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# Refining gold with glass – an early Islamic technology at Tadmekka, Mali

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ABSTRACT

We describe two crucible fragments from an early Islamic context at the West African site of Tadmekka, in the Republic of Mali. They are made from a very sandy fabric and contain numerous gold particles and mineral grains in a matrix of lightly-coloured glass-based crucible slag. We interpret these as remains of a process separating freshly-panned gold concentrate from residual mineral inclusions, by melting the concentrate together with crushed glass beads. The process has similarities in modern artisanal practice, and shows the versatility of craftspeople in this major urban trading centre famous for its gold wealth.

## 1. Introduction

Throughout history the search for gold has driven economic and military expansion of most western Asian and European empires, and the expansion of the early Islamic empires into northern Africa from the 7th century AD is no exception. Control of the trans-Saharan trade provided access to the gold fields of sub-Saharan West Africa, as fabled in their time as the gold sources of the Americas over half a millennium later (Levtzion and Hopkins, 2000). Several caravan routes led through the Sahara, linking the Islamised Maghreb with the powers south of the Sahara, including such important states as Ghana and Mali (Devisse, 1988; Mitchell, 2005: chp.5). As well as commerce, the Islamic faith moved along these routes from the earliest centuries of contact, and was progressively adopted by West African traders and rulers alike. Tadmekka was one of the earliest towns established at the Sahara's southern edge as a market for the central cross-Saharan camel caravan routes, linking the important emporium of Gao in the south with cities in what is now Algeria, Tunis and Libya in the north (Fig. 1: Map of area). Tadmekka's merchants brought gold, slaves and ivory from the south, exchanging these for North African goods, such as glass beads, copper and its alloys, or cloth. Amongst the reports of the Arabic geographers who described the town throughout the early Islamic era, al-Bakri (AD 1068) noted Tadmekka as *"a large town … better built than Ghana or Gao"*, with a richly-attired king and pure gold coinage (Levtzion and Hopkins, 2000: 84-7). The sub-Saharan economies were almost entirely pre-monetary, where items such as glass beads took on some of the roles of coinage, while the North African Islamic economy depended on gold coinage, based to a large extent on imports of fresh gold from the south. The previously much overlooked gold coinage of Tadmekka described by al-Bakri – seemingly a "bald" (i.e. unstamped) coinage connected to the trans-Saharan export of gold – is explored elsewhere, based on the discovery of coin mould fragments excavated from a metallurgical workshop (Nixon et al., 2011).

Situated in northern Mali, Tadmekka's extensive stone ruins (c. 75 ha) – today called 'Essouk' ('the market') – reflect its past significance (Fig. 2). In 2005 fieldwork was undertaken to better understand this previously unexcavated town and its trade. A 6 m-deep archaeological sequence was recorded dating to c. AD 750–1400 (Nixon, 2009, 2010). Amongst the most intriguing results have been the remains from Tadmekka's metal workshops. Although no *in situ* metal working evidence was found, a complex assemblage of slag and crucible fragments was recovered amounting to c. 70 specimens. These finds all come from secure archaeological contexts from three excavation units within different quarters of the site (see Nixon, 2009). The depths of the excavation contexts range from c. 50 cm to 6 m below the surface. The finds come from living quarters or associated courtyards. Within securely dated contexts,

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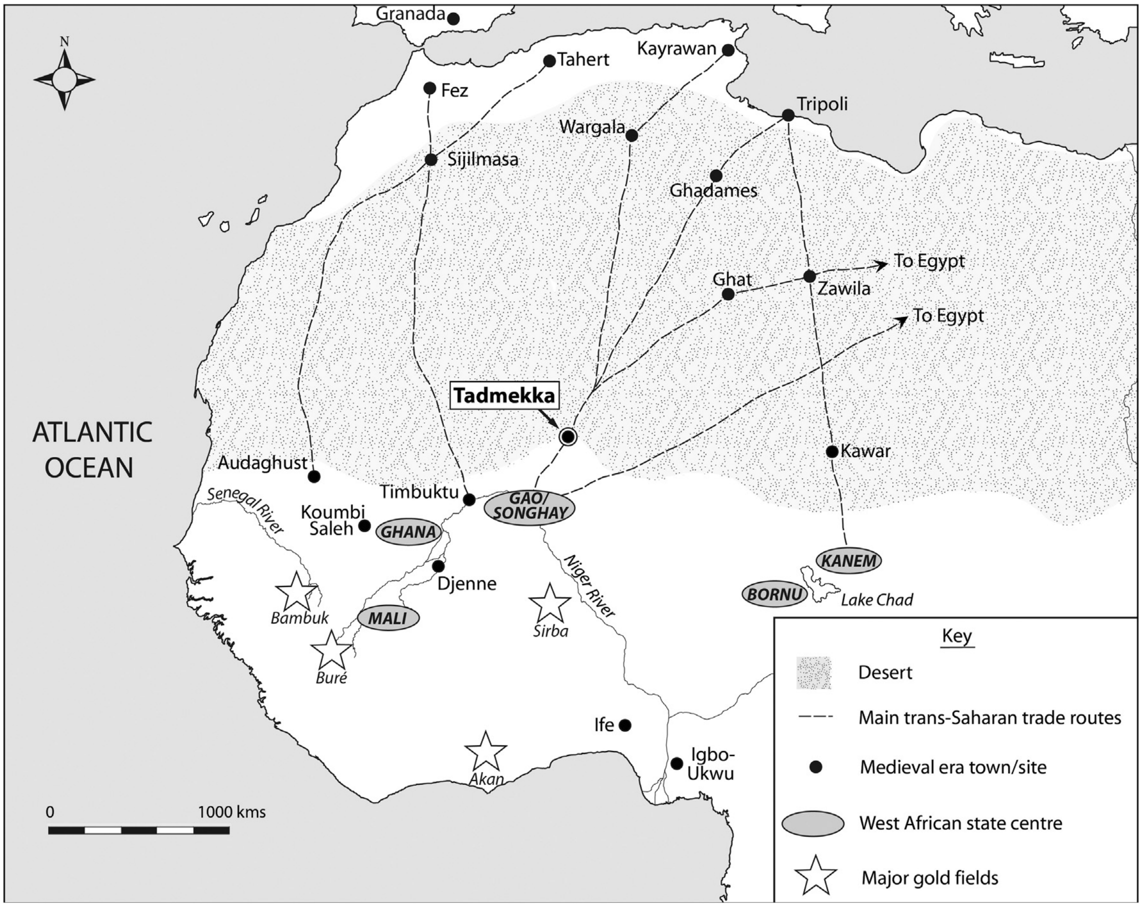

