Tracing Dacian Gold in Roman *Aurei*

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Abstract

Here the LA-ICP-MS results from 66 Roman gold coins (*aurei*) issued between AD 101 and AD 196 are presented. *Aurei* issued between AD 129 and AD 165 seemed to have been made from an antimony- and tellurium-rich gold. The Roman gold mines at Roșia Montană in Dacia, modern day Romania, produce antimony- and tellurium-rich gold, and we have precisely dated documentary evidence that suggests intensive mining activity occurred here from at least AD 131 until AD 167. The intensity of the proposed antimony- and tellurium-rich Roșia Montană 'fingerprint' in Roman gold coinage almost perfectly matches the chronological window of intensive exploitation of the Roșia Montană gold source. As such, gold from Dacia appears to have been one of the most dominant sources for the Roman supply network in the mid-second century, and the strategic importance of the province at this time should not be underestimated.

Keywords

Roman, Gold, Coins, Dacia, Roșia Montană, LA-ICP-MS

Abbreviations

RIC — Roman Imperial Coinage Series (Spink Books)

1. Introduction

The importance of the gold extraction sites in the province of Dacia, now modern day Romania, for the Roman gold supply network deserves further appreciation. The extensive mining operations in the North West of the Iberian Peninsula form a major part of the discussion of the Roman gold supply in the late first and early second centuries (Domergue, 1990, 208-15; 2008; Hirt, 2010, 34-6; 2020, 113-6). Gold from Dacia is instead more frequently associated with the spoils of Trajan's Dacian wars from AD 101 to AD 106. The Byzantine epitomator John the Lydian preserves the claim of Trajan's doctor, T. Statilius Crito, that over two million kilos of gold and four and a half million kilos of silver were captured as a result of the wars (Makkay, 1995); and an inscription in Trajan's Forum states that it was built *ex manubiis* — from the spoils of war – with the forum itself containing multiple friezes depicting the successful conquest of Dacia (Yegül & Favro, 2019, 339). The importance of Dacian mining regions is, however, evident. We have extensive evidence of the Romans intensively exploiting the gold sources within the 'golden quadrilateral' (Figure 1) centred on the Brad-Săcărâmb and Zlatna basins in Transylvania (Lim, 2018). The most comprehensive excavations have been conducted at Roșia Montană, which have revealed a sprawling network of gold mines containing over 6km of Roman tunnels, as well as timber support posts, water wheels, oil lamps and wax tablets (Cauuet, 2014; Cauuet & Tamas, 2012; Hirt, 2020, 117; Lim, 2018, 159-62). Roman gold mining activity in Dacia appears to have been at its height during the second century AD, and so the aim here is to trace the use of Dacian gold in the gold coinages produced by the Roman state at this time. This will provide the metallurgical data to underpin the importance of Roman gold extraction in Dacia.

The University of Oxford's Ashmolean Museum holds 66 *aurei* issued between AD 100 and AD 199, all of which were made available for trace element analysis using laser ablation inductively coupled mass spectrometry (LA-ICP-MS). The trace element chemistry of these coins across this century is compared here against the geological and mineralogical profile of the gold deposits at Roșia Montană. Of course, congruency in characterisations does not necessarily mean that provenance must follow. However, in this case, not only do we have extensive historical and archaeological evidence for Roman mining activity in Dacia, but we have precisely dated epigraphic and documentary evidence for activity at the Roșia Montană site. As such, not only do we have a firm understanding of the trace element 'fingerprint' that gold from Roșia Montană should produce, but we also know when this 'fingerprint' should be appearing in the chemical record.

The result of all this is that we are able to determine how important the Dacian gold mines were to the Roman gold supply network, and for how long this was the case.

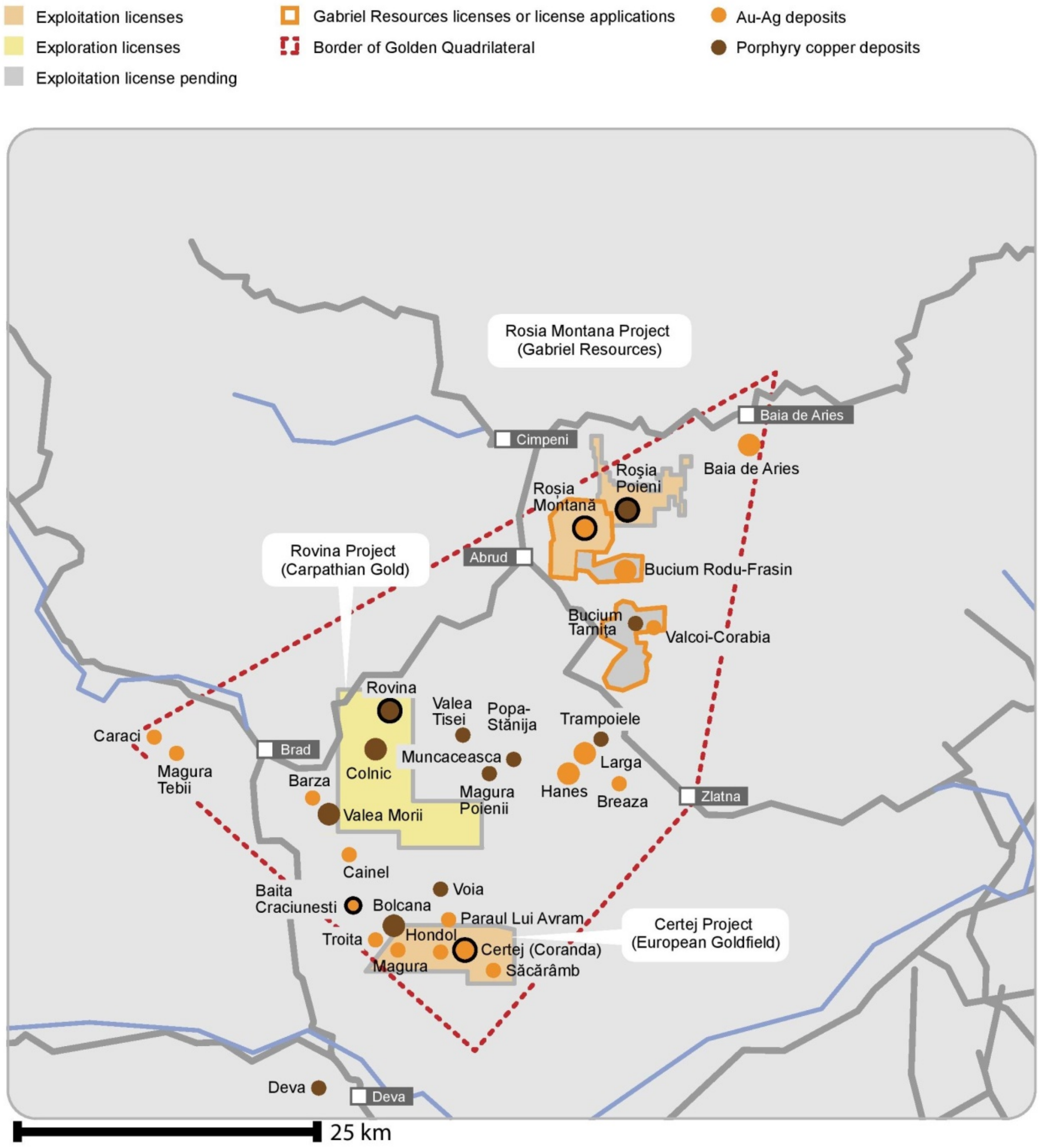

Figure 1 A map of Au-Ag and porphyry copper deposits in the 'golden quadrilateral' of Romania, reproduced with the express permission of Gabriel Resources Ltd. Gabriel Resources retains all rights to the image and any further permission to reproduce or use the image should not be inferred.

2. The Characterisation of Gold from Roșia Montană

Transylvanian gold exists as both ‘native gold’ and gold tellurides, with the main gold tellurides including Hessite (Ag_2Te), Krennerite ($(Au,Ag)Te_2$), Nagyagite ($Pb_5Au(Te,Sb)_4S_{5-8}$), Petzite ((Ag_3AuTe_2)), and Sylvanite ($(Au,Ag)Te_4$) (Constantinescu et al., 2010b, 49-50). Samples of gold taken from Roșia Montană were analysed by Constantinescu et al. (2010b) using XRF, with a variety of potential ‘discriminator elements’ being detected. These included Fe, Zn, Mn, Si and Pb. Micro PIXE analysis revealed Sb, Te, Zn and Ag rich areas on the outlying gold grains, with Micro SR-XRF confirming the presence of Te, Sb and Sn in the samples from Roşia Montană. In terms of characterisation, it is the presence of tellurium and antimony that are the most useful discriminator elements. Gold tellurides are relatively uncommon gold-bearing minerals and so tellurium-rich gold is proportionately rare in the archaeological record (Boyle, 1979; Constantinescu et al., 2010a, 1036-

7; Hauptmann et al., 1995; Morteani, 1995). As such, the presence of tellurium in an archaeological gold object immediately narrows the range of plausible sources. Roşia Montană contains multiple telluride minerals, but most importantly it contains antimony-bearing gold tellurides — like the mineral Nagyagite (Constantinescu et al., 2010b, 49-50). This, with other antimony- or tellurium-rich minerals (Baron et al., 2011, 3.1; Cauuet & Tamas, 2012, 221-2; Tămaş et al., 2006, 374-6), means it produces gold that is relatively rich in both antimony and tellurium (Constantinescu et al., 2010a, 1036; Constantinescu et al., 2010b, 54). Constantinescu et al. (2010a, 1036) state their samples of gold from Roşia Montană contained c. 0.25% (2500 ppm) of tellurium and c. 0.05% (500 ppm) of antimony. Pop et al. (2011, Tables 1 and 2) recorded concentrations of tellurium that ranged from 1300 to 2100 ppm in c. 58% to 88% pure gold samples from Roşia Montană, with antimony recorded as one of the main chemical associations.

