Title

Copper-based Metallurgy (up to 332 BCE)

Journal

UCLA Encyclopedia of Egyptology, 1(1)

ISSN

2693-7425

Authors

Rademakers, Frederik
Odler, Martin
Auenmüller, Johannes

Publication Date

2024-09-29

DOI

10.5070/G9.4307

UCLA ENCYCLOPEDIA of EGYPTOLOGY

COPPER-BASED METALLURGY (UP TO 332 BCE)

النحاس والمعادن النحاسية (حتى عام 332 قبل الميلاد)

Frederik W. Rademakers, Martin Odler, and Johannes Auenmüller

Citation:

Rademakers, Frederik W., Martin Odler, and Johannes Auenmüller, 2024, Copper-based Metallurgy (up to 332 BCE). In Anna Hodgkinson and Willeke Wendrich (eds.), *UCLA Encyclopedia of Egyptology*, Los Angeles. ISSN 2693-7425. DOI: https://doi.org/10.5070/G9.4307

4307 Version 1, September 2024, ark ID 21198/z1m38fcv

UCLA ENCYCLOPEDIA of EGYPTOLOGY

COPPER-BASED METALLURGY (UP TO 332 BCE)

النحاس والمعادن النحاسية (حتى عام 332 قبل الميلاد)

Frederik W. Rademakers, Martin Odler, and Johannes Auenmüller[*]

Kupferbasierte Metallurgie (bis 332 v. u. Z.)
Métallurgie à base de cuivre (jusqu’a 332 avant notre ère)

Copper played a central role in the material culture of ancient Egypt. Appearing in the archaeological record as early as the fourth millennium BCE, copper and copper alloys were the most widely used metals throughout pharaonic history. Significant copper ore deposits, such as those of the Eastern Desert and Sinai, were located in proximity to the Nile Valley and were usually mined through large state-organized expeditions. In addition to textual and iconographic evidence, copper alloy objects constitute a valuable source for our understanding of the procurement, use, and circulation of goods within ancient Egyptian society. With the advancement of scientific methods their analysis has become part of the wider development of archaeometallurgy, which aims to shed light on the entire production chain of metals in their historical and social contexts. Indeed, Egyptology, archaeology, and archaeometallurgy are complementary and can benefit from the same research questions.

لعب النحاس دورًا مركزيًا في الثقافة المادية لمصر القديمة. حيث ظهر في السجلات الأثرية خلال الألفية الرابعة قبل الميلاد، وكان النحاس والسبائك النحاسية أكثر المعادن استخدامًا عبر التاريخ الفرعوني. كانت ترسبات خام النحاس المهمة مثل تلك الموجودة في الصحراء الشرقية وسيناء تقع بالقرب من وادي النيل، وعادةً ما كانت تُستخرج من خلال بعثات كبيرة منظمة من قبل الدولة. بالإضافة إلى الأدلة النصية والتصويرية، تعد الأدوات المصنوعة من سبائك النحاس مصدرًا قيمًا لفهمنا لتأمين واستخدام وتداول السلع في المجتمع المصري القديم. ومع تقدم الأساليب العلمية، أصبح تحليل هذه الأدوات جزءًا من مجال الدراسة المعروف باسم "علم المعادن الأثري"، الذي يهدف إلى إلقاء الضوء على سلسلة الإنتاج الكاملة للمعادن في سياقاتها التاريخية والاجتماعية. في الواقع، فإن علم الآثار وعلم المصريات وعلم المعادن الأثري مكملان ويمكن أن يستفيدا من نفس الأسئلة البحثية.

Copper and copper alloy objects played a central role in the material culture of ancient Egypt, appearing in the archaeological record already in the Predynastic Period (fourth millennium BCE). Indeed, copper and copper alloys represent the most widely used metal types throughout pharaonic history. As such, copper alloy objects constitute a valuable material well suited to study the procurement, use, and circulation of goods within ancient Egyptian society. They are preserved in rather large numbers, their compositions vary significantly, and they appear in a variety of archaeological contexts over thousands of years (a selection of important sites is shown in Figure 1).

1. Copper and Its Metallurgy in Egypt and Nubia

The Nile Valley was surrounded by regions with significant copper ore deposits, including the Eastern Desert and Sinai, and Wadi

Figure 1. Location of the most important sites mentioned in the text, mapped on a background from Natural Earth in qGIS.

Arabah in Israel and Jordan, inhabited by local populations often hostile to Egyptians (Cooper 2020). As such, it was sometimes necessary for the Egyptians to engage in a degree of coercion and/or cooperation in order to obtain and mine the required metal ores (Morenz 2019), often in the context of large state-organized expeditions employing standardized smelting strategies on an industrial scale (e.g., Abd el-Raziq et al. 2011; Tallet 2018). At the same time, local populations often developed their own metallurgy, as described for the Sinai (Pfeiffer 2013) and further north in the Levant (e.g., Moorey 1999). In Lower Nubia, copper was used since the fourth millennium BCE by the people of the so-called A-Group culture; the copper artifacts are generally considered to be imports from Egypt (Roy 2011). The same case has been made for C-Group finds (Hofmann 1967), although more detailed archaeometallurgical studies are beginning to question these hypotheses. The Kerma culture in Upper Nubia seems to have developed its own metalworking traditions, although links with Egypt are apparent (Manzo 2016; Rademakers et al. 2022; Rademakers, Verly, Cortebeeck, et al. 2023; Reisner 1923).

