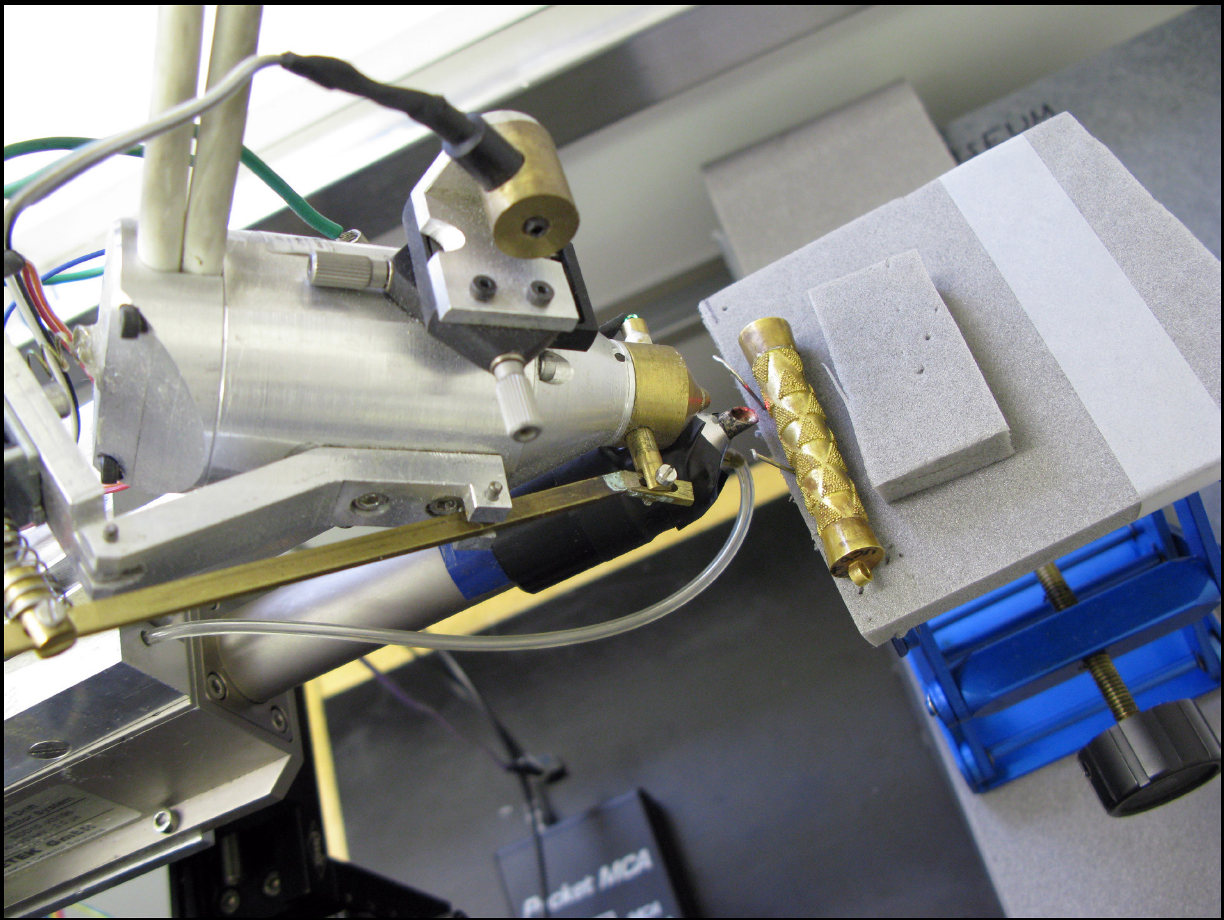
McDONALD INSTITUTE MONOGRAPHS

Ancient Egyptian gold

Archaeology and science in jewellery (3500–1000 BC)

Edited by Maria F. Guerra, Marcos Martinón-Torres & Stephen Quirke



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with contributions from
Wolfram Grajetzki, Maria F. Guerra, Marei Hacke, Mona Hess, Susan La Niece, Quentin Lemasson, Lindsay MacDonald, Margaret Maitland, Marcos Martinón-Torres, Nigel Meeks, Gianluca Miniaci, Brice Moignard, Jack Ogden, Claire Pacheco, Sandrine Pagès-Camagna, Laurent Pichon, Matthew Ponting, Campbell Price, Stephen Quirke, Martin Radtke, Uwe Reinholz, Ian Shaw, Jim Tate, Isabel Tissot & Lore Troalen

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On the front cover: *Analysis of the gold cylindrical amulet from Haraga at The Petrie Museum of Egyptian Archaeology (UC6482) using a portable XRF spectrometer*.
On the back cover: *Details under the SEM of the triangular designs of granulation on the tube of the cylindrical amulet from Haraga*.

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Editorial foreword

This volume aims to present a wide range of perspectives on early Egyptian goldwork, integrating the complementary yet distinct approaches of archaeology, materials science, jewellery and Egyptology. On one level, our primary task has been to present new analytical data on the manufacturing technology and elemental composition of dozens of artefacts preserved at six European museums. At the same time, we have sought to anchor and contextualize this new information based on current research from three perspectives: an introduction to the fundamental geochemistry and material properties of gold, a reanalysis of historical sources and of goldwork manufacturing-techniques, and a guide to the key analytical techniques employed. In this way, we wish to ensure that the volume is accessible to specialists and students from different backgrounds. We anticipate that this body of material will provide a rich source of information for further interrogation and discussion in the future, and our concluding chapter offers a first synthesis of some key points emerging from this new research. There we focus particularly on the findings that seem to us most significant, alongside open questions and suggestions for future work. In so doing, we explicitly highlight some of the many strands beyond the scope of the work presented here, hoping that they may provide pointers for others. We emphasize that the volume is addressed not only to those interested in the archaeology of Egypt in the timespan covered, but equally to scholars researching past technologies and archaeological goldwork elsewhere, who may find technical observations of broader scope that could prompt cross-cultural comparisons.

In spite of the substantial amount of data compiled here for the first time, it is important to remind ourselves of some potential biases that are inherent to this work and may thus skew our interpretations. The most important of these concerns the selection of objects. This project starts and, in many ways, remains throughout its course with the exceptional group of gold jewellery buried in Qurna, on the west bank of Thebes in Upper Egypt, with a woman and child whose names are unknown to us, at some point in the 17th or 16th century BC. Today the Qurna group is the most important Egyptian assemblage in the National Museum of Scotland, Edinburgh. In 2008, curator Bill Manley with materials scientists Jim Tate, Lore Troalen and Maria Filomena Guerra launched a programme of new analyses of the goldwork from the group. Already in this first investigation, the scope extended to comparison with jewellery from the preceding and following centuries (Tate et al. 2009; Troalen et al. 2009). With funding obtained from the CNRS, Guerra could then expand the range of collections involved in collaboration with Thilo Rehren at UCL, to include the UCL Petrie Museum of Egyptian Archaeology and the UCL Institute of Archaeology with its laboratory facilities, as well as the National Museums of Scotland and the British Museum as project partners (CNRS project PICS 5995 EBAJ-Au). On the initiative of Jim Tate, contact had been established already with colleagues Matthew Ponting and Ian Shaw at the University of Liverpool. As a result, the Garstang Museum is also participant in the wider project, together with the Manchester Museum, through the support of curator Campbell Price, and the Louvre Museum, through the support of curator Hélène Guichard and the late Sandrine Pagès-Camagna, material scientist at C2RMF (Centre de Recherche et de Restauration des Musées de France). We wish to emphasize here the fundamental role of Sandrine Pagès-Camagna in crucial stages of the project; without her participation the project could not have achieved a significant part of its aims – notably comparison between the Qurna group and the nearest securely dated examples of royal goldwork from the reigns of kings Kamose and Ahmose.

Other institutions participated with the provision of access to particularly specialized equipment: AGLAE facilities at C2RMF, Bundesanstalt für Materialforschung und –prüfung, and LIBPhys at NOVA University of Lisbon

With this new support, the research agenda was able to grow organically, adapting to fresh questions emerging from preliminary results, while contingent on the artefacts present in museums that were accessible to the project. Indeed, the history of the collections has been a significant factor, both enabling and constraining our research. The Louvre collections contain a range of jewellery from early excavations in Thebes, including representative material from the late second millennium BC settlement Deir al-Madina, and major works from 16th century royal burials uncovered during fieldwork directed by Auguste Mariette. The British Museum and the other participating museums in England and Scotland also preserve a mixture of material from documented excavations and earlier undocumented collecting practice. Here colonial history frames the kinds of material available. During and after the full British military occupation of Egypt (1882–1922), the Antiquities Service of Egypt under French Directors permitted officially recognized institutions to excavate in Egypt and, in return for the enrichment of the Egyptian Museum Cairo, to take a share of finds from excavations. Following division of finds in Egypt, excavation funding bodies based at Liverpool (since 1903) and London (since 1882) distributed finds to dozens of sponsoring museums (Stevenson 2019). The university museums in Liverpool and London were among the major recipients of these finds, and also hold substantial excavation archives. The Qurna group itself and several other sets of jewellery analysed during the project are unusual examples of this pattern of dispersal, where the vast majority of items distributed belonged to the types of objects found in large numbers in fieldwork. The project was therefore able to investigate objects from a wide social spectrum, from palace production (Qurna group, Haraga fish and cylinder, items of kings Ahmose and Kamose from Thebes) to finds in cemeteries of regional rural towns and villages (Qau, Badari, Matmar). At the same time, in expanding the chronological scope of analyses forwards to the New Kingdom and back to the late prehistory of Egypt, the participating museums could not cover every social group for every period. Most notably, and perhaps surprisingly for those outside the museum circle, these collections hold none of the major goldwork from the age of the great pyramids, the mid-third millennium BC. At that period, the concentration of power at Memphis around kingship separates the royal court from the regions, and this is reflected in the tombs of the period and in the distribution of finds. Gold and gilt ornaments are more prominent in burials at the Memphite cemeteries: Giza and Saqqara. The single outstanding assemblage of Egyptian goldwork from the mid-third millennium BC is the unparalleled burial of material related to Hetepheres, mother of king Khufu; the finds are on display in the Egyptian Museum Cairo. Egyptologists from Cairo, Vienna, Boston, Hildesheim and Leipzig directed excavations at Giza; their museums received a share in finds (Manuelian 1999). The museums in our project, from Paris to Edinburgh,

Table 0.1. *Numbers of artefacts (museum inventory numbers) analysed by site and period.*

	Dyn 1-2	First IP	Middle Kingdom	Second IP(-Dyn18)	New Kingdom	?	Total
Memphis					2		**2**
Riqqa			4		7		**11**
Haraga			13 + 1?				**14**
Lahun			5				**5**
Ghurab					1		**1**
Sidmant			1		1		**2**
Amarna					8		**8**
Qau area		15		5			**20**
Abydos	4		2 + 2?	2		3	**13**
Naqada			2				**2**
Thebes			2	2 + 7?	4		**15**
*Qurna				12			**12**
Buhen			1				**1**
?		1	5	2	22		**30**
TOTAL	**4**	**16**	**36**	**30**	**45**	**3**	**136**

are not on that distribution map. With this and other lesser gaps, our sample, however extensive, cannot and does not claim to be random or representative of an underlying population of 'Egyptian goldwork'. On our chronological range from fourth to second millennia BC, there are peaks and troughs in the frequency of artefacts, and we encourage the reader to keep these in mind graphically, in order to assess our interpretations in context and to develop their own further research agendas (see Table 0.1).