**Fig. 1.** Map showing major early Islamic Saharan trade routes, the principal West African gold fields, and sites mentioned.

the majority of the finds are found in contexts dated to the 9th–11th century AD. The finds include slags from copper and iron smelting and smithing, fragments of crucibles for steel making, coin moulds with gold prills (Fig. 3), and two crucibles for processing raw gold concentrate. The coin mould fragments have recently been published (Nixon et al., 2011); this paper now presents the crucibles used to process freshly panned gold, offering a technological reconstruction of a hitherto undocumented process that can be linked to the production of the high-purity gold seen in the coin moulds from the site.

**Fig. 2.** View across the central area of Tadmekka/Essouk, showing extensive stone ruins on the surface.

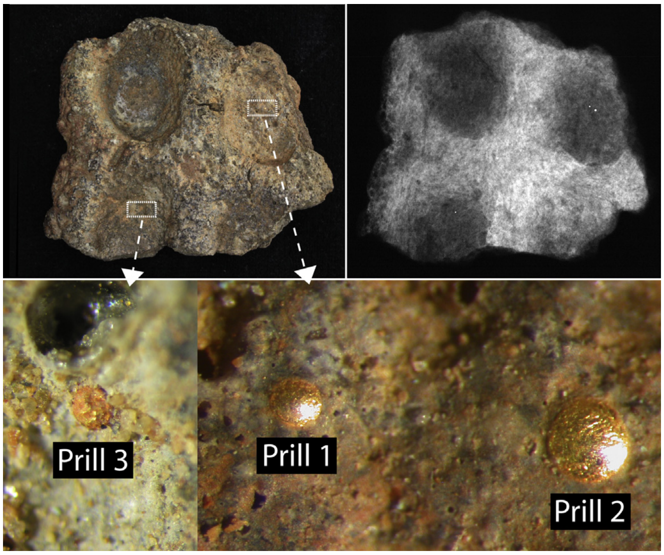

**Fig. 3.** Coin mould EKA-93 from Tadmekka. Radiograph image (top right) and close-up of individual prills trapped in surface. Photo: C2RMF, X-radiography T. Borel and optical microscopy D. Bagault.

## 2. Materials and methods

Most of the metallurgical material from the excavations in Essouk consists of relatively small fragments, such as small slag lumps and fragments of vitrified technical ceramic not exceeding a few centimetres in their maximum dimension. Visual inspection of this material was inconclusive with regard to the exact nature of metallurgical activities represented by it, and a systematic analytical programme was undertaken to maximise retrieval of information from these unpretentious but from their archaeological context highly significant finds. Each fragment was inspected using a hand lens or stereo microscope to look for metal inclusions; a small powerful magnet was employed to test the slag samples, and about half of all fragments were sectioned using a diamond-coated rotary blade to expose their internal structure. About two thirds of all sectioned pieces were then mounted for metallographic analysis by embedding them in cold-setting epoxy resin and grinding and polishing the exposed surface to a mirror-like finish using standard laboratory procedures. They were then investigated by optical and electron microscopy and analysed by energy-dispersive spectrometry (SEM-EDS). For this, the resin blocks were coated with carbon before analysis using a JEOL JSM6610LV Scanning Electron Microscope for additional imaging, and the attached Oxford Instruments X-ray detector and AZtec software to determine the chemical composition of selected areas and points in the samples.

This systematic routine analysis of visually unpromising finds helped to identify iron and copper slag, suggesting a range of metallurgical activities beyond the customary iron smithing. Significantly, it also led to the identification of two metallurgical processes entirely unexpected in this context, namely the gold refining process described here, and the first documented African crucible steel production (unpublished).

Below we present SEM-EDS data of the glass-based crucible slag coating the inside of the two crucible fragments. The quality of the EDS data was tested by analysing Corning glasses A, B and D under the same conditions and using the same instrument as the crucible samples. Table 1 shows the correspondence of measured values and published values, showing the generally very good agreement between the two even at concentrations as low as 0.5 wt%. In the absence of suitable reference materials we assume a similar quality of the EDS data for the analyses of the gold inclusions.

The two fragments of gold-working crucibles are very inconspicuous (Fig. 4); they were found within the same unit as the coin moulds (unit EKA), but in slightly younger deposits, three building horizons above that containing these coin mould fragments: contexts EKA 87 and EKA 86, within building Horizon 9. As a whole, unit EKA documented a series of 14 building horizons spanning c. AD 750–1400, over a depth of c. 6 m, recording portions of a series of buildings which were either commercial or habitation complexes. Contexts EKA 87 and 86 were excavated at a depth between c. 3 m and 2.5 m below the surface, over an area measuring c. 2.5 × 3.5 m.

The excavations took place within a space enclosed on three sides by stone walls (the c. 2.5 m measurement represents the width between two of the walls recorded; Fig. 5). It is unclear if this space is entirely enclosed by a fourth wall beyond the excavated area. Each of the contexts EKA 87 and 86 was composed of two deposits, firstly a compact sandy silt of c. 10 cm thickness, overlain by a loose sand of c. 5 cm depth. This placement of loose sand on a more compact 'bedding' deposit is a common feature throughout the sequence of the site, and has certain parallels with the practice of using loose sand as a living surface in houses in northern Mali today. These deposits are radiometrically dated to c. AD 900–1000 (a date of 895–995 cal. AD [Oxa-16769 – 1087 ± 27] was gained from context EKA 87). This room is of unknown function, but it contains further evidence of copper and iron working, as well as evidence of crucible steel working, and large quantities of vessel glass fragments and glass beads.

