Fresenius J Anal Chem (2001) 371 : 1146–1153
DOI 10.1007/s002160101082

ORIGINAL PAPER

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Investigation of contemporary gilded forgeries of ancient coins

Received: 24 July 2000 / Accepted: 8 July 2001 / Published online: 9 November 2001

Abstract Four contemporary forgeries of ancient gold coins were investigated regarding techniques used for gilding, and the composition of the gold cover and the base metal core. The forged coins are a Daric of the Persian Empire, a Gold Stater in the name of Alexander, and two Solidi of the late Roman Empire. A combination of modern analytical methods such as Scanning Electron Microscopy (SEM), Electron Probe Micro Analysis (EPMA), X-Ray Fluorescence Spectrometry (XRF), and Secondary-Ion Mass Spectrometry (SIMS) was used. The results demonstrate that the coins represent the main three technologies of gilding used in antiquity. The core of the Daric is a silver Siglos, plated by leaf gilding. The Gold Stater was forged by foil gilding using a silver core. The Roman Solidi have a core of either silver or copper and were plated by fire gilding. On account of our results it is possible to compare the forgers' profits made by use of the different technologies of forging.

Introduction

Plating of metallic objects (e.g. sculptures of copper or bronze) with gold or silver was practised in the ancient world from the beginning of the third millennium B.C. for either aesthetic reasons or with fraudulent intent. With the introduction of coinage at the end of the 7th century a new and profitable field opened up for forgers in the area of gold and silver coins. As the techniques have already been known for a long time, they only had to be adjusted to the new object, the coin.

The forgers' principles were to avoid immediate discovery of the falsification as well as the tracking of its origin and to realize the highest possible profit. What was required was a coat of precious metal (gold or silver), with a strong adhesion to the core base metal sturdy enough to resist the wear and tear of coin circulation. Most contemporary forgeries of ancient gold coins have a core of silver or copper, pure or alloyed. Due to the high specific weight of gold (19.32 g cm^{-3}), forged gold coins with a core of silver (specific weight 10.49 g cm^{-3}) or copper (specific weight 8.91 g cm^{-3}) have a much lower mass than an original of the same size. The forgers' problem was to keep the mass of his forged coins as high as possible in order to avoid detection by a different weight.

For these reasons it is understandable that contemporary forgeries of ancient gold coins are very rare compared with those of silver coins. On account of the similar specific weights of silver and copper, the mass difference between original silver and silver-plated forgeries cannot be noticed easily [1].

Generally three methods for the production of gilded coin forgeries were used in antiquity: foil gilding, fire gilding, and leaf gilding. This is known from many investigations concerning contemporary forgeries of ancient gold coins made during recent decades using modern chemical and physical methods [2].

Using foil gilding, the coin blank consisting of silver or copper was enveloped in thin gold foil, presumably thick enough to support its own weight, so that the covering procedure could easily be accomplished. The contact between foil and core was attained by hammering down the foil, followed by strong heating. The plated blank was then struck by a forged die, so that a robust coating was achieved.

In the case of fire gilding the coin blank of silver or copper was covered by gold amalgam. Afterwards the mer-

Electronic supplementary material to this paper can be obtained by using the Springer LINK server located at http://dx.doi.org/10.1007/s002160101082

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cury was removed by gentle heating and finally a stable gold cover remained on the blank. As described in the case of foil gilding, the gilded blank was struck by a false die. Depending on the amount of gold in the amalgam the gold layer is more or less robust. Fire gilding can be easily recognized by the presence of mercury in the gold layer.

Gold leaf is very suitable for the gilding of silver or copper blanks as it is easy to achieve strong adhesion to the metal underneath. This can be accomplished by heating (interdiffusion of metals) or by using organic glue (e.g. gum arabic). The disadvantage of leaf gilding is the thinness of the gold layer. After a short time of circulation the core of the coin becomes visible. For this reason only few specimens using this technique are known [3].

Sometimes ancient coin hoards contain contemporary forgeries. Via the international coin market they find their way into museums or private collections. There is increasing interest in these forgeries as they enable conclusions to be drawn about ancient metal technology. Four forged coins obtained from the coin trade by one of the authors (Reiff) have been investigated.

The aim of our investigation was to find out which of the techniques described above were used for coin forging. Therefore it was necessary to analyze the composition of the gold cover and the core of the coins, as well as to estimate the quantity of gold used for the forgery, by measuring the gold cover thickness at different points. From the results we expected to determine the profit from the procedures used. First results for the Solidi have already been published [4].