Following overview studies in the early twentieth century (e.g., Garland and Bannister 1927; Lucas 1926, updated by Harris 1962; Wainwright 1943), research into Egyptian and Nubian copper alloys remained somewhat in the background for a long time, until a recent surge in scholarly interest, triggered by the advancement of natural scientific methods. This is part of a wider development in the field of archaeometallurgy, which aims to illuminate the entire production chain of metals in their historical and social contexts (for an introduction, see Roberts and Thornton 2014). While Ogden (2000) remains a key introduction to various metals processed and used in ancient Egypt, the present discussion gives an overview of the current state-of-the-art of Egyptian copper and its alloys, set to be refined further by ongoing research. Recently, a synthesis of the current knowledge of the production and use of copper from the Predynastic Period until the beginning of the New Kingdom was published by Odler (2023a), while a new volume on ancient Egyptian gold discusses the role of copper in gold production and use (Guerra, Martinón-Torres, and Quirke eds. 2023). Some of the pieces of the gold mask of Tutankhamun comprise a few weight-percents of copper, which have been interpreted as coming from recycled gold, while higher percentages of copper seem to indicate soldering (Rehren et al. 2022: 167–169).

In general terms, copper alloys are made through multiple stages of production. First, copper ore (i.e., naturally occurring minerals rich in copper) is mined from geological deposits. Next, the ore is subjected to a primary metallurgical process: “smelting,” or extractive metallurgy. During smelting, copper is reduced (or “transformed”) from a mineral compound into its metallic form, while other constituents of the ore are removed as waste products (“slag”). Such smelting typically took place in furnaces, which are stone- and/or clay-built structures, although some (early) smelting may have taken place in crucibles. The end product of smelting is “raw copper.” Although raw copper may sometimes represent a copper alloy (e.g., early Iberian or Italian copper smelted from complex ores: Dolfini 2014; Murillo-Barroso et al. 2017 and references therein), it appears that copper smelted from ores mined in Sinai was rather pure (Abdel-Motelib et al. 2012; Rademakers, Verly, Delvaux, et al. 2018; Rademakers, Verly, Delvaux, Vanhaecke, et al. 2021). Such raw copper would then have been melted in a crucible and mixed with other components (e.g., arsenic, tin, and/or lead, in metallic or mineral form) to produce an alloy. This step, called “secondary metallurgy,” would further entail the casting of the alloy from the crucible into a mold and its further working (hot or cold) by hammering, annealing, chiseling, etc. Although the ancient lifecycle of copper alloy artifacts (e.g., Ottaway 2001: fig. 1) may terminate with their deposition in funerary contexts or loss, they could equally be recycled and re-integrated into the production chain over time. As such, copper alloy artifacts retrieved from well-dated archaeological contexts may represent stocks of metal in circulation at a certain time, which in turn can reflect long-term metallurgical practices as well as fresh production (cf. Rademakers, Rehren, and Pernicka 2017; Rademakers, Verly, Delvaux, Vanhaecke, et al. 2021).

2. Chronology of Copper Alloys in the Nile Valley

The first evidence of copper ore and alleged metalworking was uncovered at Lakeita in the Eastern Desert and is likely datable to the Predynastic Period (Debono 1951). However, the material has not been fully published or studied: a chronological revision of the context, pottery, and finds assemblage would be necessary. The earliest copper workshop remains were uncovered on Elephantine and are datable to Dynasty 0/Naqada IIIB: a crucible, presumably of an open form (rim not preserved), and copper prills (small globules or droplets formed from the molten copper) were documented (Kopp 2006: 33, fig. 12). The earliest workshop with a preserved crucible of the "standard" type with two openings, a larger one from above and a smaller hole on the side, was found at Elkab and dates to Dynasty 2 (Claes, Davey, and Hendrickx 2019). The earliest copper artifacts of yet unknown (alloy) composition were found in archaeological contexts of the Badari culture (Brunton and Caton-Thompson 1928); however, their dating needs further precision. The earliest arsenical copper objects belong to the phase Naqada II (e.g., Cowell 1987; McKerrell 1993). The earliest identified tin bronzes are known from Abydos and date to Dynasty 2 (Spencer 1980), but there are several other contexts from the same site and elsewhere providing similar material. A list of all known tin bronzes from Early and Middle Bronze Age Egypt and Nubia can be found in Odler (2023a, table 37). While arsenical copper remained the dominant alloy until and during the Middle Kingdom, tin bronze made a gradual appearance during this period, for example in ritual vessels and mirrors, but also artifacts of everyday use (e.g., Odler and Kmošek 2020; Rademakers, Verly, Delvaux, Vanhaecke, et al. 2021). In the New Kingdom the situation changed, with tin bronzes becoming the norm, while arsenical copper objects were only rarely made and used. It is becoming apparent, however, that the transition of arsenical copper to tin bronze was not sudden and complete, but rather a long-term process involving flexible adoption and choice as available copper alloys were recycled and mixed over time (e.g., Rademakers, Verly, Delvaux, Vanhaecke, et al. 2021; Rademakers, Verly, Degryse, et al. 2022; Rademakers, Verly, Cortebeeck, et al. 2023). From the late New Kingdom onwards, lead was increasingly added as an alloy component to obtain leaded tin bronze. Brass, an alloy of copper and zinc, was mostly absent from Egypt until the Roman Period, as it was elsewhere in the ancient world.

