The assay and refining of gold in the post-medieval Islamic world: Potential and reality

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ABSTRACT: This paper describes the analysis of the Moroccan gold coins, jewellery and ingots from the 17th-century Salcombe Bay Treasure. Their trace element content gives information on the likely provenance of the gold and their fineness gives information on both quality control and refining methods. These can be compared to the methods described in the contemporary Al-asdāf al-munfadda ᶜan ahkām ᶜilm sanᶜat addīnār wal-fidda, an important Moroccan treatise on gold assay and refining, complied by al-Djaznā'ī. The treatise is both technical and practical and relates specifically to gold coins, jewellery and ingots. The methods outlined in the treatise are compared with other contemporary descriptions from Europe and India.

Introduction

The well-dated gold treasure discovered in Salcombe Bay, Devon (the Salcombe Cannon Site), comprises Moroccan gold coins, small gold ingots and gold jewellery together with other artefact types (Porter and Morison 1998). The jewellery from Salcombe is mostly incomplete or fragmentary and many items are distorted or crushed. A few of the coins are also incomplete, pierced or damaged. The jewellery has clear stylistic connections with North Africa and the large majority of the coins are inscribed with the names of Saadian rulers of Morocco, struck at Marrakesh and other Moroccan mints. Considering the associated artefact types, the treasure seems to have originated from a trading vessel that came to grief in the 1630s-40s, perhaps Moroccan, Barbary pirate or likely of Dutch origin (Porter 2000). It provides excellent material to examine the reality of the control of gold fineness in the post-medieval Islamic world and the use of recycling.

The refining methods used in antiquity were cupellation, and parting using mineral salts such as common salt, saltpetre or alum. In the post-medieval period there were significant developments in the refining of gold using sulphur and sulphides as well as the increasing use of mineral acids. There are various European and Indian descriptions, together with an Islamic treatise on coin production, which includes detailed sections on precious metal refining and assay of coins, jewellery and ingots. This is the *Al-asdāf al-munfadda ᶜan ahkām ᶜilm sanᶜat addīnār wal-fidda* complied by al-Djaznā'ī in Morocco around 1600 AD (Ben Romdhane 1988a; 1988b), broadly contemporary with the treasure. It is instructive to compare the treatments recommended there for the three classes of metalwork with the evidence of treatments suggested by the composition of the gold items from the treasure.

Analytical methods

The analysis of a selection of the gold metalwork was undertaken in the Department of Scientific Research in the British Museum in order to investigate the relation-

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ship between the alloy of the ingots, the cut fragments of jewellery and the coins (Table 1; Fig 1), and obtain information on gold refining and assay. Similarly, trace elements were quantified in some items to also explore the origin of the metal (Table 2). To characterise the gold from the region, in the absence of original source material, ICP-MS analysis was carried out at the Centre national de la recherche scientifique (CNRS) and data of a representative sample of small gold nuggets from present day sources in Ghana and Ivory Coast (Gondonneau 2001; Gondonneau *et al* 2001) was included (Table 3). Since ICP-MS data does not include major elements, the small gold nuggets were also analysed by XRF and FNAA (fast neutron activation analysis) (Table 3). Larger nuggets from the same origins were analysed by PAA (proton activation analysis) (Table 3).

X-ray fluorescence (XRF)

The analytical technique used to quantify the major and minor element components in the artefacts from Salcombe Bay was XRF. The instrument used here was a bench-based air-path system using a molybdenum X-ray tube at 45kV, the beam collimated to irradiate about 1-1.5mm, and a Si(Li) detector with resolution 140eV measuring high-energy lines (Cowell 1998).

XRF is a surface analysis technique and it is necessary to be aware that ancient metalwork is rarely homogenous and gold alloys were often deliberately treated. For example, Manṣūr Ibn Bar'a's 13th century AD treatise on gold refining for the Cairo mint described how gold coin flans were to be treated to enhance their surfaces prior to being struck (Ramage and Craddock 2000, 27-54; Levey 1971, especially 35, 66). Consequently, the representative examples of jewellery and coins selected for analysis were mostly abraded with silicon-carbide

Table 1: XRF analyses of a selection of gold items from Salcombe Bay (wt%).