Experimental

Samples

The samples investigated were:

1. Daric, about 450 B.C., Persian gold coin; for comparison, Siglos, Persian silver coin, same design.
2. Gold Stater in the name of Alexander III (the Great) with the mint mark of Lampsacus (posthumous, approx. 315 B.C.).
3. Two Solidi from the Roman Emperor Constantius II (337–361 A.D.). The two forgeries are referred to below as coins A and B. The obverse and reverse of Solidus A are shown in Fig. 1a,b.

Figures of all genuine and forged coins and detailed descriptions can be found in the electronic supplementary material.

Fig. 1 Obverse (**a**) and reverse (**b**) of the forged Solidus under investigation (coin A). Actual diameter: 21 mm

Analytical methods

Four techniques were employed in this study.

X-ray fluorescence spectrometry (XRF)

A wavelength dispersive ARL 8410 spectrometer was used to obtain a first qualitative view of the elements present in the obverse or reverse surfaces of the coins.

Scanning electron microscopy (SEM)

SEM was used to investigate the surface morphology down to the micron and sub-micron scale. At some areas where the gold layer was damaged, it was possible to measure its thickness. Energy-dispersive X-ray detection (EDX) was used to obtain semiquantitative information on chemical composition in the micron range. A LEO 1530 field emission SEM with an EDAX Phoenix Si(Li)-detector was used. All SEM micrographs shown are secondary electron images taken with an accelerating voltage of 5 kV.

Electron probe microanalysis (EPMA)

EPMA was used for quantitative element analysis of the gold layer and the core of the coins. The equipment used was a Cameca Camebax SX 50 with four wavelength dispersive X-ray spectrometers (WDX). Quantitative analyses were carried out at 25 kV and 40 nA and by use of the ZAF-program provided by Cameca for matrix correction (ZAF stands for corrections of Z (atomic number), A (absorption), and F (secondary fluorescence)).

Secondary-ion mass spectrometry (SIMS)

SIMS was used to obtain concentration depth profiles of several elements. Conclusions concerning the layer thickness and homogeneity can be drawn and it is possible to perform EPMA or SEM analysis afterwards in the sputter crater. A Cameca ims 5f instrument was used. In contrast with all other applied methods SIMS damages the sample. Therefore, we only used SIMS when the coin was already damaged. In most cases it was possible to limit the crater size to less than 100 μm, so that the craters are barely visible to the human eye.

Among these analytical techniques, SEM and EPMA are established methods in numismatics [5], as is XRF [6]. To our knowledge this is the first report of the use of SIMS for the investigation of ancient coinage, whereas SNMS (Secondary Neutral Mass Spectrometry) has been used for surface analysis of ancient Arabian silver coins [7].

Results and discussion

Daric

Even without any chemical analysis there is a strong evidence that the investigated forgery has a Siglos as a core: the low mass (5.53 g) compared with an original Daric (8.35 g) is a first hint. There are some large and also more minor areas, especially on the reverse, where the gold layer is missing, revealing a silver core. At some of these sites there is a dark deposit on the surface of the core.

In order to find out the applied gilding techniques, the gold cover, the core, and the dark deposits were analyzed by EPMA/WDX. Table 1 shows the results of these measurements and also those obtained from analysis of a genuine Siglos (5.45 g) of the same type.

There is no significant difference between the composition of the core of the forged coin and that of a genuine Siglos. This confirms the assumption that the forgery is a Siglos covered by a gold layer. As the gold cover does not contain any mercury (also confirmed by XRF) the forgery was not achieved by fire gilding.

The dark deposit mostly consists of silver, some oxygen, and chlorine. This is obviously a corrosion product consisting of silver chloride and silver oxide. The presence of corrosion products in areas where the gold cover is missing, caused by long deposit in the earth, might be evidence of the contemporary origin of the forgery.

Table 1 Concentrations of selected elements in the gold layer, the dark deposit, and the silver core of the forged Daric, in comparison with the concentrations in a Siglos. All concentrations (% m/m) were measured by EPMA with WDX detection. Data are given as $\overline{x} \pm 1$ s, – = below significance level

Element	Gold layer	Dark deposit	Silver core	Siglos, surface
Au	94.4 ±1.5	1.9±0.4	1.1±1.4	0.8±1.4
Ag	3.4 ±1.0	75.7±5.3	96.3±2.0	96.3±1.8
Cu	0.7 ±0.4	–	2.1±1.4	1.8±1.1
C	–	–	0.7±0.4	0.7±0.3
Hg	<0.01	–	–	–
O	0.7 ±0.3	9.4±7.1	–	–
Cl	0.06±0.02	8.4±2.6	–	–
Pb	–	0.4±0.3	–	–

In order to decide which of the two remaining techniques of gilding (leaf gilding or foil gilding) was used we investigated the thickness of the gold cover. If it is significantly less than that of gold foil supporting its own weight, foil gilding can be excluded. In the literature no specification for gold foil exists. Obviously the thickness is dependent on the composition. In Ref. [8] a figure of 68 μm is given for the thickness of the electrum layer of a plated forgery, consisting of equal amounts of gold and silver, mixed with grains of sand.