The crucible fragments are both very small (c. 2 $cm^3$) and only vaguely identifiable as such by their shape. The fabric differs from that of the coin moulds in that it is very light-coloured, sandy and dominated by badly-sorted quartz grains (Fig. 6), probably added as temper. Attached to the concave surfaces of the samples are relatively large agglomerates of transparent glassy slag, one appearing light blue (86A) and the other pale green (87E).

## 3. Results

The fabric of both crucible fragments is very rich in mineral inclusions, mostly angular to well-rounded but badly-sorted quartz, with comparatively little matrix material (Fig. 7). The transition from this fabric to the glassy slag is relatively sharp, but there is enough penetration of glass into the fabric to indicate that

**Table 1**
Comparison of measured and published values (in weight %) for Corning Reference Glasses A, B and D. SEM-EDS analyses courtesy M. Gill. n.f. = not found.

| | $Na_2O$ | MgO | $Al_2O_3$ | $SiO_2$ | $K_2O$ | CaO | $TiO_2$ | MnO | FeO | CuO | $P_2O_5$ | PbO | BaO | $Sb_2O_3$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Corning A measured | 14.1 | 2.6 | 0.9 | 67.6 | 3.0 | 5.3 | 1.0 | 1.1 | 1.0 | 1.3 | n.f. | n.f. | n.f. | 1.9 |
| Corning A published | 14.3 | 2.7 | 1.0 | 66.6 | 2.9 | 5.0 | 0.8 | 1.0 | 1.1 | 1.2 | 0.1 | 0.1 | 0.6 | 1.8 |
| Corning B measured | 16.6 | 1.0 | 4.1 | 62.2 | 1.1 | 8.9 | n.f. | 0.2 | 0.3 | 2.9 | 0.9 | n.f. | n.f. | 0.8 |
| Corning B published | 17.0 | 1.0 | 4.4 | 61.6 | 1.0 | 8.6 | 0.1 | 0.3 | 0.3 | 2.7 | 0.8 | 0.6 | 0.1 | 0.5 |
| Corning D measured | 1.0 | 2.6 | 0.8 | 33.6 | 2.8 | 5.1 | 0.7 | n.f. | 0.3 | 1.1 | n.f. | 39.2 | 12.5 | n.f. |
| Corning D published | 1.1 | 2.8 | 0.9 | 34.9 | 2.8 | 5.1 | 0.8 | – | 0.3 | 1.1 | 0.1 | 36.7 | 11.4 | – |

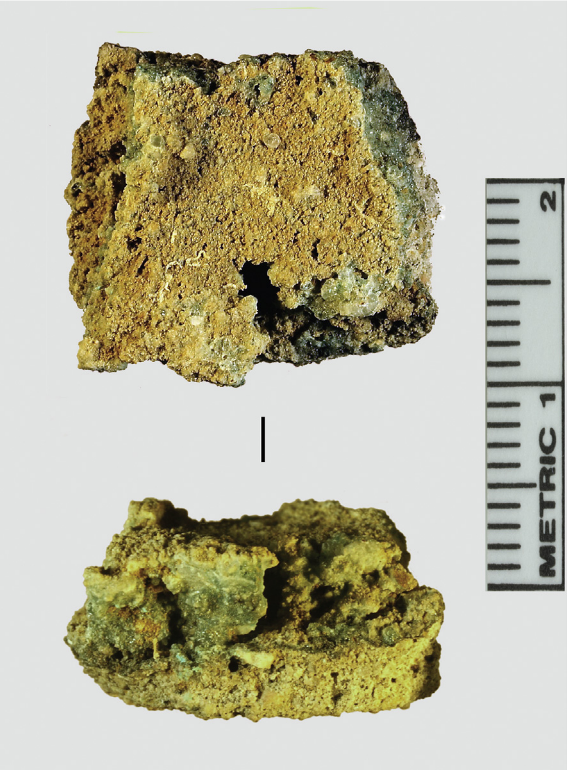

**Fig. 4.** Upper surface and profile of crucible fragment EKA 87E, prior to sectioning for analysis.

the process was not very quick. The area near the interface between the crucible fabric and the glass-based crucible slag contains numerous minute gold particles, often intimately intergrown with other heavy mineral inclusions (Fig. 8a,b). Further away from the ceramic the glassy slag contains still numerous grains of minerals such as quartz, magnetite, zircon and several other heavy minerals (Fig. 9), but far less gold. Notably, the range of minerals in the glassy slag is very different from the minerals seen as inclusions in the crucible fabric; it is therefore unlikely that the minerals in the slag originate from the crucible fabric. Instead, it is assumed that they were part of the charge of the crucible, together with the gold.

The prills have from 93 to 98 wt% gold, the balance being mostly silver and between one quarter and one half of one percent of copper, and occasionally iron (Table 2). The difference in composition between different particles within the same sample is remarkable. It indicates that these are indeed residual individual gold particles, and not prills separated from a single larger pool of liquid gold; the latter would be far more homogenous.

The crucible slag contains a large number of minerals, mostly quartz and feldspar, but also heavier minerals such as ilmenite, magnetite, zircon and others. Most of these are clearly residual mineral grains in various stages of reaction with the surrounding glass; the magnetite in particular appears to have interacted quite strongly with the surrounding glass, as can be seen in its composition (Fig. 10).

In addition, there are also numerous areas rich in newly-formed crystals, predominantly calcium-rich silicates related to the pyroxene family. It is difficult to say whether these are completely recrystallised original diopside grains, or whether they crystallised from the glass due to local chemical heterogeneities.

Despite the numerous inclusions, the glassy slag itself is clear and shows the same pale blue to green colours already seen in the un-mounted specimens. Its composition is unlike any slag or vitrified ceramic seen in other metallurgical crucibles (Rehren, 2003). Its most prominent feature is the high soda content, of around 13 wt%. This, and the rather low concentration of iron oxide (2–3 wt%) sets it apart from any typical metallurgical slag, or vitrified crucible ceramic. Instead, the melt composition resembles typical soda-based glass, with a low lime and relatively high alumina content (Table 3).