It should be acknowledged that both tellurium and antimony barely make it through the Roman gold refining process: the median concentration of tellurium in Roman gold coinage is 0.31 ppm and the median concentration of antimony is 1.28 ppm (Green, 2021, Table 18). The Roman refining process involved the melting, cupellation and/or cementation of the extracted gold (Blet-Lemarquand et al., 2017; Craddock, 1994, 2000a; Guerra & Calligaro, 2004; Healy, 1979; Ramage & Craddock, 2000, 11). Cupellation involved adding significant quantities of lead to the impure gold, then melting them together in a porous clay crucible - the cupel. A current of air was then passed over the top, which oxidises the base metals either driving them off as vapours or into the porous walls of the cupel. Blet-Lamarquand et al. (2017, Table 1) show that gold that originally contained 60 ppm of antimony only contained 3 ppm after melting and 0.2 ppm after cuppelation. Salt cementation was used to part the silver from the gold. This process revolves around heating argentiferous gold foil with salt in a sealed container that contained water vapour and ferruginous siliceous material – the iron oxide and silica could be provided by brick dust or the porous earthenware walls of a ceramic parting vessel. The sodium chloride decomposes in the presence of silica and alumina, provided by the brick dust or clay, to first produce hydrogen chloride. Hydrogen chloride attacks metal salts to form chlorides – copper salts form cupric chlorides, for example - that eventually dissociate and evolve chlorine gas. Silver reacts with chlorine gas to produce silver chloride, a volatile compound that separates from the more inert gold. The hydrogen chloride also reacts with the iron oxides present to form ferric chloride – this reacts with silver, as well as eventually breaking down into more hydrogen chloride and chlorine gas (Craddock, 2000b, 180-2). Silver from deeper within the metal then diffuses towards the surface, where it reacts with chlorine and the process continues (Meeks, 2000, 145). Base metals are attacked by hydrogen chloride, chlorine gas and the highly reactive ferric chlorides (Craddock, 2000b, 180-1). The cementation process would almost certainly have affected the trace element composition of the gold; indeed the surfaces of the parting vessels analysed by Meeks (2000) were enriched with silver salts along with a variety of other metals. Tellurium specifically reacts with halogens like chlorine to form halides and so it is unlikely to have endured this particular part of the Roman refining process unmolested. As such, while we will never see the exact concentrations of tellurium and antimony from our potential gold sources literally transposed to the gold coinage, it can be quite safely assumed that a source that contained elevated concentrations of these elements compared to other sources will result in gold that is relatively richer in these elements.

Indeed, the presence of antimony alongside tellurium allows for the gold from Roşia Montană to be discriminated even from other geographically close Transylvanian sources. For example, the gold from the Musariu deposit (worked in antiquity at Ruda-Brad) – approximately 30 km south west of Roşia Montană – is tellurium-rich, but is not characterised by the presence of antimony by Constantinescu et al. (2010b, 55). An electrum grain included in pyrite sampled from a porphyry copper deposit at Colnic, approximately 30 km south west of Roşia Montană, was also tellurium-rich (c. 1300 ppm), but seemingly did not contain an appreciable concentration of antimony (Cioacă et al., 2014).[1] Of the nine electrum grains sampled from minerals at the porphyry copper deposit at Bolcana, six contained 100 ppm of tellurium or less (Cioacă et al., 2010). The gold sampled in quartz and bornite essentially contained none, while the four grains sampled in chalcopyrite ranged from 100 to 2100 ppm tellurium, with a mean of 900 ppm. Antimony was not collected. Finally, Pop et al. (2011, Table 1) did not record antimony as a main chemical association with the tellurium-rich gold at Boteș or Valacoi-Corabia, both of which are located at Bucium approximately 5 km south-east of Roşia Montană.

However, it should be acknowledged that other Transylvanian gold sources can contain both tellurium and antimony. In some of these cases the scale of the antimony and tellurium inclusions in the gold from Roşia Montană can allow us to discriminate between sources. For example, the gold deposits at Valea Morii – approximately 40 km south west of Roşia Montană – contain both of these elements. Here, however, both elements occur in significantly lower concentrations compared to Roşia Montană: samples analysed by Constantinescu et al. (2010a, 1036) contained approximately ten-times less tellurium and half as much antimony compared to their samples from Roşia Montană. A potential source that begins with up to ten-times less tellurium and half as much antimony as Roşia Montană is, then, likely to produce gold that is comapratively much less rich in these elements. This would enable it to be discrimated from the products of Roşia Montană.

There are, however, sites where we know that tellurium-rich gold could be exploited in the Roman period, but we lack the precise and comprehensive analyses of samples of gold from these sites to be able to differentiate the concentration of antimony (or other trace elements) from that of Roşia Montană. In some cases, the evidence suggests that these sites were not particularly intensively mined by the Romans. For example, in the Roman period Baia de Arieș appears to be a late second-/early third-century gold-washing site (Lim, 2018, 207) and the evidence for intensive Roman exploitation at Rodu-Frasin is as-of-yet muted compared to the neighbouring sites at Valacoi-Corabia (Lim, 2018, 186), which seem to not have been characterised by the presence of antimony (Pop et al., 2011, Table 1). On this theme, we should probably exclude the gold deposits at Romanian porphyry copper sites as well. In the Roman period it appears that even copper was not extracted from these porphyry copper sites, with the majority of our evidence for Roman copper extraction in this province concentrated in the south west (Lim, 2018, 221). These low-grade copper ores require the movement of huge volumes of rock, which means even modern commercial operations have problems with economic feasibility. Gold in bulk rock samples from these sorts of deposits seems generally to be 2000 to 7000 times less abundant than copper and present as fine particles trapped within the lattice structure of pyrites[2] (Cioacă et al., 2014, Table 3, Fig. 7). As such, it is improbable that the Romans could prospect gold at these deposits let alone move the volumes of rock required to justify exploiting them – there were far more accessible and richer gold deposits in Dacia anyway.

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[1] Antimony was collected and presented throughout the rest of the work. Other trace elements (c. 100 ppm) were presented from the electrum grain – the deduction here is that Sb was <100 ppm.

[2] This can be referred to as 'invisible gold'.

This means we can quite safely exclude the gold-rich porphyry copper deposits at Roşia Poieni, Bucium–Tarniţa, Colnic, Rovina, Valea Morii and Bolcana.

However, this does leave us with a few notable cases such as Stănija (c. 18 km south west of Roşia Montană) and Săcărâmb (c. 40 km south) where we know there was significant Roman activity (Lim, 2018, 189-93); initial elemental analysis of gold samples suggest the gold exploited here was tellurium-rich and the gold deposits seem to be associated with antimony to some degree (Pop et al., 2011, Table 1 and 2), but we lack the comprehensive trace element analysis of these samples to discriminate them from Roşia Montană based on their antimony, or any other trace element, content. At this point, we are reliant to some extent on an argument from silence: we lack evidence from these sites that they had the same scale and intensity of mining operations as at Roşia Montană, meaning it is probable that Roşia Montană contributed the majority of the antimony- and tellurium-rich gold seen in the Roman supply network. There is also no guarantee that the chronology of their exploitation matches that of Roşia Montană either.

Broadly speaking, then, it seems that when the necessary comparative data exist it is possible to differentiate the chemical profile of the gold deposit at Roşia Montană from other Dacian sources, and when left with sources that may potentially overlap with the chemical signature of Roşia Montană we currently lack evidence that they were exploited as intensively in the Roman period. Roşia Montană remains exceptional in Dacia for the degree of its exploitation in antiquity. As such, if we see antimony- and tellurium-rich gold in second-century coinage, then we can be confident it is coming in great part from Roşia Montană.

Nevertheless, when this antimony- and tellurium-rich gold source is detected in Roman *aurei* is it perhaps safer to refer to it as 'Dacian gold', given that we know the Romans were exploiting multiple Transylvanian deposits (Lim, 2018), and some of these may well have contained antimony and/or tellurium? Caution here, however, may well be more misleading: as shown above we know that many Dacian gold deposits do not produce antimony- or tellurium-rich gold in the same way as the Roşia Montană deposit does. This particular signature cannot come from any old Dacian mine. So perhaps the best epithet for this is 'antinomy- and tellurium-rich Dacian gold'. It is clear though that Roşia Montană was where the most intensive Roman operations were in this region (Baron et al., 2011; Cauuet, 2014; Lim, 2018; Wilson et al., 2011), and we can probably be quite confident in attributing it primary responsibility for any 'Dacian' signature, but especially for any antimony- and tellurium-rich gold from this province. Indeed, we have epigraphic and documentary evidence providing a date of no later than AD 131 for the start of *intensive* mining operations at Roşia Montană (though we would expect operations to have begun earlier), and documentary evidence indicating that operations in many of the mining galleries ceased in AD 167, although a few galleries were worked again at some point in the third century AD. This evidence is dealt with in more detail in the discussion section. As such, we have a relatively narrow date range in which to expect gold from these particular mines to be particularly prevalent. It follows, then, that if our 'antimony- and tellurium-rich Dacian gold' signature rises when activity at Roşia Montană intensifies and falls at the time when operations cease, it is even more probable that Roşia Montană was providing the bulk of this antimony- and tellurium-rich gold used to make Roman coinage.

3. Materials and Methods

As part of the *Gold Coinage in the Roman World Project*, 573 Roman gold coins in the Ashmolean's collection were made available for analysis using XRF and LA-ICP-MS. Here the LA-ICP-MS results from 66 second-century *aurei* are presented. The earliest coin has an earliest issue date of AD 101 and the latest an earliest issue date of AD 196. The full major and trace element results for all the coins analysed as part of this project, including additional trace elements for the coins presented here, can be found in tables 19 and 20 of Green's (2021) doctoral thesis.