The layered structure of the gold cover might be an indication of leaf gilding. One would expect several layers of gold leaf to be necessary to achieve a sufficiently durable surface. Such a layered structure can clearly be seen in some places of the forged Daric, as illustrated in Fig. 2a, which shows an SEM image of an area where the gold layer is damaged. At least three layers are clearly visible.

The structure is even more visible in a flake of gold that was taken off the coin surface. Fig. 2b shows an SEM image of the flake. It is evident that the gold layer consists of several different leaves, each approx. 1 μm in thickness. Such values were indeed achieved in antiquity. It can be concluded from the statements of Pliny the Elder (23–79 A.C.) [9] that gold leaf with a thickness down to approx. 0.35 μm could be hammered in ancient times. However, he mentioned that somewhat thicker material was used for gilding the statue of Fortuna in Praeneste. Today gold can be extended to a thickness of nearly 0.1 μm. A single leaf is shown in Fig. 2c (the upper side of the leaf has been in contact with the coin). In both images some small crystals between the gold leaves are discernible. EDX shows mostly silver and chlorine, as can also be seen from the element distribution map in Fig. 2d. According to these results and their appearance, the crystals are silver chloride.

Figure 3 shows a SIMS depth profile of the gold layers. Though the depth resolution is poor due to the high surface roughness and the irregular thickness of the gold layer, it is apparent that it is not homogeneous. The slight fluctuations of the gold intensity are also an indication that there is a structure in the gold layer and that it, in fact, consists of several layers of gold. In the interface region a significant increase of the copper concentration was measured, followed by a comparable decrease as moving into the core. This might be indicative of a copper-containing solder.

Considering the non-homogeneous structure and the roughness of the gold layer, the thickness of approx. 20 μm measured by SIMS is not very reliable and probably too high. Nevertheless the SIMS profile confirms that the gold cover is much too thin for foil gilding. There can be no doubt that the core is leaf-gilded.

With regard to the forgers' profit the following calculation can be made: The total surface covered by gold is approx. 5 cm^2. On the basis of a calculated average thickness of the gold cover of approximately 10 μm, the total amount of gold needed for gilding is about 0.1 g, which is