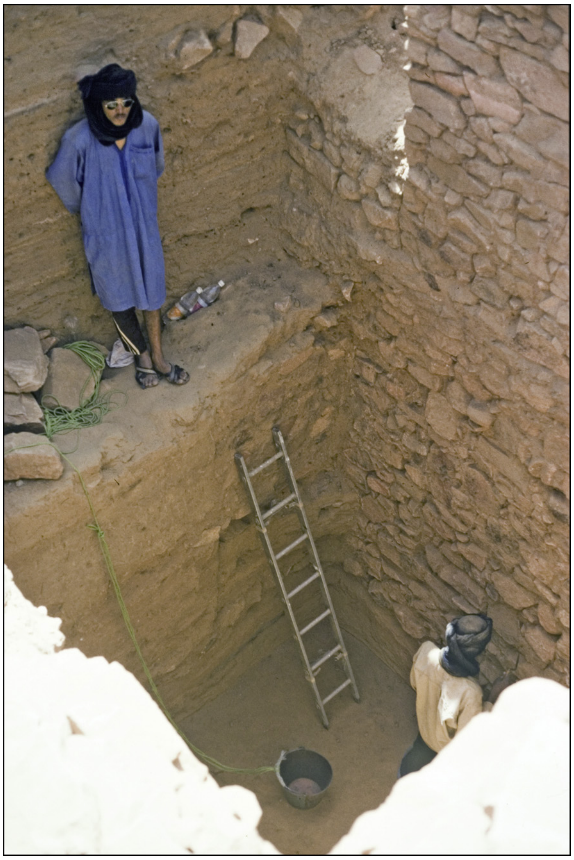

**Fig. 5.** Excavation at Tadmekka, in area EKA. The crucible fragments were found at c. 2.5–3 m depth. On the right side of the image can be seen a superimposed series of stone walls, representing multiple occupations.

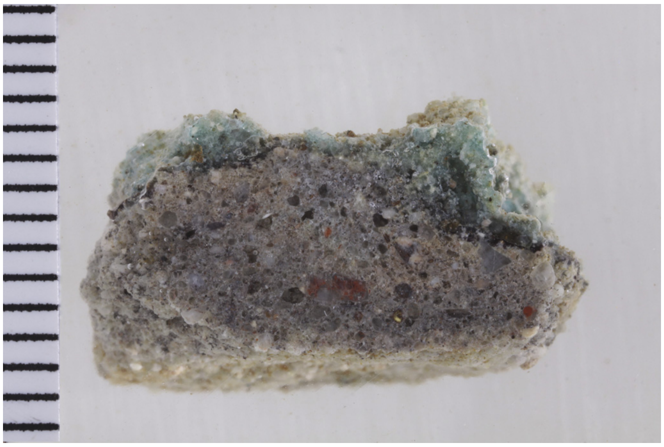

**Fig. 6.** Mounted and polished crucible fragment EKA 86A. Note the pale sandy fabric and the light blue colour of the glass-based crucible slag. Scale in mm.

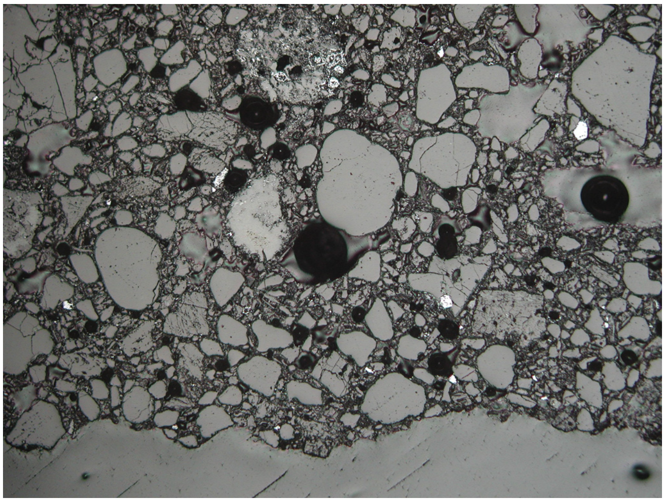

**Fig. 7.** Optical micrograph of the sandy fabric of crucible fragment EKA 87E. Width of image c 2 mm.

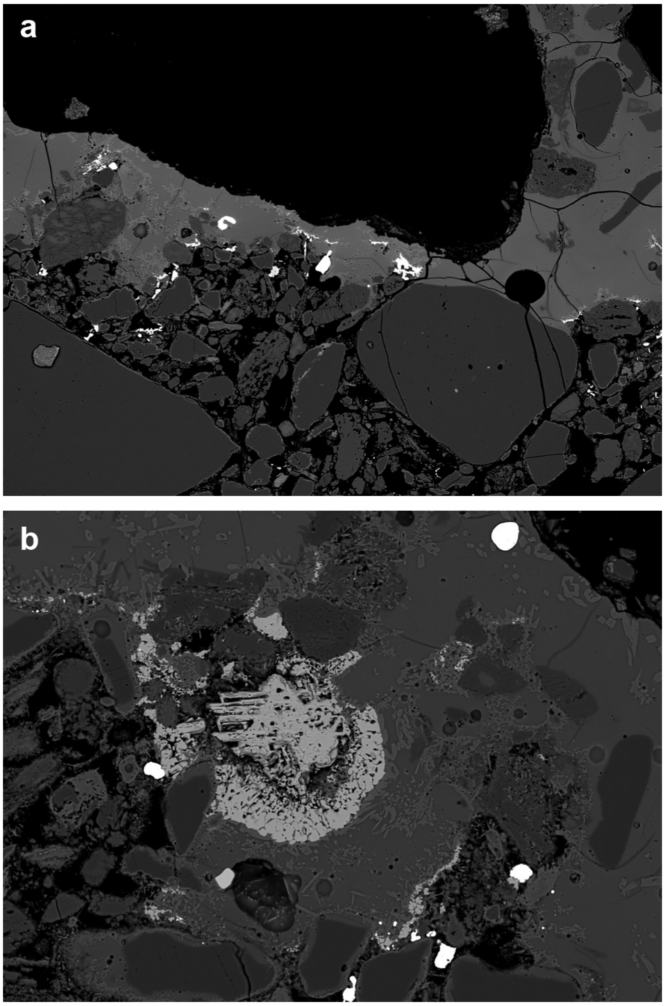

**Fig. 8.** a: Transition between crucible fabric (bottom) and glassy slag (centre, light grey). Note the gold particles in the centre (bright). BSE image, crucible fragment EKA 87E. Width of image = 1.7 mm. b: BSE image of magnetite grain (centre, light grey) and gold particles (bright) in crucible fragment EKA 86A. The magnetite grain is partly re-crystallised (outer rim), while the core still has its original structure. Width of image = 0.5 mm.

