

Fifteen Shades of Green: Reassessing the Origin of Green Staining in Archaeological Cremation Burials

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Abstract

Green staining on cremated bones is a common phenomenon observed in archaeological cremation burials. It has frequently been interpreted as evidence of copper-based pyre goods. Previous studies on this topic have produced inconclusive results with some of them recorded copper residues in green staining whereas others identified iron as the main causal factor.

In this study, we analyzed bone samples exhibiting green staining from prehistoric cremation burials as well as experimentally cremated pig bones. The chemical composition of the samples was examined using scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDS), and cluster analysis (17 samples with 73 measured spectra).

Two statistically meaningful clusters were identified. One cluster contained significantly higher amounts of copper than the other; however, no significant differences in iron content were observed between the clusters. Additionally, the green staining in each cluster could be distinguished based on their visual characteristics. Green staining associated with copper residues typically formed superficial crystalline encrustations and is most likely caused by post-depositional contact between bone fragments and copper alloys. In contrast, the underlying elements responsible for green staining in the second cluster could not be identified. In this group, the staining appears as diffuse discolorations directly affecting the bone matrix. We therefore suspected that chemical processes occurring during the cremation, rather than direct contact with copper, are primary cause of this type of green staining.

Keywords: copper residues, metal discolorations, cremated bones, bone diagenesis, grave goods

1. Introduction

The thermal transformation of the human body during cremation is a complex process influenced by multiple interacting variables, including temperature, duration of heat exposure, oxygen availability, pyre construction, and the presence of associated materials. These factors affect both the macroscopic and microscopic properties of bone, resulting in heat-induced shrinkage, fragmentation, warping, and characteristic color changes. Typically, cremated bones exhibit shades ranging from black and grey to blue and white, reflecting progressive thermal decomposition of organic and inorganic components under varying combustion conditions (Holden et al., 1995; Shipman et al., 1984; Walker et al., 2008). In addition to these well-understood color changes of cremated bones, atypical discolorations had been documented, including yellow, pink, red, and green shades (Dunlop, 1978; Wahl, 1981). These discolorations are still insufficiently understood. For example, rust-red coloration had been interpreted as hemoglobin residues (Malinowski & Porawski, 1969) and green discolorations (stainings) associated with copper. Green staining had been frequently documented in both archaeological cremation burials and modern crematoria contexts and is frequently considered significant for reconstructing funerary practices and the presence of metal artefacts associated with the deceased.

In inhumations, green staining on skeletons is frequently documented and results from direct contact between the body and copper-alloy artefacts. At Franzhausen I, for example, such staining was used to reconstruct the presence and position of artefacts during decomposition, even when those items had been removed during post-depositional grave reopening and were no longer recoverable at excavation (Sprenger, 1999). The time required for skeletal tissues to incorporate copper corrosion products during decomposition is not firmly established, though a timeframe of up to three generations is sometimes inferred. In theory, cremating a skeleton after decomposition could include bones already green-stained by contact with copper corrosion products. However, for prehistoric Europe there is little evidence that bodies were intentionally left to decompose before cremation; the prevailing assumption is that fresh bodies were burned.

In cremations, bronze artefacts can come into contact with the body at two stages of the funerary sequence. First, dress elements and jewelry may have been worn on the body, pins may have fastened the shroud, and grave gifts may have been placed on the pyre and burned together with the body (pyre goods). Second, additional metal artefacts may have been introduced after the burning, at any stage of the collection, manipulation, and deposition of cremated human remains (grave goods *sensu stricto*). Pyre goods may sometimes be distinguished from grave goods by traces of fire on the artefacts, or by archaeological context observation (Sørensen & Rebay-Salisbury, 2023). Both pyre goods and grave goods may contribute to the discoloring of cremated human remains during post-depositional processes.

One explanation for green staining is the presence of copper or copper-containing alloys in close association with the body during cremation (Becker, 2001; Jaskulska, 2020; Waltenberger et al., 2023; Williams, 2004). From a chemical perspective, copper becomes highly reactive at elevated temperatures. Beginning at approximately 300–350°C, metallic copper and copper alloys oxidize to form cuprous oxide (Cu₂O) and cupric oxide (CuO), typically appearing red or black (Dunlop, 1978; Mimura et al., 2006). These oxides may further react with chlorine to produce copper chlorides such as atacamite and paratacamite, or with carbon dioxide to form carbonates such as malachite and azurite. These compounds are characteristically green or blue-green in color and form oxidation layers on the surface of an artefact. These products may deposit on adjacent bone surfaces, producing localized green staining. According to the Cu-Sn phase diagram, at temperatures over 850 °C, copper with 10% Sn melting begins and a fully liquified phase appears above 1000°C (melting interval) while pure copper melts at temperatures exceeding 1084 °C (Haubner et al., 2024; Massalski & Okamoto, 2001), potentially enhancing its interaction with surrounding materials. In addition, research showed that complex post-depositional processes, impacted by various factors (e.g., soil humidity, oxygen supply, soil acidity, soil composition), take place on the surface of copper-based artefacts and cause reactions with surrounding material. Especially when copper-based objects are directly situated on a bone, ceramic etc. metal corrosion products can also be found on the bones (Oudbashi et al., 2013).