No	Description	Sample	Au	Ag	Cu	Zn
Ingots						
448	Ingot, fragment	drilling	59	31.4	9.8	< 0.3
449	Ingot, finger shape, cut	drilling	83	11.1	5.4	< 0.3
450	Ingot, finger shape, cut	drilling	84	10.8	5.5	< 0.3
451	Ingot, broken spill?	drilling	80	11.9	8.0	< 0.3
452	Ingot, fragment	drilling	56	35.3	9.1	< 0.3
453	Ingot, small, cut	drilling	75	16.5	8.0	< 0.3
455	Ingot, finger shape, cut/broken	drilling	81	11.3	7.4	< 0.3
456	Ingot, finger shape, cut/broken	drilling	83	11.8	5.2	< 0.3
457	Ingot, bun shape	drilling	82	12.4	5.9	< 0.3
458	Ingot, irregular shape	drilling	82	12.7	5.8	< 0.3
459	Ingot, cut/broken	drilling	82	12.9	5.2	< 0.3
460	Ingot, small bun shape	drilling	83	12.7	4.6	< 0.3
461	Ingot, irregular shape	drilling	84	11.4	4.9	< 0.3
462	Ingot, finger shape, cut/broken	drilling	65	13.5	16.4	4.7
Jewellery						
463	Pendant, missing inlays? Back	abraded	87	10.5	2.7	< 0.3
464	Pendant, openwork, fractured. Back	abraded	82	16.3	1.6	< 0.3
467	Bracelet fragment? crushed	abraded	87	8.8	3.8	< 0.3
469	Pendant, with filigree & granulation. Back	abraded	83	14.7	2.1	< 0.3
470	Pennanular brooch, tube	abraded	79	17.8	3.1	< 0.3
470	Pennanular brooch, pin	not prepared	90	9.0	1.3	< 0.3
471	Ornament, with filigree & granulation	abraded	86	9.8	4.2	< 0.3
478	Earring part? twisted	not prepared	64	31.0	6.0	< 0.3
479	Earring, bent	not prepared	85	9.0	6.0	< 0.3
483	Ornament, tubular, bent, crushed	abraded	72	20.6	7.4	< 0.3
484	Ornament, tubular, bent, cut	abraded	84	11.1	5.3	< 0.3
485	Ornament, tubular, bent, crushed	abraded	94	4.5	2.0	< 0.3
488	Ornament, tubular, bent	abraded	84	10.7	4.9	< 0.3
489	Ornament, tubular, tube part	abraded	95	2.6	2.1	< 0.3
490	Ornament, tubular, bent	abraded	92	6.0	2.3	< 0.3
493	Ornament, tubular, crushed	abraded	75	18.1	6.5	< 0.3
495	Ornament, tubular, cut	abraded	79	14.7	6.5	< 0.3
496	Ornament, tubular, bent	abraded	75	16.8	8.1	< 0.3
497	Ornament, tubular, cut	abraded	82	11.9	5.8	< 0.3
498	Ornament, tubular, bent	abraded	84	12.6	3.2	< 0.3
Coins						
246/0001d	al-Mansur	abraded	94	5.5	0.5	< 0.05
63/0002d	al-Mansur?	abraded	97	2.6	< 0.05	< 0.05
105/0003d	al-Mansur	abraded	91	7.9	0.7	< 0.05
167/0001h	al-Mansur	abraded	77	22.2	1.3	< 0.05
394/0002h	Zaydan	abraded	87	10.9	2.4	< 0.05
410/0069h	Zaydan	abraded	95	4.0	1.1	< 0.05
365/0013	Zaydan	abraded	87	12.6	0.3	< 0.05
353/0021	Zaydan	abraded	98	1.8	0.2	< 0.05
388/0048	Zaydan	abraded	91	8.3	0.6	< 0.05
0193		abraded	98	1.9	< 0.04	< 0.05
0228		abraded	97	2.6	0.5	< 0.05
271	Zaydan	abraded	95	4.8	0.5	< 0.05
165/0031	al-Mansur	abraded	98	1.7	0.2	< 0.05
0065	Zaydan?	abraded	91	7.4	1.4	< 0.05

Notes: The precision of the quantitative results is about ± 2-5% relative for gold and about ± 10-20% relative for the other alloying components; the accuracy is similar. Traces of lead were also detected in most of the jewellery and ingots but not quantified (see Table 2). The detection limits for zinc vary for the artefact types due to spectral interference from copper and the presentation of drilling samples, *ie* in gelatine capsules.

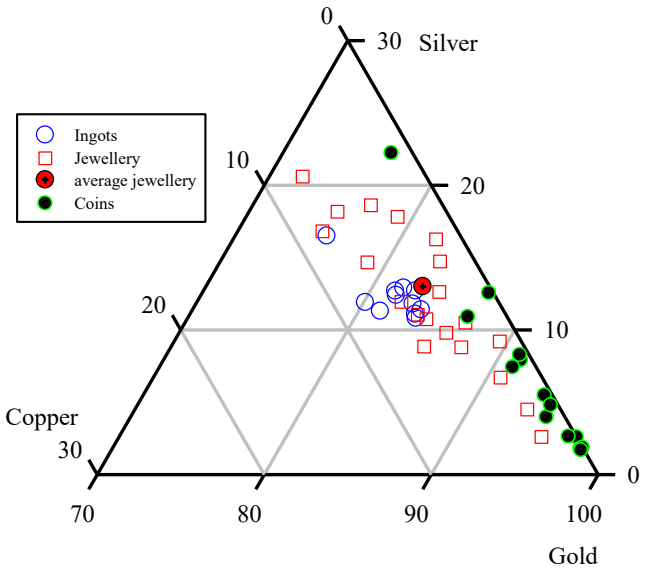

Figure 1: Gold, silver and copper contents of a selection of the Salcombe Bay gold analysed by XRF.

paper on an area of about 2mm^2 (similar to the X-ray spot size) to expose the bulk metal and analysed *in situ*. The ingot drillings were analysed contained within small gelatine capsules, tipped to form a bulk area. The standards used for calibration were in the same form (*ie* solid or drilled) and same presentation, as the artefacts or the drilled samples. The analyses of the West African nuggets were performed on cut samples (presented in capsules) thus avoiding any surface enrichment of gold through environmental leaching of silver (Guisti 1986). The gold alloy standards used included those prepared for a previous experimental investigation of the accuracy of specific gravity analysis of ternary gold alloy coins (Oddy and Blackshaw 1974) and also BNF (Wantage) standard reference gunmetal and leaded bronze alloys (*eg* C71x07 and C50x21). Note the good agreement between XRF and FNAA analyses of the small nuggets (Table 3).

