the gold raw material and that the proportions of Ag in metal objects thus can be compared with available ore data. Overall, the median Ag content of

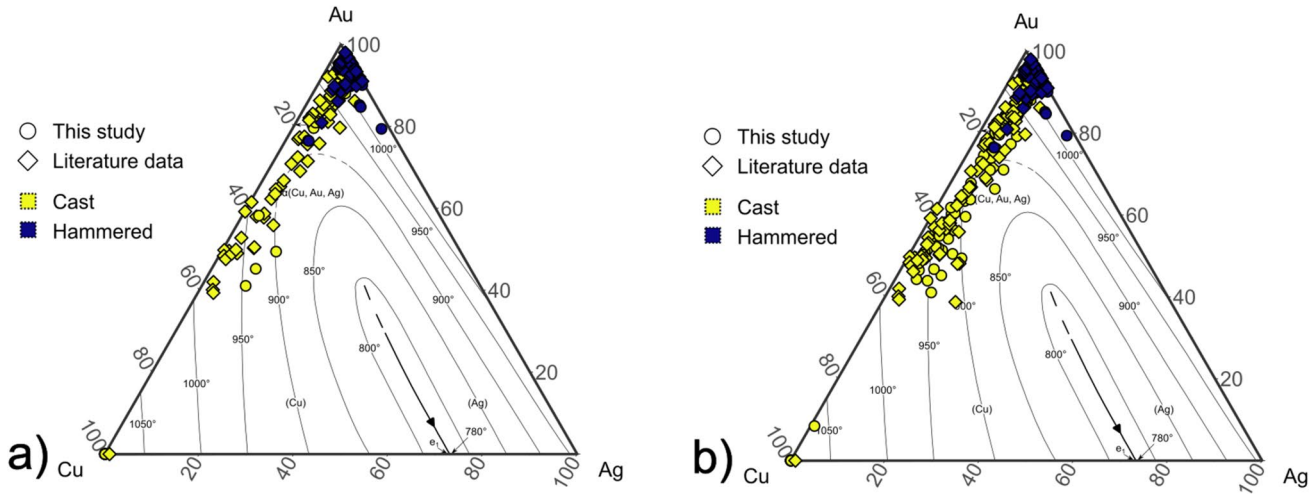


Fig. 7 Ternary diagrams of Cu, Ag, and Au contents of pre-Columbian Costa Rican metal objects analysed for this study (circles) and taken from literature references (diamonds) [28–34]. The fill colour of the symbols refers to the predominant manufacturing technique of the objects, i.e. casting for (semi-)plastic versus hammering for sheet objects. Isolines represent liquidus temperatures in the Cu-Ag-Au ternary system [41]. **a** Only data from measurements carried out at the interior of the objects and from surface analyses of *guanín* objects which are not gilded or corroded. The copper objects analysed in this study typically are corroded but were found to consist of unalloyed Cu with Ag and Au contents < 0.1 wt% and thus were included in the ternary diagram regardless of their conservation state. **b** Full analytical dataset including gilded and corroded *guanín* objects

pre-Columbian Costa Rican objects is within the compositional range of (fossil) placer gold from the Osa peninsula determined by electron microprobe analyses applied to polished mounted sections of gold grains ([10] 3.96 wt% Ag in unleached core areas), and by fire assay of gold grains ([36] 5.0 ± 0.1 wt%). Objects with higher Ag proportions partially are stylistically similar to metal artwork from Colombia (e.g. Quimbaya-style object MNCR 26559, Ag/(Ag + Au) = 18.0 as mean of two analyses) and therefore might be identified as imports. Others have object shapes that occur in a wide geographical framework, such as double-headed bird pendants of the so-called Initial Style of pre-Columbian metalwork (e.g. BCCR-O-1383, Ag/(Ag + Au) = 28.7) [37, 38], and thus might have not been manufactured from Costa Rican raw material sources. A few objects ($n = 11$) were made of unalloyed copper. No relationship with metal composition and shape (e.g. avian-shaped, anthropomorphic, zoomorphic) was discernible for the gold (alloy) objects. This observation does not change when only taking literature data of measurements performed at the interior of the objects into account [31, 32, 34]. The copper objects investigated here are either bells or anthropomorphic figures. However, this appears not to be representative, as, for example, the collections of the MNCR and the Museo del Oro Precolombino (Museos del Banco Central de Costa Rica) [39] also contain avian-shaped and zoomorphic objects as well as beads and earrings made of copper.