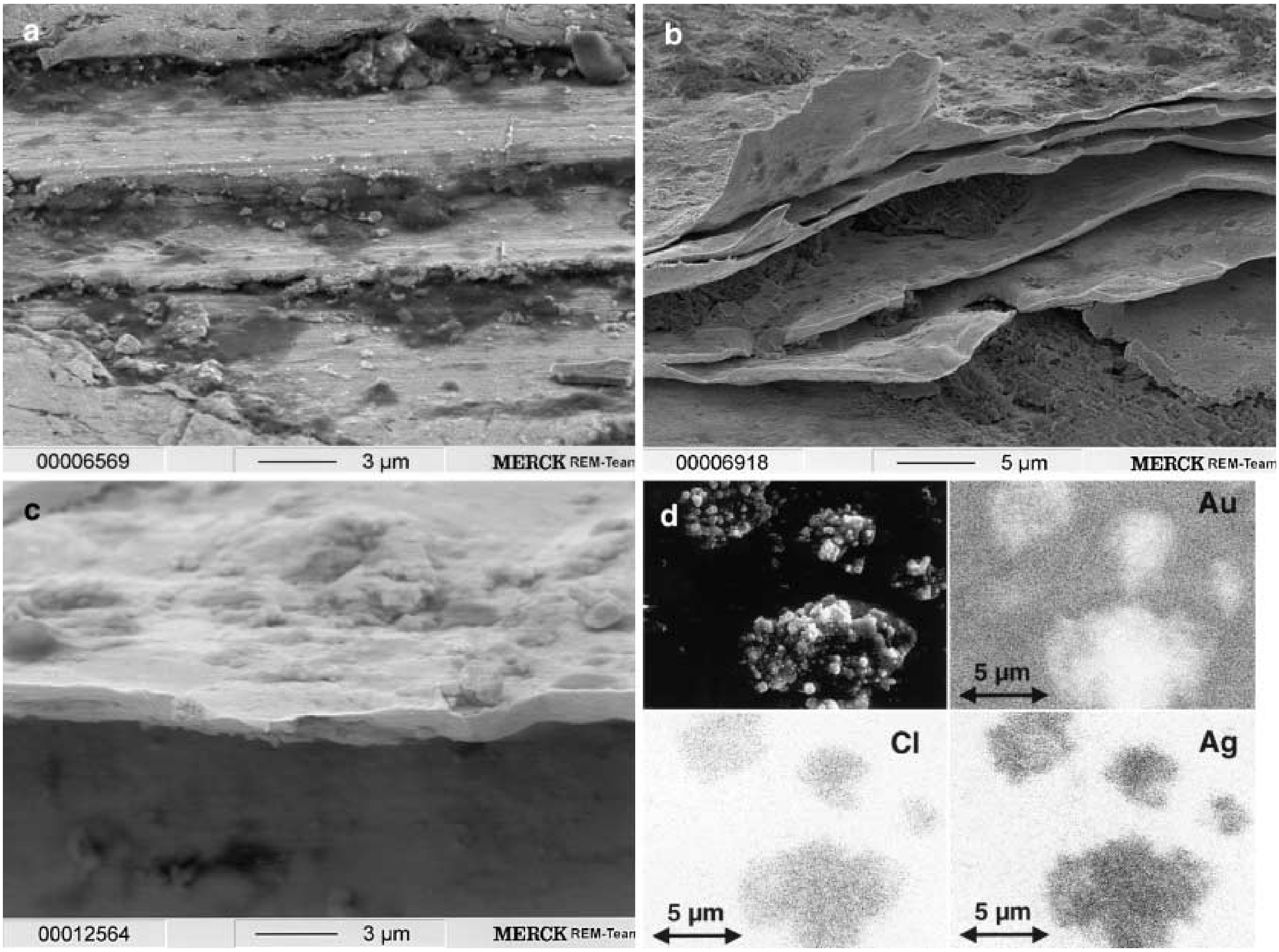

Fig. 2 **a** SEM image of an area on the obverse of the forged Daric, where the gold cover is damaged and different individual gold layers can be seen. **b** SEM image of a small flake of gold taken from the surface of the forged Daric. **c** SEM image of a single gold leaf taken from the area shown in **a**. **d** EDX elemental distribution maps of the crystals shown in **a** (enlarged)

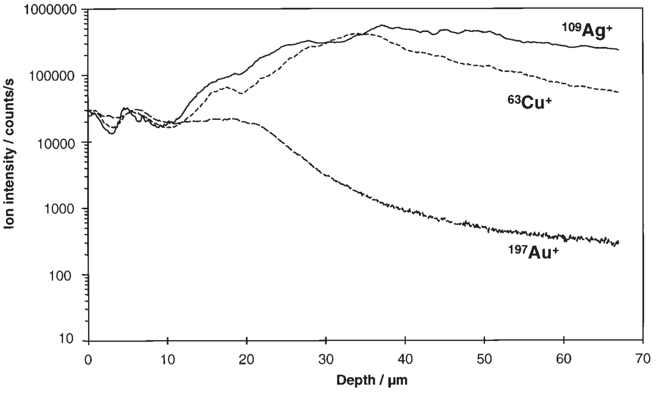

Fig. 3 SIMS depth profile of the gold layer of the forged Daric. Primary ions: O_2^+, 8 keV, 10 nA, detection of positive secondary ions

less than 1% of the mass of a genuine Daric. As the value of a Daric was equal to 20 Sigloi, the total material costs of the forged Daric were less than 6% of an original gold coin. Moreover it was easy to produce this forgery as there was no need for a forged die.

It can be assumed that such falsifications were not used in daily circulation, as they would have been detected very soon. However, one can imagine that sometimes they were mixed among original pieces on occasion of major monetary transactions (e.g. commerce, payment of tribute, war chest for paying mercenaries). As far as we are aware no Daric originating from a Siglos has yet been described. H.P. Wells [1] reported that M.J. Price of the British Museum has suggested the Persian Daric as an important earlier gold class where a precedent to these plated coins might appear.

Gold Stater

The next coin investigated was a Gold Stater which cannot be an original coin due to the lower mass of 5.66 g compared with 8.56 g for an original Gold Stater. It is far better preserved than the Daric and damaged only in some areas.