The LA-ICP-MS measurements were conducted on a Perkin Elmer NexION quadrupole mass spectrometer coupled to a New Wave Research UP213 Nd:YAG laser at the University of Oxford's Department of Earth Sciences. In total 573 Roman gold coins from the Ashmolean's collection were analysed on this set-up. Custom sample holders were designed and built in cooperation with the museum's conservation department; these were able to hold approximately 40 coins vertically within the laser ablation chamber so that edges of the coin could be sampled. By sampling the edges rather than faces of the coins, the detrimental effect of destructive sampling on the aesthetics of the coin could be kept to a minimum.

A beam diameter of 50 µm was used for all coins. This resulted in a crater that was approximately 0.05 mm across, which is barely visible with the naked eye and often smaller than some of the imperfections on the edges of the gold coins analysed. The craters themselves were approximately 80 to 100 microns deep. Three spots were analysed on each coin. The analysis of each spot on a coin involved determining the background counts for the first 20 seconds of each 60-second analysis. Counts were then collected for the mass of each isotope during the 40 second period of ablation. The effect of any background interference was minimised by including a c. 40-second 'wash-out' period between each spot analysed. Raw counts were collected on the ICP-MS in peak-hopping mode and displayed in time-resolved format. The following isotope masses were counted: ^{32}S, ^{47}Ti, ^{51}V, ^{52}Cr, ^{55}Mn, ^{56}Fe, ^{59}Co, ^{60}Ni, ^{63}Cu, ^{66}Zn, ^{69}Ga, ^{73}Ge, ^{75}As, ^{77}Se, ^{95}Mo, ^{97}Mo, ^{101}Ru, ^{103}Rh, ^{105}Pd, ^{107}Ag, ^{111}Cd, ^{113}In, ^{115}In, ^{118}Sn, ^{121}Sb, ^{125}Te, ^{183}W, ^{185}Re, ^{193}Ir, ^{194}Pt, ^{195}Pt, ^{203}Tl, ^{205}Tl, ^{208}Pb and ^{209}Bi. Yields were calibrated on a NIST 610 glass standard, which was the primary standard used. A USGS glass standard — BCR-2G — was used as a secondary standard to monitor the accuracy of the calibration. Every nine to eighteen spots analysed all the standards were re-analysed to avoid calibration drift; fewer spots were analysed between the re-analysis of the standards at the beginning of the analyses as this is when the potential drift was at its greatest. Silver was used as the internal standard for all the coins analysed as all the gold coins in the museum's collection consisted of at least c. 0.1% silver. The silver content of each coin was determined through XRF (mean absolute error ±0.06, precision ±0.02). For the data reduction process the LADR software package[3] was used. This package was able to identify and remove transient spikes in the spectra, correct for interferences, take account of secondary standards to correct for matrix effects, and calculate the margin of error for the analytical totals returned.

The use of a non-matrix matched standard – commonly a NIST 610 or 612 standard — alongside an internal standard determined by a second technique is a well-established analytical protocol (Resano et al., 2010). It has been used for the study of ancient glass (Shortland et al., 2007), human dental remains (Cucina et al., 2007), medieval pottery (Duwe & Neff, 2007), pre-historic pigments (Resano

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[3] https://norsci.com/?p=ladr

et al., 2007) and renaissance silver coins (Gentelli, 2019). Of these examples, Gentelli's (2019) is probably the most similar study to the work conducted here and is also the most recent – it involved normalising the counts-per-second data against a NIST 612 standard and using a NIST 610 standard to check for instrument drift. This is very similar to the procedure followed here for the analysis of the gold coins.

The quality of LA-ICP-MS results is routinely assessed through the use of an 'uncertainty' figure, most commonly expressed at the 2 sigma (2σ) level for each individual data point or using 95% confidence interval for a population (Lin et al., 2016). The LADR software package is able to calculate the uncertainty for each of the isotope masses measured on each spot analysed, taking into account a range of possible sources of error. The degree of uncertainty can then be expressed from a 1 to 5 sigma level – the 2 sigma level was used here. There are a variety of sources of uncertainty in LA-ICP-MS that include: the precision of the signal; the quantification precision observed on the calibration standards; the uncertainty from the misfit of the calibration model; the uncertainty associated with the heterogeneity of the analyte element and the internal standard element within the calibration standards; the variation of the secondary standard correction factor over the length of the analytical session; and the uncertainties associated with the known values of the analyte mass and the internal standard element within the calibration standard. The 'full analytical uncertainty with secondary standard correction' option[4] within the LADR package takes into account all of these known sources of uncertainty, producing a comprehensive 2σ uncertainty value for every data point. Here it is expressed as a relative percentage. The mean 2σ uncertainty for tellurium across the 66 *aurei* analysed was c. 43% and for antimony it was c. 7%.

The use of trace element compositions obtained through LA-ICP-MS for provenance studies of gold is a well-established and robust method (Blet-Lemarquand, 2006; Blet-Lemarquand et al., 2015; Gauert et al., 2016; Gondonneau & Guerra, 2002; Grigorova et al., 1998; Guerra et al., 1999; Watling et al., 1994).

4. LA-ICP-MS results

Table 1 contains a brief catalogue of the 66 coins analysed alongside their tellurium and antimony contents as determined by LA-ICP-MS.

Emperor	Type	Start Date	End Date	Mint	Sb (ppm)	Te (ppm)
Trajan	RIC 49	101	102	Rome	0.50	2.81
Trajan	RIC 90	103	111	Rome	0.30	0.31
Trajan	RIC 207	103	111	Rome	1.87	4.58
Trajan	RIC 275	112	114	Rome	2.16	0.18
Trajan	RIC 294	112	114	Rome	6.64	0.68
Trajan	RIC 253	112	114	Rome	4.41	1.36
Trajan	RIC 319	114	114	Rome	9.50	3.48
Hadrian	RIC (2nd ed.) 29	117	117	Rome	3.33	0.94
Hadrian	RIC (2nd ed.) 50	117	117	Rome	2.58	1.53
Hadrian	RIC (2nd ed.) 2448	117	118	Rome	3.86	1.88

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[4] See LADR manual - https://norsci.com/?p=ladr-support

Hadrian	RIC (2nd ed.) 120	117	117	Rome	3.90	2.09
Hadrian	RIC (2nd ed.) 201	119	120	Rome	2.06	0.27
Hadrian	RIC (2nd ed.) 586	121	123	Rome	3.75	0.41
Hadrian	RIC (2nd ed.) 508	121	123	Rome	7.72	1.15
Hadrian	RIC (2nd ed.) 711	124	125	Rome	4.49	0.95
Hadrian	RIC (2nd ed.) 781	125	127	Rome	16.43	0.25
Hadrian	RIC (2nd ed.) 934	128	129	Rome	24.10	0.67
Hadrian	RIC (2nd ed.) 1061	129	130	Rome	24.44	1.07
Hadrian	RIC (2nd ed.) 1477	130	133	Rome	10.82	0.80
Hadrian	RIC (2nd ed.) 1565	130	133	Rome	18.29	1.62
Hadrian	RIC (2nd ed.) 2210	136	136	Rome	82.69	2.23
Hadrian	RIC (2nd ed.) 2366	137	138	Rome	6.62	0.48
Hadrian	RIC (2nd ed.) 2624	137	137	Rome	14.61	1.53
Hadrian	RIC (2nd ed.) 2647 (denarius type)	137	137	Rome	29.47	3.23
Antoninus Pius	RIC 75C	140	143	Rome	47.49	3.11
Antoninus Pius	RIC 352A	141	141	Rome	15.35	2.77
Antoninus Pius	RIC 356A	141	141	Rome	52.99	3.97
Antoninus Pius	RIC 349Aa	141	141	Rome	11.60	6.26
Antoninus Pius	RIC 109C	143	144	Rome	25.02	1.40
Antoninus Pius	RIC 113	143	144	Rome	5.28	2.78
Antoninus Pius	RIC 494A	145	161	Rome	1.22	0.21
Antoninus Pius	RIC 432A	145	160	Rome	6.14	0.74
Antoninus Pius	RIC 501	145	161	Rome	3.43	0.87
Antoninus Pius	RIC 503Ba	145	161	Rome	10.34	1.92
Antoninus Pius	RIC 147D	145	161	Rome	55.90	5.41
Antoninus Pius	RIC 177D	148	149	Rome	8.91	2.97
Antoninus Pius	RIC 445Ac	148	149	Rome	15.47	3.20
Antoninus Pius	RIC 199A	150	151	Rome	11.54	3.11
Antoninus Pius	RIC 213	151	152	Rome	3.10	0.26
Antoninus Pius	RIC 213	151	152	Rome	5.46	1.31
Antoninus Pius	RIC 233D	153	154	Rome	3.19	1.58
Antoninus Pius	RIC 464A	154	155	Rome	3.73	0.17
Antoninus Pius	RIC 469A	156	157	Rome	8.25	1.95
Antoninus Pius	RIC 279C	157	158	Rome	3.78	0.85
Antoninus Pius	RIC 313A	160	161	Rome	9.32	2.12
Marcus Aurelius	RIC 704	161	176	Rome	1.19	0.00
Lucius Verus	RIC 487	161	162	Rome	0.13	0.12
Lucius Verus	RIC 472	161	162	Rome	5.26	0.22
Marcus Aurelius	RIC 435	161	180	Rome	20.67	5.40
Lucius Verus	RIC 470	161	162	Rome	18.60	9.62
Marcus Aurelius	RIC 717	161	176	Rome	20.51	14.04
Marcus Aurelius	RIC 77	162	163	Rome	10.02	2.95
Lucius Verus	RIC 499	163	163	Rome	2.59	1.26
Marcus Aurelius	RIC 783	164	180	Rome	1.09	0.17
Marcus Aurelius	RIC 127	164	165	Rome	2.99	4.50

Lucius Verus	RIC 551	165	166	Rome	7.62	0.34
Marcus Aurelius	RIC 184	168	168	Rome	0.94	0.10
Marcus Aurelius	RIC 616	175	176	Rome	0.76	0.38
Commodus	RIC 287	178	191	Rome	0.12	0.20
Commodus	RIC 275	180	180	Rome	2.22	0.82
Commodus	RIC 40	181	182	Rome	0.31	0.15
Commodus	RIC 164	187	188	Rome	1.09	0.00
Commodus	RIC 179	188	189	Rome	4.93	1.47
Septimius Severus	RIC 536	193	196	Rome	0.67	0.31
Pertinax	RIC 11	193	193	Rome	31.99	3.53
Septimius Severus	RIC Caracalla 3	196	196	Rome	1.08	0.00

Table 1 A catalogue of the *aurei* analysed alongside their antimony and tellurium concentrations, as determined by LA-ICP-MS.