As expected, gilding (and post-depositional corrosion) has a pronounced effect on the surface analyses (Fig. 7b). This is evident by the comparison of our analyses performed at the surface and measurements of the exposed interior of the same object done by Schlosser [34]. For example, pXRF surface analyses of a gilded and corroded *guanín* object (IV Ca 32016) determined mean values of 49.4 wt% Au, 46.2 wt% Cu, and 3.31 wt% Ag on the basis of four individual measurements at different spots. Analysis with synchrotron radiation-based XRF performed at a previously abraded gold testing spot of the same object revealed a composition of 40.0 wt% Au, 57.0 wt% Cu, and 2.77 wt% Ag [34], evidencing the comparatively Cu-richer and Au-poorer composition of the unaltered heart metal. Objects altered by gilding and corrosion as seen by the naked eye or determined by digital microscopy were therefore excluded from the interpretation.

Cast (semi-)plastic objects are distinguished from hammered sheet metal artwork by their overall higher Cu contents and weights (Fig. 8a). Cast objects show a wide and continuous range of Cu abundances up to 57.4 wt% Cu (IV Ca 34198), with most objects possessing significantly gold-richer alloy compositions (median 11.1 wt% Cu). The minimum and maximum weights of the investigated cast objects were 1.2 g (IV Ca 34205) and 365 g (IV Ca 32027), respectively, with a median value of 15.4 g. While sheet metal objects in comparison mostly have lower Cu contents (median 1.29 wt% Cu), this is not the general rule and maximum Cu values of 18.7 wt% (MNCR 20473) have been determined. The variation of Cu contents in sheet objects is virtually continuous until up to 4 wt%. The weights of sheet objects range between 0.1 g (BCCR-O-0242; E-749 ES Ent.31 290) for thin foils and 193.5 g (BCCR-O-0626) for discs, with a median value of 9.25 g. The sheet metal objects