Despite this plausible pathway, empirical findings regarding the origin of green staining remain inconsistent and rare. In a large-scale study of modern cremations, Dunlop (1978) documented green and pink staining in 172 of 846 cases. While pink staining correlated with elevated copper concentrations verified by X-ray fluorescence analysis, green staining did not consistently show increased copper levels. His experimental cremations of animal bones suggested that copper wire in direct contact with bone produced pink staining, whereas stainless steel could induce green staining. Dunlop therefore proposed that pink staining was associated with copper residues, while green staining might be related to iron. This interpretation, however, is difficult to reconcile with archaeological evidence from Bronze Age cremation burials, where green-stained bones are common but iron artefacts absent. In numerous cases, green staining occurred without associated metal objects recovered during excavation (e.g., Teschler-Nicola, 1985, Williams et al., 1991). One explanation proposed was that copper artefacts were present during cremation but were not collected together with the cremated remains (Kühl, 1987; McKinley, 1994), or were removed from the cremation burial after a certain time period (Sorensen & Rebay-Salisbury, 2023). Alternatively, small bronze artefacts may have been overlooked or taphonomically altered. Waltenberger et al. (2023), for example, identified micro-scale bronze coil beads in Late Bronze Age urns through micro-excavation and CT scanning; in some cases, the artefacts were heavily corroded and disintegrated easily. Metal objects visible on CT scans of en-bloc recovered urns were not always identifiable during micro-excavation.

Yet even targeted elemental analyses have yielded contradictory results. Kühl (1987) did not detect copper in all samples of green-stained prehistoric cremated bone using X-ray fluorescence analysis and suggested a possible taphonomic origin involving soil processes and iron compounds. Similarly, Schutkowski & Hummel (1991) proposed manganese deposition as a potential cause of green staining. In contrast, Lohne & Agelarakis (2014), using multi-element ICP-MS on Classical period cremated bones from

Greece, identified elevated copper concentrations in 14 of 15 green-stained samples and attributed the staining to metal objects.

Taken together, previous research suggested that green staining on cremated bone is a multifactorial phenomenon, potentially resulting from different chemical and taphonomic processes that may produce visually similar staining. However, systematic comparative analyses integrating microstructural and multi-elemental data across archaeological and experimental contexts remain limited. The aim of the present study is therefore to investigate green staining on cremated bones from diverse archaeological and experimental settings in order to clarify its potential causes. Using scanning electron microscopy (SEM-EDS), and an exploratory statistical approach, we analyze elemental compositions and microstructural features associated with green staining. By identifying recurring element combinations and contextual patterns, this study seeks to establish a more robust interpretative framework for understanding green staining in cremated human remains.

2. Material and Methods

We analyzed 17 cremated bone samples containing green staining with various shades and different origins (Table 1). 13 samples originated from Late Bronze Age cremation burials from Austria. The sites Franzhausen-Kokoron and Unterradlberg are both located in the Traisen Valley in eastern Austria just a few kilometers apart from each other and were both recovered in rescue excavations in the last decades. Unterradlberg dates to the transitional period from the Middle to the Late Bronze Age (1500-1250 BCE). The site contained four burial mounds with primary and secondary depositions and a minimum of 14 individuals recovered within a central grave chamber and around the tumulus (Blesl & Krumpel, 2003; Blesl et al., 2002; Skerjancz et al., in print). Franzhausen-Kokoron comprises 403 cremation burials dating to 1000-800 BCE (Lochner & Hellerschmid, 2009, 2016). Additionally, we included four samples from modern experimental cremations in this study (Fritzl & Konrad, 2020; Grömer, 2020). In this experiment, fleshed extremities from *Sus scrofa domestica* were cremated together with pyre offerings, including some iron artefacts and ceramic vessels.

Table 1: Summary of the sampled cases containing green stainings.

Sample code	Site	Time period	Grave no.	Age at death	Sex	Bone fragment	Bronze artefacts
GS01	Franzhausen-Kokoron	Late Bronze Age	11	20-46	Unidentified	Cranium	Fibula, needle fragment, bracelet fragment, knife (from filling)
GS02	Franzhausen-Kokoron	Late Bronze Age	25	12-19	Unidentified	Tibia	2 rings (from filling)
GS03	Franzhausen-Kokoron	Late Bronze Age	132	20+	Probably female	Cranium	2 rings (from urn)
GS04	Franzhausen-Kokoron	Late Bronze Age	255	19-22	Possible male	Rib	Needle (from filling), bronze wire (from urn)
GS05	Franzhausen-Kokoron	Late Bronze Age	425	3-12	Unidentified	Diaphysis	-
GS06	Franzhausen-Kokoron	Late Bronze Age	659	19-24	Possible female	Humerus	Needle fragment (from urn)
GS07	Unterradlberg	Late Bronze Age	628	20+	Unidentified	Diaphysis	
GS010	Franzhausen-Kokoron	Late Bronze Age	488	20-42	Unidentified	Ribs	Bracelet fragment (from filling)