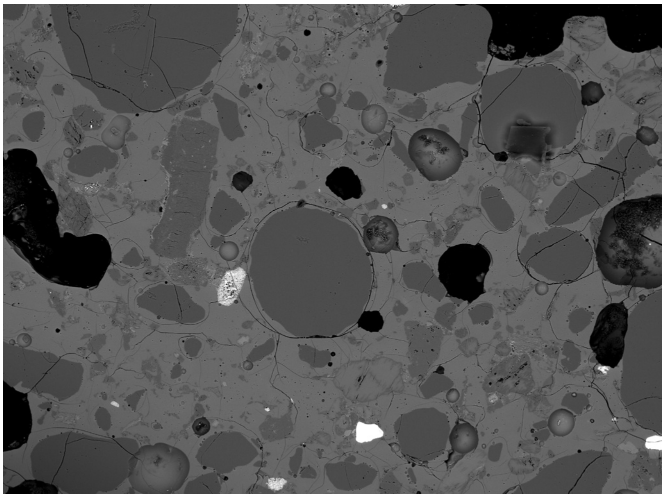

**Fig. 9.** BSE image of mineral grains embedded in the glassy slag. Crucible fragment EKA 86A. Width of image = 2.5 mm.

## 4. Discussion

The two crucible samples share sufficient similarities to link them to the same process. Both have a very sandy fabric and contain a slag composed of an alumina-rich soda glass with countless mineral inclusions, as well as tiny particles of gold with very low silver and almost negligible copper content. The fragments were found in stratigraphically closely related contexts, and there is a small chance they may even come from the same vessel.

The nature of the glass-derived slag, its range of mineral inclusions and the gold prills identify these samples as fragments of crucibles used for the processing of raw gold. This processing most likely aimed to separate panned gold particles from mineral contamination contained in the concentrate, by melting the gold and floating the mineral particles off in a light slag melt. This interpretation is based on the compositional range of the individual gold particles found in the crucible, indicating that they were not left behind from a single homogenous melt but represent discrete particles; also, the range and quantity of minerals floating in the glassy slag is consistent with a panned gold concentrate. To achieve this separation, the metalworker chose glass as the flux, creating a melt bath to facilitate the agglomeration of the gold particles into a single larger pool of gold, and upon cooling a brittle and light-coloured transparent slag which would easily reveal and release any gold trapped in it. The Tadmekka crucible fragments are therefore technologically distinct from the coin mould fragments found in the same excavation, and to our knowledge

**Table 2**
SEM-EDS analyses of individual gold particles within the two crucible fragments, in weight %. The data reported here is in good agreement with that obtained using a different instrument reported earlier (Nixon et al., 2011: 1363). n.f. = not found.

| 86A | 1a | 1b | 1c | 2a | 2b | 2c |
|---|---|---|---|---|---|---|
| Au | 93.1 | 93.1 | 92.8 | 95.7 | 98.3 | 98.0 |
| Ag | 6.4 | 6.3 | 6.3 | 4.2 | 1.5 | 1.3 |
| Cu | 0.2 | 0.2 | 0.6 | 0.1 | 0.2 | 0.2 |
| Fe | 0.3 | 0.3 | 0.4 | n.f. | n.f. | 0.5 |

| 87E | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Au | 97.9 | 97.8 | 96.8 | 98.2 | 98.0 |
| Ag | 1.8 | 1.9 | 2.9 | 1.2 | 1.5 |
| Cu | 0.3 | 0.2 | 0.2 | 0.2 | n.f. |
| Fe | 0.0 | 0.1 | 0.1 | 0.3 | 0.5 |

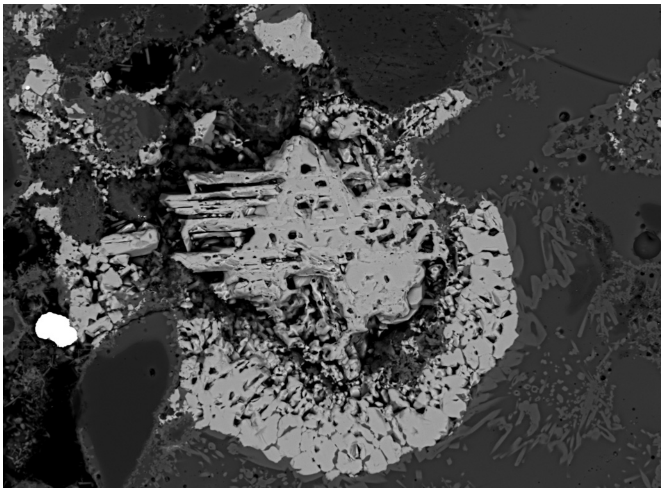

**Fig. 10.** Close-up BSE image of magnetite crystal in Fig. 8b. The core is relatively pure magnetite with 90–95 wt% iron oxide; the balance is manganese, titanium and magnesium oxide. The outer rim has reacted intensively with the surrounding melt, and has about 15 wt% MnO, 10 wt% MgO and 4–5 wt% each CoO, CuO and ZnO. The balance is iron oxide. Most of the transition metals are thought to come from the glass. Width of image = 0.25 mm.

archaeologically unique in their slag composition, while sharing with them the high purity of the gold. The coin moulds have only a very faint layer of superficial vitrification of their ceramic, due to the reaction of the fuel ash with the ceramic material (Heinrichs and Rehren, 1996; Nixon et al., 2011). In contrast, the crucibles have a thick layer of soda glass slag, and contain not only pure gold prills, but a raft of heavy minerals and quartz grains.