Another delimiting factor in the selection of objects derives from our focus on technique, directing our attention predominantly to jewellery, rather than other gold elements such as the prominent use of sheets for gilding larger substrates of wood or plaster. Gold foils were included for comparative purposes, particularly in the investigation of composition, but to a lesser extent. Furthermore, within the rich repertoire of Egyptian gold jewellery, we took a particular interest in select assemblages, starting with the Qurna group itself, and within these certain specific features, such as the small beads found in the child's coffin and the adult's girdle. While these are fascinating manifestations of both technology and consumption, they are not necessarily representative of a broader corpus. We would also emphasize that we sought primarily artefacts with well-recorded archaeological contexts, as these evidently allow for more robust inferences, and provide the most secure foundations on which to build further research. Where the museums could provide access to material not from documented excavations, but acquired before 1970, we have included certain items if they helped to complete gaps in understanding, as a secondary circle of supplementary information. In each such case we have done our utmost to investigate their authenticity and source, but undeniably any interpretation based on an unprovenanced object will have to remain tentative. Indeed, one of our analytical investigations demonstrated the risks in building historical conclusions on material without documented excavation context; a gold shell inscribed with the name of king Taa, who reigned close in time to the Qurna group, presents disconcerting features more consistent with modern rather than with ancient manufacture.

A final and equally important constraint concerns the background and expertise of the editors and contributors to this volume. While together we span interdisciplinary breadth, and have found synergies in our research, inevitably there remain areas beyond our interests and access, and indeed beyond the time scope of the project. For example, our data may be used as a starting point to address issues of provenance, but targeted consideration of the extraction methods and possible geological sources of gold is not addressed in detail in this volume. Instead, much more emphasis has been placed on issues of technology, and the application of the results to a concluding interpretation of the Qurna group. We look forward to seeing how others may take up such topics, and feel sure that the woman and child of Qurna will continue to pose new questions.

Finally, for the opportunity to share our discussions and findings with a wider research audience, we would like to express our gratitude to the McDonald Institute for Archaeological Research for including this volume in its series.

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Chapter 1

Gold, an exceptional material

Maria F. Guerra

With gold occurring as a native metal, its first use doubtless arose by chance. Since its discovery, skilled workers have produced gold items by exploiting different sources of gold, and by experimenting and developing a wide variety of techniques to use the metal and modify the properties of its alloys. Based on the earliest gold objects excavated in Egypt and by considering metallurgical practices and mineral resources in Egypt and adjacent regions, this chapter discusses some particular alloys as well as some of the most frequent jewellery-making techniques employed in Egypt.

Why gold?

Gold is a rare resource compared to the world production and reserves of other minerals (Nishiyama & Adachi 1995). In 2019, 3,300 tons of gold were produced in the world, 130 tons of new and old scrap was recycled, and the reserves were estimated to 50,000 tons (U.S.G.S. 2020).

Indeed, about 99 wt% of the Earth's crust is formed of nine elements only. Among them is oxygen, with a crustal abundance of more than 45 wt%, and iron, one of the metals used in the past, with a crustal abundance of about 6 wt% (Skinner 1979; Rankin 2011). All the other elements together make up the remaining 1 wt% of the Earth's crust, including gold with a crustal abundance of only 0.004 ppm (i.e. 0.0000004 wt%). Similarly, silver and copper have low crustal abundances of, respectively, 0.008 ppm and 68 ppm (Skinner 1979; Rankin 2011).

The chemical symbol of gold is Au, from its Latin name *aurum*. This transition metal, with atomic number 79, has a melting point of 1064.43 °C and high density, 19.32 $g.cm^{-3}$ at 20 °C (Renner et al. 2012). Because of its electronic structure, gold has high resistance to corrosion (Rapson 1996; Blaber et al. 2010). By alloying gold with other metals – in the case of ancient goldwork, typically silver and copper – gold-base alloys can be obtained with different chemical properties. Contrary to pure gold, these alloys corrode in the presence of gaseous pollutants (Rapson 1996; Corti 2014; Tissot et al. 2019). For example, the reddish coloured spots at the surfaces of certain Egyptian objects (Lucas 1948; Tissot et al. 2015 and section 6.8) are usually due to tarnishing, i.e. development of sulphides under certain environmental conditions.

Resistance to corrosion has always given a special role to gold, but even though this characteristic is necessary for some goals, it does not entirely justify the prestige of this metal among all the others. In fact, other mechanical and physical properties of gold also play an important role on its widespread use and appreciation. Among the physical properties, the high thermal and electrical conductivity of gold and its high coefficient of expansion can be mentioned. The first has to be considered when soldering gold parts, and the second one when casting gold alloys. However, in the case of jewellery and other prestigious objects, special attention has to be given to the optical properties of gold, because they influence our perception of the objects.

Gold has high reflectivity and can be given a different colour by alloying with various metals. By adding copper and silver to gold, it is possible to obtain alloys ranging from yellowish to whitish-greenish and reddish. It is also possible to increase the reflectivity of the gold alloys by addition of silver, because this metal has higher reflectivity than gold (Roberts & Clarke 1979; Loebich 1972). Several other properties change significantly when gold is alloyed with variable amounts of silver and copper. Figure 1.1 shows the ternary gold-silver-copper diagram with a representation of the relation between composition

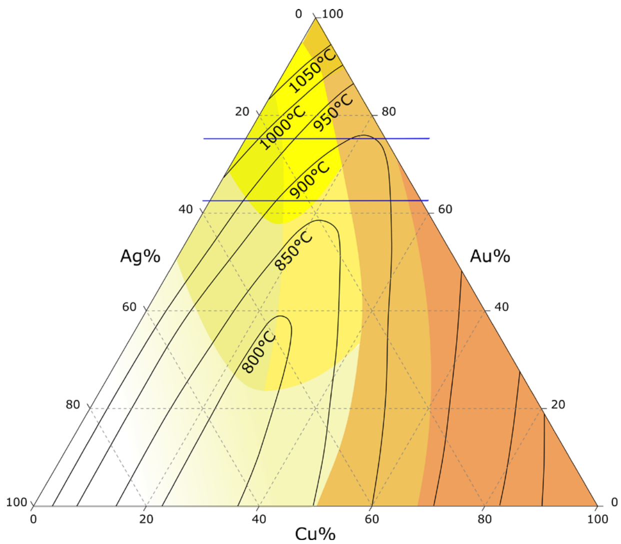

Figure 1.1. *Projection on the room temperature plane of the Au-Ag-Cu ternary phase diagram of some isotherms on the liquidus surface, as well as the relation between composition and colour of the alloy. For a given gold concentration (carats), the colour changes with the varying concentrations of copper and silver. The two blue lines show the different colours and nuances attained by alloys of 18 and 15 carats (containing respectively 75 wt% and 62.5 wt% gold) depending on the amounts of silver and copper added. Drawing A. Mattei based on Rapson (1990) and McDonald & Sistare (1978).*

and colour of the alloys, as well as some isotherms indicating their melting temperatures (based on Rapson 1990; McDonald & Sistare 1978). The melting point of the gold alloy depends on the amounts and melting points of the alloying elements (961 °C for silver and 1083 °C for copper), and has a major role in skilled soldering processes.

The mechanical properties rule the transformation of gold into, for example, very small and thin components like foils, wires and granules. Those properties, which are among others malleability, ductility, elasticity, hardness and tensile strength (Grimwade 2009), play a major role when producing an object by gilding. This technique, consisting on the application of thin gold layers on organic and inorganic substrates, was widely used in the past (Oddy 1981). In Ancient Egypt, where gilding and plating[1] were regularly used (James 1972; Nicholson 1979), the technique is represented in tomb scenes (Scheel 1986) such as in the Middle Kingdom rock-cut tomb-chapel of Baqet III at Beni Hassan (Newberry 1893b, 47, pl. 4), shown in Figure 1.2.

Since the discovery of gold as a new and fascinating material, certainly by chance, highly skilled gold workers experimented and developed a wide variety of techniques to produce jewellery, coins and other types of items, by exploiting the many different forms, colours and lustres that gold may take. The particular chemical, physical and mechanical properties of gold enabled the creation of a wide variety of objects produced over time to accomplish many different functions. Historically a symbol of power and wealth, a standard of value, a means of exchange and an expression of faith, gold has more recently incorporated less 'emblematic' forms but important roles in other domains such as electronics and medicine.

Exploiting gold sources

A wide number of gold deposit types, formed at different geological times and containing different amounts of gold, occur unevenly distributed throughout the world (Frimmel 2008; Foster 1993). Metals occur in rocks, commonly as compounds, in so-called primary deposits. In these deposits, several elements combined form sulfides, oxides, carbonates, sulfates, silicates, and so on (Crockett 1993; Paterson 1990). However, some elements, the so-called native ones, can occur uncombined. Gold is one of them and, in this case, the most common deposits are the lode ones, essentially gold veins in quartz, or reef gold.