3. Archaeological Evidence of Copper (Alloy) Production

Every step of the production chain of copper and copper alloy objects, as outlined in section 1, creates particular reflections in the archaeological record (for some general examples, see, e.g., Bayley et al. 2001; Hauptmann 2007, 2020). However, our current understanding of ancient Egyptian copper (alloy) production is strongly skewed towards the study of finished artifacts (mostly in museum or other collection contexts), while the underlying technological choices as well as employed materials remain poorly studied for most of pharaonic history.

3.1 Mining

Mining refers to the extraction of ore from geological deposits. Various mining methods in existence today (e.g., room-and-pillar mining, stope mining, and open-pit mining: Brady and Brown 2004) have their origin in antiquity (e.g., Craddock 2010). As far as Egypt and Sudan are concerned, more research has been conducted on ancient quarrying (i.e., stone extraction) technology (e.g., R. Klemm and D. Klemm 2008; Harrell and Storemyr 2009; Abd el-Rahman et al. 2013; Cech, Rehren, and Mohamed 2018) than on ancient (ore) mining techniques. For the latter, archaeological surveys present the main source of information, usually without excavations or in-depth studies (but see the excavation at Gebel el-Zeit: Castel and Soukiassian 1989), while geological literature offers secondary information (e.g., Afia 2006a, 2006b, 2006c; Hussein and el Sharkawi 1990).

Currently available evidence shows that a very wide range of geological deposits was explored and exploited in ancient times, covering both the Egyptian and Nubian Eastern Desert, as well as the Sinai Peninsula. As far as copper mining is concerned, the southern Sinai represents the major source exploited throughout pharaonic history, with a strong focus on the region surrounding Umm Bogma, including the sites Wadi Ba'ba, Wadi Kharig, Wadi Maghara, Wadi Nasb, Wadi Qenaieh, and Serabit el-Khadim (e.g., Abdel-Motelib 2012; Petrie 1906; Rademakers, Verly, Delvaux, Vanhaecke, et al. 2021; Rothenberg 1987). Evidence for copper ore exploitation in the Eastern Desert is currently best identified for the Predynastic and Old Kingdom periods (Kmošek et al. 2018; Rademakers, Verly, Delvaux, et al. 2018; Odler 2023a: 97–154), in contrast to evidence for the continued exploitation of Eastern Desert gold (R. Klemm and D. Klemm 2013), although future work may change this picture.

To understand the diachronic development of mining technology, the overall design of the underground mines and their ventilation can be studied (e.g., Castel and Soukiassian 1989; Shaw and Durucan 2008), the best-studied examples of extraction strategies being represented by stone quarries (e.g., Van der Perre 2015). Furthermore, the techniques used to extract the ore and surrounding host rock can be examined. Such techniques typically involve stone hammers of various typologies (in most cases, hard, igneous rock hammers were brought to the mines)—possibly preceded by fire setting—as well as copper alloy chisels. Various tools were employed to remove different rock types or to work in varied settings, often leaving diagnostic negative traces on the remaining host rock—a field of study recently gaining momentum (e.g., Davey 2001 – 2002; Harrell and Storemyr 2009; Kelany 2015; Verly et al. 2019).

Beyond the direct evidence obtained from the mines themselves, mining activities are attested by formal rock inscriptions as well as rock graffiti left during the often large-scale expeditions mounted by the pharaonic state. The study of these inscriptions provides further details on the dating, size, and overall organization of mining expeditions (e.g., Abd el-Raziq et al. 2002; Eichler 1993; Hikade 2001; Mumford 2006; Seyfried 1981; Shaw 1998; Tallet 2012, 2015, 2016–2017, 2018; Odler 2023a) and thus offers an invaluable counterpart to the archaeological data gathered by the excavation of mining sites.

It is important to note that some mining may leave little to no trace in the archaeological record. Informal mining, likely involving local populations, would not necessarily be recorded in either graffiti or rock inscriptions. Furthermore, certain types of raw material sourcing may take precedence in such inscriptions, e.g., masking the acquisition of copper or other minerals in the context of a (state-run) gold-mining expedition. Finally, certain types of geological deposits may have been readily accessible at the surface, requiring little extractive effort. Such may have been the case for the mining of Eastern Desert cassiterite, one of the most important ore minerals for tin. While cassiterite occurs primarily in hydrothermal veins within granites, requiring hard-rock mining for extraction, it is equally found in wadi placer deposits, which may have been more extensively exploited during the New Kingdom (R. Klemm 1998; Rademakers, Rehren, and Pusch 2018 and references therein).