Where does this soda glass come from? The most prominent glass at the time would have been the typical Islamic plant-ash glass, with a few weight percent alumina, potash and magnesia, and several percent lime. Detailed analyses of nearly 100 glass vessel and window fragments and more than 60 beads from Tadmekka will be reported in the forthcoming excavation monograph (Lankton, forthcoming). In essence, these analyses confirm that the vast majority of glass found at the site is plant ash glass with 2–4 wt% each magnesia and potash, less than 3 wt% alumina, and 5–10 wt% lime. Only five beads bear a certain compositional resemblance with the glass in the crucibles, mostly on account of their elevated alumina and relatively low lime levels. Two are of a glass type called m-Na-Al 2, which is predominantly found in northern and western India, but also in eastern Africa and spans the date range from the 9th to the 19th century AD (Dussubieux et al., 2010). Finding this glass type as far west as Tadmekka is unusual but not entirely unreasonable (Lankton, forthcoming). Three other beads are of a composition indicative of plant ash glass, but with elevated alumina levels; no parallels for this glass type are easily found (Lankton, forthcoming). However, the best match of the glassy slag in the crucibles is with another one of the alumina-rich mineral natron glass groups summarised recently by Dussubieux et al. (2010), called m-Na-Al 3 (Table 4). This glass type, though, initially identified by Lankton et al. (2008), is mostly found at a site in Thailand where it is dated to the 4th to 3rd centuries BC. It is unlikely that this particular glass was available in the late 1st millennium AD in western Africa.

**Table 3**
Composition of glass in the two crucibles (SEM-EDS analyses of small areas, avoiding mineral inclusions; values in weight %). The glass analyses are similar enough across the two crucibles to justify a joint average. n.f. = not found.

| | 87E | 87E | 87E | 87E | 86A | 86A | Average |
|---|---|---|---|---|---|---|---|
| | Site 2 | Site 7 | Site 8 | Site 10 | Site 12 | Site 13 | |
| $Na_2O$ | 13.6 | 12.2 | 12.7 | 12.0 | 14.6 | 13.7 | 13.1 |
| MgO | 1.8 | 1.4 | 1.3 | 1.4 | 1.7 | 0.9 | 1.4 |
| $Al_2O_3$ | 3.2 | 5.5 | 6.1 | 6.7 | 5.7 | 6.3 | 5.6 |
| $SiO_2$ | 65.6 | 68.8 | 67.4 | 67.5 | 64.1 | 63.9 | 66.2 |
| $SO_3$ | 0.3 | 0.4 | 0.3 | 0.5 | 0.3 | 0.2 | 0.3 |
| Cl | 0.6 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| $K_2O$ | 2.3 | 2.9 | 2.6 | 3.0 | 2.1 | 2.0 | 2.5 |
| CaO | 3.0 | 2.5 | 2.4 | 3.4 | 2.4 | 3.0 | 2.8 |
| $TiO_2$ | 0.3 | 0.6 | 0.7 | 0.5 | 0.3 | 0.3 | 0.5 |
| MnO | 1.8 | 0.5 | 0.4 | 0.3 | 1.9 | 3.3 | 1.4 |
| FeO | 1.4 | 3.0 | 3.2 | 2.9 | 2.3 | 2.0 | 2.5 |
| CuO | 5.1 | 1.6 | 1.6 | 1.2 | 2.3 | 1.9 | 2.3 |
| ZnO | 1.1 | n.f. | 0.6 | n.f. | 1.6 | 1.5 | 1.2 |

Instead, we may have to consider that the current glass composition is different from the original composition of the glass added to the charge. It is clear that the glass melt has strongly reacted with the minerals floating in it, partly by absorbing some of the more easily melting minerals such as feldspars and ilmenite, and partly by crystallising newly-formed phases such as calcium silicates similar in composition to diopside. The former would have increased the concentration of the melt in alumina, while the latter would have reduced its content in lime and magnesia. The recrystallisation of magnetite would have strongly influenced the levels of transition metals in the glass, by incorporating manganese, iron, cobalt, and zinc as well as magnesium into the recrystallised magnetite crystal, as seen in the example presented above. It is therefore more likely that the glass slag composition is very different from the original composition of the glass added to the crucible charge and matches the Thai glass composition by coincidence, rather than due to long-distance trade in this particular glass.

Despite the obvious interaction between mineral grains and glass melt, most of the minerals would simply remain suspended in the molten slag, while the much heavier and more liquid gold would settle at the bottom of the crucible beneath the glass melt. To our knowledge no such flux-driven crucible process for separating gold from a heavy mineral concentrate has to date been identified archaeologically anywhere in the world. However, this is common practice today amongst amateur gold panners who want to avoid working with toxic mercury to collect their gold and prefer using borax as flux. Importantly, there also exists an historical description of a similar separation of gold using crushed bottle glass, from a nineteenth-century Australian gold prospector: "*Rough gold smelting on the mine is effected with a flux of borax, carbonate of soda, or, as I have often done, with some powdered white glass.*" (Johnson, 1904, 141).

**Table 4**
Comparison of the composition of the glassy slag in the crucibles (first column) with a glass group from Thailand (m-Na-Al 3) and two types of glass beads from Tadmekka (ESKb m-Na-Al 2 and ESKb v-Na-Al). See text for discussion. n.r. = not reported.

| | Average | | $N = 2$ | $N = 3$ |
|---|---|---|---|---|
| | Crucible glassy slag | m-Na-Al 3 | ESKb m-Na-Al 2 | ESKb v-Na-Al |
| | Tadmekka | Dussubieux et al., 2010 | Lankton, forthcom. | Lankton, forthcom. |
| $SiO_2$ | 66.2 | 66.8 | 62.5 | 58.5 |
| $Na_2O$ | 13.1 | 14.6 | 17.1 | 17.3 |
| $K_2O$ | 2.5 | 3.3 | 3.1 | 2.3 |
| $Al_2O_3$ | 5.6 | 7.1 | 9.4 | 7.2 |
| CaO | 2.8 | 2.9 | 2.6 | 4.6 |
| MgO | 1.4 | 1.3 | 0.5 | 2.2 |
| FeO | 2.5 | 2.0 | 1.5 | 5.8 |
| $TiO_2$ | 0.5 | 0.3 | 0.5 | 0.6 |
| MnO | 1.4 | 0.1 | 0.1 | 0.3 |
| CuO | 2.3 | 0.5 | 0.3 | n.r. |
| ZnO | 1.2 | 0.0 | n.r. | n.r. |