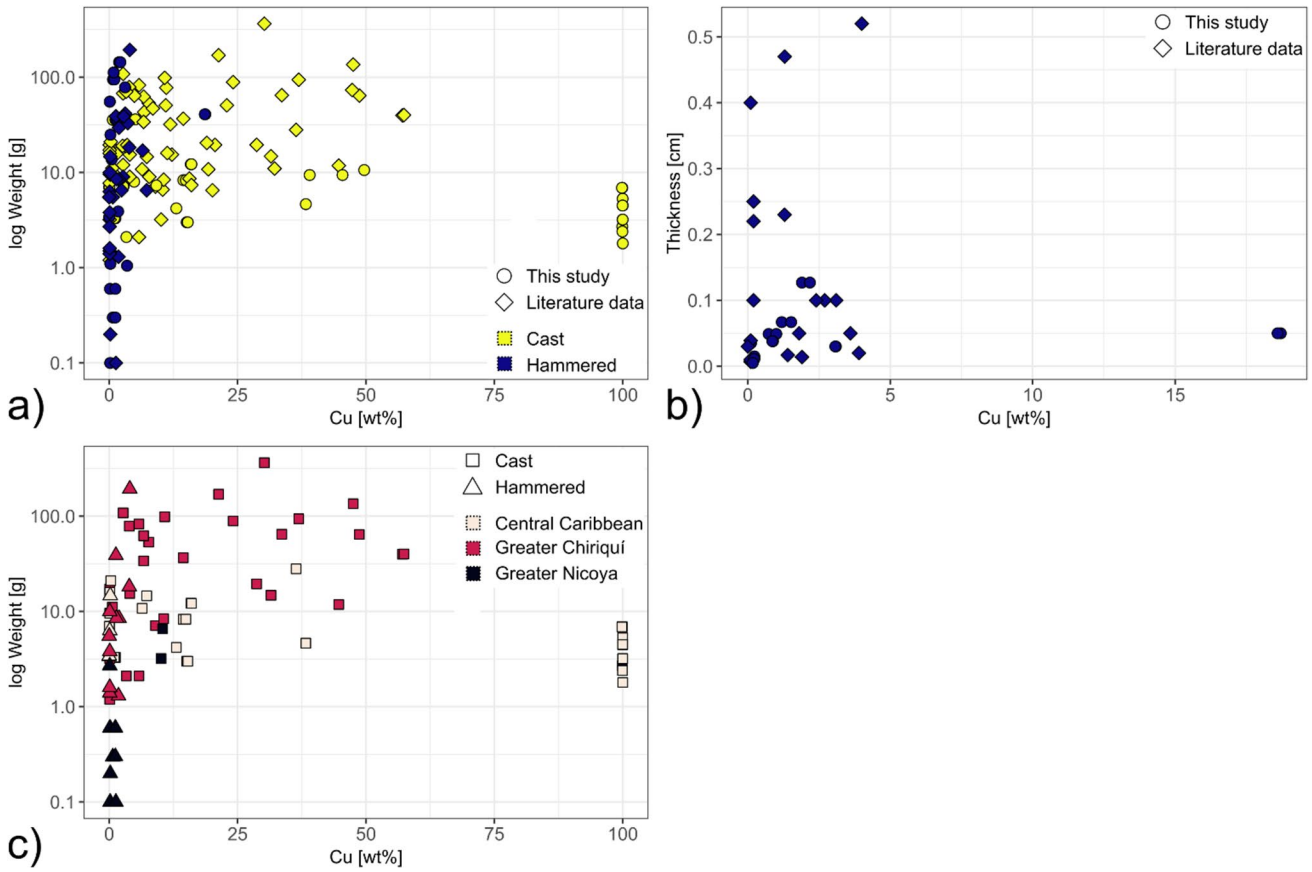


Fig. 8 Binary diagrams of Cu contents of pre-Columbian Costa Rican metal objects in comparison with other characteristics. **a** Weight of the investigated objects (logarithmic scale) versus their Cu contents. Differences in shape and fill colour of the symbols are as in Fig. 7. **b** Thickness of sheet objects versus their Cu contents. Different symbol shapes are as in Fig. 7. **c** Weight of the investigated objects (logarithmic scale) versus their Cu contents, with the fill colour of the symbols distinguishing the provenance of the objects from different archaeological regions in Costa Rica (as shown in Fig. 1). Symbol shapes refer to the predominant manufacturing techniques of the objects by casting (squares) or hammering (triangles)

are up to 0.52 cm thick, with a median value of 0.044 cm. No correlation between the thickness of the sheet metal objects and their Cu contents is discernible (Fig. 8b). The unalloyed copper objects generally have a small size with weights between 1.8 g (C-27 HM 85) and 6.9 g (A-10 LF 757), and a median value of 4.5 g.

Discussion

Technological Considerations

This study has shown that Costa Rican practices for the making of different types of objects were varied and imaginative. For example, detailed objects were produced by very complex wax forming. Cold-working techniques, e.g. chasing, decoration, cutting and piercing, have also been applied. The wax forming step with its filigree details and intricate attachments extensively required fine motor skills. Casting was carried out by applying various techniques. Burrs can point to the use of two-piece moulds besides the lost wax casting technique. The bells were cast in one-piece moulds as can be deduced from the absence of circumferential seams or burrs. Their clappers were generally cast separately, but if integrated into the casting of the bell, they must have been first cast, then wrapped with moulding material, and integrated into the bell wax model and its outer mould. Removal of the moulding material after the casting subsequently released the clappers inside the bell. Faulty castings could have been the result of uncontrolled temperatures during casting and solidification, an incorrect assessment of the physical properties of the chosen metal or alloy, or a lack of appreciation for a perfect object. Granular inclusions in the metal presumably are heavy minerals, indicating the use of alluvial gold won by panning and imperfect separation of mineral components. Slipped filigree details and casting residues were accepted. Dendritic structures are even visible to the naked eye, and their topography is surficially preserved,