3.2 Smelting

Smelting refers to the metallurgical process whereby raw copper is extracted from copper ore. During smelting, the ore is subjected to high temperatures in a low-oxygen atmosphere to reduce copper minerals into metal. This requires a substantial amount of organic fuel (e.g., wood, charcoal, dung) and oxygen for its combustion. In many ancient smelting technologies, the copper physically separates (by density) from the mass of nonmetallic waste (slag). In some cases (currently not identified in Egypt), the slag needs to be crushed in order to extract the metallic copper prills that are embedded/trapped in it.

Smelting is typically achieved in clay-lined furnaces of varying shapes and sizes, although it may occasionally have taken place in crucibles (acting as miniature furnaces). Given the scale of such crucibles, with useful volumes usually not exceeding a few 100 ml, these refractory vessels typically constitute rather early smelting devices or possibly assaying vessels (i.e., vessels used for ore quality tests). Smelting furnaces are most frequently encountered in workshops close to copper mines. For example, ore mined in Sinai was usually gathered, in Sinai, at centralized workshops for smelting (Petrie 1906; Rademakers, Verly, Delvaux, Vanhaecke, et al. 2021) and the raw copper subsequently transported to the Nile Valley. Ain Soukhna constitutes an unusual Middle Kingdom diversion from this standard *modus operandi*, when ore mined in Sinai was shipped across the Red Sea for smelting (e.g., Tallet 2016 – 2017).

Smelting operations can leave characteristic archaeological traces, although these are not always well preserved. Complete furnaces are rarely encountered, exceptions being the Middle Kingdom structures at Ain Soukhna, where careful curation in the intervals between expeditions has resulted in their nearly perfect preservation (Abd el-Raziq et al. 2011; Verly 2017b), as shown in Figure 2. In other cases, furnace structures are preserved without their internal clay lining (e.g., in Sinai: Tallet, Castel, and Fluzin 2011). Where furnaces were built without an underlying stone construction, any clay superstructure can be expected to have been lost. In such cases, a furnace base might be found, provided the clay was sufficiently vitrified and subsequently left in situ. Indeed, high temperature exposure results in the vitrification of the hottest zones within a furnace. Vitrified segments of furnace linings were often replaced over time and can be found as diagnostic material among the waste deposits of smelting workshops. Beyond the furnaces themselves, remains of fuel, ore, slag, and copper are typical remnants encountered in smelting workshops (cf. Abd el-Raziq et al. 2011 and Verly et al. 2021 for examples from Ain Soukhna). Yet it must be remembered that (apart from slag) these are precious commodities within an ancient expeditionary (and broader) economy, so limited archaeological recovery is expected. Indeed, careful excavation is essential to document the sometimes scarce and ephemeral evidence of metallurgical processes.

Raw copper, the precious end product of smelting, is rarely encountered in great quantities at metallurgical workshops. At Ain Soukhna, a bag of raw copper prills was found next to a buried individual (Abd el-Raziq et al. 2011). This likely constituted the form in which copper was brought to the Nile Valley (Verly 2017b), although (raw) copper ingots may have been cast on site, too. Bar-shaped ingots may have been cast at Old Kingdom Buhen as hinted at by elongated "ingot molds" (O'Connor 2014), although further analysis is needed to confirm their precise function, as they may have served for the production of other objects (e.g., chisels). By contrast, slag—a mixture of (partially) molten ore, furnace clay, fuel, and copper—constitutes a waste product rarely removed (far) from smelting contexts. While some smelting technologies may produce relatively limited slag, it is often abundant at large-scale and long-term smelting sites. The slag heaps at Bir Nasb constitute the best-known example from the Sinai Peninsula, where an estimated 100,000 tons of slag reflect the production of over 5,000 tons of raw copper over time (Rothenberg 1987).

Within Nubia, it remains unclear for now if and where primary copper production took place. Little survey data currently exist to identify whether Nubian Eastern Desert deposits were mined for copper ore. Indirect evidence from the composition of Nubian artifacts may point in this direction, but more targeted fieldwork is required to assess the scale and technology of mining and smelting there. At Old Kingdom Buhen, copper smelting did take place, likely relying on

Figure 2. Example of a Middle Kingdom smelting workshop at Ain Soukhna. The closed workshop space, internally divided in two, contains four column-shaped furnaces used for copper smelting (F88-89-90-91), constructed in sandstone with an internal lining (Verly 2024).

locally mined ores (El Gayar and Jones 1989a, 1989b). Copper smelting is equally attested at Middle Kingdom Buhen, in this case performed in crucibles (Davey, Santarelli, and Rehren 2021). Both the Old and Middle Kingdom evidence suggests the smelting of copper ores with compositions distinct from those mined in Sinai; the use of copper possibly extracted from such ores has tentatively been identified at New Kingdom Amara West (Rademakers, Auenmüller, Spencer, et al. 2023).

3.3 Secondary metallurgy

Secondary metallurgy involves the transformation of raw metal into alloys and the subsequent transformation of those alloys into final objects of a particular shape and/or functionality. Alloy production can involve the melting of freshly smelted copper (cf. above) with an alloy component such as arsenic, tin, or lead (in metal or mineral form) to create a new alloy, but may equally involve the recycling of existing alloys (as shown in the examples in Figure 3). Object production can involve high- and low-temperature techniques.