GS12	Franzhausen-Kokoron	Late Bronze Age	662	7-19	Unidentified	Cranium	Bracelet fragment (from urn)
GS13	Franzhausen-Kokoron	Late Bronze Age	683	24-34	Male	Rib	-
GS14	Franzhausen-Kokoron	Late Bronze Age	567	4-7	Unidentified	Cranium	Needle fragment (from urn)
GS15	Franzhausen-Kokoron	Late Bronze Age	336	24+	Probably female	Tibia	Knife fragment (from filling)
GS16	Franzhausen-Kokoron	Late Bronze Age	606	9-12	Unidentified	Temporal bone	Melted bronze fragment (from filling)
GS17	Experimental cremation (Sus scrofa)	Modern	11-1	Juvenile	Unidentified	Epiphysis	Iron artefact
GS18	Experimental cremation (Sus scrofa)	Modern	11-2	Juvenile	Unidentified	Diaphysis	Iron artefact
GS19	Experimental cremation (Sus scrofa)	Modern	5-2	Juvenile	Unidentified	Epiphysis	Iron artefact
GS20	Experimental cremation (Sus scrofa)	Modern	9-2	Juvenile	Unidentified	Epiphysis	Iron artefact

Scanning electron microscopy (SEM) using a Zeiss EVO 60 XVP with an Oxford Instruments analytical device, an ULTIM Max 170 with AZtec software) at VIAS, University of Vienna, was used to examine the staining further. The surface of the experimental samples was left untreated, while the archaeological material had been washed with water after the archaeological excavation. After mapping zones of interest in conventional SEM imaging focused on the artefact surface, we analyzed the staining further with backscattered electron (BSE) mode. In BSE imaging, a high-energy electron beam is directed on the sample's surface and electrons are elastically scattered by atomic nuclei; regions with higher mean atomic number (Z) exhibit increased backscatter yield and therefore appear brighter in grayscale. Additionally, we aimed to gain information on the elemental composition with energy-dispersive X-ray spectroscopy (EDS) with following operating conditions: accelerating voltage 20 kV, working distance 8.5 mm, beam current 100 µA, detector dead time 30–40 %, and acquisition time 180 s. To ensure beam current stability, cobalt standards were measured repeatedly. Numerous certified reference materials are used to test the analytical device: CCU-1e, BAM-M376a, BAM-M397, BAM-374 (ERM-EB374), BAM-375 (ERM-EB375), BAM-377 (ERM-EB377), BCR-691, MBH-31X 7835.5 A-C (batch A), MBH-31X CZ114 A-C, MBH-31X 7835.8 A3, MBH-31X TB 4 A4, MBH-32X Sn7 A, MBH-32X LB 17 A1, MBH-36X CuAs 3, MBH-36X CuAs 4, MBH-36X SP2 A-C (batch A), MBH-37X 218 B-C (CHARM-set, Mehofer & Kucera, 2005). Repeated measurements were conducted at predefined sampling locations including visually unaffected as well as green stained areas to identify compositional differences of the sampling matter. Both localized point measurements as well as spatially more extensive areal measurements were undertaken. The measurement results were normalized and documented in mass percent. The detection limit (LOD) of SEM-EDS is, generally speaking, at 0.5-1% but dependent on the selected elements, the sample matrix and geometry, its surface conditions (e.g., surface corrosion), measurement conditions, and sensitivity of the used detector. In addition, cremation leads to substantial heterogeneity in bone material, both within and between samples, with some bones being more porous than others. Elemental concentrations were initially divided into minor (<1%) and major (≥1 %), but due to the afore described limitations, the concentration data were subsequently reduced to nominal variables recording only the presence or absence of each element for further analysis.

The statistical analysis was conducted in R statistics (version 4.5.2). To explore similarities and differences among the element compositions of the green stained bone samples, we employed a hierarchical cluster analysis using the Ward.D. agglomeration method with a binary distance matrix. This approach groups samples based on their elemental profiles, allowing us to identify patterns or clusters that may reflect different causes of green staining. A dendrogram was generated with each sample annotated by its site of origin, visible metal traces (identified via BS mode), observed color shades and an interpretation of the likely cause of green staining based on element signatures (categorized as iron oxides, copper oxides, or mixed signals). This visualization allowed us to assess whether samples with similar staining causes formed cluster naturally. The analysis was performed in three steps. First, all detected elements were included to obtain an initial overview of clustering patterns. Second, the dataset was refined by excluding elements that are part of the natural bone matrix or likely introduced through soil contamination (Al, Ca, K, Mg, N, Na, Ni, P, S, Si, Ti), retaining only elements suspected to influence green staining: Cu, Fe, Zn, Sn, Mn, Cl, and F. This step was intended to produce clearer and more meaningful clusters. Finally, to characterize the clusters, we tested differences in the element concentrations using Chi2-tests and Fisher's exact tests with Bonferroni-Holm corrections applied to adjust for multiple comparisons and reduce the risk of false positives. This combination of exploratory clustering and statistical testing provided a framework for linking elemental composition to potential causes of green staining in cremated bones.

3. Results:

Figure 1 shows the variability of observed green staining. Initial differences were already observable at the microscopic level, with green staining ranging from bluish-green to emerald-green hues. Microscopic examination provided further insights: In some cases, the green staining appeared diffuse and seemed to have penetrated the bone matrix (Figure 2a), whereas in other samples the green staining consisted of powdery or crystal-like encrustations on the bone surface, suggesting direct contact with copper-based metal inside the urn (Figure 2b). Both features could also occur within a single green staining (Figure 2c).

Figure 1: Variability of observed green staining: Cases a-c and g-k represent examples of green staining grouped in Cluster 1 (no traces for copper). Cases d-f and l-m represent cases from Cluster 2 (associated with copper). Sample numbers: a) GS05, b) GS20, c) GS17, d) GS12, e) GS03, f) GS04, g) GS18, h) GS17, i) GS06, j) GS14, k) GS19, l) GS10, m) GS02. Photos by C. Bieber.