Table 2 Concentrations of selected elements in the gold layer and the core of the forged Gold Stater. All concentrations (% m/m) were measured by EPMA with WDX detection. Data are given as $\bar{x} \pm 1$ s

Element	Gold layer	Core
Au	89.3±0.8	0.5±0.1
Ag	9.6±0.8	98.6±0.3
O	0.5±0.5	0.4±0.2
Cu	0.2±0.1	0.2±0.1
Si	0.1±0.1	–
Hg	0.2±0.1	0.1±0.1

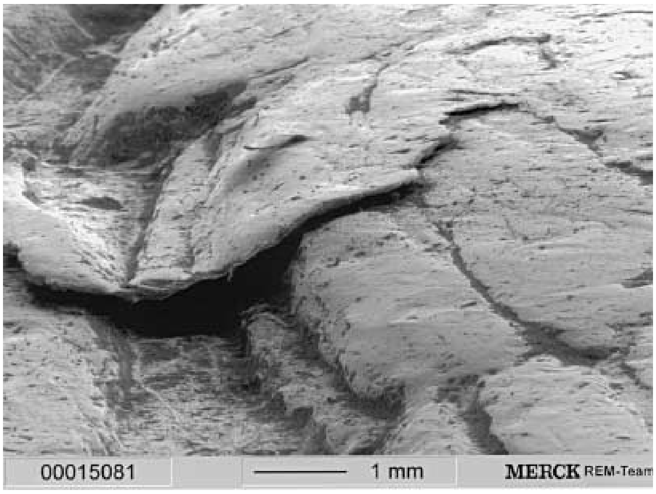

Fig. 4 SEM image of an area on the obverse of the forged Gold Stater

Table 3 Concentrations in the gold layer and the core of both forged Solidi. All concentrations (% m/m) were measured by EPMA with WDX detection. Data are given as $\bar{x} \pm 1$ s.

Element	Coin A layer	Coin A core	Coin B layer	Coin B core
Au	83.1±1.7	0.8±0.5	88.3±1.7	0.5±0.7
Ag	5.2±0.9	95.7±0.9	2.4±0.1	0.1±0.1
Cu	0.3±0.1	2.3±0.2	0.3±0.1	96.9±1.8
Hg	10.8±2.2	–	8.3±1.0	–
C	–	1.3±0.4	–	2.3±0.8

The first analytical method to be used was XRF. The spectrum shows major peaks for gold and silver, but hardly any mercury. The assumption that the core might be of silver and that fire gilding can be excluded were confirmed by EPMA measurements.

Table 2 shows the results of EPMA/WDX measurements of the core (damaged edge of the coin) and the gold cover of the coin (area on the reverse).

To determine whether foil or leaf gilding was applied, an attempt was made to obtain information regarding the structure and thickness of the gold cover. An SEM image taken near the test cut at the edge of the coin shows the homogeneous structure of the gold cover with a thickness of approx. 30 µm. This order of magnitude is confirmed by the fact that in one area on the obverse of the coin a gold layer can be found with a thickness of approx. 30 to 50 µm; this is shown in an SEM image in Fig. 4. The thickness was also measured using a stylus profilometer at three different places near the test cut at the edge and data between 25 and 45 µm were found. From these results gold leaf can be excluded, as the cover is much too thick for gold leaf. Nevertheless the measured data for the thickness are probably not high enough for a self-supporting gold foil. Considering the fact that most measurements were made near the edge of the coin, where the thickness might be lower due to the wear and tear of circulation, it is possible that it is higher in the center of the coin. The results show that there is at least some variation in thickness. It is very likely that a gold foil was used for this falsification, whether supporting its own weight or not.

Considering the amount of gold to be used for this falsification and calculating with a thickness of 25–50 µm for the cover, approx. 300–600 mg of pure gold was needed for a surface of 6.5 cm^2. The material costs (gold cover and silver core) compared with the value of a genuine Gold Stater amount to approx. 9–12%.

Solidi of the late Roman Empire

The low masses of Solidus A (3.10 g) and Solidus B (2.61 g) compared with the mass of an original Solidus (4.42–4.48 g) is a first indication that Solidi A and B are forged. This finding is supported by the optical appearance, especially of coin B on which the gold cover is badly damaged and a dark material different from gold is apparent. XRF analysis on the obverse and reverse of both coins provided insight into the elements present on the surfaces. As expected, the main element we found was gold (approx. 50%) with a remarkably high mercury content (approx. 10%). Coin A showed approx. 30% of silver and coin B approx. the same amount of copper. Both coins obviously have only a thin gold cover over a core of silver (coin A) and copper (coin B), respectively. With this knowledge quantitative analysis in different areas of the coins was carried out using EPMA with WDX detection. Table 3 shows the quantitative results. They confirm those of XRF analysis, according to which coin A has a thin gold cover above a core of silver and coin B has a copper core under the gold cover. The high percentage of mercury in the gold cover demonstrates that the technique used by the forger was fire gilding.