Inductively coupled plasma mass-spectrometry (ICP-MS)

ICP-MS was used in this work to measure the concentration of trace elements in both the small nuggets and the selected objects from the Salcombe treasure. In this case, a sample in solution, which was entirely consumed during analysis, was required. For details of the methodology and calibration see Gondonneau *et al* 2001 (especially their table 3). Drillings, taken with a 0.8mm drill-bit, and scrapings, taken with a scalpel, from the jewellery, coins and ingots from Salcombe Bay were analysed for their trace element contents (Table 2). All samples weighed between 5 and 25mg. The gold nuggets or grains, being very small, were entirely dissolved for the ICP-MS analysis, after XRF analysis

Table 2. ICP-MS analyses of a representative selection of gold items from Salcombe Bay (ppm).

No	Ti	Cr	Fe	Ni	Zn	As	Ru	Rh	Pd	Sn	Sb	Te	Ir	Pt	Pb	Bi
Ingots																
448	nd	nd	143	nd	0.5	29	0.04	0.01	1	32	1	1	0.1	7	26	5
449	0.1	2	788	nd	45	nd	1	0.5	1	55	26	7	1	3	718	21
450	0.1	2	652	nd	94	nd	1	0.9	2	52	23	8	2	4	841	43
451	0.1	3	1289	nd	181	nd	1	0.5	1	88	24	7	1	3	889	42
452	5.4	17	195	43	1141	126	0.04	0.1	1	194	50	0.2	0.03	6	441	5
457	6.6	1	768	72	56	55	2	2.1	3	126	34	5	2	10	254	33
458	0.2	3	1371	49	85	79	0.02	0.1	1	54	33	8	0.1	6	535	75
459	0.1	1	1559	45	155	148	0.03	nd	1	147	32	20	0.1	4	251	37
Jewellery																
463	7	nd	497	23	34	44	0.02	0.02	1	52	12	1	0.2	4	280	12
467	nd	32	2622	26	106	44	0.05	0.01	1	84	15	4	0.01	1	162	18
468	0.1	3	510	nd	1	21	0.02	0.02	1	9	2	0.04	nd	2	83	1
471	6	nd	753	4	100	11	0.01	0.01	0.4	68	3	1	nd	0.2	113	20
493	6	3	290	28	13	24	0.03	0.002	1	30	17	5	0.002	1	28	12
494	8	3	1185	20	64	20	0.02	0.03	1	42	9	1	0.06	8	37	3
497	15	0.4	607	16	141	43	0.1	nd	1	51	11	2	0.07	1	90	9
Coins																
246	4	8	2819	12	130	10	nd	0.02	0.4	110	9	6	0.1	2	106	21
63	2	1	1163	5	21	8	0.001	0.02	0.4	30	2	0.2	0.1	0.2	5	0.3
105	4	13	2986	5	55	7	nd	0.03	1	37	3	9	0.02	1	34	13
167	2	1	669	5	27	7	nd	0.03	0.4	45	4	1	0.02	1	213	5
394	2	2	767	nd	94	22	0.004	0.001	1	161	12	1	0.3	0.3	92	5
410	nd	143	1457	30	60	27	nd	0.1	0.5	43	9	4	0.3	8	112	10

Notes: nd = not detected

of the major elements.

Source of the gold from Salcombe Bay

The importance and size of the Arabic Empire led to the exploitation of many sources of gold, such as the Nubian and Ethiopian mines as well as those in the area of the Red Sea and Yemen. However, from an economic point of view, one of the most important events in the Arabic Empire was the opening of trade across the western Sahara and the exploitation of a new source of gold in ancient Sudan, the West African region corresponding to modern Ghana, Mali, and Mauritania (Insoll and Shaw 1997; Garrard 1982; Nixon *et al* 2011). Analyses of current gold sources in Ghana are reported by Bowell (1992). Nevertheless, there are persistent claims for a trans-Saharan trade in gold from the Byzantine period (Phillipson 2017). According to the Muslim geographers, this gold was used for the dinars of the Western Arabian empire. This gold, said to be of high purity, might have been used in mints directly, without refining (Messier 1974). The trade, following the ancient caravan routes, continued through the centuries, beyond the reconquest of Spain.

Many of the gold coins from Salcombe Bay are issues of the Sa'dian sharif of Morocco, Ahmad al-Mansur (1578-1603), or his son, Zaydan al-Nasir. In 1591 al-Mansur took control of the Saharan gold trade through Gao and Timbuktu, which was exploiting sources in West Africa such as Bambuk, Bure and Sirba, and diverted the gold to his treasury. Gold from this region was exploited throughout the Islamic period and has been shown from analyses of coins to be rather distinctive, generally with low levels of elements such as platinum, palladium, rhodium and tin that are common impurities in other gold sources (Gondonneau and Guerra 2002; Roux and Guerra 2000; Nixon *et al* 2011).

The West African nuggets analysed by Gondonneau *et al* (2001) and by PAA were also found in general to have a low concentration of trace elements, and in particular to have very low quantities of antimony, tin and the platinum group elements (PGE): platinum, palladium, ruthenium, rhodium and iridium (Table 3; Fig 2). The coins, jewellery and ingots from Salcombe Bay selected for analysis all have the low PGE contents commensurate with a West African source for the gold (Table 2). The antimony levels are variable, being very low in some items, especially the coins, but higher in others such as the ingots. It is likely that this antimony was present in the copper additions made to the alloys. The lead content is of considerable importance in determining the likely treatment and alloying of the gold. Freshly-mined gold usually has very low lead contents. Such lead as is found in the gold artefacts could originate either from any added copper or added silver.