particularly in slightly oxidised objects. Piercings of discs are manufactured variably. It is impossible to decide at what point in time the piercings were made and whether the person(s) manufacturing the objects created them or the person eventually wearing them—provided that these persons were different in the first place. They were sometimes integrated into decorative elements and were therefore executed with great care to not harm the object's decoration. Other piercings were carried out rather hastily and impaired the overall appearance. With matching geometry in their cross sections, a set of fine metal chisels from the collection of the MNCR may indicate as to what kind of tools were used to punch the holes.

Material Choice

Technological considerations are evident for the general material choice of the objects. The different range and distribution of Cu contents in hammered and cast metal objects reflect the adjustment of metal compositions to the manufacturing processes. The observation that hammered metal objects tend to have comparatively lower Cu contents than cast objects can be linked to the better malleability of pure gold since hardness increases notably with rising Cu (and Ag) content [40]. The wider range of Cu contents and significantly higher median Cu value determined for cast objects can be linked to the lowered liquidus temperatures of (argentiferous) Cu–Au alloys (minimum of c. 900 °C for the investigated artefacts; Fig. 7a) in comparison with pure Au (1064°) [41], thus facilitating the casting process. Widespread application of depletion gilding observed for the studied cast objects ensured that the reddish hues of Cu-rich gold alloys were masked by a golden surface colour. The access to raw materials appears to have been a further crucial factor. The heaviest hammered as well as cast objects investigated in this study originate from the Greater Chiriquí archaeological region in the south of Costa Rica (Fig. 8c), where archaeological sites with finds of metal objects are located close to the (fossil) placers of the Osa and Burica peninsulas and the copper deposits of the Cordillera Talamanca. Gold panning by indigenous people in southern Costa Rica is described in historical reports from Spanish conquistadors, e.g. in the letter of Juan Vázquez de Coronado written in 1563 [42]. Communities lacking direct access to gold and/or copper mineralisations had to rely on trade to obtain the necessary raw materials for local artefact production or receive metal artefacts by gift exchange [43]. Unworked cast metal ingots of gold, copper, or gold-copper alloy are known from grave contexts in the Isthmo-Colombian region, e.g. from Sitio Conte, Panama [12], or from votive offerings of Muisca people (where these ingots are called *tejuelos*) [44]. Apart from their utilisation as grave goods and offerings, possibly to signify a transformative state [45] or relating to the goldsmithing activities of the deceased, they presumably also functioned as precursor materials used by metal workshops for object manufacture and therefore might have been traded to or exchanged with communities as "ready-to-melt" ingots.

Concluding Remarks

It is noticeable that the various successive production steps are characterised by objectively different levels of quality. This is especially true for the iconographically rich pendants. Chronological and regional differences likely played a role but, in light of the de-contextualised state of the objects, would require the identification of workshop circles or goldsmiths based on detailed stylistic analysis. The greatest attention was paid to wax modelling, whereas casting was often imperfect and could not transfer the original outline of the wax moulds to the cast objects. It thus becomes clear that the effort required for high-quality production and common notions regarding the value of the finalised product (metal value, artistic expression, and perfectionism) do not necessarily coincide here. Concerning effort, the focus is definitely on the production step of wax model production ([cf. [46]). But what about the value? By modern rational standards, great value should lie firstly in the choice of metal, i.e. the value of gold itself. This is determined by the material costs, the availability of the metal, and its amount required for object manufacture. At least in parts of Costa Rica, particularly the Greater Chiriquí region, gold seems to have been abundant and rather easily accessible from local mineralisation, i.e. placers, as indicated by the overall notably heavier weights of metal objects originating from this area. Frequently observed remains of degasification channels and metal burrs suggest that metal either was readily available and thus had not to be saved at all costs or that, due to certain beliefs or customs, the objects were preserved as-cast from the wax mould. Historical sources demonstrate that gold was appreciated for its material qualities in southern Central America, and its use in gift exchange indicates that gold was prized for its power to obtain goods and knowledge [43, 47], while not necessarily possessing the same intrinsic value as in European societies. The manifold imperfect castings were not discarded, and the metal was not put back into the recycling process. Considering Costa Rica as a whole, the flawed objects were brought into use parallel to more perfect ones. However, blatant miscasts such as the frog pendant from the Reventazón area (see above) are rarely preserved and either might have been remelted already in the pre-Columbian period or in modern times to retrieve the metal for their material value, deeming such objects not attractive enough to be sold off to collectors. Secondly, great value should lie on the particular production