Among the world gold deposits are those named secondary, where gold occurrence results from chemical and physical processes affecting primary deposits. These deposits are formed by weathering, desegregation and leaching of the host rocks where native gold is contained. Subsequently, by transportation and concentration of the resulting gold-bearing debris (with high specific gravity), placer deposits are formed. These

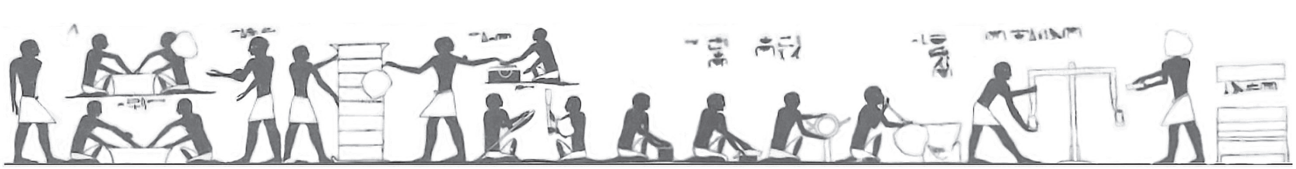

Figure 1.2. *Scene from tomb 15 at Beni Hassan containing the burial of Baqt III and representing a workshop scene where different types of objects are plated and gilt (detail from Newberry 1893b, pl. 4).*

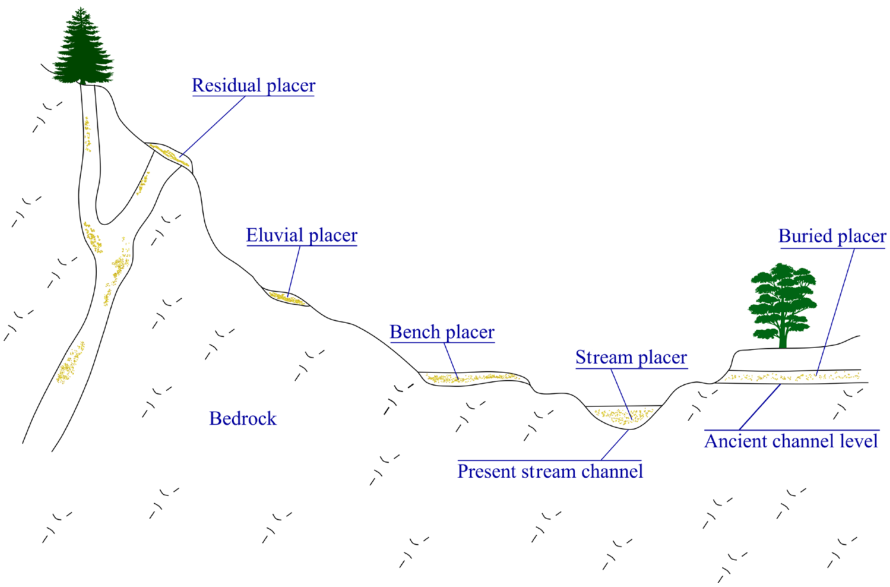

Figure 1.3. *Formation of gold placer deposits, representing the main types: alluvial or stream deposits, eluvial deposits, bench or terrace deposits and residual deposits. Drawing A. Mattei based on Moen (1979).*

deposits are of different types, as shown in Figure 1.3 (based on Moen 1979), and to which can be added other types (Arndt et al. 2015; Botros 2004; Stanaway 2012). However, they can roughly be separated in eluvial, when adjacent to the primary deposits (concentration by gravity), and alluvial, when formed by the action of moving water and concentration by gravity (Boyle 1979, 1987).

Table 1.1 (from Boyle 1979) summarizes the major gold-bearing minerals that can occur in nature; there, it can be observed that native gold is in fact a gold-base alloy, as it typically occurs together with other metals. The most common natural alloying element of native gold is silver, present in amounts usually ranging from 5 wt% to 15 wt%, the so-called argentian gold, but attaining sometimes higher amounts (Jones & Fleischer 1969; Boyle 1979, 1987). When silver reaches about 20 wt%, the alloy is commonly named electrum.[2] Occurrence of gold containing about 40 wt% is observed in some mining regions of the world, such as in the rich mining regions of the Southern Apuseni Mountains (Romania), in particular in the Roșia Montană-Bucium district (Pop et al. 2011; Popescu et al. 2013).[3] Evidence of ancient exploitation of these mines was reported by several authors (Cauuet et al. 2003; Cauuet & Tamas 2012). Occurrences of gold containing more than about 40 wt% silver, known as aurian silver, are rare, even though küstelite containing until about 80 wt% silver was found in a few deposits in association with native silver, argentite, and silver sulfosalts (Jones & Fleischer 1969; Petrovskaya 1979), like in Russia (Kravtsova et al. 2015; Zhuravkova et al. 2017).

Occurrences of native gold containing high copper contents are also rather infrequent; copper is commonly present in reef and placer gold in amounts under 1 wt%. An average value of 0.17 wt% Cu was obtained for 500 placer gold grains from Northern Ireland by Moles et al. (2013). The presence of auricupride and cupriferous gold could be identified only in a few

Table 1.1. *List of gold minerals as provided by Boyle (1979).*

Gold	(Au)
Argentian gold	(Au,Ag)
Cuprian gold	(Au,Cu)
Palladian gold	(Au,Pd)
Rhodian gold	(Au,Rh)
Iridic gold	(Au,Ir)
Platinum gold	(Au,Pt)
Bismuthian gold	(Au,Bi)
Gold amalgam	Au, Hg, ?
Maldonite	Au, Bi
Auricupride	AuCu
Palladium cuproauride	(Cu,Pd), Au
Uytenbogaardtite	Ag, AuS_2
Calaverite	AuTe
Krennerite	$(Au,Ag)Te_2$
Montbrayite	$(Au,Sb)_2Te_3$
Petzite	Ag_2AuTe_2
Muthmannite	(Ag,Au)Te
Sylvanite	$(Au,Ag)Te_4$
Kostovite	$AuCuTe_4$
Nagayagite	$Pb_3Au(Te,Sb)_4S_{5\text{-}8}$
Aurostibite	$AuSb_2$
Fishesserite	Ag_2AuSe_2

placer deposits, for example in the Urals (Zaykov et al. 2017) and in British Columbia (Knight & Leicht 2001).

Placer deposits account for more than two-thirds[4] of the total world gold supply (Yeend & Shawe 1989). In these deposits, gold is concentrated in the form of grains of different shapes and dimensions, from dust to nuggets – the latter being visible in water streams.[5] The variety of the gold grains in alluvial deposits depends, among others, on the distance of transport to the primary source, the type of source mineralization, and on fluid dynamics in the water stream (Chapman et al. 2002; Townley et al. 2003; William-Jones et al. 2009).

Since the beginning of the use of metals, gold from placer deposits has played an important role in the economic world systems, because it is more abundant and easier to recover than when present in lodes. In placers, it is possible to recover the gold grains by simple hand washing. The process of panning gold separates the light minerals from the heavy and dense ones, where gold grains are contained. The rotary motion induced to the pan (corresponding to spinning the recovered materials in a truncated conical basin, Fig. 1.4) separates the minerals by density, allowing the less dense to be washed out. Gold grains and other heavier minerals remain in the central concavity of the pan.

In fact, gold grains are typically recovered together with so-called 'black sands', consisting of other heavy minerals such as iron and titanium oxides (for example ilmenite and magnetite). Another mineral sometimes associated with placer gold is cassiterite, a tin oxide mineral (SnO_2) that occurs quite frequently in eluvial and alluvial deposits, including in the African continent (Falcon 1982; Kinnaird et al. 2016). Among the heavy native metals that concentrate in placer deposits can be found platinum. With a density of 21.4 $g.cm^{-3}$, platinum belongs to the platinum-group elements (PGE). The six PGE, platinum (Pt), palladium (Pd), rhodium (Rh), ruthenium (Ru), iridium (Ir) and osmium (Os), have equivalent chemical and physical properties. They occur frequently in magmatic ore deposits but, like gold, they also occur associated in alluvial deposits (Weiser 2002; Cabri et al. 1996), often in grains and rarely in nuggets[6] (Peterson 1994). They commonly occur in the African continent in deposits situated in Zimbabwe and South Africa (Zientek et al. 2010; Thormann et al. 2017; Oberthür 2018). These minerals occur irregularly in Egypt (Helmy et al. 1995; Elhaddad 1996; Ahmed 2007), concentrated in the Eastern Desert and north of Sudan (Bouabdellah & Slack 2016), in Ethiopia (Molly 1959; Ottemann & Augustithis 1967) and Tanzania (Evans et al. 2012). The PGE grains are recovered with gold, but due to their density, they are not eliminated and thus remain in the pan.

In mining sites where not enough water is accessible, gold can be recovered from gold-bearing sediments collected to be washed in basins or to be transported to other sites where they can more easily be processed.[7] Transportation of high amounts of heavy gold-bearing sediments for processing is however not an easy task. Another option is concentration using a technique

Figure 1.4. *On the left, gold panning in Lusitania as represented in book VIII of* De Re Metallica *by Georgius Agricola. On the right, a modern pan containing gold nuggets.*

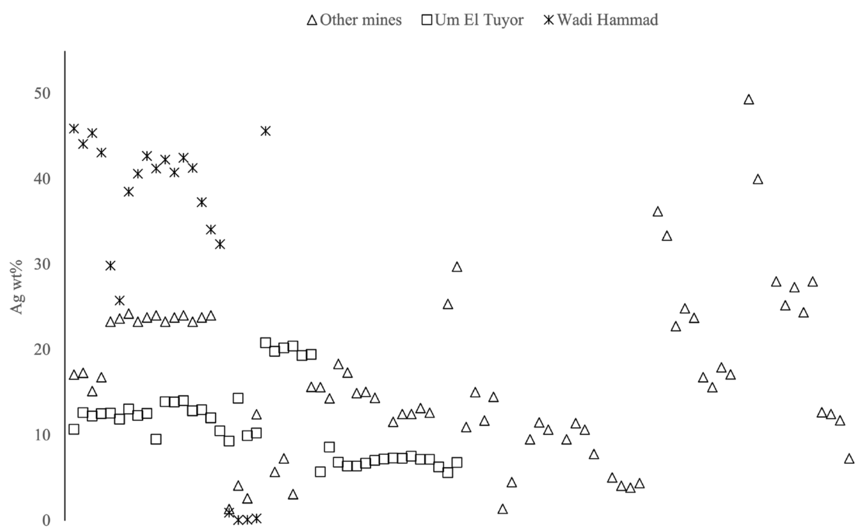

Figure 1.5. *Diagram showing the amounts of silver contained in gold grains from several mines situated in the Egyptian Eastern Desert (data from Osman et al. 1997, 2000; Zoheir 2004, 2011, 2012; Harraz 2002; Helmy et al. 2004; Shalaby et al. 2004; Zoheir & Akawy 2010; Zoheir & Lehmann 2011; Darwish 2012; Emam 2013; Helmy & Zoheir 2015; Abdel-Karim & El-Shafei 2018).*

named dry-washing.[8] Widely employed during the California gold rush, initially by the Mexicans (Young 1965; Taylor Hansen 2007, 2008; Limbaugh & Fuller 2004), winnowing[9] is well described by W.R. Ryan who travelled in California in the 19th century.[10] It involves shaking the auriferous sediments in a textile, throwing them in the air and blowing during descent to eliminate the light materials and only recover the heavy ones.