Taking tellurium first, it is clear that while it is present in very low concentrations there are distinct peaks that can be observed across the second century (Figure 2). Between AD 101 and AD 117, seven of the eleven *aurei* analysed contained 1 ppm or greater of tellurium. This tellurium peak seems to tail-off over the 120s, but by AD 129 another rise in the concentration of tellurium can be detected. These elevated levels last for approximately three decades, with 26 of the 38 coins analysed between AD 129 and AD 164 containing 1 ppm or greater of tellurium. There is a sharp decline after this point – only two of the eleven remaining coins from the late second century contained greater than 1 ppm of tellurium. In sum, there is a short peak in the early second century, a clearer, longer peak between AD 129 and AD 164, and two outlying coins at the end of the second century.

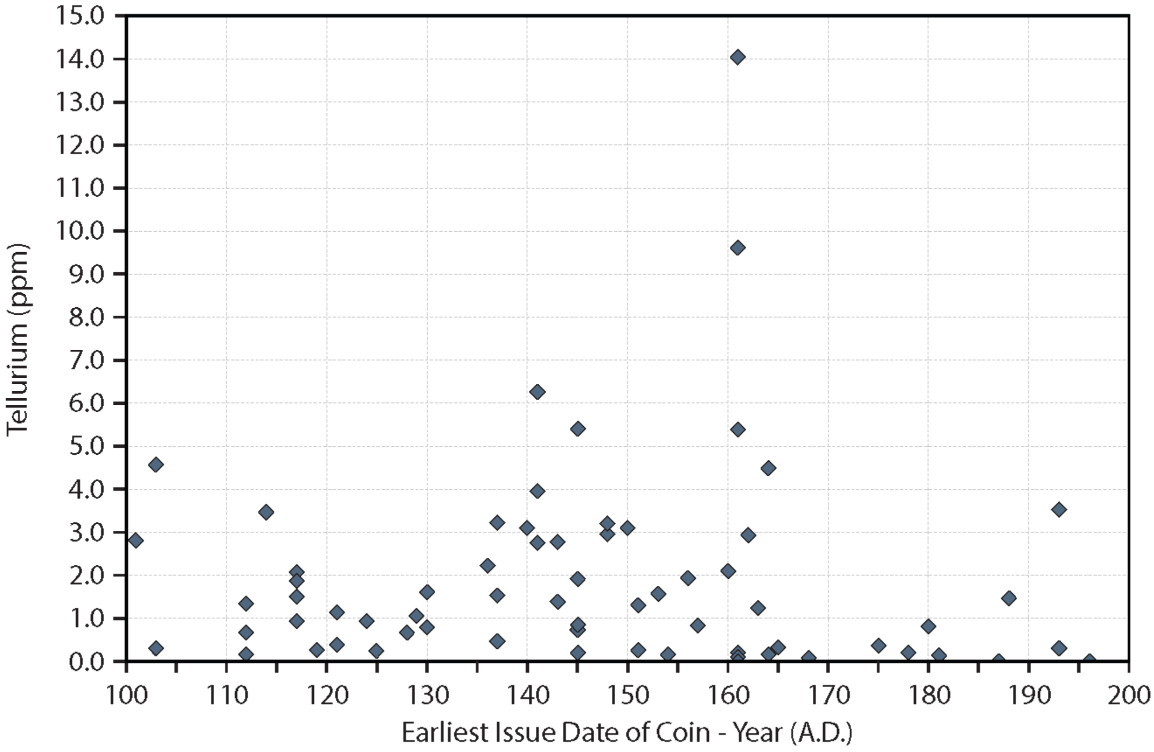

Figure 2 The concentration of tellurium in *aurei* issued between AD 101 and AD 196.

The pattern for antimony is somewhat neater (Figure 3). There is a cluster of relatively low antimony coins for the first quarter of this century, followed by a sharp rise around AD 125 to AD 130. There is then a relatively smooth rise and fall until AD 165, after which point there is a sharp drop in the concentration of antimony that lasts until the end of the second century, with the exception of one outlying antimony-rich coin. From AD 101 to AD 124 the mean concentration of antimony is 4 ppm, from AD 125 to AD 150 it is approximately 22 ppm, and from AD 151 to AD 165 it has dropped to 7 ppm. For the remainder of the century *aurei* generally contain 2 ppm or less of antimony, with the exception of the outlying coin from AD 193 containing c. 32 ppm. Relatively speaking the most consistently elevated concentrations of antimony can be seen between AD 125 and the early 160s.

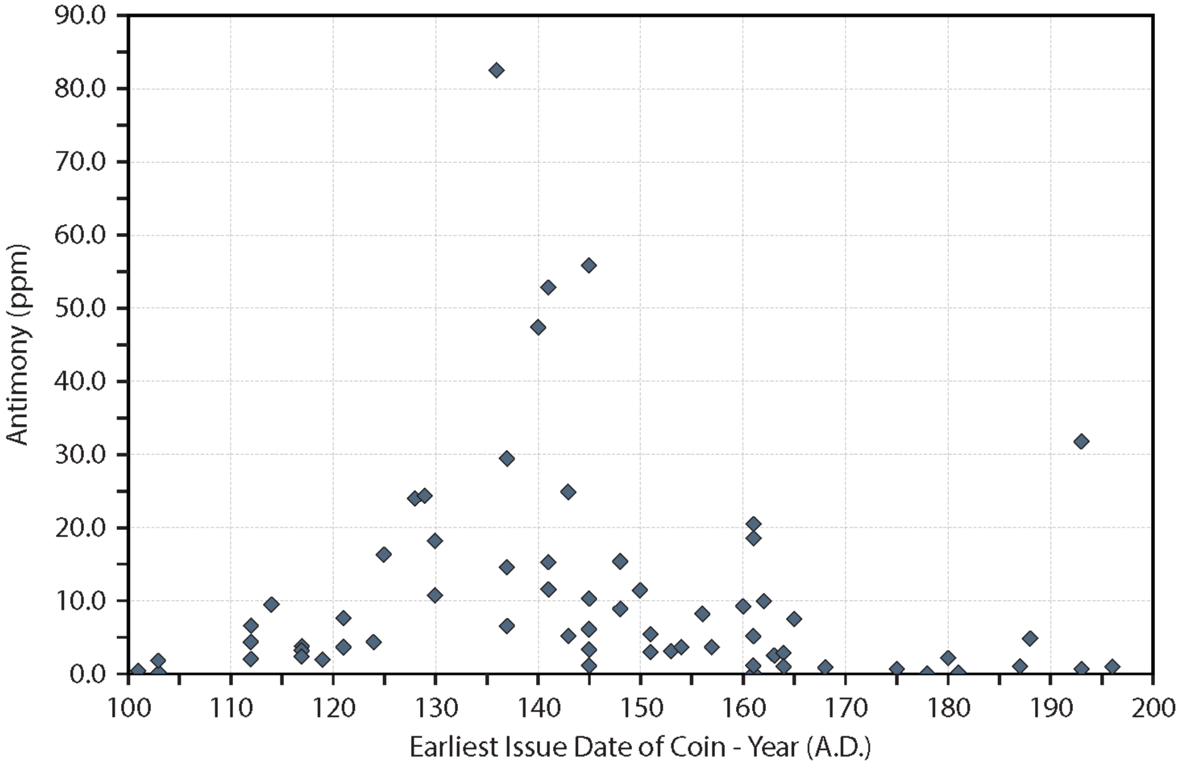

Figure 3 The concentration of antimony in *aurei* issued between AD 101 and AD 196.