The melting and/or alloying takes place in crucibles, which are ceramic vessels constructed to be handled at temperatures of c. 1200°C without breaking or excessive chemical interaction (on refractory vessels: Freestone and Tite 1986; Craddock 2014a, 2014b). Such crucibles (see examples in Figure 4) are the most important evidence for these processes and are commonly found in metallurgical workshops. In contrast to primary smelting, usually conducted close to the mines, secondary metallurgy is best known from settlement environments. Sites yielding abundant evidence for crucible metallurgy include Pi-Ramesse (Pusch 1990; Rademakers, Rehren, and Pernicka 2017; Rademakers, Rehren, and Pusch 2018) and el-Amarna (Eccleston and Kemp 2008; Nicholson 2007;

Figure 3.
Front and side views of two examples of copper processed in the Ramesside workshops at Pi-Ramesse. At top: a fragment of an oxhide ingot made of raw Cypriot copper. At bottom: a copper scrap intentionally folded and wrapped in textile for later recycling (cf. Rademakers, Rehren, and Pernicka 2017; Rademakers, Rehren, and Pusch 2018).

Figure 4. Side and front exterior views of two Middle Kingdom crucible types of varying size. At top: a vessel used for arsenical copper processing, 7.4 cm wide, 8.8 cm long, 7.4 cm high. At bottom: a vessel used for raw copper melting, 11.8 cm wide, 13.3 cm long, 14.8 cm high (Verly 2024).

Rademakers fc.; and see the *Bibliographic Notes* for further examples). Yet crucibles for secondary metallurgy are equally found at primary production sites, such as Ain Soukhna (Abd el-Raziq et al. 2011), Serabit el-Khadim, and Wadi Maghara (e.g., Davey 1985).

Charcoal-filled crucibles were commonly placed in a bed of charcoal for additional heating from below, with air being blown onto the charcoal inside the crucible to melt the metal charge (i.e., the metal and mineral components processed within the crucible), since air blown directly onto the metal would oxidize and "burn" it. During the Old and Middle Kingdoms, air was commonly forced into the crucibles using lung-powered blowpipes (with clay nozzles), while foot-powered pot bellows attached to clay *tuyères* (nozzles directed into a furnace or hearth) became the norm from the New Kingdom onwards (Davey 2021). In contrast to crucibles, such blowpipes and *tuyères* were often not fired before use and are only partially preserved in the archaeological record (e.g., Abd el-Raziq et al. 2011; Rademakers, Rehren, and Pusch 2018). Crucible heating may have taken place in ephemeral structures, such as simple pits with or without clay lining, leaving few archaeological traces (e.g., Hodgkinson 2018; Pusch 1990; Rademakers, Rehren, and Pusch 2018; Stevens and Eccleston 2007). In some cases, however, dedicated crucible heating structures can be recognized, for example, in smaller melting "furnaces" at Middle Kingdom Ain Soukhna (Abd el-Raziq et al. 2011) and in the so-called "melting batteries" at New Kingdom Pi-Ramesse (Pusch 1990, 1994). These typically differ from the kilns and ovens used for pottery and faience production (Nicholson 2010), which are closed structures neither allowing for crucible manipulation nor localized heating to c. 1200°C. Post-holes for roofing structures should equally be looked for, as the temperature of hot metal had—prior to the development of modern measuring devices—to be estimated based on its color in the shade (i.e., darkness), or at night (e.g., Verly 2024; Verly et al. 2020).

The newly created alloy could then be cast into different types of molds, such as open sand or stone molds, bi-valve stone molds, or closed ceramic molds (Auenmüller fc. b). The ceramic and stone molds for artifact production tend to have the shape of the final, intended object (e.g., Odler 2023a: 286-291, figs. 112-114). An assemblage of artifact molds from Mine L at Serabit el-Khadim indicates that secondary metallurgy could have taken place also very close to the mining sites. The artifacts presumably cast with those molds allow us to date the corpus to the New Kingdom (Beit-Arieh 1982, 1985; Odler 2023a: 288–291). Little research has been done on stone molds used for copper alloy casting, of which a few examples are known from (probable) gold casting. Ceramic molds were made for lost-wax (also known as *cire perdue*) casting, a technique during which an object was first shaped in wax, then covered in layers of clay and heated to fire the clay and remove the wax. The hollow mold was then filled with liquid metal upon casting, and finally broken to remove the cast metal object. Such molds are thus almost invariably broken into small, friable, relatively non-diagnostic pieces, which often remain undetected during excavation unless careful attention is given (e.g., through noting smooth gray interior surfaces of ceramic fragments). A remarkable exception is the casting mold assemblage from Qubbet el-Hawa, which has provided many unique insights into (Late Period) lost-wax casting technology and the materials used in the process (Fitzenreiter et al. eds. 2014; Fitzenreiter, Willer, and Auenmüller 2016).