Figure 2. Examples of surface characteristics: a) green staining with diffuse appearance directly discoloring the bone matrix (GS05), b) green staining forming superficial crystalline encrustations (GS04), c) green staining showing encrustations as well as a discoloration of the bone matrix (GS03). Photos by C. Bieber

SEM-EDS showed that some green staining was visible using the BSE imaging, indicating the presence of metallic residues. This was confirmed in sample GS13, where melted copper was found adhering to the bone surface (Figure 3a). EDS measurements consistently detected copper residues in these cases. However, in other instances, the green staining did not produce a distinct signal in BSE imaging (Figure 3b). Detailed macroscopic pictures of all green staining together with the corresponding EDS measurement reports are provided in the Supplementary Information S1.

Table 2: Summary of the EDS results. All spectra per green bone sample were summarized in the detected elements. Color descriptions are determined based on the hexagonal color codes (see S1 for further details).

Sample code	detected major elements	Detected minor elements	Surface texture
GS01	Ca, Cl, Cu , O, P	Al, Mg, S, Si,	Crystalline surface deposition
GS02	Ca, Cl, Cu , O, P,	Al, Fe , K, Mg, Si	Crystalline surface deposition
GS03	Al, Ca, Cl, Cu, Fe , Mg, O, P, Si	Fe , K, Mg, Na, S	Crystalline surface deposition and staining of the bone matrix with blurred margins
GS04	Ca, Cl, Cu , O, P	Al, Mg, Si	Crystalline surface deposition
GS05	Ca, O, P, Si	Al, Cl, F, Fe , K, Mg, Na, S, Si,	Staining of the bone matrix
GS06	Al, Ca, Fe , N, P, O, Si	Cl, Cu , K, Mg, Na, S, Sn	Surface staining with distinct margin
GS07	Ca, O, P	Al, Fe , Mg, Na, Si,	Staining of the bone matrix with blurred margins
GS010	Al, Ca, Cu , O, P, S, Si	Fe , K, Mg, P	Crystalline surface deposition
GS12	Al, Ca, Cu, Fe , O, P, Si	K, Mg, P, S, Sn	Crystalline surface deposition
GS13	As, Ca, Cu , O, P, Sb, Si, Sn	Ag, Al, Cl, Fe , K, Mg, Ni, S	Melted bronze
GS14	Al, As, Ca, Cu , O, P, Si	Ag, Cl, Fe , K, Mg, S, Sn	Crystalline surface deposition and staining of the bone matrix with blurred margins
GS15	Al, Ca, Cl, K, O, P, Si	Fe , Mg, Na	Staining of the bone matrix with blurred margins
GS16	Ca, Cu, Fe , P, O, Si, Sn	Al, Cl, Fe , Mg, P, S, Si	Crystalline surface deposition and staining of the bone matrix with distinct margins
GS17	Al, Ca, Cr, Cu, Fe , K, Mg, Na, O, P, S, Si, Sn	Al, Cl, Cr, Cu, Fe , Mg, Mn , S, Si, Ti	Staining of the bone matrix with blurred margins
GS18	Ca, Cr, Cu , K, Mg, Na, O, P, S	Al, Ca, Cl, Cr, Cu, Fe, Mn , Si	Staining of the bone matrix with blurred margins
GS19	Ca, Fe , K, Mg, Na, O, P	Al, Cl, Fe, Mn , S, Si, Ti	Staining of the bone matrix with blurred margins
GS20	Ca, Fe , K, Mg, Na, O, P	Al, Cl, Fe , S, Si, Sr, Zn	Staining of the bone matrix with blurred margins

Figure 3: Green staining characterized by scanning electron microscopy (SEM) in backscattered electron (BSE) mode and by macroscopic photography. (a) Sample GS10, clearly showing metal-related signals associated with the green staining. (b) Sample GS7, showing no detectable metal-related signals within the green-stained area in BSE mode (Photos by C. Bieber).

A cluster analysis including all spectra (green staining and controls) and all elements did not yield meaningful groupings, for the limitations of the used analytical results see below. In this initial analysis, three clusters emerged: one containing most experimental samples, one containing only archaeological samples, and a third mixed cluster comprising archaeological samples and two experimental samples. Both green staining and control spectra were evenly distributed across these clusters.

When the dataset was reduced to major elements only, two clusters became apparent: one cluster contained only experimental samples, while the other contained all archaeological samples along with two experimental cases (GS17: spectrum 60 & GS19: spectrum 68). Next, we included both major and minor elements but excluded the control measurements, which produced two clusters with a clear separation between experimental and archaeological samples (Figure 4a). Finally, we performed a cluster analysis using only elements likely associated with the green staining and not linked to soil contamination or the natural bone matrix. These elements were Cu, Fe, Zn, Sn, Cl, F, Mn. This analysis yielded two clusters: one mixed cluster containing both archaeological and experimental samples, and a second cluster consisting exclusively of archaeological samples.