The major sources of European gold through the 17th century were from West Africa, coming via Morocco, and from South America (Blanchard 1989, 24-5), particularly from New Granada (present day Colombia) (Ridgway 1929; see also Guerra 2004, table 2), as well as from indigenous sources from the mines of central Europe and the Alps. It is instructive to compare the analyses of the Salcombe Bay gold with those of typical European gold coins, including a group of seven Portuguese gold coins struck from 1483 to 1521 by Alphonse V, John II and Manuel I of Portugal (Guerra and Magro 2000), with some later French, British and Portuguese gold coins (Morrisson *et al* 1999) (Fig 2).

Between 1483 and 1521 the gold-bearing regions previously exploited by the last Muslim dynasties in West Africa were controlled by the Portuguese from São Jorge da Mina (Elmina), in Ghana, providing every year to the Portuguese crown about 500kg of metal (Magalhães

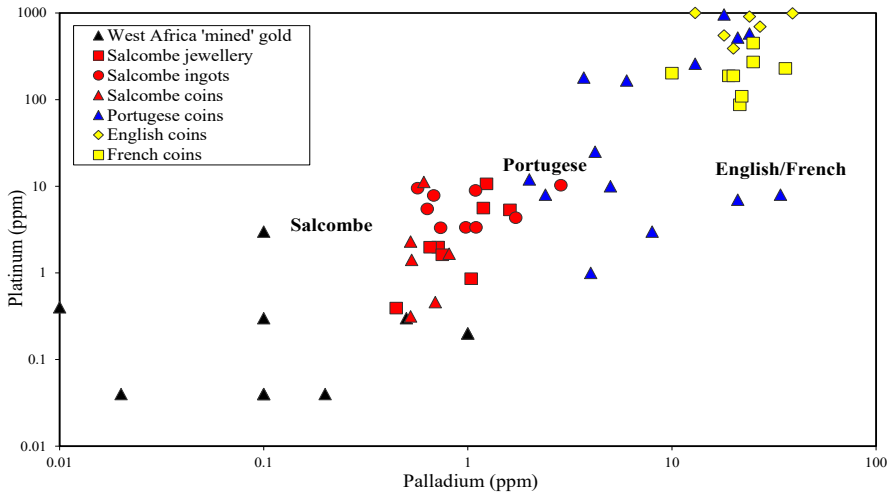

Figure 2: Platinum and palladium contents of a selection of Salcombe Bay items, post-medieval European gold coins, and some gold nuggets from West African sources that are likely to have supplied Morocco.

Godinho 1991). Figure 2 shows the good agreement between the composition of the early Portuguese coins and the objects from Salcombe Bay but with large differences from the other, later European coins. The latter are characterised by high concentrations of platinum and palladium, typical of South American gold (Guerra 2004), about 10 to 1000 times the amounts in the West African sources. It is noticeable in Table 2 that the platinum and palladium contents of the ingots, and to some extent the jewellery, are mostly slightly higher than in the nuggets (Table 3). This suggests that some gold from other sources, most likely those also available to Europeans, could have been included in the jewellery and ingots. Only a very small percentage of this gold mixed with that from the West African sources would cause a significant increase in the amounts of palladium and platinum.

Evidence for refining and alloying the gold from Salcombe Bay

The three categories of goldwork comprising the material from Salcombe Bay (coins, jewellery and ingots) each have distinctive compositions (Table 1), making it possible to judge the extent to which the gold was refined or alloyed and this is reflected in the different refining techniques recommended in al-Djaznā'ī's treatise, discussed below.

Overall, all three categories are of what would today be considered fine gold (typically between 18 and 23 carat in modern terminology), but with considerable variation within each category. Native gold regularly contains up to 40% of silver, but rarely contains more than a percent of copper (often much less) and only small traces of lead (Antweiller and Sutton 1970; Wise 1964, 3).

Coins

The coins are generally of high purity, but with some variation. Five of the 14 coins have less than 3% of silver which is the minimum silver content detected in the freshly mined nuggets (Table 1). Thus, it is very likely that the gold in these particular coins was refined by salt cementation, as recommended by al-Djaznā'ī, and then used without alloying. None of the coins have less than 1.7% of silver, which suggests that the process was not especially rigorous in removing all of the silver. Other coins, such as 105 with 7.9% silver but only 34ppm lead may be of gold that was used directly without refining or alloying.

Coins 167, 246 and 410, with 22.2% silver + 213ppm lead, 5.5% silver + 106ppm lead and 4.0% silver + 112ppm lead, respectively, suggest that additional silver was added to the gold in these cases. The low overall lead content (Table 2) shows that the gold itself was never refined by cupellation. This is of some significance as it suggests that the coins were made only from freshly mined gold rather than using all available gold, including scrap, which would have required cupellation.

The copper content of the coins is more equivocal, being very low but apparently above that to be expected in freshly mined gold as indicated by the analyses (Table 1). It was probably picked up adventitiously during the various refining and melting operations. The deliberate addition of such tiny amounts of copper seems pointless.

Thus, the coins are likely to have used freshly mined gold as their primary source, confirming Messier's (1974) suggestion. Some were made of gold that had been refined by salt cementation to a maximum purity of about 98%, and some may have been made from intrinsic (naturally-occurring) gold without either refining or alloying. Yet others are likely to be of gold to which some silver had been added.

Jewellery

As might be expected, considering it is likely to have originated from multiple workshops, the jewellery has a much wider range of composition, although generally still of high-quality gold. The copper content of all the items strongly suggest that it was added to the gold, very likely to improve the strength of the metal and hence its resistance to wear. Unfortunately, it is difficult to be certain on the origin of the silver. Only 463, with 10.5% silver + 280ppm lead, would seem likely to have been alloyed with additional silver, and conversely 493, with 18.1% silver + 28ppm lead, would seem likely to be of unrefined and unalloyed gold. Otherwise, it is difficult to determine the source of the silver based on the lead content. Given the various possible sources of the traces of lead, potentially being associated with the copper or silver, and if from the silver once again being potentially associated with the silver ore or the cupellation processes used to refine it, the silver in the remainder of the jewellery items could represent either the original intrinsic content, separate additions or a mixture of the two. Any added silver is likely to have originated in the Americas, which was the predominant source in the post-medieval world, but more local sources are possible (Baron *et al* 2020).