Following casting, copper alloy objects could be further worked. Certain object types were brought into their final shape, for example, by hammering and/or cutting. This is particularly the case for thin sheet-like objects, such as the copper alloy model tools from the Tomb of Khasekhemwy (Kmošek et al. 2018; Rademakers, Verly, Delvaux, et al. 2018), the copper alloy statues of king Pepy I from Hierakonpolis (the only preserved metal-sheet statuary of Bronze Age Egypt: Eckmann and Shafik 2005), and the (Hittite) shields that would have been manufactured using the flat limestone molds found at Pi-

Ramesse (Pusch 1990). Weapons and tools were often hardened or equipped with a cutting edge through cycles of hammering and annealing (i.e., heating the metal to relieve the stress built up in it during hammering; e.g., Kmošek et al. 2018; Lang 1987; Odler and Kmošek 2020, 2021; Odler et al. 2021), but similar techniques were applied on model tools as well (Maddin et al. 1984). Beyond their manufacture, metal tools such as chisels had to be re-sharpened and hardened using these methods throughout their lifetime. The typical, and mobile, toolkit for these operations included (stone or metal) hammers, anvils, tongs and pincers, and a hearth (fire). Such toolkits have rarely been found in situ but are often represented in tomb imagery (e.g., Scheel 1985).

3.4 Copper alloy objects

As a final category, the copper alloy objects themselves can be mentioned. The vast majority and best-preserved examples are known from funerary contexts, especially when considering objects of higher economic value, social prestige, and substantial size, such as mirrors, weapons, and vessels. While significant numbers of metal artifacts are encountered in settlement sites, these tend to be much smaller daily-use objects, such as fishhooks, needles, and small chisels, or fragments of originally larger prestige artifacts (e.g., Predynastic and Early Dynastic material from Tell el-Farkha in Czarnowicz 2012 and Old Kingdom Giza material in Odler et al. 2021; Odler and Kmošek 2022). Complete larger objects are more rarely recovered from specialized workshop settings, such as chisels from mining areas (Verly et al. 2019) or a complete horse bit from the chariot workshops at Pi-Ramesse (Pusch 1990; Herold 1998). However, the capacity for copper alloys to be infinitely re-melted, re-alloyed, and re-shaped has resulted in a situation where especially large-scale copper alloy objects are generally missing from the archaeological record, whereas countless small ritual bronzes and bronze cult paraphernalia have been deliberately deposited—and thus taken out of the material circulation—in sacred caches or other kinds of deposits in the first millennium BCE (Auenmüller fc. a). As such, our view on copper alloy objects is strongly biased in terms of their size and find context. While some objects may have been purpose-made for funerary use, others had a life cycle preceding their deposition, which may or may not have involved their owner for the afterlife (e.g., Rademakers, Verly, Delvaux, et al. 2018).

4. Methods of Analysis

4.1 Archaeological excavation and survey

Excavation provides primary information on the ancient contexts of the production of copper alloys as well as their use. While many Egyptian copper alloy objects (like other types of material culture) are currently housed in museums and other collections worldwide, the majority of these lack detailed contextual data because they were collected or purchased without information on their provenance or because their archaeological contexts were poorly recorded upon archaeological excavation. Detailed contextual information is essential for the reliable dating of artifacts (or at least their deposition), but equally provides insight into their (final) use in domestic, funerary, ritual, or other settings. Today's excavations can provide far better detail on find contexts, improving our understanding of the spatial distribution of metal finds, especially in settlement contexts.

The detailed excavation of metal production contexts requires a specialized approach, ideally involving an archaeometallurgy specialist on site. As discussed above, the evidence varies for different steps of the production chain, and some elements may be ephemeral (e.g., hearths or roofing structures) or highly fragmented (e.g., mold fragments, charcoal, casting spills), while others are simply unfamiliar to many field archaeologists. The recognition of key metallurgical features is essential towards the reconstruction of metallurgical processes in their particular contexts. As such, careful excavation methods, including micro-stratigraphy of (waste) deposits, sieving, and high-resolution spatial documentation, are crucial. Furthermore, 3D-photogrammetry of different stages of the excavation can aid the specialist's post-excavation assessment of the workshop environment. The geochemical mapping of workshop surfaces (floors and structures), using a hand-held portable X-ray fluorescence (pXRF) instrument, adds another important layer of information otherwise lost during excavation. Surface contamination can reveal the spatial organization of an ancient workshop down to the level of object handling by craftspeople. Color documentation (colorimetry) of furnaces, crucibles, and other heat-exposed surfaces can further aid the identification of key process parameters (e.g., Verly et al. 2021). Finally, it is essential for all production waste to be carefully sampled and stored for post-excavation study by an archaeometallurgy specialist (cf. section below on archaeological science).

Archaeological surveys play a key role in the identification of mining and metallurgical sites, as well as in understanding their broader role in the ancient landscape(s). As it stands, a large number of ancient mining and smelting sites in Egypt and Sudan are known from field surveys (e.g., Abdel-Motelib et al. 2012; Rothenberg 1970; Rothenberg et al. 1998; Tallet 2012). These provide a general overview of their distribution in time and space. Yet most of these sites remain for now only known through survey: the lack of targeted excavation is responsible for the huge gap in our current understanding of the technologies practiced there. This can be contrasted to the long-time archaeometallurgical research projects in the Arabah Valley (Israel, Jordan), showcasing the deeper insights which can be obtained regarding mining and smelting communities over several millennia (e.g., Ben-Yosef 2018; Levy, Ben-Yosef, and Najjar 2018).