Interestingly, patterns in the characteristics of green staining were also observed (Figure 4b): Cluster 1 included 19 cases, where the green staining directly penetrated the bone matrix. Additionally, one sample (GS14: spectrum 27) showed both penetration and encrustation; one case (GS13: spectrum 11) contained melted copper attached to the bone; and one case (GS16: spectrum 38) displayed only an encrustation. Cluster 2 contained predominantly samples with encrustations (11 cases), three cases showing both encrustations and staining (GS03: spectrum 1 & 2, GS14: spectrum 28) and three cases with staining only.

We further classified the cases based on the oxide type suspected to cause green staining according to the EDS results (Figure 4c). Cluster 1 primarily contained cases where iron oxides were suspected to cause the green staining, including most cases with indefinite element residues. Cluster 2 largely contained cases where copper oxides were the main suspected cause. However, two indefinite cases and one case suspected to involve iron oxides were also found in Cluster 2.

Figure 4: Results of the cluster analysis. (a) Cluster analysis performed using only major elements. Two clusters were identified, separating the archaeological samples from the experimental samples. (b) Cluster analysis using only elements suspected to be associated with the green staining. Overall, a clear separation between cases with blurred staining directly discoloring the bone matrix and cases with superficial encrustations can be observed. (c) The same cluster analysis as in (b), but with samples labelled according to our interpretation of the causes of green staining based on the detected elements.

This suggested that Cluster 1 may represent green staining associated with iron oxides, whereas Cluster 2 may represent copper oxide-based green staining. We further tested for group differences and compared the presence of iron and copper between the two clusters. No significant difference was found for iron (Fe major: χ^2 -test: $p = 0.282$), whereas copper was significantly more abundant in Cluster 2 (Cu major: Fisher's exact test: $p < 0.001$), supporting the hypothesis that Cluster 2 corresponds to copper oxide green staining. Additionally, a significant difference was found in the observed surface characteristics with Cluster 1 containing significantly more green staining which discolors the bone matrix and Cluster 2 more encrustations (Fisher's exact test: $p < 0.001$). We also compared the presence of iron and copper in the green staining spectra with the control spectra to avoid effects of soil contamination on the samples. Here we could not detect any significant differences between the green staining and controls in Cluster 1 and Cluster 2.

4. Discussion

Green staining is a frequent phenomenon in both archaeological and modern cremated remains and are commonly interpreted as copper salts. Their correct identification has important implications for forensic and archaeological interpretation. In forensic contexts, failure to recognize metal-induced discolorations could lead to erroneous conclusion regarding cause of death or postmortem alterations. In archaeology, green staining on cremated bones is often taken as indirect evidence for pyre or grave goods made of copper alloys. However, our results clearly demonstrate that green staining is much more variable than previously assumed and cannot automatically be regarded as evidence for copper-based metals in funerary contexts. Chemical analysis is therefore essential before drawing interpretative conclusions.

Cremation burials in archaeological contexts generally followed a two-step burial ritual process, beginning with the burning of the body on a wooden pyre and followed by the deposition of the cremated remains. Archaeological evidence frequently indicated that individuals were cremated together with clothing, personal ornaments, and additionally pyre goods such as ceramic vessels and food offerings.

These items often included metal objects (Kühl, 1987; McKinley, 1994; Mittermair, 2022; Waltenberger et al., 2023).

Experimental studies by Dunlop (1978) and the experimental material analyzed in the present study showed that green staining can develop during cremation even in the absence of copper or copper alloys. Consequently, a post-depositional soil influence can be excluded in these cases. This finding challenges earlier studies that attributed green staining to manganese interactions in the burial soil as hypothesized by Schutkowski & Hummel (1991) and Kühl (1994). Moreover, in our archaeological samples, manganese was not detected, further making this explanation unlikely. Interestingly, three out of four experimentally cremated pig samples revealed traces of manganese. This may be explained by the cremation of modern iron replicas together with the bones. Manganese is commonly used in modern steel production (Olsen et al., 2007) and may therefore have contributed to the observed staining. Similar observations were made in earlier experiments by Dunlop (1978) in which animal bones burned on steel trays developed green staining. Based on these findings we initially hypothesized that the two groups identified in the cluster analysis might represent green staining caused by copper oxides and by iron oxides respectively. However, statistical evaluation showed that the main difference between the clusters was the amount of copper, while iron was present in both groups with no significant differences. These results confirmed that copper causes green staining, but they also demonstrate that not all green staining is indicative of copper.

In modern cremations, various alloys originating from medical implants may be present, including titanium, stainless steel, cobalt-chromium alloys, and gold. These materials typically do not produce green residues. Titanium forms stable white oxides, chromium and nickel from stainless steel tend to produce dark gray discolorations and gold is largely inert at cremation temperatures (Dunlop, 1978). This limits the range of metals capable of producing green staining and makes copper-bearing materials the most plausible source. Nevertheless, cremation processes generate a broad spectrum of bone discolorations (Figure 5), including yellow, pink, and red, brown, and green hues (Dunlop, 1978; Malinowski & Porawski, 1969; Wahl, 1981). The causes of many of these color changes remain poorly understood and are thought to be related to chemical reactions between bone minerals and organic body tissue during the cremation process.