We obtained additional results concerning homogeneity and thickness of the gold cover by SIMS depth profiles, shown for Au, Ag, Cu, and Hg in Fig. 5 for coin B. The gold cover seems to be relatively homogeneous. Its thickness in uncorroded areas is approx. 20 µm. The layer thickness of coin A is comparable with that of coin B.

The continuity of the mercury content over the whole depth of the gold layer excludes the possibility of cold mercury gilding, where mercury is needed as a solder under a gold foil.

Calculating on the basis of a thickness of 10–25 µm for the cover approx. 130–325 mg of gold was needed for a surface of 7 cm^2. The material costs for coin A (gold cover

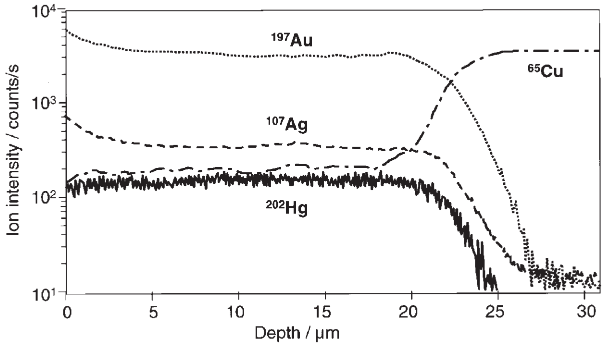

Fig. 5 SIMS depth profile of the obverse of the forged Solidus (coin B) at a place where the gold layer is not damaged. Primary ions: O_2^+, detection of negative secondary ions

and silver core) amount to approx. 9–13% of the value of an original Solidus. For coin B they are only 3–7 % as the value of the copper is negligible.

Depth of information, lateral and depth resolution of the methods used

For qualified interpretation of results obtained by a multimethod approach as applied in this paper, it is important to take into account the variations in the analyzed volumes under the given experimental conditions. This shall be done now for XRF, EPMA/EDX and WDX, SEM-SE, and SIMS. Such a survey is especially important for a composite material such as coated coins.

XRF

It should be evident from the results presented above that XRF is a method that allows a rapid survey of the elements present in the gold layer and the core of the investigated coins. It is on the basis of respective results that further investigations with EPMA and SIMS were opted for. Classical XRF has no lateral resolution and the analyzed area in the ARL instrument used amounted to about 2 cm^2. The depth resolution of XRF, on the other hand, varies greatly. This is important in order to judge whether the obtained analytical information stems only from the gold layer or also from the base material – at least for inspected surface areas where the gold layer is still fully intact. Fig. 6, therefore, shows the dependence of the maximum escape depth as a function of the energy of the characteristic X-rays for the three matrices of interest in this study, i.e. copper, silver, and gold. The maximum escape depth is the depth from which 99% of the generated characteristic X-rays are emitted according to respective equations and data given elsewhere [10]. As can be deduced from Fig. 6, the depth of information varies from, e.g., ≤0.5 µm for light elements with K_α energies in the region of and below 1 keV to 30 µm for $AgK_{\alpha 1}$ (22.16 keV) in gold. It is anticipated for these calculations that all considered characteristic X-rays are well excited by a proper choice of experimental conditions. This great variation of information depth in XRF is seldom realized and certainly a disadvantage of this method. It is interesting to note that for the second-period elements XRF is rather a surface-sensitive than a bulk method of analysis, with a depth of information in the range of much less than 500 nm in heavy matrices.