Because gold is visible in placer deposits, these are supposed to be the earliest sources exploited by humans. In Egypt, several representations and inscriptions are related to the exploitation of placer deposits, but also of reef gold[11] (see Chapter 2). As gold veins in quartz are also visible to the naked eye, the exploitation of lode deposits has to be considered among the earliest sources of gold. Klemm & Klemm (2013) and Klemm et al. (2001) suggested a very early exploitation of mined gold,[12] with improvement of the tools used at the beginning of the Old Kingdom,[13] and the increase in the New Kingdom of evidence on auriferous quartz exploitation perhaps related to access, for example, to the rich Wadi al-Allaqi gold deposits (see Chapter 2).

Auriferous quartz veins were found in the past certainly when searching for reliable and richer sources of gold; this stage corresponds to the beginning of gold prospection. The exploitation of gold in quartz veins does not need complex technologies, but it requires a large skilled workforce for crushing, grinding and washing. In fact, concentration can start by simple rock crushing with a hammer, a long and hard work; the crushed rock has to be ground, but this operation may be simplified by milling. Gold is then concentrated, an easy but time-consuming task when hand washing is used. By repetition of the separation and concentration processes, the gangue is removed. In order to improve the washing process, panning can be replaced by sluicing, another less manual technique that has been proved to be widely used in the past, including in Egypt.[14] It consists of flowing a water stream in a sluice (a platform placed in slope) to concentrate the gold by gravity (Silva 1986). All the above processes need large quantities of water, except if the gold is concentrated using dry-washing. However, the productivity of dry-washing might be low, when considerable amounts of gold dust are blown with the sands.[15]

When gold became a social necessity, large supplies of raw material were regularly required, and both placer and mined gold were certainly exploited. The intense search for mining regions is well represented by the most ancient record of gold quarrying areas in the Eastern Desert, made under the reign of Ramses IV. This papyrus, in the collection of the Egyptian Museum of Turin (papyrus 1879,1969,1899), contains notes indicating possible exploitation of both gold and electrum (Harrell & Brown 1992) in an area that corresponds today to Bir Umm Fawakhir and Wadi al-Sidd, at about 4 km from Wadi Hammamat (Meyer et al. 2003). Interestingly, by the end of the 1940s gold containing 20 wt% silver was exploited by the Egyptian Mining Company at Wadi al-Sidd in quartz veins located where the 'mountain of gold and silver' is represented in the Turin papyrus (Goyon 1949). The composition provided for the exploited gold grains matches A. Murr's unpublished data provided by Klemm & Klemm (2013) on the composition of native gold from several Egyptian and Nubian primary deposits. It was shown that the silver contents vary roughly from 10 to 30 wt% in Egypt and mainly from 5 to 20 wt% in Nubia (Klemm & Klemm 2013, 42). Additional data published for gold grains in minerals collected in Eastern Desert mines tend to confirm these high Ag contents in gold.

This range is well represented by gold grains from the Umm al Tuyor mine (Zoheir 2004) with Ag contents varying from about 5 to 20 wt%. However, both Ag-rich electrum and high purity gold grains have been identified for example at Wadi Hammad (Osman et al. 2000), where gold of two fineness populations coexist, one with almost 50 wt% Ag and another one of high purity. The results published for these grains expand the possible range of silver contents in Egyptian gold. Published data for the gold grains from several gold mines exploited in Egypt are plotted in Figure 1.5. The silver contents are shown to fall generally under 30 wt% and most typically under 20 wt%. One of the two gold nuggets found in one of the earliest burials excavated at Elkab by Quibell (1898, 7)[16] is in the collection of the Ashmolean Museum (E.455) and was analysed by Stos-Fertner & Gale (1979), showing this expected composition: 84.8 wt% Au, 15.3 wt% Ag and <0.1 wt% Cu.[17] The gold content found for this nugget is lower than the value found by Gänsicke & Newman (2000) for one nugget in a pendant from tomb Beg. W. 859 at Meroë,[18] dated to the Napatan Period, in the collection of the Museum of Fine Arts in Boston (MFA 23.311), which contains 91.2 wt% Au and 8.5 wt% Ag.

Towards a gold metallurgy?

> *Necessity is not the mother of invention - only of improvement. A man desperately in search of a weapon or food is in no mood for discovery: he can only exploit what is already known to exist. Discovery requires aesthetically motivated curiosity, not logic, for new things can acquire validity only by interaction in an environment that has yet to be. Their origin is unpredictable. A new thing of any kind whatsoever begins as a local anomaly, a region of misfit within the preexisting structure* (Smith 1977, 114).

A good number of archaeological finds across the world provide evidence of early exploitation of gold and reveal that its transformation into objects varies over time and from one location to another. However, much remains to be investigated with regard to the beginnings of the use of gold and the development of gold metallurgy.

With gold occurring as a native metal, it is not surprising that someone could have found one day a nugget by chance. Because of the high lustre and yellow colour of gold, the earliest objects might have had an exclusively aesthetic function. It is easy to imagine gold nuggets perforated and strung with beads made from other colourful materials. The production of colourful beads using different raw materials emerged before the beginning of agriculture in Eastern Mediterranean and Near East (Bar-Yosef 2013), as well as in the African continent (Zilhão 2007). It is interesting to notice that in the Near East, during the transition to agriculture, many green minerals were already transformed into beads and amulets, like apatite, amazonite and serpentinite, and including copper-bearing minerals, such as malachite, chrysocolla and turquoise (Bar-Yosef & Porat 2008). The use as raw materials of copper-bearing minerals and other metallic ores (Weeks 2012) which could be worked using a mechanical *chaîne opératoire*,[19] explains their exploitation before the development of metallurgical copper melting and smelting.[20] This sequence is documented, for example, in the Iranian plateau. In the Anarak region, malachite was mined from the 9th millennium BC onwards, but copper only started to be worked in the 7th millennium BC (Roberts et al. 2009).

It is challenging to suggest precise dates for the beginning of metallurgy. Obtaining small objects by cold-hammering native metals seems feasible without too many difficulties and it leaves little archaeological evidence. This operation requires the use of a mechanical *chaîne opératoire*, which, as mentioned, was developed quite early for other materials. The major technical challenges are associated to actions requiring high temperatures and temperature control, for example when annealing, used to soften the metal after hammering, or when melting metals, knowing that alloying results in specific melting points. These problems have to be considered for the earliest productions in both gold and copper. In the case of copper, the chief change corresponds however to the transition between melting and smelting, because in addition to temperature control, it is necessary to use reduction and oxidation processes and to know that copper can be extracted from particular ores (Muhly 2006; Mille & Carozza 2009; Roberts 2014; Stöllner 2014).

Therefore, the technical sequence of metallurgical innovation is typically the following (Montero 2014; Craddock 1995): pre-metallurgy, when the use of native metals was achieved by first cold working, secondly annealing and at last melting, followed by metallurgy when mineral reduction was accomplished. In spite of such metallurgical challenges, in Eurasia the earliest evidence for the exploitation of copper ores and naturally occurring copper are (presently) dated to the 11th–9th millennium BC (Nezafati et al. 2008). Based on archaeological finds it was also possible to say that annealing of copper was already carried out in eastern Turkey in the 9th millennium BC, and copper smelting in Serbia in the 6th millennium BC (Roberts 2009; Roberts et al. 2009; Maddin et al. 1999; Radivojevic et al. 2010). The number of objects dated to the earliest periods is quite small, even if in Turkey forty objects made of native copper were found at Çayönü Tepesi (Maddin et al. 1991) and sixty-five beads of native copper and malachite were excavated at Aşıklı Höyük (Yelözer 2018). The number of excavated copper objects only increases from the 7th millennium BC onwards (Yalçin 2017), which should correspond to certain technological developments in metallurgical processing. In fact, among those objects, one copper amulet dated to the 6th millennium BC from Mehrgarh in Pakistan revealed the very early use of lost-wax casting (Moulhérat et al. 2002; Thoury et al. 2016).

The timelines for the use of copper and gold seem to be quite different. In fact, the earliest gold objects found so far in the Mediterranean area were excavated in Bulgarian sites, dating roughly from the mid-5th millennium BC (Higham et al. 2007, 2018; Boyadzhiev & Aslanis 2016) and a few in Romania (Radivojević & Roberts 2021). While at Durankulak[21] only 16 of the 235 excavated tombs contained gold ornaments, basically gold beads (Todorova 2003; Avramova 1991), and only one perforated gold disc was recently excavated at Tell Yunatsite,[22] the 1972–1991 excavations of almost 300 burials at Varna revealed about 3 000 gold objects (Ivanov 1982). The richest graves at this site include tomb 1, containing 215 gold objects, tomb 4 containing 320, tomb 36 containing 854 and tomb 43 containing 1001 (Ivanov 1982). In addition to gold objects of different sizes and types, sometimes quite heavy (Kostov 2017), and to grave goods in other materials expected for the period of inhumation (flint, obsidian, shell, etc.), the graves also contained heavy copper tools and weapons (Slavchev 2010; Hansen 2013; Chapman et al. 2006; Krauß et al. 2017).