The experimental samples tended to form subclusters in all cluster analyses and showed to be different in comparison to the archaeological samples. This observation was not surprising as the experimental samples were modern animal bones cremated under (likely) different conditions in comparison to the prehistoric ones and had not been buried for millennia. Nevertheless, these samples are located within Cluster 1 containing green staining not related to copper contact further supporting the hypothesis that this type of green staining is associated to the burning process. The samples forming Cluster 1 exhibited blurred green staining that penetrated and directly affected the bone matrix, in contrast to the surface encrustations observed in Cluster 2. If this staining resulted from chemical reactions during cremation, the responsible organic compounds may have been transformed into inorganic residues that produced the green coloration, because all analyzed samples were fully calcined at high temperatures and the survival of originally organic components is minimal. Although an association with iron was considered, iron is ubiquitous in soils and was likely detected partly due to adhering soil residues (Colombo et al., 2014; Cornell & Schwertmann, 2003). Because the archaeological bones were washed after the excavation but still retained visible soil contamination, it was not possible to distinguish between iron derived from cremation residues and iron originating from the burial environment using our dichotomous data. Notably, Dunlop (1978) also failed to detect copper in some green-stained samples from modern cremations, although pink staining was associated with brass heated up at temperatures around 800°C. Other color alterations appeared to be rare in the archaeological context as examined. Among 879 cremation burials from the urnfield culture from sites in the Traisen Valley in Austria analyzed by LW in recent years, only two cases showed pink discoloration, and one showed a yellow-orange discoloration.

In contrast, green staining occurred in 51 cases (5.8%) with four cases exhibiting melted copper attached to the bones. Rust staining associated with iron artefacts associated with was identified in 27 cases (3%; all from the Early Iron Age).

Figure 5: Observed green, yellow and red staining in modern human cremated remains (Photo: Lukas Waltenberger).

Beyond elemental composition, the two clusters were also distinguished by their macroscopic characteristics. Cluster 1 predominantly comprises green staining that penetrate and stain the bone matrix. Cluster 2 mainly included encrustations on the bone surface. These encrustations were likely caused by cupric salts deposited during post-depositional processes. In such cases, copper-based metals in contact with the bone within the urn may have oxidized in the soil, forming brittle patinas adhered to the bone surface. Some samples indeed contained bronze artefacts recovered from the urn (see Table 1), although the precise spatial relationships were not documented during excavation. It is therefore unclear whether the analyzed bone fragments were deposited in direct contact with these artefacts. Small copper objects may also have been destroyed during the excavation or disintegrated by taphonomic processes (Kühl, 1987; Waltenberger et al., 2023).

This study had several limitations. In particular, the quantitative results obtained by energy-dispersive X-ray spectroscopy were, due to above mentioned restrictions not sufficiently reliable. Therefore, the analysis was restricted to nominal information (absence vs. presence of elements), rather than relying on relative concentration values. This methodological constraint may explain why the green staining in Cluster 1 could not be conclusively identified. Furthermore, we recorded control spectra on the same fragments to disentangle elements originating from contaminations from elements limited to green staining areas. We could not trace any significant differences, for instance, in the copper concentrations between green staining and the control. However, this might be a bias as our control spectra were usually measured just outside the green staining to avoid a bias caused by heterogenous contamination. Usually, the measured controls were just 250 to 1000 µm off the green staining. The results suggested that the measured copper in the controls were likely caused by residues of the green staining. Future research should therefore employ mass spectrometry to obtain quantitative elemental data and to allow more detailed investigation of possible organic or inorganic compounds responsible for green staining.

In summary, at least two different mechanisms for green staining on cremated bones could be identified (see Figure 2). One type formed crystalline encrustation associated with copper alloys and post-depositional soil processes. The other type appeared as a diffuse discoloration penetrating the bone matrix and was likely related to chemical reactions during cremation rather than copper-based artefacts. These findings demonstrate that some green staining can indeed serve as evidence for copper-based objects, but they likely develop after burial in post-depositional processes. In some cases, melted copper was attached to the bone fragments and may serve as evidence for pyre goods (e.g., GS13). The second type of green staining, in contrast, does not indicate the presence of copper alloys and instead reflects intrinsic chemical processes during cremation. We recommend using incident light microscopy to recognize the encrustations and to differentiate discoloration types prior to interpreting green staining.

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6. Competing interests

The authors declare no competing interests.