We have argued elsewhere (Nixon et al., 2011, and see below) that the gold from Tadmekka is unusual for its very high natural fineness, regularly exceeding 950/1000. Alternatively, the high purity of the gold could indicate that it had been refined through parting, a process known at least since the sixth century BC when the first known gold coinage emerged in Lydia (Turkey) (Ramage and Craddock, 2000). However, the fact that the high-purity gold in the crucibles appears to be primary gold, as indicated by its association with other heavy minerals in the glassy slag, together with the similarly low but still significant levels of silver present in the gold seen in the coin moulds, and the absence of any characteristic refining waste such as copper- or silver-rich slags or ceramics argue against the Tadmekka goldsmiths having used parting to attain this high purity.

Little can be said about the crucibles themselves, apart from the observation that they are made from a very sand-rich fabric and light-firing clay. This sets them apart from the domestic pottery, but also from the coin moulds, and indicates a conscious choice in raw material selection. Technologically this makes sense for two reasons. During the melting process, estimated to require around 1050–1100 °C to ensure melting of the gold and sufficiently low viscosity of the glass melt to facilitate separation of the lighter minerals from the heavier metal, such a fabric will not melt and bloat as much as less sandy and more ferruginous material. Therefore, fewer gold prills would end up trapped in the sticky surface of the molten crucible ceramic. Then, after the crucibles had reached the end of their useful life they would be crushed to retrieve any gold prills that did end up in its fabric; a friable quartz-rich fabric would be much easier to crush sufficiently fine to liberate even small prills from the matrix, ensuring a better recovery of this gold. This practice, known from medieval Europe and still common today, would also explain why the two fragments are so small, and why not more of this material has been found during the excavations. This makes it also impossible to determine the scale of production represented by these two fragments; their relatively small size does not exclude a larger routine operation processing significant quantities of gold concentrate. Elsewhere, small crucibles were used for large-scale production by increasing the number of crucibles used rather than their individual size (e.g. Rehren, 1999; Rehren and Papakhristu, 2000).

## 5. Wider significance

Direct archaeological evidence for the processing of freshly mined gold is extremely rare. The mining itself can leave significant remains if it took place in hard rock, such as exhausted veins visible as clefts in the surrounding host rock, spoil heaps of finely crushed quartz gangue, grinding tools such as hammer stones, anvils and mill stones, and installations for the separation of the dense gold dust from the crushed quartz. Klemm and Klemm (2013) have documented this in detail from the Egyptian gold sources, and similar evidence is known elsewhere in the Islamic world, though less-well preserved or documented (e.g. in the southern Arabah Valley, Gilat et al., 1993, but see Shaw and Rothenberg, 2000 for a critical review of this site). Throughout history, however, much gold has been won through an archaeologically far less visible process, namely the washing or panning of gold dust and nuggets from sediments, also known as placer deposits. Best known today from the stereotypical images of the American gold rush, such activities leave little if any archaeological remains as they consist of shifting and washing loose sediment, and use mostly ephemeral installations and tools (but see Phillipson, 2006 for more solid installations for gold washing from Aksum in Ethiopia). The final product of this operation, whether starting with hard rock or loose sediment, is a fine gold concentrate intermixed with residual other minerals. The mechanical separation of gold from those other minerals is never complete; the better the concentrate, that is the higher the gold content, the larger is the possibility that part of the gold is lost to the tailings (Shaw and Rothenberg, 2000). Thus, a certain amount of contamination from residual minerals is normally accepted and expected in the gold concentrate in order to ensure a high recovery rate of gold and to minimise gold losses. The raw gold or bullion contains typically a proportion of silver with it, ranging from just a few percent in some placer deposits, to around 25% or more in some freshly-mined gold from quartz veins. The further processing of the concentrate requires a metallurgical process, either through amalgamation and subsequent evaporation of the mercury to obtain pure bullion, or through other processes involving melting of the gold dust into bullion, typically in the form of bars.

Most archaeological evidence for gold working is restricted to secondary metallurgy conducted in goldsmiths' workshops, such as re-melting, casting and refining of recycled scrap gold to produce new artefacts (Eluère, 1993; see also Nixon forthcoming for a summary of West African archaeological evidence of gold finds). The main evidence for primary gold refining is the excellent study of the workshop remains from 6th century BC Sardis, the capital city of the famous Lydian King Croesus in western Anatolia (Ramage and Craddock, 2000). The general scarcity of gold working remains in the archaeological record is probably due to the reworking of much of such workshop waste to retrieve any gold lost during processing. This limits our understanding of early workshop practice to the few historical sources that concern themselves with such technical matters, such as Theophilus Presbyter (Hawthorne and Smith, 1963; Dodwell, 1971) in medieval Europe, or the Islamic sources mentioned above (Dunlop, 1957; Ehrenkreutz, 1953; Levtzion and Hopkins, 2000). The identification of the two crucible fragments from Tadmekka therefore provided a rare opportunity to expand our knowledge of primary gold processing in an urban context, and to discuss their possible technological relationship to the coin mould fragments mentioned above (Nixon et al., 2011).