5. Discussion

Roman *aurei* from the mid-second century were clearly produced using a gold stock that contained antimony and tellurium. It should be stressed that this does not mean that *aurei* were made exclusively from gold from a single antimony- and tellurium-rich source, but rather they were produced from a stock of gold that was, for a period of time, *dominated* by antimony and tellurium. The Romans were almost certainly exploiting a number of gold extraction sites at any one time. We know, for example, that the various gold mines in the North West of the Iberian Peninsula - modern-day Spain and Portugal - were an important part of the Roman supply network in the first and second centuries (Hirt, 2010, 34-6; Redentor, 2010; Redondo Vega et al., 2015; Sánchez-Palencia et al., 1990; Sánchez-Palencia et al., 2018; Wahl, 1993). These sources are, however, clearly not the cause of our antimony- and tellurium-rich gold. Gold ores in the North West of the Iberian Peninsula are sulphide ores, rather than tellurides, and are generally hosted in quartz veins alongside multiple pyrite minerals (FeS_2), galena (PbS) and sphalerite ((Zn, Fe)S) (Gómez-Fernández et al., 2012, 72-3; Hillman et al., 2017, 1470; Newman, 2001, GG1; Sánchez-Palencia et al., 2018). A similar characterisation can be made of the Dolaucothi gold mine in Wales, active by the late-first century AD (Annels & Roberts 1989, 1299-302; Burnham & Burnham, 2004). There is attested mining activity in Dalmatia – modern day Croatia and Bosnia – at this time (Glicksman, 2018, 268-70; Hirt, 2010, 74) and some gold deposits here are associated with tellurium, although there does not seem to be an antimony- and tellurium-rich source (Jurković, 1995, 12, Table 5). There is, however, strong evidence for the migration of mine workers out of Dalmatia and into Dacia in the early second century (discussed below), suggesting a decline in Dalmatian mining activity at this time. Then, of course, we have our material from Dacia. All these sources would have contributed to the Roman gold 'mix', alongside any recycled metal. With this in mind, we are unlikely to be able to determine when the first and last drops of gold from a particular source entered the Roman mint. Many gold sources from the same region are chemically too similar and there is too much baseline 'chaos' in the trace element profile of the gold for this kind of high resolution analysis to accurately take place. What the data can help us to determine is when certain geological sources were *dominating* the Roman gold supply: in this case we clearly have a tellurium and antimony 'fingerprint' standing out from the background 'noise' of the Roman gold mix for a few decades.

In terms of tracing gold from Roșia Montană we are concerned with tracing coins that have been struck from an antimony- *and* tellurium-rich gold. As such, some context is required to define what concentration makes a coin 'relatively rich' in either of these two elements. For tellurium this is quite straight forward. As part of the *Gold Coinage in the Roman World Project*, 572 Roman gold coins dating between 46 BC and AD 477 were analysed using the methodology outlined above. Appreciable concentrations of tellurium were rare in this data set: the median concentration was 0.31 ppm and the mean was 0.67 ppm – as such, a concentration of 1 ppm or greater represents a coin that is relatively rich in tellurium (Green, 2021). Indeed, with *aurei* regularly containing greater than 1 ppm of tellurium in this century, it is a clear that a tellurium-rich gold source was exploited. Antimony is somewhat more complex. While it generally occurs in very low concentrations across the 572 gold coins analysed – the median concentration was 1.28 ppm – there were peaks in the middle of the first, second and third centuries AD (Green, 2021). This causes an elevated mean figure of 4.34 ppm. While many of the second-century *aurei* presented here contain a considerably 'above average' concentration of antimony, a few cluster close to this mean figure. As such, a relatively arbitrary boundary needs to be drawn for what constitutes an antimony-rich coin. For tellurium a figure of approximately 1.5x the mean was used, and so this has been repeated here: a concentration of 7 ppm of antimony or greater will be considered to be 'relatively antimony-rich.' Plotting the antimony concentration of only the second-century *aurei* that contained 1 ppm of tellurium or greater allows for the clear identification of an antimony- and tellurium-rich gold source in the middle of the century (Figure 4). This is a unique fingerprint within Roman gold coinage: only 1/124 gold coins analysed by Green (2021, Table 20) issued between 50 BC and AD 99 contained greater than 1 ppm of tellurium *and* 7 ppm of antimony; and only 2/73 gold coins analysed between AD 200 and AD 300 would be considered antimony- and tellurium-rich under this metric. There is a clearly distinguishable antimony- and tellurium-rich gold source in use during the mid-second century AD.

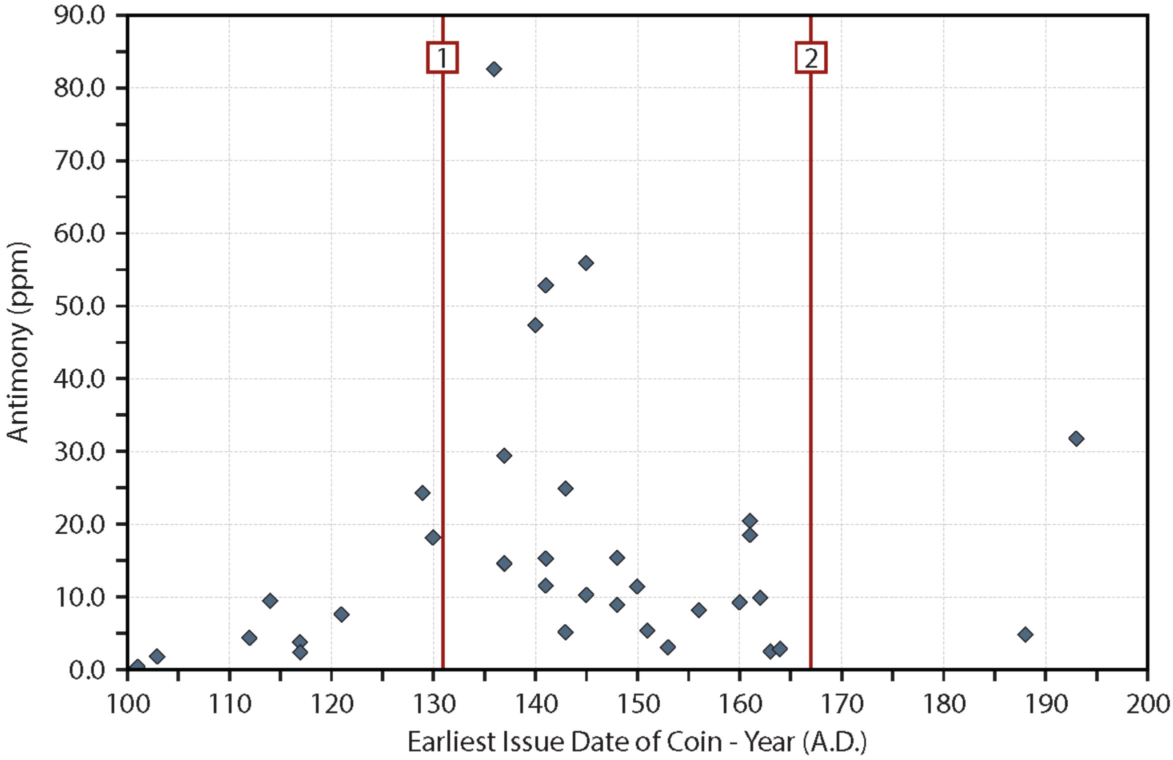

Figure 4 The concentration of antimony in *aurei* issued between AD 101 and AD 196 that contained ≥1 ppm tellurium. 1) The earliest attested date for Dalmatian migration into Alburnus Maior. 2) The date of the last wax tablet from Roșia Montană.

It is probable that Roșia Montană is the major source of this gold, however, can we go beyond calling it 'antimony- and tellurium-rich Dacian gold'? Indeed, most of the recent trace element work on Roman gold coinage has largely focused on characterisation using platinum and palladium ratios (Blet-Lemarquand et al., 2017; Blet-Lemarquand et al., 2015; Suspène et al., 2011; Suspène et al., 2018), and there is understandable reticence to move from characterisation to provenance when dealing with archaeological metals (Pernicka, 2014). However, the use of 'discriminator elements' to 'fingerprint' metal sources for provenance studies is well established (Gauert et al., 2016; Gondonneau & Guerra, 2002; Grigorova et al., 1998; Watling et al., 1994). Furthermore, in the specific case of Roman exploitation of Dacian gold sources we have precisely dated epigraphic and documentary evidence that allows us to move much more confidently from characterisation to provenance.

First, we have epigraphic and documentary evidence for the migration of Dalmatian workers to the mining district of Alburnus Maior, the settlement that is effectively located at the Roșia Montană gold mines. It should be acknowledged that we have evidence for a variety of different ethnic and social groups within Alburnus Maior, including Greeks, Roman citizens, military personnel and, notably, Dardanians who migrated from what is now the central Balkans (Wollmann, 1989). This latter group are attested to in inscriptions, through dedications to *Dea Dardanica* ('Dardanian Goddess') and through the presence of specific types of burial (Wilson et al., 2011, 72). Indeed, Eutropius (VIII, 6, 2), writing in the mid-fourth century, tells us that the emperor Trajan had transplanted an infinite number of men from across the Roman world to populate the countryside and cities of Dacia. Here, however, the focus will be on the Dalmatian ethnic group. Distinctively

Dalmatian names and tribal names are recorded at Alburnus Maior in a variety of inscriptions and in administrative documents preserved on wax tablets (Glicksman, 2018, 276-8; Hirt, 2010, 355; Piso, 2004, 273, 95). The wax tablets provide the best evidence for the chronology of the arrival of Dalmatians into Dacia as they occasionally have consular dates recorded alongside the business transaction, contract or agreement on the tablet. These tablets mention: *collegia* of Dalmatian ethnic groups, such as the *genio collegi Sardiatarum (Corbier et al., 2006, #1491)* for the Sardeates from Western Bosnia; areas occupied primarily by particular Dalmatian tribes, such as the associated settlement occupied by members of the Pirustae tribe, the *Vicus Pirustarum* (Russu, 1975, I, 226, #39 - TabCerD IX); and Dalmatian individuals involved in gold mining, such as *Titus Beusantis qui et Bradua* who was recorded employing a man to work in the gold mines (Glicksman, 2018, 277; Hirt, 2010, 232-3; I, 236, #42 - TabCerD XII).