Only a few gold objects dated from late 5th to mid-4th millennium BC, and likely associated with Varna (Alram-Stern 2012; Maxwell et al. 2018), have been found in adjacent areas such as Greece and the Aegean Sea.[23] For example, two ring pendants, two holed bands, one disc and one ring were found at Aravissos and one gold ring was found at Sitagroi (Macedonia); one perforated gold disc was found at Ftelia (Mykonos), one perforated band in the Zas cave (Naxos) and one bead at Strofilas (Andros) (Zachos 1999; Maxwell et al. 2018; Todorova & Vajsov 2001; Televantou 2008). These objects are made by hammering gold into sheet, cutting to the shape and perforating for application. Complex mountings make an appearance later, based on the archaeological finds during the 4th millennium BC. The gold dog-shaped pendant dated to the Late Uruk period, found by R. de Mecquenem during the 1939 excavations of the acropolis at Susa, evidences the technologies available for gold. The pendant was lost-wax cast and the suspension ring was joined to the dog's body by using a hard soldering process[24] (Duval et al. 1987; Eluère 1998). The use of hard soldering processes was identified in other gold objects dated to the 3rd millennium onwards (Roberts 1973). Examples of the metallurgical complexity attained for productions in gold and silver in the first half of the 4th millennium BC can be found in northern Caucasus, among the grave goods of tombs associated to the Maikop culture. These tombs, recently radiocarbon dated (Korenevskij 2012), yielded a large number of gold objects of different types and dimensions, made using several techniques (Korenevskij 2012; Hansen 2014).

It is interesting to consider the earliest gold finds in the Southern Levant. This is a group of eight rings in gold and electrum found together with heavy copper objects in the Chalcolithic burial cave of Nahal Qanah in Israel (Gopher et al. 1990). These rings, made by pouring the metal into open ring-shaped moulds of different dimensions, are reminiscent of those often represented among the tributes in Egyptian tomb scenes. The technique employed is not surprising, because the many heavy copper objects contained in the hoard of Nahal Mishmar, dated to the 2nd half of the 5th millennium BC, are cast too (Shalev & Northover 1993; Moorey 1988; Gilead & Gošić 2014). Casting was in use early in Southern Levant (Rowan & Golden 2009; Golden 2014). A cast awl recently found at Tel Tsaf dates the emergence of copper metallurgy in that area to late 6th-early 5th millennium BC (Garfinkel et al. 2014).

Grave goods in the Southern Levant are regularly related to Egypt[25] (Rowan 2013; Mączyńska 2013; Braun 2013), it is worth noting that the rings in gold and electrum from Nahal Qanah are dated to the 2nd half of the 5th millennium BC and are therefore older than the earliest gold artefacts in Egypt. Even though, Egyptian tombs dated to the Badarian period (end 5th millennium BC) contained copper objects, such as the copper beads and pin from tombs 5413 and 5111 excavated at Badari (Brunton & Caton-Thomson 1928), the oldest gold objects found in Egypt appear in a period when gold was already in use in surrounding areas of influence.

The oldest known Egyptian gold objects were excavated in Predynastic sites (see Chapter 2). It is only during the Naqada period (4000–3000 BC), when the first signs of mummification could be identified, that burials started to contain gold objects (Grajetzki 2014). Some tombs seem particularly rich. One of these, excavated at Hierakonpolis (T11) and dated to Naqada III, in spite of having been looted still contained fly-shaped and shell-shaped amulets in lapis lazuli, blades in obsidian and crystal, and beads in silver, gold, garnet, turquoise and carnelian (Adams

2002). In Egypt, gold is found among the grave goods from Naqada II onwards (Midant-Reynes 2000). One example is the diadem from tomb 1730 excavated at Abydos, in Upper Egypt, discussed in section 7.2.2. So far, only one exceptional group of eighteen gold and silver beads and one silver pendant is dated to Naqada I. In the collection of Musée d'Art et d'Histoire in Brussels (E.02931, E.02971 and E.02972), they were found in tombs H17 and H41 excavated at Mahasna (Ayrton & Loat 1911, pls. 13-3, 16-3; Baumgartel 1960; Eyckerman & Hendrickx 2011). It is noticeable that although no evidence on silver exploitation in Egypt is known, several small silver objects were excavated in early tombs (Baumgartel 1960), such as the hollow silver beads and jar cap from tomb 1257 at Naqada (Petrie & Quibell 1895) and the beads and pendant from the mentioned tombs at Mahasna. The analysis of the beads and the pendant from tomb H41 and two beads from tomb H17 (Hauptman & von Bohlen 2011) has shown that three of them contain more than 20 wt% gold and a fourth more than 30 wt%.[26]

The number of gold objects increases in Early Dynastic tombs. Some of them delivering quite impressive objects. We can mention Khasekhemwy's sceptre, rings and vessel with lid (MFA 01.7285, 01.7351, 01.7287), the decorative strips from tomb 3504 at Saqqara, Menes' gold bar (OI-UC E5934) inscribed with the name of Aha and the four bracelets (Cairo JE 35054) from the tomb of Djer (Emery 1954; Petrie 1901,1902). However, none of these objects are as sumptuous or delicate as those found inside the tomb of Hetepheres (Dunham 1958; Reisner 1955), dated to the 4th Dynasty. The tomb goods include gold drinking cups, a gold razor, a gilded carrying chair, etc. The most remarkable item is the gilded wooden box containing silver bracelets inlaid with butterflies. These bracelets, restored by W. A. Stewart (Reisner 1929), were originally 20.

Thus, overall, existing archaeological evidence for the area considered here shows that the use of copper precedes that of gold. The development of gold metallurgy obviously requires access to 'visible' gold, which constrains the number of locations favourable to that development. When both metals coexist, knowing that both occur in native forms, there is no particular explanation for processing one but not the other. We can however speculate on some motives. The different crustal abundances of copper and gold make higher the probability of finding copper than gold. Even if both were simultaneously found, when copper is more abundant than gold, the quantities available may change the development of experiments carried out to transform the metals into objects. Certainly, both metals were quickly hammered into foils, but the use of a mechanical *chaîne opératoire* limits the function of the objects obtained. Therefore, those metals should have become interesting raw materials only when, at least, melting became available.

Possibly a similar melting process was initially employed for both metals, because copper and gold have comparable melting points. However, the properties of these metals are quite different. It is possible that copper accomplished a true utilitarian role – fabrication of tools and weapons, for example – whilst gold retained an aesthetic one. Therefore, the insistent demand for copper objects necessary for everyday life could have accelerated the development of copper metallurgy, and could have occupied the most skilled artisans. In fact, the development of metallurgy has to rely on copper not on gold, because gold does not require the development of smelting. At least in some places, copper might have somehow relegated gold to a less important position in a conceivable 'technological scale', limiting the search for the metal, or the type of productions using the metal, and delaying the development of a gold metallurgy.

From grain to object

The presence of gold flakes and of quartz and feldspar inclusions identified in early Bulgarian and Greek gold objects (Eluère & Raub 1991a,b; Maniatis et al. 2000) seems to show that, even if during a short time, placer gold was 'unskilfully' worked at the beginning of its use by processing gold nuggets. However, the aesthetic repertoire accessible is quite limited when simply cold-hammering native gold into foils and cutting these into a desired shape for decoration. Objects obtained this way would quickly have become aesthetically unsatisfactory.

The production of objects in gold requires several steps that can be separated into three main phases associated to different crafts: (1) prospecting and mining of alluvial and reef gold followed by transportation to centralized sites; (2) metallurgical processing of gold grains and production of ingots; (3) production of objects (forming, mounting, decorating, finishing). These phases are briefly discussed below.

Gold alloys: accidental or controlled

The first phase of an object manufacture consists of two separate parts. The first, prospecting for gold, involves expeditions and evaluation of possible deposits for exploitation. The second one, mining, consists of the separation and concentration of placer gold and releasing the reef gold from the quartz rocks followed by separation and concentration of the gold grains (Cauuet et al. 2018 describes the processing steps in

Celtic gold mines, on the basis of the archaeological remains and experimentation). To accomplish this are necessary miners and administrative staff, who controlled the work done by the miners and the quantities of produced gold. Gold is then transported to centralized sites, either under the form of grains, in bags, or as ingots (in Egyptian tomb scenes the tribute payments are represented by both bags and ring ingots). When transportation of ingots is preferred to gold grains, perhaps because in this case counting replaces weighing,[27] the gold grains have to be melted *in situ*, before transportation, an action that involves metalworkers and administrative control. Like in military logistics, the mining sites have to be protected and staff to move the gold, which includes safeguarding, supplying, supporting, etc., is also necessary.[28] The tomb scenes and the inscriptions referring to the exploitation of gold in Egyptian mining regions are discussed in Chapter 2.

The second phase is the work of metallurgists. This phase was not entirely accomplished in an initial period, when gold was used as recovered or found. By melting the gold nuggets, flakes and dust it is possible to obtain a mass of gold that can be formed by hammering, but it is necessary to be technologically able to reach the melting point of gold. When still inaccessible, a mass of gold could have been obtained by sintering[29] gold dust at about 600°–650°C (Raub 1995). Sintering (powder metallurgy) is a thermal process that consists of the agglomeration of particles (powders) by diffusion bonding and inter-granular grain growth to obtain a solid structure. When put in a crucible and taken to a temperature under the melting point, the particles develop necks at the areas of contact,[30] according to several parameters such as the particles size, the temperatures attained, the heating time, etc. (German 2014).

Where copper metallurgy was known, gold melting should have been quickly attained. It is possible that, at least during the earliest periods, copper and gold were under the responsibility of the same metalworkers, processed using the same crucibles and furnaces. The work of gold is in fact only evidenced in tomb scenes dated to the Middle Kingdom onwards. Technological improvements are visible in New Kingdom scenes such as the replacement of blowpipes by bellows to facilitate the high temperature required in furnaces.[31] Different authors (Garenne-Marot 1985; Davey 2012) discuss this replacement, the furnace types and the crucible shapes, but they focus on melting, smelting and casting of copper. This may be explained by the lack of vestiges from gold processing. For example, among the crucibles in the collection of the Petrie Museum, only an unprovenanced one (UC899) may have been used for precious metals, whereas all the others have remains from copper processing (Davey 1985).