The relatively high lead content of all but one of the ingots shows that they are unlikely to have constituted a direct

Table 3. Analyses of a selection of West African gold nuggets.

		XRF analyses (%)				FNAA analyses (%)			ICP-MS analyses (ppm)												
Small gold nuggets/flakes		**Au**	**Ag**	**Cu**	**Zn**	**Au**	**Ag**	**Cu**	**Pb**	**Pd**	**Pt**	**As**	**Sb**	**Sn**	**Te**	**Zn**	**Ti**	**Fe**	**Ni**	**Ru**	**Rh**	**Bi**
Kuma1	Ghana	94	6	<0.2	<0.3	94.3	5.7	nd	1	0.02	0.04	77	0.5	3	0.05	4	2	nd	nd	0.05	nd	0.1
Kuma2	Ghana	96	4	<0.2	<0.3	96.2	3.8	nd	4	0.5	0.3	30	nd	18	0.4	19	12	3170	6	nd	0.05	0.4
Kuma3	Ghana	97	3	<0.2	<0.3	96.2	3.0	0.85	2	0.2	0.04	86	2	29	nd	6	3	nd	0.1	nd	0.05	0.1
Ojan1	Ghana	89	11	<0.2	<0.3	88.9	11.1	nd	7	1	0.2	41	nd	42	nd	28	16	3196	3	nd	0.1	0.2
Ojan2	Ghana	93	7	<0.2	<0.3	93.2	6.8	nd	3	1	0.2	133	6	17	0.2	12	5	61	1	nd	0.04	1
Ojan3	Ghana	91	9	<0.2	<0.3	91.3	8.7	nd	6	0.1	3	257	1	29	0.5	28	16	626	2	nd	nd	0.2
201	Ghana	95	5	<0.2	<0.3	95.0	5.0	nd	54	0.01	0.4	66	1	11	0.7	10	5	1395	0.4	nd	nd	3
Atte	Ghana	94	6	<0.2	<0.3	94.2	5.8	0.003	2201	nd	0.1	178	1390	30	22	548	5	1887	4	nd	0.03	60
Kor2	Ghana	93	7	<0.2	<0.3	93.7	6.3	nd	0.03	nd	0.04	23	3	2	nd	1	2	351	0.5	nd	nd	0.01
Akro	Ghana	91	9	<0.2	<0.3	91.1	8.9	nd	3	nd	0.04	73	nd	7	0.2	20	17	nd	0.7	nd	nd	0.2
Zere10	Ivory Coast	93	7	<0.2	<0.3	89.2	10.7	0.12	0.2	0.002	1	16	42	3	0.2	1	6	795	0.2	nd	nd	0.4
Bouf3	Ivory Coast	97	3	0.2	<0.3	96.6	3.2	0.18	76	nd	0.3	13	nd	3	1.8	12	3	586	3	nd	nd	10

		FNAA analyses (%)			PAA analyses (ppm)							
Large gold nuggets		**Au**	**Ag**	**Cu**	**Pb**	**Pd**	**Pt**	**As**	**Sb**	**Sn**	**Te**	**Zn**
Nanga1	Ghana	92.6	6.2	0.01	1	1	1	41	1	1	1	1
Nanga2	Ghana	94.9	2.6	0.01	1	1	1	82	1	1	1	1
Traor1	Ghana	91.9	2.6	0.01	1	69	1	83	1	1	1	1
Traor2	Ghana	98.0	1.6	0.03	1	1	1	7	1	1	1	1
Kassim	Ghana	96.1	3.3	0.00	1	1	1	1	1	1	1	49
Zere6	Ivory Coast	90.3	9.5	0.03	269	1	1	1	1	1	1	5
Zere8	Ivory Coast	93.6	6.3	0.02	1	1	1	2	1	1	1	8
Zere1	Ivory Coast	91.7	6.5	0.02	1	1	1	65	1	1	21	1
Zere9	Ivory Coast	91.8	7.4	0.02	1	1	1	18	1	1	1	1
Zere3	Ivory Coast	92.6	6.6	0.01	1	1	1	3	53	1	1	97
Zere4	Ivory Coast	96.5	2.4	0.01	1	1	1	332	1	1	1	133
Zere5	Ivory Coast	59.8	39.5	0.02	1	1	1	1	1	1	1	198
Bouaf1	Ivory Coast	72.3	27.6	0.01	1	1	1	1	2	1	1	13
Bouaf2	Ivory Coast	88.2	9.2	0.04	1	1	1	1	1	1	1	1

Notes: The small nuggets/flakes (not grains) were dissolved for ICP-MS analysis. Data from Gondonneau 2001, Annexe 7. Ir was sought but not seen. nd = not detected.
The large nuggets were not sampled but were analysed by PAA.

source of gold for the jewellery although the converse may be the case. The low overall lead content of the jewellery gold shows that it is unlikely to have been cupelled prior to use. Thus, the jewellery is likely to have been made originally from unrefined gold, to which small quantities of copper were certainly added, and some may have had additions of silver.