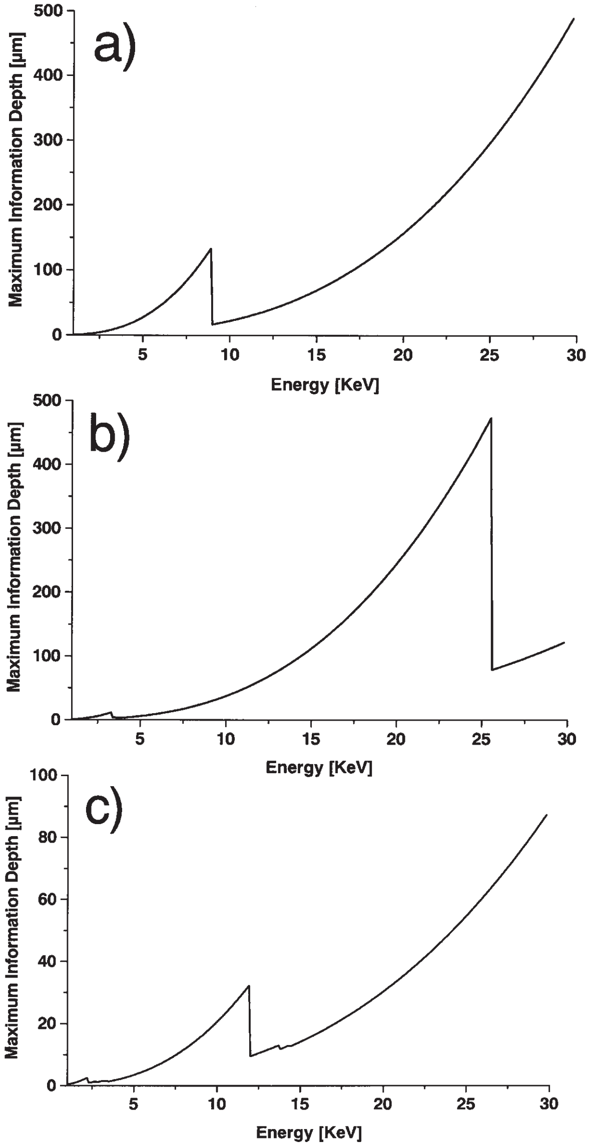

Fig. 6 Depth of information in (**a**) copper, (**b**) silver, and (**c**) gold in XRF as a function of energy of respective characteristic X-ray lines for energies between 1 and 30 keV

Similar considerations are, of course, also of importance for the investigation of other objects of cultural heritage such as antique and medieval glass or paintings [11, 12].

EPMA/WDX and EDX

It is well known that the electron interaction volume in matrices of medium atomic number (Cu: 29) to higher

(Ag: 47) and to high atomic number (Au: 79) and for primary electrons with energies of 20 keV is in the range from 2.3 (Cu) to 1.6 μm (Au) (Bethe-range) [13]. The X-ray generation range is always smaller than the volume of interaction for the primary electrons and again very dependent on the respective energy. For light elements with $K_{\alpha1,2}$ energies below 1 keV (C, N, O, F, Ne) only the escape depth has to be considered, since the respective X-rays generated farther away from the sample surface are completely absorbed. The situation changes with rising Z. For Ag K_α, on the other hand, the depth of information in gold of about 40 μm is far greater than the X-ray generation range of approximately 1 μm under the given experimental conditions. Hence, only the X-ray generation range has to be considered with respect to lateral and depth resolution in this case. For intermediate energies of characteristic X-ray lines the situation is not so straightforward. However, the actual depth of information can always be obtained by comparing the calculated maximum escape depth with the calculated X-ray generation range for the X-ray line in question and under the given experimental conditions (matrix composition and accelerating voltage used).

The lateral resolution for element mapping also is matrix-dependent since the pear shaped interaction volume of the primary electrons is widened to a semicircular volume by the rising number of back-scattered electrons. (The back-scatter electron coefficient rises from 0.06 for C to 0.30 for Cu and to 0.50 for Au [13]. Its dependence on the accelerating voltage is insignificant.) Hence, we can summarize that it is easy to quickly obtain semiquantitative results with EPMA/EDX with a lateral and depth resolution in the single micron range. Since the gold layer is at least about 5 to 10 μm thick even for leaf-gilded coins, it can be anticipated that quantitative analysis of the gold layers is not hampered by interference from the core of the coins wherever an intact surface is evaluated by EPMA/WDX. EPMA in combination with WDX is the most reliable method to obtain quantitative information of the composition of the coins with a lateral resolution in the single micron range at best. The respective advantages over EPMA/EDX are far superior spectral resolution and higher count rates [14, 15].

SE-imaging in the SEM

SEM with a field emission gun as primary electron source yields secondary electron (SE) images with unsurpassed quality due to highest beam brightness and still excellent focusing of the beam. Again lateral resolution is hampered by a rising yield of secondary electrons generated by back-scattered electrons with rising atomic number of the matrix: the ratio of SE generated from back-scattered electrons to SE generated from primary electrons changes from 0.18 for C to 0.90 for Cu and 1.00 for Au [13]. For the low to medium magnifications used in this work this is, however, of no concern. Secondary electrons originate from an average depth of 1–10 nm.

SIMS

SIMS provides a detection sensitivity for most elements which is far superior to the sensitivity of all other topochemical methods and reaches the ng g^{-1}-level in favorable cases [14, 15]. The lateral resolution of SIMS is comparable with that of EPMA in conventional instruments although now instrumentation with a resolution in the 10 nm range has recently become available. The depth resolution lies in the range 5 to 20 nm.