It is difficult to make inferences about the early history of certain metallurgical steps such as gold alloying and refining, even if attempts at adjusting the natural composition of gold alloys are expected to take place early. Alloying gold with different amounts of copper and, perhaps, in some cases, with silver, would have been necessary to produce gold-base alloys of different colours and properties, as discussed in Chapter 5. In addition, since gold naturally contains variable amounts of silver and copper and is recovered together with other minerals, it is likely that gold refining techniques were developed quite early. Refining, however, requires the development of two sets of technology: cupellation, which separates gold from 'base metals' such as copper, and parting, which separates gold from silver (typically by cementation, initially using the salt process). Cupellation consists of melting lead with the natural gold alloys under oxidizing conditions. All base metals form oxides and are collected by the litharge (lead oxide), whereas the noble silver and gold are separated as a solid mass (Bayley 2008). Another metallurgical process is however necessary to separate silver from gold. Parting was accomplished initially by adding to gold a cement, which contained a salt as an active constituent. When heating the closed crucible for a long time, silver was transformed into silver chloride, a compound that was easily removed from the gold (Bayley 1990).

In spite of the described metallurgical steps, some elements or compounds are not easily eliminated providing clues on the type of gold employed, namely placer or reef gold. As mentioned, cassiterite and PGE are panned with gold from placer deposits. Both can hardly be eliminated during gold processing. In fact, even though tin has a low melting point, pure tin dioxide melts at about 1630°C, and the PGE have melting points ranging from 1554°C to 3050°C,[32] that is, much higher than the melting point of gold. The presence of tin in gold alloys can thus be related to the exploitation of placer deposits, except in a few cases where tin presence may derive from the remelting of alloys containing this element (Guerra 2014). Concerning PGE inclusions, their presence was identified at the surface of many ancient gold objects, including Egyptian ones (for example Ogden 1972; Meeks & Tite 1980; Troalen et al. 2014; Guerra & Pagès-Camagna 2019), and this presence was associated to the exploitation of ancient placer deposits. However, while the presence of PGE inclusions in gold objects indicates the use of placer gold – entirely or partially when reuse by melting is practiced – their absence does not indicate the use of reef gold. In fact, the presence of PGE in alluvial deposits depends on mineral occurrences in the mining area.

The goldsmith's craft

The third and last phase of goldworking is the work of goldsmiths. It consists of manufacturing an object using either natural or artificial gold-base alloys and potentially employing a large variety of techniques (Untracht 2011). These techniques have been discussed by many authors for particular regions and periods (Ogden 1982; Higgins 1980; Nicolini 1990; Maryon 1971; Maxwell-Hyslop 1971), including ancient Egypt (Williams 1924; Vernier 1907; Andrews 1990; Wilkinson 1971; Aldred 1971; Ogden 1990, 2000; Scheel 1989).

The production of a gold object by a goldsmith may involve a variable number of techniques that correspond to distinct steps of production. Briefly discussed below, they can be summarized as follows: shaping to the form, assembling the parts, decorating and finishing.

Shaping to the form

In Egypt, the work of metals is already represented in tomb scenes dated to the Old Kingdom,[33] for example at Deir al-Gebrawi (tombs of Djau and of Rahem-Isi, Davies 1902 vol 2, 10, pl. 10; 24, pl. 19). These scenes represent metalworkers hammering and melting metals, using open furnaces and blowpipes to increase the fire temperature. It is interesting to consider in Figure 1.6 the detail of a scene related to the work of copper, from the 5th Dynasty tomb of Wepemnefret at Giza[34] (discussed in Chapter 2, the scene is shown in Fig. 2.16). S. Hassan (1936, 192–3, fig. 219) describes four metalworkers smelting the metal; above them is inscribed 'Make great haste. Place it to its sole (bottom of the oven)', which corresponds to blowing to increase the temperature and achieve melting/smelting. Another metalworker is pouring the metal into a mould. On the left, two men are hammering the metal into sheets. The use of annealing is indicated by 'Boil that. It is hard', 'There is no hollow if it is boiled perfectly'. This scene represents the thermomechanical process of alternate cold-hammering and annealing (heating), in sequences that have to be suitable for the alloys. Annealing, usually associated to quenching (rapid cooling), softens the metal that has become brittle when cold-hammered. By releasing the internal stress induced by plastic deformation, the metal recovers ductility making repeated cold-hammering possible without cracking and fracture (Maryon 1971; Fischer-Bühner 2010). Softening temperatures of metals are very variable and depend on application time.[35] In the case of metals like copper, hammering and annealing are also used to increase hardness.[36] High hardness must be attained when producing tools and weapons (Odler 2016; Stocks 2016).

An object or a part of an object can be shaped either by plastic deformation or by casting. It is possible to obtain gold sheets, solid forms, and hollow containers such as bowls and basins using plastic deformation. If beating gold into foils is an unvarying and repetitive work, hollowing by raising, spinning, sinking, etc. gold sheets, as well as transforming an ingot into a solid object are the work of skilled goldsmiths. These goldsmiths must have knowledge on how to use different hammers and anvils and how to anneal and quench. On the contrary, artisans who dedicate their entire time to beating gold into foils do not need knowledge of the other complex techniques necessary to make a diversity of objects in gold.

Gold is such a malleable and ductile material that it can be reduced to a foil of 50 nm in thickness (Nutting & Nuttall 1977). Today, gold leaves are regularly obtained by reduction of gold sheets in a rolling mill to about 25 μm thickness; the resulting leaves are then cut into small squares, piled up with goldbeater's skins, and reduced by beating to 1.6 μm thick; a second operation of cutting, piling up and

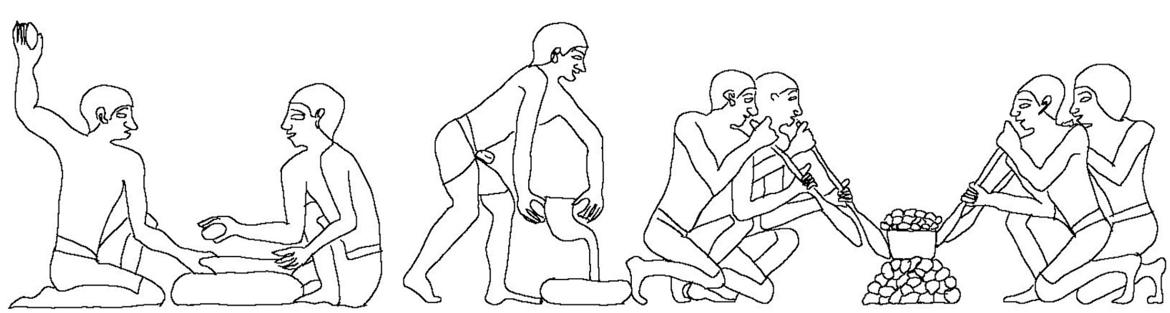

Figure 1.6. *Detail of a scene from the Old Kingdom tomb of Wepemnefert at Giza showing several metallurgical processes, including hammering and possibly annealing. Drawing M.F. Guerra based on Hassan (1936, fig. 219).*

hammering results in 0.10 μm thick leaves (Ashby & Jones 2013). Ancient foils are however thicker. Those employed in Egypt range from 1 μm to 10 μm thick (Hatchfield & Newman 1991). Two gilded papyri in the collection of the British Museum, New Kingdom papyrus 9040 produced for Neferrenpet, the 'chief of the makers of thin gold' (see Chapter 2), and papyrus 10472, dated to the 20th Dynasty and produced for Anhay, Chantress of Amun, were decorated with 6 μm and 9 μm thick gold leaves, respectively (James 1965, 1972). In the collection of the Louvre Museum, one unprovenanced gilder book (N 3041) contains eight 5 μm thick gold leaves (Darque-Ceretti & Aucouturier 2012), and the small gold leaf fragments (E 33058) found at Elephantine in a tomb dated to the Late Period are as thin as 1.2 μm (Darque-Ceretti et al. 2011).

Transforming a gold mass into an object by plastic deformation is however a time-consuming process, in particular when several components with the same shape are necessary. This work can be accomplished by casting, which is the second major shaping technique. Casting involves pouring molten metal into a mould. This thermal process requires the use of other tools, equipment and knowledge. The metal can be poured into moulds made in one or two (bivalve) pieces in stone, clay and sand. This technique is easily employed to obtain small solid forms such as finger-rings. A few stone moulds kept in different collections demonstrate that Mycenaean gold signet rings were made this way (Konstantinidi-Syvridi & Kontaki 2009) as well as jewellery from Enkomi and Tell Akko among others (Golani 2019). Despite the regular representation in the Egyptian tomb scenes of metal pouring, it is difficult to understand whether this action corresponds to the shaping of an ingot or an object.[37]

To allow more creative possibilities when casting, it is necessary to use the lost-wax process, a technique that certainly became popular very rapidly. One Babylonian text dated to the 2nd millennium BC attests to its regular use by describing that wax was given to a metalworker to make a bronze key (Hunt 1980). When producing an object by lost-wax casting, a model made in wax is covered with clay, except for a small hole through which the melted wax can run out when heated (lost-wax) leaving a hollow shape inside the mould. Molten metal is then poured into the cavity left by the wax. After solidification of the metal, the mould is broken to release the object (Noble 1975). A solid cast requires too much metal and metal shrinkage when cooling may cause problems. The use of a central core made from sand or clay reduces the required metal mass. As the mould is broken, the object obtained by lost-wax casting is unique and this technique is therefore unsuitable for mass production.

Assembling, decorating and finishing

Goldsmiths with expertise on either plastic deformation or casting might also need to be skilled in assembling the parts that constitute an object, and on decoration and finishing techniques. The order of the decoration and assemblage operations depends on the type of object and on the goldsmith's choice. Decoration may be achieved either by addition of materials or by modifying the gold surface. It is possible to modify the surface texture or to draw a motif using several techniques that employ different tools. Typical among them is engraving, which consists on incising motifs by removing material on the obverse side.[38] Other common techniques are stamping, chasing and repoussé, which are used to form reliefs by plastic deformation. When chasing and stamping, the force is applied on the obverse side; repoussé or embossing involves working from the reverse. Stamping is a less time-consuming process when repeated motifs are applied.

Several materials can be applied on gold substrates to obtain polychrome effects or to modify the perception of the surface texture. Because gold objects are parts of our imaginary, they have to offer a certain visual perception (see Chapter 5). The added materials include gemstones, glass and vitreous materials like enamel, natural materials like bone and ivory, and metals. Metallic components are used either to obtain a polychrome effect, for example whitish and yellowish areas, or to form monochromatic patterns by using small gold components, chiefly wires and granules.