Ingots

The ingots are perhaps the most interesting pieces, in particular their relationship to the jewellery. Physically they are rather crude open mould castings, many have been cut from larger pieces and one, 451, appears to be a spill of molten metal, suggesting little care over their production. They display some regularity of composition. Basically two types seem to be present, the first represented by the two high-silver ingots, 448 and 452, with 30-35% of silver and 10% of copper, and the second by the remainder of the ingots with approximately 10-13% of silver and 4.6-8% of copper.

There are two possible explanations for the origin of the ingots. One is that they were independently and deliberately manufactured to a controlled composition. If that was the case, for example, in contrast to the coins and jewellery, the lead content suggests that the silver was an addition to the gold (with the exception of ingot 448, where the very low lead content suggests that the silver is intrinsic). Further, the ingots all contain copper, once again likely to be a deliberate addition, except for ingot 462 which had an addition of brass (assuming that all of the zinc came with the copper then this would originally have been a brass with approximately 25% zinc). With the exception of ingot 462, the copper:silver ratio in the gold is approximately 1:2. This is possibly not just an accidental figure. Such an alloy would preserve the golden colour of the adulterated metal, and has been encountered before, for example in Celtic gold coinage (Cowell 1992). With ingot 462 the addition of a high-zinc brass, which was already a golden colour, meant that even more base metal could be added and still preserve the colour. If, as is likely, the main assaying method was the touchstone without the refinement of acid treatment (see below), these ingots could have passed as pure gold, although ingots 448 and 452 with only 59-56% of gold would surely have been perceptibly 'light', in both weight and colour. In order to achieve their uniformity of composition it is possible that the gold had originally been refined to purity and then carefully alloyed (with the exception of ingot 448, which appears to be an intrinsic alloy of gold and silver to which copper was added). Al-Djaznā'ī stated that ingots should only be refined by cupellation. If this were the case the silver would have been retained. Thus, given deliberate controlled manufacture, the ingots could be of refined gold to which silver and copper were added in carefully controlled amounts.

However, an alternative, and the most likely, origin for the ingots is that at least the majority were not of controlled manufacture but are simply the result of melting down (recycling) fragments and complete items of jewellery similar to those now present in the Salcombe Bay Treasure, as bullion. In support of this it can be seen from Figure 1 and Table 1 that the average composition of the jewellery is very close to that of the majority of the ingots. Despite their wide range of individual compositions, the average for those jewellery items analysed on abraded surfaces is 83.6% gold, 12.2% silver and 4.2% copper, which is comparable with most of the ingots in Table 1, 455-461 for example. As noted above, most of the jewellery is incomplete and fragmentary and many items are distorted or crushed, presumably with the intention of reducing their bulk for transportation. What better way to accomplish this but by melting them down into convenient-sized ingots? Of course, the XRF and ICP-MS analyses of the jewellery relate only to the main gold alloy components of each item but also present in the jewellery would be joining, solder alloys and some non-gold components, such as brass, misidentified as gold. These areas were deliberately avoided in the XRF analysis and the sampling for ICP-MS. Thus, the presence of elevated levels of lead (and tin) in most ingots compared with the jewellery (Table 2), and the significant zinc content of one ingot, may be explained by fortuitous inclusion of such construction components and other scrap during the recycling process. This explanation for the origin of at least some of the ingots is plausible but cannot be conclusively proved since the mechanism relies on the recycling of items not now present in the Treasure but assumed to be of the same range of compositions as those that now remain. Nevertheless, it seems the likely origin. Returning to the coins, as noted above, a few of these are also incomplete, with cuts, pierced or damaged in some way suggesting that they were to be traded as bullion, along with the other gold items.

The treatise of al-Djaznā'ī

The *al-asdāf al-munfadda ᶜan ahkām ᶜilm sanᶜat ad-dīnār wal-fidda* is an important and detailed manual of the assaying and refining of precious metals and the production of coins, the principal stages being refining the metal and striking the coins. It is believed to have been written in Morocco by al-Djaznā'ī in the decades

around 1600 AD (Ben Romdhane 1988a; 1988b). The most complete version which Ben Romdhane used for his translation is dated to 1089 AH / 1768 AD and is preserved in Bibliothèque nationale de Tunisie. A shorter 18th-century version (dated to 1166 AH / 1747 AD) is preserved in a private collection in Tangier.

From its precise and detailed instructions, it is clear that this was a practical working manual, not just a theoretical treatise, although the author seems to have known of earlier Islamic treatises on coining and precious metal refining, especially the Moroccan treatise, the *al-Dawha al-mushtabika fī dawābit dār al-sikka* of Abū-l-Hasan Alī ibn Yūsuf al Hakīm, compiled in the 14th century AD (Mu'nis 1959; Levey 1971).

The treatise is logically set out and describes the appropriate methods to assay and refine precious metals from a variety of sources, including freshly mined gold, ingots, coins and scrap jewellery, prior to being made into coins.

Assay

Various non-destructive tests are described by Al-Djaznā'ī including the reaction to being struck or heated. The sound made when dropped or struck against a hard surface could indicate a suspicious hardness in the metal. Similarly, if the metal began to split on hammering this could indicate the presence of excessive amounts of copper. A sample could be strongly heated and if it remained yellow or white this was a good sign of purity, but if it darkened with a black or bluish hue, this could indicate that the metal was adulterated with lead.

The main non-destructive assay technique was the touchstone. The method as described in Al-Djaznā'ī's text was just the simple comparison of the streak made on the stone by the unknown against the standard needle without recourse to acid treatment to detect and remove copper.

The assay of gold by specific gravity is not mentioned, although it had been included in Al-Hakīm's treatise, centuries before. Al-Djaznā'ī's omission of the technique from his practical treatise probably reflects its failure as a real working technique.