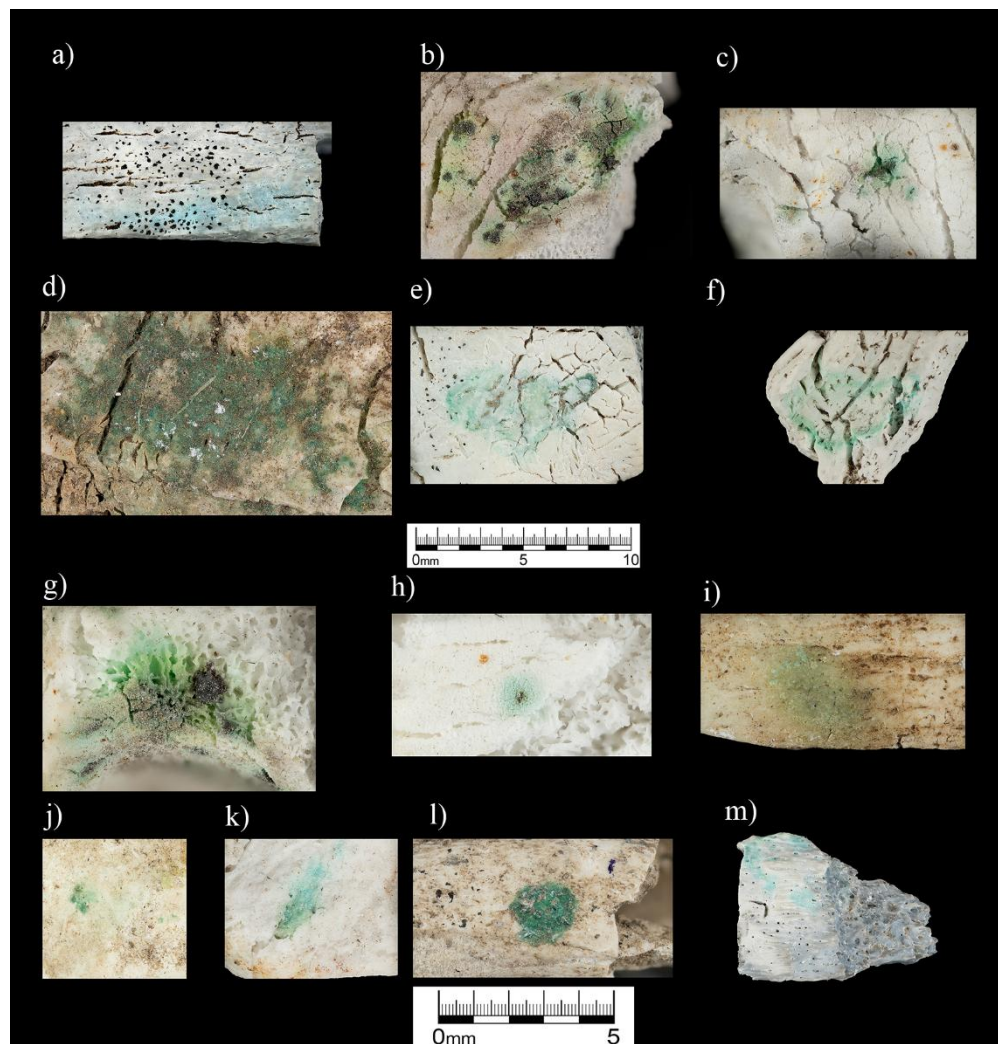
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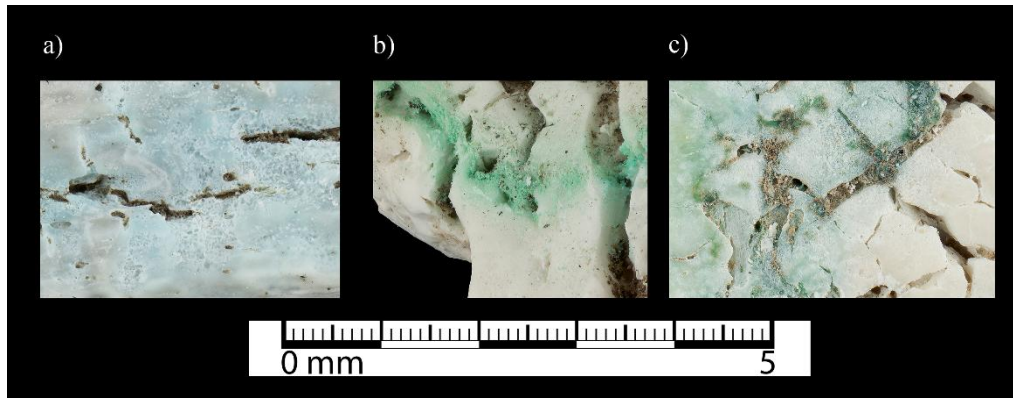
8. Figures



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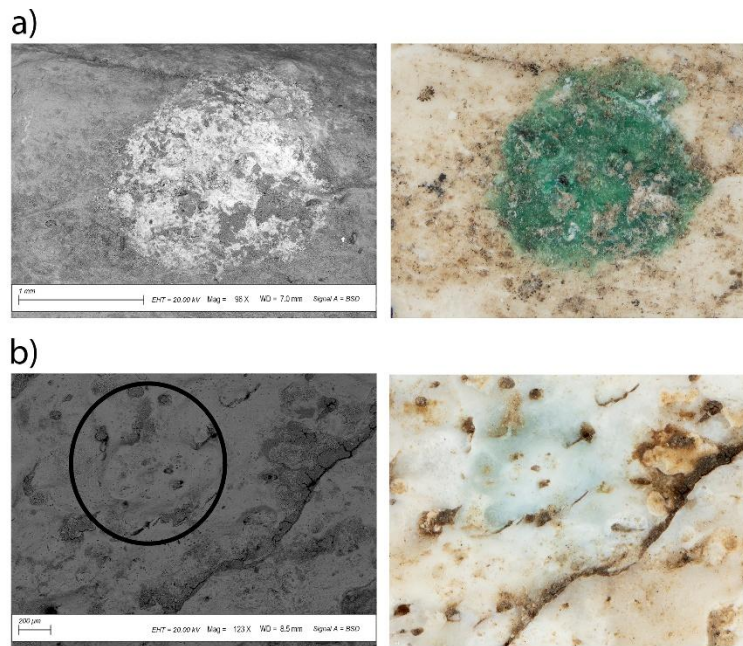
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Figure 1: Variability of observed green staining: Cases a-c and g-k represent examples of green staining grouped in Cluster 1 (no traces for copper). Cases d-f and l-m represent cases from Cluster 2 (associated with copper). Sample numbers: a) GS05, b), GS20, c) GS17, d) GS12, e) GS03, f) GS04, g) GS18, h) GS17, i) GS06, j) GS14, k) GS19, l) GS10, m) GS02. Photos by C. Bieber.