The earliest record for the migration of Dalmatians into Dacia is this tablet detailing the contract of *Titus Beusantis,* which dates to the 6th of February AD 131 (Glicksman, 2018, 278; Piso, 2004, 301). Dalmatia had a long history of mining activity (Bojanovski, 1982, 96; Glicksman, 2018, 273-5; Hirt, 2010, 73-4; 2020) and, given that we have direct evidence for these Dalmatians working at the Roșia Montană gold mines, it is probable that migration was of experienced miners into the operations at Roșia Montană. Furthermore, the trapezoidal cross-section of the Roman mining galleries may well have been an import of Roman practice via these Dalmatian and/or Dardanian mine workers (Wilson et al., 2011, 9). This provides us with a 'no later than date' for intensive exploitation here of AD 131. Second, the latest of these wax tablets found within the galleries at Roșia Montană provide us with a 'no earlier than' date for the cessation of operations. The last wax tablet from the mine dates to the 29th of May AD 167 and is a receipt for the repayment of a loan (Piso, 2004, 298; Russu, 1975, I, 238, #43 - TabCerD XIII). Activity at the Dacian mines must have been interrupted by the invasion of Dacia by the Vandals and the Sarmatian Iazyges in AD 167, presumably at some time in the summer (Wilson et al., 2011, 25). This was an invasion which, ultimately, led to the death of the governor of Dacia, Lucius Calpurnius Proculus, and formed the first of a series of invasions and counter-offensives that made up the Marcomannic wars. The initial invasions of Dacia presumably caused the abandonment of the various documents in the galleries, and the continued offensives against the Sarmatian Iazyges in AD 175 and against the Iazyges and 'free Dacians' from AD 180 to AD 182 presumably blocked the resumption of intensive activity. Radiocarbon dating of charcoal and wooden remains found in some galleries suggests a resumption of mining activity sometime in the late second or early third century (Cauuet & Tamas, 2012; Wilson et al., 2011, 38), although the activity during this time is clearly nowhere near as intensive as during the mid-second century. In all, then, we have a relatively narrow window between AD 131 and AD 167 (Mrozek, 1989) in which we should expect to see intensive gold extraction at Roșia Montană. These dates have been marked on Figure 4.

The antimony- and tellurium-rich fingerprint seen in the second century falls almost perfectly between these two dates (Figure 4). The dominance of the proposed Roșia Montană 'fingerprint' coincides with the time period for which we have evidence for the intensive extraction of gold from Roșia Montană by the Romans. Of the 24 coins that contained 1 ppm or greater of tellurium *and* 7 ppm or greater of antimony, 19 were issued during this window of archaeologically attested intensive activity at Roșia Montană between AD 131 and AD 167. Of course, this AD 131 start date is the *latest possible* start date for intense activity and one should expect some coins matching the Roșia Montană 'fingerprint' to have been issued slightly before this date. This is the case here, with two antimony- and tellurium-rich coins having earliest issue dates of AD 129 and AD 130, but such coins were almost entirely absent before AD 129. If anything there is remarkable congruency between the start of the proposed Roșia Montană 'fingerprint' and the archaeologically attested latest start date of intensive operations here.

While relatively tellurium-rich coins are present between AD 100 and AD 125, the majority of these contain an unremarkable concentration of antimony (Figure 3) – only two of the sixteen *aurei* analysed from this date range can be said to be both relatively antimony- *and* tellurium-rich (Table 1). The majority of the gold-tellurides exploited by the Romans in this particular period are clearly coming from somewhere else: there are tellurium-rich coins presented here that pre-date the end of the Dacian Wars in AD 106 (Figure 2). The tellurium-rich gold at the very beginning of this century may well be coming from the mines in the neighbouring province of Dalmatia – there are deposits here associated with tellurium, but not antimony (Jurković, 1995, 12, Table 5), and Dalmatian mining activity in the first and second centuries is well established (Glicksman, 2018, 268-70; Hirt, 2010, 73-4). After the end of the Dacian wars we cannot exclude the recycling of tellurium-rich Dacian gold objects. The Dacian's were certainly panning alluvial gold (Constantinescu et al., 2010a, 1037-8; Wilson et al., 2011, 52-3), but there does not appear to be any strong evidence for pre-Roman underground mining: Cauuet and Tamas (2012, 233) tentatively advance pre-Roman underground mining at Roșia Montană, but the associated radiocarbon dates do not necessarily support this hypothesis and it is probable that the trapezoidal mining galleries were a Roman import rather than a Dacian phenomenon (Wilson et al., 2011, 9, 52-3; 2013, 10-2). Ultimately, it is probable that panned alluvial gold was the dominant, and perhaps exclusive, source in pre-Roman Dacia. This panned gold does not always seem to be strongly associated with tellurium, with primary, mined gold being strongly associated with this element instead (Constantinescu et al., 2010a, 1036). For example Constantinescu et al. (2010a, 1037) state that LA-ICP-MS analyses of one of the pre-Roman, Dacian gold 'Sarmizegetusa' bracelets (c. 100-70 BC) revealed significant traces of Sn, Sb, Pd and Pt, which was consistent with their view that an unrefined, panned gold was used to produce these bracelets. This means that even if recycled Dacian treasure did make its way into the Roman mint, there is certainly no guarantee that it would have necessarily been tellurium-rich. As such, tellurium-rich gold from a different mining region is much more probable in the early second century.

While we should be careful not to base any conclusions on just the two antimony- and tellurium-rich coins from AD 114 and AD 121, it is worth discussing avenues for further investigation. It is not implausible that these two coins could represent the first small injections of gold from early second-century workings at Roșia Montană (Figure 4) – activity at the mine has a broad second-century start date (Baron et al., 2011; Cauuet, 2014). Alternatively, the chemical profile of the coin struck under Trajan may well be an artefact of the mixing of two separate antimony-rich and tellurium-rich gold sources. We know that Trajan withdrew older gold coinages from circulation, presumably melting them down to strike new coins, and minted 'restoration issues' that were essentially copies of the older types that had been removed from circulation (Komnick, 2001, 110-78; Meadows & Williams, 2012, 42-9; Woytek, 2010). These are, however, possibilities to explore with the analysis of more *aurei* from this time period. What is clear is that antimony- and tellurium-rich gold was not particularly important within the Roman gold supply network during the Trajanic and early Hadrianic periods, meaning Roșia Montană could not have been intensely exploited before c. AD 125. Indeed, the overall pattern for tellurium across the early 120s is a decline from the peak seen at the very start of Hadrian's reign, rather than intensification (Figure 2), meaning it is improbable any new tellurium-rich gold sources are being intensively exploited at this time. In the coins analysed here this trend only seems to reverse from AD 129 onwards, which is the point that antimony- and tellurium-rich coins begin to be regularly seen as well. This suggests that the 'no later than date' for intensive Roman activity at Roșia Montană could potentially be pushed back to AD 129. Unfortunately, the Ashmolean collection lacks sufficient *aurei* issued between AD 125 and AD 130 to determine at exactly what point in the middle of Hadrian's reign intensive activity really began, but there is clearly scope for further fruitful investigation here. Broadly speaking, however, the historical narrative arising from the chemical data is congruent with that of the archaeology of Roșia Montană: the gold deposits here were not intensively exploited until the middle of Hadrian's reign and this intensive exploitation began no earlier than AD 125, potentially no later than AD 129 and certainly by the 130s.

The dominance of this fingerprint in the 130s and 140s coincides neatly with the earliest attested dates of significant migration of Dalmatian workers into Alburnus Maior. If these people had been moved specifically to work at the mines at Roșia Montană as part of an intensification of operations, then it should be no surprise that we see a surge of antimony- and tellurium-rich gold in the Roman gold supply at this time. Between AD 129 and AD 149, 14 of the 20 coins analysed can be described as antimony- and tellurium-rich (Table 1). Again, the archaeology and chemical data are in good agreement: the Roșia Montană 'fingerprint' is most 'intense' when our material and documentary evidence suggests mining activity was at its peak here. From AD 150, it would appear that the dominance of the Roșia Montană source was fading, with only seven of the nineteen coins analysed between AD 150 and AD 167 falling within the Roșia Montană 'fingerprint'. 11 of the 19 coins, however, contained 1 ppm of tellurium or greater; so other tellurium-rich Dacian gold deposits may well have become increasingly exploited at this time, although clearly not to the same degree as Roșia Montană. Again, Roman mining activity beyond Roșia Montană, but with Roșia Montană as the most important site, fits well with the current interpretation of the evidence of Roman gold exploitation in Dacia (Lim, 2018). There is not, however, a slow decline into obscurity for Roșia Montană: the 'fingerprint' abruptly stops in the mid-160s (Figure 4). Of the ten coins analysed that were issued between AD 168 and AD 196 only one, from AD 193, contained above average concentrations of both antimony and tellurium (Table 1). Considering the last wax tablet from Roșia Montană dates to AD 167, presumably because mining operations were interrupted due to the Marcomannic Wars that ran from approximately AD 166 to AD 180, then a sharp drop-off in the antimony- and tellurium-rich fingerprint makes sense if this gold was primarily being supplied by activity at Roșia Montană. While we should be careful not to over-interpret the chemical profile of a single coin, a small injection of antimony- and tellurium rich gold in the late second century is in tune with radiocarbon dates from some mining galleries suggesting a small amount of late second- and third-century activity at the mine (Cauuet & Tamas, 2012, 235; Wilson et al., 2011, 38).

Clearly then, this antimony- and tellurium-rich 'fingerprint' is, in large part, a product of Roman gold mining activity at Roșia Montană. These particular set of mines were undoubtedly integral to the Roman gold supply network during the mid-second century. Between AD 129 and AD 167, 21 of the 39 *aurei* analysed (c. 54%) fell within the Roșia Montană fingerprint. The mines seem to have been most intensively exploited up to approximately AD 150, with 15 of the 21 coins analysed from this period (c. 71%) being classified as antimony- and tellurium-rich. While it would be unwise to use these proportions as a direct proxy for the overall contribution of Roșia Montană to the total Roman gold stock, it must be conceded that for this 'fingerprint' to regularly appear in the chemical record, then Roșia Montană must have been one of the, if not *the*, most dominant gold sources in the mid-second century.