4.2 Experimental archaeology

Experimental archaeology can be defined as a research tool employed towards understanding excavation sites, including particular features, man-made materials, and the remains associated with their production (e.g., Rademakers, Verly, Téreygeol, et al. 2021 and references therein). It employs rigorous protocols to test particular hypotheses, validated against the archaeological evidence (e.g., Verly and Longelin 2019) and sometimes iconography (e.g., Stocks 2023; Verly 2017a), and is clearly distinct from experiential replications. When employed as a scientific tool, it represents an essential step in interpreting technological features related to ancient metallurgy and has been a cornerstone of archaeometallurgical research since its inception (e.g., Rothenberg ed. 1990; Tylecote and Merkel 1985). In the context of Egyptian metallurgy, however, it has not been widely employed, although the earliest published experiments with arsenical copper in relation to Egyptian metallurgy took place in the 1950s (Maréchal 1957). More recently, a realistic understanding of the functioning of Middle Kingdom smelting furnaces could only be obtained through more than 50 experiments (representing over 4,500 working hours), as described by Verly et al. (2021), while targeted experiments using crucibles made of the same materials as those excavated at el-Amarna illustrated the temperatures attained in small furnaces used for crucible heating at this site (Eccleston 2008). Experimental archaeology can thus inform the interpretation of excavated features and provide details on different steps of the metallurgical process.

Furthermore, the excavation of features built for the experiments improves the excavation of their archaeological counterparts in long-term projects, aiding the identification of previously unknown technological features (e.g., waste deposits related to smelting: Verly et al. 2021). As such, it gradually improves the detail recorded during archaeological excavation (which can be understood as an "experiment" that can never be repeated).

Finally, the scientific analysis of experimental products provides reference data for the interpretation of archaeological remains analyzed in the same manner. For example, analysis of experimental Ain Soukhna smelting products has aided the interpretation of the archaeological remains, and more broadly the composition of Middle Kingdom copper alloys (Rademakers et al. 2020). Similarly, the analysis of experimental casting molds has deepened technological insights into Late Period molds found at Qubbet el-Hawa (Auenmüller, Verly, and Rademakers 2019) and has hinted at previously unknown rituals possibly associated with their use (Verly et al. 2022).

4.3 Archaeological science

The analysis of copper alloys and production waste using analytical chemistry techniques adds a crucial layer of information to their overall study. The applied methodology varies depending on the type of material being analyzed (metal, ore, slag, technical ceramic) and the material characteristics one wishes to understand (microstructure, mineralogy, elemental composition, isotopic composition). Broadly speaking, two main research questions can typically be distinguished regarding either production techniques or material provenance, even though these should always be considered together to arrive at coherent interpretations (e.g., Rademakers, Verly, Delvaux, et al. 2018, 2021; Rademakers et al. 2020; Rademakers, Verly, Delvaux, Vanhaecke, et al. 2021).

While various handbooks introduce the full range of available analytical and natural scientific methods (e.g., Malainey 2011; Pollard and Heron 2008; Price and Burton 2012; Scott 1991), we highlight below which types of analyses can be employed to characterize different types of material, and which questions can be addressed by doing so. The most important techniques employed offer insight into the samples'

- Microstructure, e.g.,
  Optical Microscopy (OM),
  Scanning Electron Microscopy (SEM)
- Mineralogy, e.g.,
  Optical Microscopy (OM),
  X-ray Diffraction (XRD)
- Elemental composition of microscopic phases, e.g.,
  SEM with Energy Dispersive Spectrometry (SEM-EDS)
- Bulk and trace elemental composition, e.g.,
  X-ray Fluorescence (XRF),
  Neutron Activation Analysis (NAA),
  Inductively Coupled Plasma - Optical Emission Spectroscopy (ICP-OES),
  Quadrupole - Inductively Coupled Plasma - Mass Spectrometry (Q-ICP-MS)
- Lead isotope (LI) ratio composition, e.g.,
  Multi-collector - Inductively Coupled Plasma - Mass Spectrometry (MC-ICP-MS)

4.3.1 Ore

Ore is typically characterized in terms of its mineralogy to understand the type of deposit it derived from (linking it to particular geological environments and potential mines) and its behavior during smelting (different ore types require different smelting conditions for successful metal extraction). Furthermore, bulk, minor, and trace element concentrations as well as LI ratios are determined for ore samples to compare them with the composition of copper and its alloys in order to establish potential metal provenance.

The most important copper ore deposits in ancient Egypt were those from the Sinai Peninsula and the Eastern Desert. The 2006 and 2008 archaeometallurgical expeditions reported by Abdel-Motelib et al. (2012) cover a huge range of deposits exploited in antiquity and provide elemental and LI ratio data for 95 samples, covering ore, slag, and metal from 27 mining, smelting, and settlement sites in Sinai and the Eastern Desert (building on the work by Beit-Arieh 2003 and Pfeiffer 2013). This groundbreaking study is of key importance towards understanding available ore sources, yet it remains preliminary in terms of covering many millennia of metallurgical activity across a huge mining district, especially in the case of Eastern Desert copper ores.