The only certain methods of assay were cupellation, fire assay and acid dissolution. As well as being methods of assay they were also the principal means of refining the precious metals, and Al-Djaznā'ī describes them in some detail.

Refining

Cupellation was the standard method for the removal of base metals from gold or silver. Al-Djaznā'ī stated that the cupels were to be made of the ashes of animal bones mixed with clay and plaster. The gold or silver was first melted in the cupel and then either lead or galena, lead sulphide, was added. Al-Djaznā'ī's instruction to use galena is unusual, but in the very strong oxidising atmosphere of the cupellation operation either lead metal or galena would rapidly oxidise to lead oxide and absorb the base metals. The gold was then melted and assayed by touchstone, and if not sufficiently pure the operation was repeated a second and even a third time, and finally without further addition of galena or lead. This was in effect just a remelting, followed by the addition of *tincal* (borax) or *shalumman*. S*halumman* is mentioned frequently in the treatise; its identity is unknown but as it was always associated with *tincal* as an alternative, so presumably it was a similar flux. The fluxes used in similar preliminary refining operations in European procedures often used borax in conjunction with potassium nitrate (saltpetre) and sodium carbonate, the latter available in the Islamic world as the familiar natron, from Egypt (Eissler 1888, 145-7; Clark 1909, 34-5).

To remove silver from gold the usual method employed was fire-refining, known as parting or cementation. As described by Al-Djaznā'ī the gold was first hammered to thin leaves and then cut up into small pieces. This was to ensure that a large surface area was in contact with the astringent vapours in the parting vessels. The bottom of a ceramic vessel was lined with a layer of cement, then a layer of gold leaves was added followed by more cement in alternating layers continuing until the vessel was full. It was then sealed with damp clay. The cement was composed of ground fired red and white clay mixed with common salt either in the ratio of one part clay to two parts salt or equal parts of clay and salt. The crucibles were carefully stacked in the furnace, using pottery sherds to keep them apart if necessary. As crucibles from several goldsmiths would be fired together, al-Djaznā'ī recommended that each be carefully marked so that there could be no dispute after the parting was complete, further evidence that this was a practical manual. More clay dust was sprinkled over the crucibles and the furnace mouth was then stopped up with bricks, although still allowing some air to enter.

The form of the furnace is not described in the treatise, but the remains of a gold refinery survive at the El Badi palace in Marrakesh (Figs 3 and 4). The furnace probably dates from the stripping of the palace by

Figure 3: Remains of the furnace in the gold refinery of the El Badi palace in Marrakesh, c 1m in diameter. It is of the standard two part type with the fire beneath; the parting vessels sat on the floor of the upper chamber. The complete absence of vitrification shows that cupellation was not performed here.

Moulay Ishmail in the 17th century AD, and thus must be broadly contemporary with Al-Djaznā'ī's treatise. In all probability some of the operations carried out at the refinery at Marrakesh were similar to those described in the treatise. The fire was carefully started using brushwood such as broom, olive or even acorns as fuel. This may seem strange but several other early treatises on parting recommend similar seemingly insubstantial fuels, and it was essential that the impure gold did not melt before the end of the process, especially as heavily alloyed gold would melt at a lower temperature than the pure metal. It was also essential for the chemistry of the process that the combustion produced large quantities of water vapour. Inside the crucible the salt would disassociate producing hydrogen chloride, and would react with iron in the ferruginous red clay to produce ferric chloride, both highly astringent vapours. It was recommended that the operation should commence in the morning around midday and continue overnight until the following afternoon. The fire was then extinguished and after an hour's cooling the crucibles removed. They were emptied into a basin of water and gently tapped to ensure that all the gold was collected. If one of the crucibles had broken during the parting then the furnace would have to be carefully swept out to recover the gold. There is no mention of the recovery of the silver salts that would have collected in the spent cement and in the crucible walls, but this would have certainly been done by smelting with lead or galena to collect any silver, followed by cupellation.

The refining of gold with acid is also described in some detail by Al-Djaznā'ī. The acid, in Ben Romdhane's French translation, is named as *aqua fortis*, this was the usual post-medieval European name for nitric acid,

Figure 4: Tall chimney leading from the furnace shown in Figure 3. This would have created a great updraft, requiring careful control of the air entering the furnace as Al-Djaznā'ī instructed. It would also have been necessary to remove the noxious fumes from the refining operations.

which was the acid used for gold refining. It was produced by strongly heating a mixture of potassium nitrate (saltpetre) with either calcined ferrous sulphate (green vitriol) or potassium aluminium sulphate (alum) in an alembic or similar distillation apparatus. The reaction released nitrogen oxides from the saltpetre and these fumes were condensed and dissolved in water in the separate collecting vessel to form nitric acid. However, Al-Djaznā'ī apparently stated that alum was to be calcined and then mixed with *sal-gemmae* which is usually translated as rock salt, that is sodium chloride, with no mention of the essential saltpetre. It seems likely that *sal-gemmae* is a mistake or mistranslation and that

saltpetre was intended. It could be argued that saltpetre was present but omitted from the recipe as written, and that rock salt was indeed added to the acid so produced. This would have created a form of the mixed nitric / hydrochloric acid known as *aqua regia*, which was already known and used in the post-medieval period and which has the property of dissolving gold. However, Al-Djaznā'ī described how the finely divided gold was to be covered by the acid and warmed. The solution effervesced and the operation was repeated several times until only the pure gold remained which was to collected and washed in pure water. The gold was not dissolved and thus the acid really was *aqua fortis* and not *aqua regia*, and *sal-gemmae* must have been a mistranslation for saltpetre.