6. Conclusion

At minimum, we have shown that an antimony- and tellurium-rich Dacian gold was the dominant source of gold used to strike Roman gold coinage in the mid-second century. Furthermore, we have shown that with the appropriate discriminator elements combined with sufficient archaeological context, it is possible to provenance the antimony- and tellurium-rich gold used to strike *aurei* between AD 129 and AD 167 in large part to the mines at Roşia Montană. Given that the 'intensity' of this 'fingerprint' matches the time-period during which our archaeological evidence suggests that mining operations at Roşia Montană were most intensive, we can be confident that the increased exploitation of the Roşia Montană gold source caused the elevated antimony and tellurium concentrations in the gold coinage produced at this time. Roşia Montană was probably the most dominant Dacian gold source anyway, and so it is even more probable that it was the dominant source of this antimony- and tellurium-rich Dacian gold. The chemical data encourage an historical narrative that is in good agreement with the existing interpretation of the archaeology of Roşia Montană.

Gold from Dacia appears to have been one of the most dominant sources for the Roman supply network between AD 129 and AD 150, with it remaining important until the interruption of operations in AD 167 during the Marcomannic Wars. With this in mind, the strategic importance of Dacia within the Roman Empire at this time should not be underestimated.

7. Bibliography

Annels, A. E., & Roberts , D. E. (1989). Turbiditc-Hosted Gold Mineralization at the Dolaucothi Gold Mines, Dyfed, Wales, United Kingdom. *Economic Geology, 84*, 1293-314.

Baron, S., Tămaş, C. G., Cauuet, B., & Munoz, M. (2011). Lead isotope analyses of gold–silver ores from Roşia Montană (Romania): a first step of a metal provenance study of Roman mining activity in Alburnus Maior (Roman Dacia). *Journal of Archaeological Science, 38*(5), 1090-100. doi: https://doi.org/10.1016/j.jas.2010.12.004

Blet-Lemarquand, M. (2006). Analysis of Kushana Gold Coins: Debasement and Provenance Study. In F. De Romanis & S. Sorda (Eds.), *Dal denarius al dinar: l'orient e la moneta romana* (pp. 155-71). Rome: Istituto italiano di numismatica.

Blet-Lemarquand, M., Nieto-Pelletier, S., Téreygeol, F., & Suspène, A. (2017). Are Platinum and Palladium Relevant Tracers For Ancient Gold Coins? Archaeometallurgical and Archaeometric Data to Study An Antique Numismatic Problem. In I. Montero Ruiz & A. Perea (Eds.), *Archaeometallurgy in Europe IV* (pp. 19-28). Madrid: Consejo Superior de Investigaciones Científicas.

Blet-Lemarquand, M., Suspène, A., & Amandry, M. (2015). Augustus' gold coinage: investigating mints and provenance through trace element concentrations. In A. Hauptmann & D. Modarressi-Tehrani (Eds.), *Archaeometallurgy in Europe III Proceedings of the 3 rd International Conference Deutsches Bergbau-Museum Bochum June 29 – July 1, 2011* (pp. 107-13). Bochum: Deutsches Bergbau-Museum.

Bojanovski, I. (1982). Antičko rudarstvo u unutrašnjosti provincije Dalmacije u svjetlu epigrafskih i numizmatičkih izvora. *Arheološki radovi i rasprave, 8-9*, 89-120.

Boyle, R. W. (1979). The geochemistry of gold and its deposits. *Geological Survey of Canada Bulletin, 280*.

Burnham, H., & Burnham, B. (2004). *Dolaucothi-Pumsaint : survey and excavations at a Roman gold-mining complex, 1987-1999*. Oxford: Oxbow.

Cauuet, B. (2014). Gold and silver extraction in Alburnus Maior mines, Roman Dacia (Rosia Montana, Romania). Dynamics of exploitation and management of the mining space. In L. Fontes (Ed.), *Paisagens Mineiras Antigas na Europa Ocidental. Investigação e Valorização Cultural.* (pp. 81-104). Boticas: Câmara Municipal de Boticas.

Cauuet, B., & Tamas, C. G. (2012). Les travaux miniers antiques de Rosia Montana (Roumanie). Apports croisés entre archéologie et géologie. In A. Orejas, C. Rico & J. Sánchez Palencia (Eds.), *Mineria antigua: estudios regionales y temas de investigacion actual* (pp. 219-41). Madrid: Casa de Velazquez.

Cioacă, M. E., Munteanu, M., Qi, L., & Costin, G. (2014). Trace element concentrations in porphyry copper deposits from Metaliferi Mountains, Romania: A reconnaissance study. *Ore Geology Reviews, 63*, 22-39. doi: https://doi.org/10.1016/j.oregeorev.2014.04.016

Cioacă, M. E., Popescu, C. G., & Munteanu, M. (2010). Contribution to the Gold Geochemistry from the Porphyry Cu-Au Mineralisation of Bolcana Deposit, Metaliferi Mts. *Romanian Journal of Mineral Deposits, 84*, 48-50.

Constantinescu, B., Oberländer-Târnoveanu, E., Bugoi, R., Cojocaru, V., & Radtke, M. (2010a). The Sarmizegetusa bracelets. *Antiquity, 84*(326), 1028-42. doi: 10.1017/S0003598X00067053

Constantinescu, B., Pauna, C., Vasilescu, A., Constantin, F., Cristea-Stan, D., Popescu, G., & Neacsu, A. (2010b). Some applications of X-ray based elemental analysis methods for studies on Romanian gold minerals. *Romanian Reports in Physics, 62*(1), 47-56.

Corbier, M., Le Roux, P., Dardaine, S., Fauduet, I., & Ndione, J. (2006). *L'Année épigraphique 2003*. Paris: Presses Universitaires de France.

Craddock, P. (1994). *Early metal mining and production*. Edinburgh: Edinburgh University Press.

Craddock, P. (2000a). Historical Survey of Gold Refining: 1 Surface Treatments and Refining Worldwide and in Europe Prior to AD 1500. In A. Ramage & P. Craddock (Eds.), *King Croesus' Gold: Excavations at Sardis and the History of Gold Refining* (pp. 27-53). Cambridge, MA: British Museum Press.

Craddock, P. (2000b). Replication Experiments and the Chemistry of Gold Refining. In A. Ramage & P. Craddock (Eds.), *King Croesus' Gold: Excavations at Sardis and the History of Gold Refining* (pp. 175-83). Cambridge, MA: British Museum Press.

Cucina, A., Dudgeon, J., & Neff, H. (2007). Methodological strategy for the analysis of human dental enamel by LA-ICP-MS. *Journal of Archaeological Science, 34*(11), 1884-8. doi: https://doi.org/10.1016/j.jas.2007.01.004

Domergue, C. (1990). *Les mines de la Péninsule Ibérique dans l'antiquité romaine*. Rome: École française de Rome.

Domergue, C. (2008). *Les mines antiques : la production de métaux aux époques grecque et romaine*. Paris: Picard.

Duwe, S., & Neff, H. (2007). Glaze and slip pigment analyses of Pueblo IV period ceramics from east-central Arizona using time of flight-laser ablation-inductively coupled plasma-mass spectrometry (TOF-LA-ICP-MS). *Journal of Archaeological Science, 34*(3), 403-14. doi: https://doi.org/10.1016/j.jas.2006.06.001

Eutropius. Breviarium historiae Romanae

Gauert, C., Schannor, M., Hecht, L., Radtke, M., & Reinholz, U. (2016). A Comparison of In Situ Analytical Methods for Trace Element Measurement in Gold Samples from Various South African Gold Deposits. *Geostandards and Geoanalytical Research, 40*(2), 267-89. doi: 10.1111/j.1751-908X.2015.00362.x

Gentelli, L. (2019). Enhancing Understanding of the Emergence of Global Trade: Analysis of 17th- to 19th-Century Spanish Coins Recovered from Western Australian Shipwrecks Using Laser

Ablation – Inductively Coupled Plasma – Mass Spectrometry (LA–ICP–MS). *Archaeometry, 61*(3), 701-19. doi: https://doi.org/10.1111/arcm.12444

Glicksman, K. (2018). Metal mining in Roman Dalmatia. *Opuscula archaeologica, 39/40*, 261-83.

Gómez-Fernández, F., Vindel, E., Martín-Crespo, T., Sánchez, V., González Clavijo, E., & Matías, R. (2012). The Llamas de Cabrera gold district, a new discovery in the Variscan basement of northwest Spain: A fluid inclusion and stable isotope study. *Ore Geology Reviews, 46*, 68-82. doi: https://doi.org/10.1016/j.oregeorev.2012.02.001

Gondonneau, A., & Guerra, M. F. (2002). The Circulation of Precious Metals in the Arab Empire: the Case of the Near and the Middle East. *Archaeometry, 44*(4), 573-99.

Green, G. A. (2021). *Gold Coinage in the Roman World: Function and Production.* (Doctor of Philosophy), University of Warwick.

Grigorova, B., Smith, W., Stülpner, K., Tumilty, J. A., & Miller, D. (1998). Fingerprinting of Gold Artefacts from Mapungubwe, Bosutswe and Thulamela. *Gold Bulletin, 31*(3), 99-102. doi: 10.1007/BF03214770

Guerra, M. F., & Calligaro, T. (2004). Gold traces to trace gold. *Journal of Archaeological Science, 31*(9), 1199–208.

Guerra, M. F., Sarthre, C.-O., Gondonneau, A., & Barrandon, J.-N. (1999). Precious Metals and Provenance Enquiries using LA-ICP-MS. *Journal of Archaeological Science, 26*(8), 1101-10. doi: https://doi.org/10.1006/JASC.1999.0405

Hauptmann, A., Rehren, T., & Pernicka, E. (1995). The composition of gold from the ancient mining district of Verespatak/Roşia Montană, Romania. In G. Morteani & J. P. Northover (Eds.), *Prehistoric Gold in Europe* (pp. 369-81). Germany: Kluwer Academic Publishers.