Gold wires of 15 μm are regularly produced nowadays (Mukoyama 2010), which is far from the about 120 μm thick wires made by the Etruscan and considered to be the thinnest wires made in the past (Guerra 2006, 2007). Wires can be hollow or solid and they may be formed by hammering, drawing, and twisting (Oddy 1977, 2004; Nestler & Formigli 1994; Nicolini 1990; Thouvenin 1971). They can be bent to different shapes, twisted together to form threads, modified by chasing, etc. (Ogden 2004; Nicolini 1990; Guerra 2008). Their surface morphology depends on the shaping process: facetted when hammered, scratched when drawn, with longitudinal seams when strip-drawn and with helicoidal seams when strip-twisted (Oddy 1977, 2004). Further discussion on wire production is presented in Chapter 4.

Granulation was already in use in the 3rd millennium BC (Wolters 1981, 1982), but the exact techniques employed in the past are not fully understood (further discussion is presented in Chapter 8). Spherical granules are nowadays industrially produced in various metals and alloys by solidification at high cooling rates of molten metals using techniques based on fragmentation and impact (Neikov 2019), but the production of gold granules is still a manual process. Small pieces of regular sizes cut out of a thin gold sheet are placed in a charcoal block containing hemispherical cavities; the block is heated with a torch or in a kiln to melt the metal. Due to surface tension (to attain the minimum ratio surface area-to-volume) the liquid metal takes a spherical shape.

Wires and granules are then joined to the base plate. It has been suggested by several authors that granules were soldered to the metal base employing an organic glue and copper compounds, such as malachite and azurite. This process is called colloidal soldering or diffusion bonding (Wolters 1982; Parrini et al. 1982): the copper compounds are reduced to metallic state by action of the carbon in the organic compounds, which results in the formation of metallic copper which acts as a filler.

Many other joining processes may be employed to assemble gold parts (Maryon 1941; Tylecote 1978; Grimwade 2009; Jacobson & Humpston 2010; Roberts 1973). They use either a mechanical or a thermal process. The mechanical joining is obtained by fastening the two parts with wires, attaching them with rivets, by folding the sheets edges, etc. Thermal joining is obtained either by soldering or by welding.

Welding is a heating-melting-solidification process that consists of heating the joint of the two parts to a temperature above the melting point; the molten metals fuse together during re-solidification creating a homogeneously recrystallized interface. Presently, laser heating is quite frequently used in jewellery to obtain very thin joints without the use of a filler (Miller et al. 2007; Grimwade 2009). In fact, fusion welding may use a filler to ease the joining, but it may be carried out without a filler. When no filler is used, the process is called autogenous welding (a process suggested to have been used in past, for example Loepp & Mass 2017). Another technique is diffusion welding, often employed to join parts made from different metals, for example when gilding copper. In this solid-state process (no liquid phase is formed), coalescence is obtained by pressure alone or by pressure and heat. In the case of copper gilding, high pressure is applied on a gold sheet placed over a copper substrate. This assemblage may also be submitted to high temperature, below the melting point, because when the temperature is raised the migration rate of the atoms across the planes (diffusion) increases.

The second joining possibility is soldering, which is also a heating-melting-solidification process. The key difference with welding is that soldering is based on the melting of a filler alloy, or solder. In the case of gold jewellery, the solder is usually a gold alloy with a lower melting point than the pieces to be joined. When molten, the solder penetrates by capillary flow the space between the parts to be joined and spreads by dissolution, allowing the parts to hold together after re-solidification of the joint. Fluxes are regularly used in this process to avoid re-oxidation of the surfaces during soldering. Because of the high temperatures attained when soldering parts in gold, the process is named brazing or hard soldering. Soft solders are used when joining metals at temperatures below 450°C.

Hard soldering the multiple tiny parts that constitute a gold object is a process that can only be accomplished by a highly skilled goldsmith. To achieve the mounting of complex objects it is often necessary to use several base-alloys and solder alloys with different melting points and thus of different compositions. The analysis carried out by Roberts (1973, 119) of a New Kingdom sequin in the collection of the British Museum revealed the use of alloys with quite small melting point differences.

When soldering complex objects, the temperatures attained for each action of soldering in parts already soldered must be situated below their melting points. Otherwise, soldering new parts would unsolder parts already soldered. Nevertheless, the choice of the solder composition has to consider other properties of the alloy, including its colour. To obtain an imperceptible joining the colours of both the base-alloy and the solder have to be similar. Another property that has

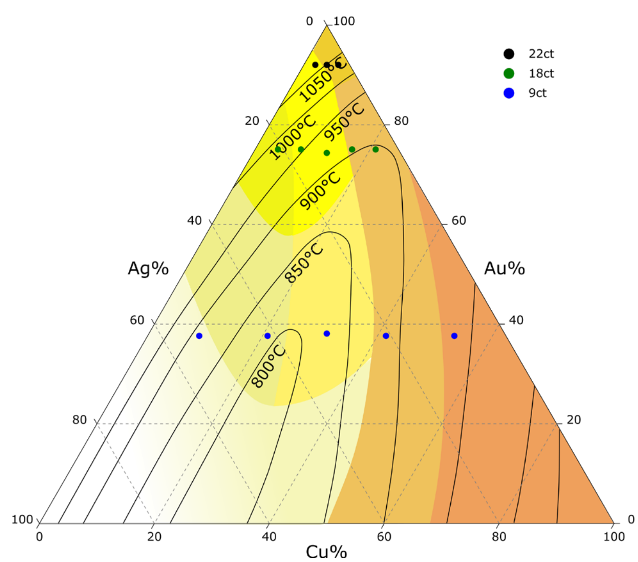

Figure 1.7. *Representation of some solder alloys in the Au-Ag-Cu ternary phase diagram. The solders with distinct silver-to-copper ratios provided for 9, 18 and 22 carat base alloys by Jacobson & Humpston (2010) have different colours and melting points. Drawing A. Mattei based on Rapson (1990) and McDonald & Sistare (1978).*

to be considered is fluidity. In the case of gold ternary alloys, fluidity decreases with decreasing silver-to-copper ratios (Jacobson & Humpston 2010). Figure 1.7 shows the ternary colour gold-silver-copper diagram from Figure 1.1 where are represented the colours and the melting points of solders with distinct silver-to-copper ratios suggested for 18 and 22 carat base alloys (see table 8.5 in Jacobson & Humpston 2010).

After assembling and decorating the object, this can be finished by using mechanical and chemical processes. Therefore, finishing it is the final stage of the object fabrication that involves surface treatments improving the quality of the manufacture process and changing our visual perception of the object. Chemical processes are employed to remove soldering residues by pickling or to colour the surfaces by patination (Pacini 2009; Hughes 1993; Ogden 1993). The aim of the mechanical processes (flattening, smoothing and removing) is either to decrease the surface roughness, by polishing[39] and burnishing, or to modify the surface texture by planishing. Planishing is a plastic deformation process that consist on flattening by hammering the entire surface to make invisible any mark from the previous work. Burnishing is also a mechanical deformation process achieved by friction with a hard surface. Polishing is a process of removal by abrasion that consists on removing scratches using abrasives with variable particle sizes (Faccenda & Corti 1999). The decrease of surface roughness results in an increase of the reflection of light and therefore an increase of surface reflectivity.

Notes

1. Gilding is the application of a thin gold layer, for example a gold leaf or gold powder, on the surface of another material. We consider gold plating as the application of thicker coatings, employing techniques that include the use of electron-currents.
2. In his Natural History (book 33, 26) Pliny the Elder refers to electrum, a natural or an artificial alloy of gold containing one-fifths of silver (Rackham 1961, 63). In the middle 6th century, Isidore of Seville (Etymologies, book 6, 26) gives the meanings of electrum: 'Electrum is so named because it reflects in the sun's ray more clearly than silver or gold […] is more refined than all the other metals. […] There are three kinds. […]'. He defines the first, amber, as 'liquid electrum', the second, found naturally, as 'metallic electrum', and the third 'made from three parts of gold and one part silver', specifying that 'there is no difference between natural electrum and manufactured' (Barney et al. 2006, 332). See also discussion provided by Schliemann (1885, 569–70) on electrum excavated at Troy.
3. Transylvanian gold samples were analysed by Pop et al. (2011) and Popescu et al. (2013), showing that in Romanian gold and silver mining regions of the Southern Apuseni Mountains gold contains silver amounts reaching sometimes 42 wt%. The analysis of gold grains from Ada Tepe in Bulgaria where a gold mine was exploited during the Bronze Age (Popov & Nikov 2018) has shown two electrum mineralizations, one characterized by 70.83 wt% Au, 29.17 wt% Ag and the other by 74.03 wt% Au, 24.73 wt% Ag, 1.24 wt% Cu (Marinova 2012). Gold grains from the Armenian regions of Sotk and Fioletovo may also contain silver amounts reaching about 45 wt% (Wolf et al. 2013). In Egypt, analysis by Osman et al. (2000) of gold grains from the Eastern Desert mines of Wadi Hammad has shown the presence of high silver amounts, reaching about 44 wt%.
4. At present, about 40% of the world gold production comes from quartz-pebble conglomerate deposits, such as those of the Witwatersrand Basin in South Africa, which are paleoplacer deposits that suffered modifications after initial sedimentation (Boyle 1979; Taylor & Anderson 2010).
5. In general, the gold particle sizes in alluvial deposits range from 100 μm to 5 mm (Mitchell et al. 1997). Very big nuggets were also reported. Among the biggest ones is the *Welcome Stranger* found in 1869 in Australia and weighing about 72 kg (see Dwyer 2002).
6. Harris & Cabri 1991 have provided a classification for the PGE alloys based on their composition.
7. In the north of Ethiopia, peasants migrate during the dry season to regions where gold-bearing rivers exist in order to collect in small plastic bags soil sediments containing gold dust to be washed for gold (Smidt & Gebremichael 2012).
8. Dry-washers are employed in desert regions where little water is available (Silva 1986, 10–12).
9. Winnowing is among the techniques employed in Egypt to process cereals, to separate the grains from the straw using fans (Murray 2000), which is represented in tombs (Samuel 1993).
10. 'There was no water near, although I noticed several holes, which had evidently been sunk in quest of it. These men were actively pursuing a process that is termed "dry-washing". One was shovelling up the sand into a large cloth, stretched out upon the ground, and which, when it was tolerably well covered, he took up by the corners, and shook until the pebbles and larger particles of stone and dirt came to the surface. These he brushed away carefully with his hand, repeating the process of shaking and clearing- until the residue was sufficiently fine for the next operation. This was performed by the other men, who, depositing block of wood, which they held in their hands, dexterously cast the contents up before them, about four feet into the air, catching the sand again very cleverly, and blowing at it as it descended. This process being repeated, the sand gradually disappeared; and from two to three ounces of pure gold remained at the bottom of the bow' (Ryan 1850, 13–14).
11. For example, Sahathor, 'assistant treasurer' under Amenemhat II, in his expedition to Sinai and Nubia refers to gold panning: 'I visited the Mine-land (Sinai) as

a youth, and I forced the (Nubian) chiefs to wash gold' (Breasted 1906a, 274). At Wadi Mia, in the Red Sea hills at the foot of Gebel al Atawi, an inscription indicates the exploitation of reef gold: 'the mayor and overseer of the priests of Nekhbet Renny, on the occasion of coming in order to quarry stone and bring gold' (inscription SL12 in Rothe et al. 2008, 231).