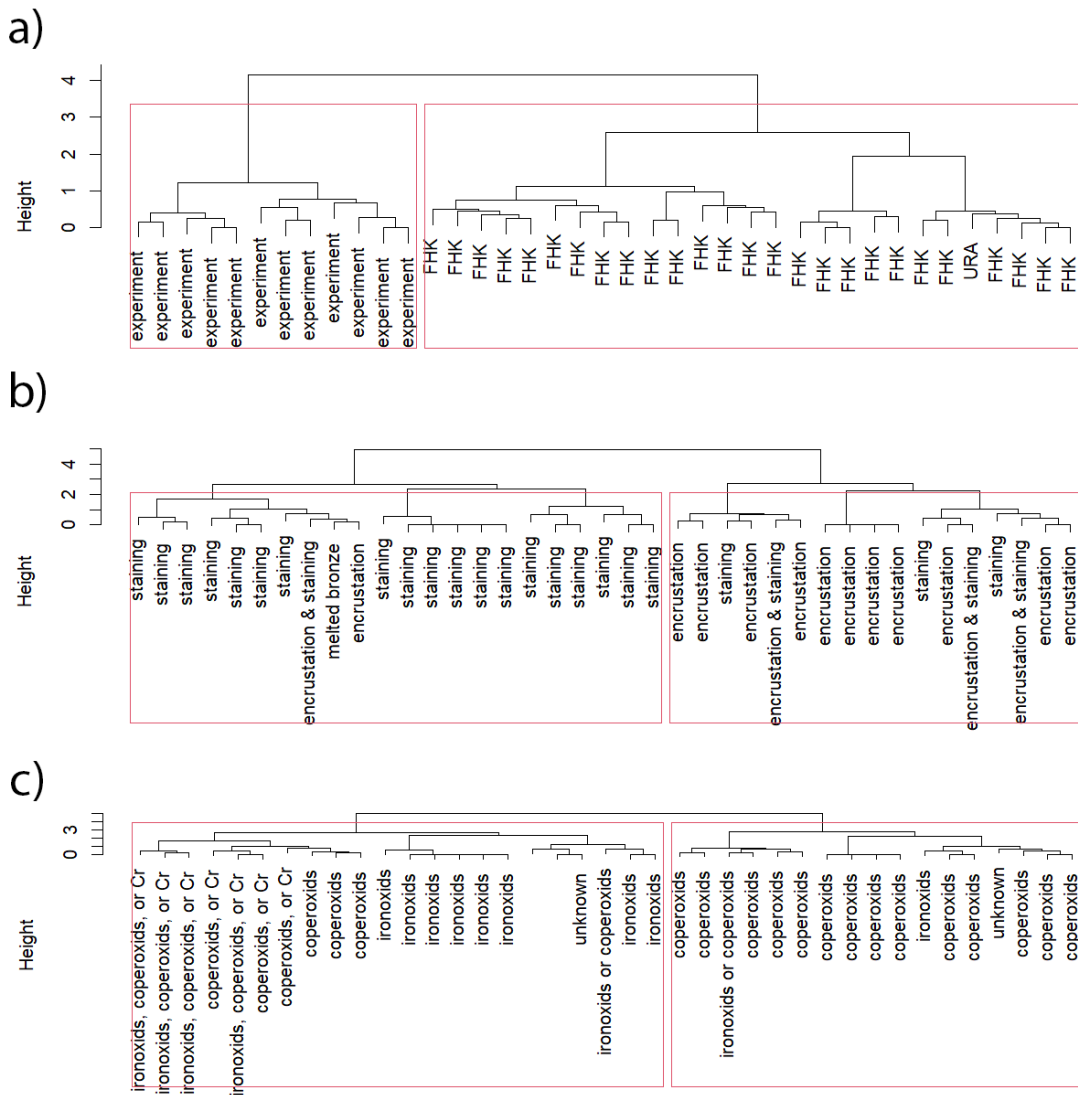


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Figure 2: Examples of surface characteristics: a) green staining with diffuse appearance directly discoloring the bone matrix (GS05), b) green staining forming superficial crystalline encrustations (GS04), c) green staining showing encrustations as well as a discoloration of the bone matrix (GS03). Photos by C. Bieber



499 Figure 3: Green staining characterized by scanning electron microscopy (SEM) in backscattered electron (BSE) mode and by macroscopic photography. (a) Sample GS10, clearly showing metal-related signals associated with the green staining. (b) Sample GS7, showing no detectable metal-related signals within the green-stained area in BSE mode. Photos by C. Bieber.



500 Figure 4: Results of the cluster analysis. (a) Cluster analysis performed using only major elements. Two clusters were identified, separating the archaeological samples from the experimental samples. (b) Cluster analysis using only elements suspected to be associated with the green staining. Overall, a clear separation between cases with blurred staining directly discoloring the bone matrix and cases with superficial encrustations can be observed. (c) The same cluster analysis as in (b), but with samples labelled according to our interpretation of the causes of green staining based on the detected elements.



501 Figure 5: Observed green, yellow and red staining in modern human cremated remains (Photo: Lukas Waltenberger).

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