Healy, J. F. (1979). Mining and Processing Gold Ores in the Ancient World *Journal of Metals*, 11-6.

Hillman, A. L., Abbott, M. B., Valero-Garcés, B. L., Morellon, M., Barreiro-Lostres, F., & Bain, D. J. (2017). Lead pollution resulting from Roman gold extraction in northwestern Spain. *The Holocene, 27*(10), 1465-74.

Hirt, A. (2010). *Imperial Mines and Quarries in the Roman World: organizational aspects, 27 BC-AD 235*. Oxford: Oxford Univeristy Press.

Hirt, A. (2020). Gold and silver mining in the Roman Empire. In K. Butcher (Ed.), *Debasement: Manipulation of Coin Standards in Pre-Modern Monetary Systems* (pp. 111-24). Oxford: Oxbow Books.

Jurković, I. (1995). Bakovici: The Bigest Gold Deposit of Bosnia and Herzegovina. *Rudarsko-geološko-naftni zbornik, 7*, 1-15.

Komnick, H. (2001). *Die Restitutionsmünzen der frühen Kaiserzeit : Aspekte der Kaiserlegitimation*. Berlin: De Gruyter.

Lim, S. Y. (2018). *Mining Under Empire: Exploiting the Metal Resources of Roman Dacia.* (D. Phil), Oxford.

Lin, J., Liu, Y., Yang, Y., & Hu, Z. (2016). Calibration and correction of LA-ICP-MS and LA-MC-ICP-MS analyses for element contents and isotopic ratios. *Solid Earth Sciences, 1*(1), 5-27. doi: https://doi.org/10.1016/j.sesci.2016.04.002

Makkay, J. (1995). The Treasures of Decebalus. *Oxford Journal of Archaeology, 14*(3), 333-45. doi: https://doi.org/10.1111/j.1468-0092.1995.tb00067.x

Meadows, A., & Williams, J. (2012). Moneta and the Monuments: Coinage and Politics in Republican Rome. *Journal of Roman Studies, 91*, 27-49. doi: 10.2307/3184768

Meeks, N. D. (2000). Scanning Electron Microscopy of the Refractory Remains and the Gold. In A. Ramage & P. Craddock (Eds.), *King Croesus' Gold: Excavations at Sardis and the History of Gold Refining* (pp. 99-156). Cambridge, MA: British Museum Press.

Morteani, G. (1995). Mineral economics mineralogy, geochemistry and structure of gold deposits. In G. Morteani & J. P. Northover (Eds.), *Prehistoric Gold in Europe* (pp. 97-113). Germany: Kluwer Academic Publishers.

Mrozek, S. (1989). Le travail des hommes libres dans les mines romaines. *Mineria y metalurgia en las antiguas civilizaciones Mediterraneas y Europeas, II*, 163-70.

Newman, H. (2001). The Mineral Industry of Portugal. In U. S. D. o. t. Interior & U. S. G. Survey (Eds.), *Minerals Yearbook, Volume 3: Area Reports: International 1997* (pp. GG1-GG4). Washington: United States Government Printing Office.

Pernicka, E. (2014). Provenance Determination of Archaeological Metal Objects. In B. W. Roberts & C. Thornton (Eds.), *Archaeometallurgy in Global Perspective. Methods and Syntheses* (pp. 239-68). New York: Springer.

Piso, I. (2004). Gli Illiri ad Alburnus Maior. In G. Urso (Ed.), *Dall'Adriatico al Danubio: l'Illirico nell'età greca e romana* (pp. 271-307). Pisa: ETS.

Pop, D., Ionescu, C., Forray, F., Tămaş, C. G., & Benea, M. (2011). "Transylvanian gold" of hydrothermal origin: an EMPA study in an archaeological provenancing perspective. *European Journal of Mineralogy, 23*(6), 911-23. doi: 10.1127/0935-1221/2011/0023-2156

Ramage, A., & Craddock, P. (2000). Prologue. In A. Ramage & P. Craddock (Eds.), *King Croesus' Gold: Excavations at Sardis and the History of Gold Refining* (pp. 10-3). Cambridge, MA: British Museum Press.

Redentor, A. (2010). Aproximação a um esboço social da área mineira romana da Serra da Padrela (Tresminas e Campo de Jales). In C. M. Braz Martins (Ed.), *Mineração e povoamento na antiguidade no Alto Trás-os-Montes occidental* (pp. 121-62). Porto: CITCEM.

Redondo Vega, J., Alonso-Herrero, E., Santos-González, J., González-Gutiérrez, R. B., & Gómez-Villar, A. (2015). La Balouta exhumed karst: a Roman gold-mine-derived landscape within the Las Médulas UNESCO World Heritage Site (Spain). *International Journal of Speleology, 44*(3), 267-76.

Resano, M., García-Ruiz, E., Alloza, R., Marzo, M. P., Vandenabeele, P., & Vanhaecke, F. (2007). Laser Ablation-Inductively Coupled Plasma Mass Spectrometry for the Characterization of Pigments in Prehistoric Rock Art. *Analytical Chemistry, 79*(23), 8947-55. doi: 10.1021/ac0712953

Resano, M., García-Ruiz, E., & Vanhaecke, F. (2010). Laser ablation-inductively coupled plasma mass spectrometry in archaeometric research. *Mass Spectrometry Reviews, 29*(1), 55-78. doi: https://doi.org/10.1002/mas.20220

Russu, I. (1975). *Inscripțiile Daciei Romane: Vol. 1, Introducere istorică şi epigrafică, diplomele militare, tabliţele cerate*. București: Editura Academiei Republicii Socialiste România.

Sánchez-Palencia, F. J., Fernández-Posse, M. D., Manzano, J. F., & Orejas, A. (1990). La zona arqueológica de las Médulas (1988-89). *Archivo español de arqueología, 63*(161), 249-64.

Sánchez-Palencia, F. J., Romero, D., & Beltrán, A. (2018). Geoarqueología del oro en la zona minera de Pino del Oro (Zamora). In C. Rico & A. Orejas (Eds.), *Mélanges de la Casa de Velázquez: Los metales preciosos: de la extracción a la acuñación (Antigüedad - Edad Media)* (Vol. 48-1, pp. 63-87): Casa de Velázquez.

Shortland, A., Rogers, N., & Eremin, K. (2007). Trace element discriminants between Egyptian and Mesopotamian Late Bronze Age glasses. *Journal of Archaeological Science, 34*(5), 781-9.

Suspène, A., Blet-Lemarquand, M., & Amandry, M. (2011). Les monnaies d'or d'Auguste: l'apport des analyses élémentaires et le problème de l'atelier de Nîmes. In N. Holmes (Ed.), *Proceedings of the XIVth International Numismatic Congress, Glasgow, 2009* (Vol. 1, pp. 1073-81). Glasgow: International Numismatic Council.

Suspène, A., Blet-Lemarquand, M., Hochard, P.-O., Flament, J., & Gehres, B. (2018). Un exemple d'enquête numismatique et archéométrique : les aurei des Libérateurs Brutus et Cassius dans le cadre du projet Aureus. *Bulletin de la Société Française de Numismatique, 73*(6), 210-6.

Tămaş, C., Bailly, L., Ghergari, L., O'Connor, G., & Minuţ, A. (2006). New Occurrences of Tellurides and Argyrodite in Roşia Montană, Apuseni Mountains, Romania, and Their Metallogenic Significance. *The Canadian Mineralogist, 44*, 367-83.

Wahl, J. (1993). Três Minas. Vorbericht über die archäologischen Ausgrabungen im Bereich des römischen Goldbergwerke 1986/7. In H. Steuer & U. Zimmermann (Eds.), *Montanarchäologie in Europa. Berichte zum Internationalen Kolloquium „Frühe Erzgewinnung und Verhüttung in Europa" in Freiburg im Breisgau vom 4.–7. Okt. 1990* (pp. 123-52). Sigmaringen: Archäologie und Geschichte, Band 4.

Watling, R. J., Herbert, H. K., Delev, D., & Abell, I. D. (1994). Gold fingerprinting by laser ablation inductively coupled plasma mass spectrometry. *Spectrochimica Acta Part B: Atomic Spectroscopy, 49*(2), 205-19. doi: https://doi.org/10.1016/0584-8547(94)80019-7

Wilson, A., Mattingly, D., & Dawson, M. (2011). Statement of Significance: Cârnic Massif, Roşia Montană, jud Alba Romania [Press release]

Wilson, A., Mattingly, D., & Dawson, M. (2013). Response to D. Jennings, A Critical Analysis of the Report: 'Statement of Significance: Cârnic Massif, Roşia Montană, jud Alba Romania' by A Wilson, D Mattingly and M Dawson [Press release]. Retrieved from https://hdl.handle.net/2381/14294480.v1

Wollmann, V. (1989). Nouvelles données concernant la structure socio-ethnique de la zone minière de la Dacia Superior. *Mineria y metalurgia en las antiguas civilizaciones Mediterraneas y Europeas, II*, 107-18.

Woytek, B. (2010). *Die Reichsprägung des Kaisers Traianus (98-117)*. Wien: Verlag der Österreichischen Akademie der Wissenschaften

Yegül, F., & Favro, D. (2019). *Roman Architecture and Urbanism: From the Origins to Late Antiquity*. Cambridge: Cambridge University Press.

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9. Author Contributions

Green: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Validation; Visualization; Writing - original draft

Smythe: Investigation; Methodology; Resources; Visualization; Writing – review and editing