Conclusions

The results show that three typical methods for forging ancient gold coins were used. The forger had to take several parameters into account. These are: strong attachment of the gold layer to the core, tight fit and seal between the layers, complete sealing of the exterior surface, resistance against mechanical stress, a mass close to that of the original, and of course the profit to be gained. He had to find a compromise between these conditions which depended on the target group to be reached, and also on his technical means. How this compromise was established in the case of the coins investigated is shown in Table 4.

The highest profit rate could be made with Solidus B, having a fire-gilded copper core. Due to the poor state of the actual appearance of coin B nothing can be said about its acceptance in ancient times. The appearances of Solidus A and the Gold Stater after many centuries embedded in soil are still very good and demonstrate the advantages of the silver core, although the material costs for this forgery are essentially higher. Assuming forgers had the free choice among the techniques possible they seemed to prefer copper as the core metal of their forgeries. This can be concluded from the record of 44 forgeries [2]: 32 had a copper core, only ten a silver core. Apparently the forgers preferred highest profit over highest safety. When the style of the design of these forgeries was similar to that of an original coin, the only noticeable feature for the ancient user was the difference in their mass, compared with the original. As there was usually no possibility for the user of the forgery to control the mass of the coin, pieces containing a silver core were almost safe from discovery even after a long time of circulation due to the excellent adherence of the gold layer to the silver core.

In the case of the Daric leaf gilding was the only technique possible. Gold could not been hammered down on the Siglos without destroying the already struck design. Fire gilding cannot achieve a smooth surface without subsequent striking with a hammer.

Although fire gilding as well as leaf gilding were possibilities open to the forger of the Gold Stater, he chose foil gilding. Presumably he considered it the safest option.

From the numismatic point of view the following results are remarkable: the Daric with the Siglos as a core is, according to our knowledge, the first one ever described. To attain an efficient stability for the cover, the forger used layers of gold leaf applied one on the top of the

Table 4 Comparison of data relevant to the profit made from forgeries using different techniques

Forged coin	Method used for gilding	Metal cover	Thickness of cover [µm]	Amount of gold needed [mg]	Metal core	Mass of forgery/mass of genuine coin	Surface to be gilded	Material costs compared with genuine coin
Daric	Leaf gilding	Au≈94%	5–10	50–100	Ag (genuine Siglos)	0.64	≈5 cm^2	6%
Gold Stater	Foil gilding	Au≈89%	25–50	300–600	Ag≈99%	0.66	≈6.5 cm^2	9–12%
Solidus A	Fire gilding	Au≈83%	10–25	130–325	Ag≈96%	0.70	≈7 cm^2	9–13%
Solidus B	Fire gilding	Au≈88%	10–25	130–325	Cu≈97%	0.60	≈7 cm^2	3–7 %

Table 5 Comparison of possibilities offered by different analytical techniques for the investigation of ancient coins

Method	Lateral resolution	Rapid qualitative analysis	Quantitative analysis	Depth profile	Non-destructive
XRF	None	++	++		++
EDX	++	++	+		++
WDX	++	+	++		++
SIMS	++		+	++	

other. The thickness of the gold foil calls for further research into its handling, as it does not seem to be self-supporting. Alexander Gold Staters from Lampascus seem to have been preferred objects of falsification. An original that recently turned up on the coin market showed a deep test cut [16].

The results show that it is helpful to use a combination of different analytical techniques for the investigation of ancient coins. XRF is a method that allows a rapid survey of the elements present in the coin. With EPMA and an EDX detector it is easy to quickly obtain semiquantitative results with lateral and depth resolution in the single micron range [13]. EPMA in combination with a WDX detector is the easiest method to obtain quantitative information on the composition of small areas of the coins, again with the lateral and depth resolution in the single micron range. SEM with a field emission gun as the primary electron source yields morphological information with unsurpassed depth of field and lateral resolution in the single nanometer range in the case of objects with sharp contrast [13]. All these methods have the advantage of being non-destructive.

SIMS has not been used in numismatics before probably due to its destructive nature and high instrument cost. However, SIMS is one of the rare methods that provides information on the depth-distribution of elements and the homogeneity of thin layers. The sputter crater can be limited to an area of 100 µm×100 µm or smaller, which is hardly visible to the human eye. In addition, SIMS provides a detection sensitivity for most elements that is far better than the sensitivity of all other topochemical methods and reaches down to the ng g^{-1} level in favorable cases. The same holds for SNMS, which has been used to investigate the in-depth distribution of several elements in ancient Arabian silver coins [7].

Table 5 summarizes all methods used in this study with their advantageous features.

Acknowledgements The authors acknowledge assistance in experimental work by F.J. Stadermann, B. Thybusch, S. Riedl, and M. Ebert at TU Darmstadt and B. Jordan and H. Opfermann at Merck KGaA.

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