There is no mention of gold refining using sulphur or stibnite although the technique had been described by earlier Islamic authorities such as Alī ibn Yūsuf al Hakīm to remove copper from gold (Levey 1971, 23).

The use of amalgamation with mercury is mentioned twice, first to recover any droplets of gold left in the cupel after cupellation, and secondly, after cementation, to recover any droplets left in the parting vessel.

Al-Djaznā'ī described the refining of a number of different categories of precious metal, allocating a different method for each. These are summarised below:

- Silver was to be refined by cupellation.
- Gold that was mixed with base metals, and also that from scrap jewellery mixed with enamel (which was likely to have been a lead-based glass), was first to be cupelled, which would remove the base metals, and then cemented to remove the silver.
- Gold in ingots was to be refined only by cupellation to remove the base metals. There is no mention of either cementation or of acid treatment to remove the silver. This suggests that it was understood that the ingots had a recognised silver content that was to be preserved. This may be significant if the Salcombe ingots are not derived from recycled jewellery, as expected, since they may then have been refined in a way that retained their silver content.
- Gold ore was to be treated only by cementation after having been melted and beaten into thin leaves and thus when it was in a metallic state. This was usual practice and quite understandable as most gold straight from the ground only contains silver in any quantity.
- Although Al-Djaznā'ī prescribed cementation for treating gold mineral in general, gold nuggets were to be refined with acid. These nuggets were described as being of high purity, and it is true that gold nuggets formed in river deposits by the slow coalescing together of gold flakes over long periods do tend to be purer than the primary gold as there will have been more time for water action to remove some of the silver (Guisti 1986). Acid treatment being stronger than salt parting would be more effective.
- The gold from suspected counterfeit *dirhams* was also to be refined with acid.

Comparison of the treatise of Al-Djaznā'ī with contemporary Indian and European accounts

There are contemporary accounts of assay and refining methods from India and from Europe, including the Ā-*īn-I Akbāri* of Abū 'L-Fazl Allamī, compiled in the 1590s AD for the Mughal Emperor, Akbar (Phillott 1927) and the *Treatise on ores and assaying* by Lazarus Ercker, published in 1580 AD in Germany (Sisco and Smith 1951). Within the limits of the individual works this allows a comparison of the processes in use in the Islamic world, India and Europe at a time when the technology was changing fast.

Salt cementation was specified in the Indian accounts as the usual method for refining gold, although in India saltpetre (potassium nitrate) was the usual salt employed rather than common salt (Phillott 1927, 21-2). If the gold contained a great deal of silver then a sulphur treatment could be used instead (Phillott 1927, 26; Percy 1880, 376).

The usual procedure in European mints at this period as described by Ercker (Sisco and Smith 1951, 182-90) was for incoming gold to be cupelled and then parted by salt cementation to produce a reasonably pure gold that could then be alloyed with copper or silver to produce bullion of the required fineness. However, cementation was already being replaced by acid refining. *Aqua fortis* was recommended by other contemporary European sources, for example, acid treatment was the usual method used for parting in the 16th and 17th centuries by the Parisian goldsmiths (Allaire 1996). Surprisingly, the method was not mentioned by Abū 'L-Fazl, although mineral acids were certainly known in India by the 16th century (Rây 1956, 229-31).

Refining with elemental sulphur or sulphides such as stibnite was also described by Ercker, especially to recover small quantities of gold from silver or base metals (Sisco and Smith 1951, 171-9; Percy 1880, 360-1).

Amalgamation with mercury was a standard method of recovering small quantities of precious metals, from gilded metalwork etc in both Europe and the Middle East. In India, although a form of purification using mercuric sulphide seems to have been practiced (Rây 1956, 180-1), and mercury gilding was known, true amalgamation is not mentioned in any of the sources. Al-Djaznā'ī suggested the use of mercury to recover droplets of gold entrapped in the cupel and crucible walls, so he was clearly aware of the technique but did not include it as one of the main purification techniques.

Conclusion

The trace element content of the Salcombe Bay gold, especially the very low PGE, tin and antimony contents are characteristic of West African gold. This is consistent with the historical evidence that West Africa was the main source of gold for the western Islamic world in the medieval and post-medieval periods. The analytical evidence, especially the low lead content, suggests that the Salcombe Bay gold retained much of its intrinsic silver and such silver as was added may have come from the Americas.

The freshly mined gold will have contained no more than traces of copper, as demonstrated by the composition of the nuggets. Therefore, the small quantities of copper found in the gold were additions. The trace element content, notably antimony, indicates that the copper may have come from European sources.

Overall, this study reveals some differences between the documentary and material evidence for the refining of gold in post-medieval Morocco. Al-Djaznā'ī described a range of treatments for specific circumstances that are quite as advanced as those in Europe, and apparently superior to those in use in India. The composition of the Salcombe Bay gold is generally quite fine and is explicable in terms of al-Djaznā'ī's directions. However, the range of composition of the coins and jewellery shows little evidence for the regulation of composition and the balance of probability is that the ingots are simply derived from melted-down scrap jewellery or similar gold items. The fineness of the contemporary Moroccan gold coins demonstrates they had only been very imperfectly refined and the gold in some of the jewellery had not been refined at all before the addition of copper. This dichotomy rather suggests that although the technology was known, the political and administrative control to enforce its use was lacking.

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Images of most of the Salcombe artefacts can be viewed on the British Museum collection section of their website (https://www.britishmuseum.org/collection) and searching for Salcombe Cannon Site.
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