The absence of any other archaeological evidence for such a flux-driven crucible process prior to the modern period makes these two fragments interesting beyond the local level of Tadmekka. Around the time of the Tadmekka evidence mercury is widely known within the Islamic world for amalgam gilding (Lins and Oddy, 1975), and most likely also for the separation of heavy minerals from gold (Ehrenkreutz, 1953; Al Hassan and Hill, 1986: 247; Blanchard, 2006; Brooks, 2012). What the Tadmekka evidence clearly shows is the existence of a gold processing technology which either preceded the use of mercury in West Africa, or was some kind of complementary industry. The origin of this technology is currently unknown. It is possible that it developed in West Africa at least partly due to its remoteness from the main Islamic mercury sources in Spain and Central Asia, especially in such a frontier context of the early gold trade as we see at Tadmekka, where glass cullet would have been more easily available than mercury. The occurrence of this technology in nineteenth-century Australia is the only other evidence we are aware of for it predating the twentieth century. However, now that we know what the waste from this technology looks like archaeologically we may hope to find further evidence of this in different geographical and temporal contexts (e.g. Vanacker, 1979).

## 6. Gold in Tadmekka

The gold reguli produced in the crucibles would have been suitable to be traded for their metal content, probably going north in exchange for goods such as copper and its alloys, glass, or textiles. However, the coin moulds found in the same excavation as the crucibles indicate that the process continued locally to a second, economically more sophisticated step, the production of a coinage. The excavated fragments enable a tentative reconstruction of the steps involved in gold coin production at Tadmekka. The metal composition of the gold found in the crucibles is very similar to that found in the moulds (Nixon et al., 2011: Table 1), which suggests that the gold bullion may have been placed in the mould cups to be melted into coin shape without further refining. The technical evidence of a generally reducing atmosphere and the charcoal impressions on the vitrified surface of mould EKA-96 indicate that the moulds were fired from above under charcoal cover (Nixon et al., 2011). The curved shape of the base of the moulds and the naturally curved surface of the liquid metal would have resulted in an irregular 'lentil' shaped flan or coin blank, at a rate of around 30 flans in a firing and potentially many firings being done each day. Customarily these blanks would then have been made into coins during striking; however, we argued based on historical evidence that in this case, the flans were left as cast, producing 'bald' coins as mentioned in the contemporary literature (Nixon et al., 2011: 1354-55). We cannot determine whether the moulds and crucibles were designed for single or multiple use, but it seems likely that any parts no longer to be used would be crushed for extraction of remaining gold prills, and it is probably only due to good luck that a few coin mould and crucible fragments escaped this final step, probably due to their gold content being nearly invisible (see Fig. 3).

There are a number of wider conclusions that can be drawn from our results, concerning the nature of the gold source, and the type of workshop present at the time. High-purity gold is often linked to parting and cupellation, two other very specialist operations (Ramage and Craddock, 2000). Since the purity of the Tadmekka gold used in the coin moulds (>98%) significantly exceeds previous findings for medieval West African gold (92–94%: Messier, 1974; Roux and Guerra, 2000) it is necessary to address this point. We believe that this high purity is due to the gold's origin from supergene gold deposits. Such deposits form when primary gold, typically containing 5–35% silver, naturally dissolves under specific climatic conditions and over geological time-spans and is reprecipitated in soils and sediments in a highly pure form (see Guerra and Rehren, 2009, and references therein). Such deposits are accessible through panning or surface mining, which would be consistent with the evidence from the crucibles where we see the extraction of high-purity gold from heavy mineral concentrates. This fits also with analyses of modern West African nuggets (>97%: Gondonneau et al., 2001), and medieval descriptions of sourcing high-quality gold from soils and streams in West Africa (Levtzion and Hopkins, 2000). It is therefore not unreasonable to assume that such gold deposits existed within the reach of Tadmekka's trading network, providing the necessary raw material for its mint.

From the recovery of the excavated coin moulds and crucibles alone we cannot say we have excavated an *in situ* gold working workshop in unit EKA. Certainly none of the structures allow us to say this. However, the recovery of gold working remains from different building horizons in EKA does lend weight to the idea that for several generations this area of the site was a gold working zone. Likewise, recovery of other metal working remains such as crucibles for steel production and iron and copper slags provides further basis for arguing that this structure was situated in a small but relatively versatile and sophisticated metal working quarter. Of particular interest is the fact that from within the context where we find the crucible fragments we also see numerous fragments of glass and glass beads. This intensity of glass remains is not seen elsewhere within the stratigraphy, and could potentially indicate the processing of both metal and glass in the same workshop or area (cf. Rehren et al., 1998 for a Late Bronze Age Egyptian example of such an association, and Crew and Rehren, 2002 for an Iron Age Irish example). However, we have shown above that the Tadmekka goldsmiths were processing gold using crushed glass as a flux, rather than working glass as a material in its own right. The presence of typical colourant oxides in the slag, such as manganese, copper and cobalt, indicates that the glass was from crushed beads rather than vessel glass. Regardless of whether the gold workshop is preserved *in situ*, the metallurgical remains from Tadmekka are fascinating as they document beyond reasonable doubt that there existed a sophisticated metallurgical industry processing high-quality gold at Tadmekka, supporting the historical sources as well as significantly expanding the level of detailed knowledge about this.

## 7. Conclusions

Two small fragments of crucibles from Tadmekka were found to contain natural gold and other heavy minerals embedded in a slag very similar in composition to man-made glass. We believe that the combination of a slag matrix based on proper glass with numerous mineral grain inclusions provides evidence for the separation of panned gold dust from the remaining mineral impurities. This process would have used glass from crushed beads as a flux to facilitate the agglomeration of the individual gold flakes and nuggets into a larger regulus of bullion, and its separation from the relatively lighter minerals. This process has not been described archaeologically before, and demonstrates the high level of skill of the local craftspeople. Although stratigraphically from a slightly later context than the coin moulds reported earlier, both find types can be seen as part of the same sequence of operations leading to the production of coin blanks. Historical references to 'bald', that is un-stamped, coins of high fineness from Tadmekka fit the observation made here. The scale of production is impossible to estimate, due to the limited nature of the excavation and the expected crushing and recycling of any gold-containing waste from the process. The crucible fragments were only identified as such during careful routine investigation of metallurgical waste, indicating the potential of such material to inform our understanding of past societies. The existence of multi-functional high-temperature workshops in urban centres is neither a new archaeological discovery, nor unexpected. However, documenting the details of such workshops provides unparallelled insights into the social and technological organisation of these cities, and the levels of skill of their populations.

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