12. Other more recent publications also give details on the gold deposits in Egypt, e.g. El-Wekeil & Gaafar 2014; Botros 2002, 2004, 2015; Osman 2014.
13. Some tools could have served for the exploitation of copper that also occurs in the gold mines. In fact, in the Eastern Desert gold in quartz veins is often accompanied by abundant pyrite and arsenopyrite (Khalil et al. 2016; Osman 2014). For example, the gold-copper quartz vein deposits at Umm Balad (Abd El Monsef et al. 2018) were exploited at different periods for both copper and gold (Castel et al. 1998). The same situation is observed at al-Urf (Tawab 1990).
14. Sluice boxes in wood were found in Bronze Age sites, such as in the Troiboden mining area in the Mitterberg (Stöllner et al. 2012). Those found in New Kingdom sites in Egypt were made using stones consolidated with clay (Klemm & Klemm 2013). Vercoutter (1959) describes washing tables in Nubia dated to periods that are more recent.
15. A few authors suggested the use of this technique for gold concentration in the Egyptian desert (Lepsius 1877; Neesse 2014), because in some tomb scenes related to the work of gold two man are holding a curved form (under which was sometimes placed a cup) recalling the hieroglyph for gold. However, in other tomb scenes, a broad collar represents this form indicating jewellery-making.
16. The two gold nuggets, weighing 28 g, were found in one small partially robbed stairway tomb by Quibell (1898, 7) with a single thick gold hoop bracelet and components of a string: barrel-shaped carnelian beads, small gold beads and a gold spacer with five holes. The second nugget, the bracelet and the beads joined the Cairo Museum collection in 1897 (entries 31769-72, as reported in the *Bulletin de l'Institut d'Égypte* 8, 1898, 289–90).
17. Unfortunately, gold nuggets are rarely found in excavations. Garstang (1912, 49–50) reports two pottery vases found under the foundations of a wall at Meroë (site 294, Napatan Period), one containing gold dust and nuggets and the other 'filled with gold dust and nuggets, broken glass and beads, together with three inscribed jewels of gold in the form of a pyramid, a scarab, a flat scarab-seal and three gold money-rings'. Garstang ordered in London to Hunt & Roskell Ltd. reproductions of the spacer beads, perhaps using part of the dust and nuggets, which are today in several museums (Bleiberg 2015). In the Brooklyn Museum, the two reproductions (63.35.1-2) and one original (49.29) were analysed by XRF but only qualitatively (Bleiberg 2015, 47). The World Museum at Liverpool has part of the gold dust and nuggets (49.47.1000b) and one of the gold hoops described as 'money rings' (49.47.1000a).
18. Others from Nubia pierced for hanging are also in the collection of the Museum of Fine Arts in Boston, such as the one among 21.12107 (from Begarawiyeh, Meroe, SCXXV, debris of grave), 23-M-409 (from Meroe, Beg. West 695), 18-2-294L (from Nuri, Pyramid 59, Room A). One gold nugget pierced for hangeing and inscribed with hieroglyphs was found inside tomb 2 at el-Kurru (Dunham 1950, 16, pl. 52A and B).
19. The concept of *chaîne opératoire* was developed in the 1950s by A. Leroi-Gourhan (1964) to define sequences of actions, using tools, materials, gestures, etc., which are necessary to accomplish the transformation of a material into a finished object (Audouze & Karlin 2017).
20. Smelting consists of a chemical process conducive to obtaining a metal from an ore (metallic compound) contrary to melting that is a physical phase transition from solid into liquid.
21. The many graves excavated at Durankulak only delivered a few gold objects, such as the 5 ring beads from tomb 447, the 3 specimens from tomb 732, the necklace of gold and chalcedony beads from tomb 211, and the gold amulet from tomb 694 (Slavchev 2010; Bayley 2000; Whittle 1996; Kostov 2010).
22. The bead was found during the archaeological excavations leaded at tell Yunatsite in South-Central Bulgaria by Y. Boyadzhiev and can be seen at: https://balkanheritage.org/tell-yunatsite-excavation-project/
23. Among the earliest silver objects are the beads and pendants from the Alepotrypa cave in the gulf of Diros in Greece dated to the 4th millennium BC and the pendant from Amnissos in Crete (Kouka 2008; Muhly 1983, 2006)
24. This dog-shaped pendant in gold is in the collection of the Louvre Museum (Sb 5692) where can also be found one in silver roughly half size (Sb 14495). The gold dog is made from an alloy containing 9–10 wt% Ag and 1–2 wt% Cu. The suspension ring was joint to the animals's body using a gold solder containing 15–20 wt% Ag and 5–6 wt% Cu (Duval et al. 1987; Eluère 1998). One bracelet from the same site, but dated to the 3rd millennium BC, was also analysed showing that the solder was richer in copper (Duval et al. 1989).
25. Recent archaeological finds at Khirbet al-Batrawy suggest exchange of goods between Pharaonic Egypt and Jordan during the 3rd millennium BC using a Copper Route crossing central Sinai (Nigro 2014).
26. The analysis was carried out by TXRF, a technique used for the non-destructive characterization of near-surface layers (Wobrauschek 2007; Klockenkämper & von Bohlen 2015). Hauptman & von Bohlen (2011) used a very small surface sample (some nanograms) obtained by lightly rubbing the objects with a cotton swab, but mention that the beads are of 'surprisingly dark colour and have a dull metallic lustre'. This indicates that the analytical results provide the composition not of the alloys, but of the corrosion products that had developed on the surface of the objects. As the amounts of silver increase in the corroded areas of gold alloys (further discussion is provided in Chapter 6.8 of this volume), the gold beads may contain higher amounts of gold than those provided by TXRF.
27. This is equivalent to the use in transactions of coins made based on a uniform standard of value. Therefore,

they could be counted instead of weighed. However, counting needs the definition of a 'weight standard'.

28. Several inscriptions refer to administrative staff, like scribes who counted the gold and overseers of gold-workers who controlled the production (Rothe et al. 2008), and one inscription dated to Seti I refers to 'the chief archer of the caravaneers of the gold-washing' (Breasted 1906b, 86).
29. Sintering, or powder metallurgy, was employed by the Tumaco-La Tolita culture that developed between Ecuador and Colombia. They produced remarkable jewellery in gold and in platinum (Meeks et al. 2002; Bouchard & Guerra 2009; Scott & Bray 1980), a metal with a high melting point, 1772°C, by sintering the two metals at about 1100°C (Handwerker et al. 1991; Scott 2011) or even less, until 800°C (Bustamante Salazar et al. 2006; Noguez et al. 2013).
30. The presence of sintered gold grains plastically deformed was identified in Early Bronze Age gold objects excavated in Bulgaria (Tsintsov et al. 2009).
31. See Fig 17, Chapter 2 and the scenes in the rock-cut tomb-chapels of Puyemra (Davies 1923, 70–2, pl. 23, vol 2) and of Rekhmira (Davies 1943; Wainwright 1944) at Thebes. The recently excavated tomb M.I.D.A.N.05 at Dra Abu al-Naga also has a metallurgical scene (Marini 2014).
32. The melting points of the elements of the group are the following: palladium (Pd) 1554°C, platinum (Pt) 1768°C, rhodium (Rh) 1963°C, iridium (Ir) 2446°C, ruthenium (Ru) 2333°C, and osmium (Os) 3033°C.
33. Other early representation can be seen in the tombs of queen Meresankh III at Giza (Dunham & Simpson 1974, pl. 3b), of Mereruka at Saqqara (Duell 1938, pl. 30), and of Pepyankh at Meir (Blackman & Apted 1953, 25, pl. 17).
34. Equivalent scenes can be seen in the tomb of Ti at Saqqara (Weinstein 1974; Montet 1925, 284–5) and the Middle Kingdom rock-cut tomb of Khety at Beni Hassan (Newberry 1893a, pl. 14, 58).
35. Lowry & Parker (1915) provide data for pure copper, silver and gold.
36. In the case of gold alloys, the increase of hardness is used nowadays to obtain high-carat gold jewellery (see for example Toit et al. 2002).
37. One scene in the tomb of Rekhmira is shown in Chapter 2 (Fig. 2.17a). The moulds in this tomb and in Puyemra's tombs have the same shape; see discussion by P. Montet (1925, 277) on the hieroglyph he attributed to 'ingot' in goldsmithing representations.
38. Metal inlay is also obtained by removing gold. The space left at the surface is filled with another metal.
39. Electrochemical polishing is employed to make a selective removal of surface metal.

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Ancient Egyptian gold

This book aims to provide a new level of synthesis in the study of gold jewellery made in Egypt between 3500 BC and 1000 BC, integrating the distinct approaches of archaeology, materials science and Egyptology. Following accessible introductions to the art and use of gold in Ancient Egypt, and to current advances in technical analyses, the volume presents detailed results on the manufacturing technology and elemental composition of some 136 objects in the collections of six European museums, with discussion of the findings in historical and cultural contexts. The questions generated by the jewellery buried with a woman and a child at Qurna (Thebes) led to investigation of assemblages and individual artefacts from later and earlier periods in varied social contexts, from the rural environment of Qau and Badari, to sites connected with urban or royal centres, such as Riqqa, Haraga and Lahun. A final discussion of the Qurna group provides an agenda for future research.

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