step that requires the most effort and/or the highest artistic skills—here again, the shaping of the wax models. Artisans were needed who were very imaginative, sensitive, and precise in their work. Dexterity and experience in handling the material were required. This was certainly the case for the majority of the studied objects. Thirdly, great value should also lie in the highest perfection of finishing the objects. This applies here only to a limited extent. However, the typically detailed designs of the wax models, including the common use of false filigree, made subsequent goldsmithing work, e.g. soldering, obsolete (also see [48]). Widespread use of depletion gilding and extensive polishing indicates the appreciation of golden-coloured shiny surfaces. Polishing of the objects is perfectionated, particularly in the discs, which Columbus described as "golden mirrors" ([49], p. 182). This was interpreted as having been done to impress others from a distance [50], matching Boruca oral traditions that describe the utilisation of large gold plates reflecting the sunlight ([47] and references therein).

However, for most cast filigree pendants the metal composition was often incorrectly chosen or handled with insufficient metallurgical knowledge, which led to a large number of pores and casting faults. The selection of copper-richer alloys with comparatively lower liquidus temperatures for casting and of low copper-gold for sheet metal objects, however, shows that technological aspects played a certain role and that the material used was not fully randomly chosen. Ethnographic studies document that metals were associated with symbolic properties in pre-Columbian societies [45] and thus might not have been selected for their material characteristics alone.

The question arises as to why the quality of production from the raw metal to the finished object varies so much. Differences in artistic skills and technological craftsmanship can be seen, which could be the result of practising a certain division of labour between variably experienced people. Reports that only certain clans within the tribes (e.g. for the Bribri) carried out metalworking [47] point out its special role, but may also exclude more artistically gifted and technically skilled individuals from the production of the objects.

It was observed that besides the differences in the quality of the various production steps, several objects were products of rather coarse wax modelling. Others are perfectionated pieces with finest details. This might be an effect of different levels of knowledge, as hypothesised by Martinón-Torres and Uribe-Villegas [44] in their study of Muiscan metal artwork. Inserting the clappers into the bells is a further aspect that evidences different levels of technical skills. Such observations might point to a co-existence of domestic-mode production and specialised workshops. Reports of "a hundred men who continually worked gold at Dabaibe" [47] appear to describe such specialised centres. Alternatively, locally produced in contrast to imported objects could provide an explanation for technological differences. Other observations might relate these differences with the final use and purpose of the artefacts, as objects not being displayed after manufacture and only used as grave goods or votive offerings (as known from Muisca artwork) could have been less carefully produced. Differences in the "rank" of the objects [47] might have influenced their manufacture as well.

Material supply and use have many aspects here. One question arises that concerns the use of copper for the objects. According to Hosler [23], the processing of native copper in Mexico took place before that of other metals (the Mexican "Period I"). Small, transportable beads, tweezers, needles, awls, fishhooks, rings, etc., were produced by easy-to-handle cold-working. According to Hosler, even the bells from Ecuador were cold-worked products. In Costa Rica, the metal objects with the earliest dating found in the northern and central parts of the country (Línea Vieja region and Guanacaste) [38, 51] are mostly cast and possess the same technological characteristics as objects with a later dating and de-contextualised metalwork. Cold-working as an initial technique to form objects has not yet been found in the archaeological records of Costa Rica,, despite the presence of mineral deposits such as Guayabo, where an outcrop with native copper sheets is exposed [1, 5], and verified reports of large-sized gold nuggets from the Osa peninsula with weights of up to 7.7 kg [10], that would favour this practice.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13632-025-01230-1.

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