To advance our understanding of this part of the production chain, more detailed studies of individual, well-dated mining and smelting contexts are essential. The analysis of copper ore, smelting waste, and raw copper from Dynasty 5 and 12 workshops in the Wadi Maghara, Seih Ba'ba', and Wadi Nasb by Rademakers, Verly, Delvaux, Vanhaecke, and Degryse (2021) offers a recent example. In this study, material excavated by Petrie (1906) was analyzed for its mineralogy, elemental composition, and LI ratios to characterize the specific minerals exploited during those dynasties.

Geochemical analysis of ore in the context of geological studies (e.g., Afify et al. 2022; Salem et al. 2013) can be helpful towards understanding ore deposits, but it is usually conducted from the perspective of modern economic exploitation and provides little information on specific ore types that might have been exploited by past peoples.

Isolated examples of ore analysis from archaeological contexts, such as Buhen (El Gayar and Jones 1989a) and Sinai (Bachmann 1980), do not include sufficient detail to characterize the range of ore types that may have been available at these sites at a given point in time. Nevertheless, ore fragments do occur in settlement contexts, e.g., at Old Kingdom Giza (Odler and Kmošek 2022) and Middle Kingdom Elephantine (Odler and Kmošek fc.), as well as funerary contexts, e.g., at Dynasty 0-1 Tarkhan and Abydos (Rademakers, Verly, Delvaux, et al. 2018), and more will need to be investigated in the future.

4.3.2 Primary production waste (slag)

The elemental composition and LI ratios of slag can be compared to those of ores (cf. above), to link metallurgical activity to the mining of particular deposits. Such links can be reinforced through the mineralogical and microstructural analysis of slag. Microstructural and -phase elemental analysis provides essential data to reconstruct the conditions of primary metallurgical processes (e.g., Bachmann 1982). Through such reconstructions, the diachronic development of smelting technology in relation to particular ore deposits can be traced. Such an approach is not only of interest for identifying technological changes within a particular culture but can reveal the exchange of ideas and technologies with other areas of the ancient world.

As it stands, our understanding of primary production technology remains very limited, as no detailed or systematic slag studies have been conducted (a few minor examples can be noted, e.g., Abd el-Rahman et al. 2013; Bachmann 1980; Beit-Arieh 2003; El Gayar and Jones 1989b). Yet important advances have recently been made through the study of smelting remains at Ain Soukhna, where many details of the smelting conditions were reconstructed based on new excavation evidence and on-site qualitative XRF-analysis (Verly and Rademakers fc.). Feedback between the experimental replication of this process, the results of its analytical study, and the excavated evidence has provided further insights (Rademakers et al. 2020; Verly et al. 2021), even if more detailed analysis of the archaeological remains has not been possible as yet.

This dearth of analysis of slag from Egyptian contexts may be contrasted to the rich history of analysis at sites such as Faynan (Jordan) and Timna (Israel), both in the Wadi Arabah (e.g., Hauptmann 2007; Rothenberg ed. 1990). These studies have shown how smelting technologies evolved over time in relation to the different socio-political conditions and people involved, exemplifying the scientific fertile ground still awaiting valorization in the Sinai and the Eastern Desert. Furthermore, these regional studies provide an excellent comparative basis to assess interaction between Egypt and the Levant through the lens of metallurgical technology.

4.3.3 Raw copper

The extraction of raw copper from ore is the objective of smelting. Currently, the only known examples of raw copper produced in the Sinai are in the shape of small prills or droplets (Pfeiffer 2013; Verly et al. 2021). In the smelting furnaces at Ain Soukhna, such prills were deposited at the bottom of the furnace and could be retrieved at the end of the metallurgical reduction process. It is possible, however, that raw copper formed in other shapes, including larger agglomerates, in the context of smelting technologies hitherto unknown. Raw copper prills could then be re-melted in a crucible (cf. below) to cast a larger ingot of copper, although archaeological examples from Egypt remain very scarce (an ingot from Bir Nasb, site 350A, can be mentioned as an exception; cf. Rothenberg ed. 1990: 65; Yahalom-Mack et al. 2014). Evidence of presumable ingots from Egypt was reassessed recently (Odler 2023a: 281–285, figs. 108–111), and careful attention to similar objects found in the archaeological contexts might reveal more specimens.

The analysis of raw copper typically involves its elemental and LI ratio composition. Raw copper provides a stronger baseline for understanding the composition of alloys, being situated closer to the alloys along the production chain in comparison to ore and slag. Their metallographic examination (microscopy) can highlight important inclusions reflective of the smelting process (e.g., Roman 1990).

4.3.4 Crucibles and other technical ceramics

Crucibles are highly sophisticated ceramics, capable of withstanding high temperatures, mechanical stress, and exposure to liquid metal at the same time (e.g., Craddock 2014b). Their technological history as a particular type of ceramic vessel merits dedicated study in terms of typology (e.g., Davey 1985) and fabric selection (often Nile-silt clays, yet with varying temper additions: e.g., Claes, Davey, and Hendrickx 2019; Rademakers, Rehren, and Pusch 2018; Rademakers, Verly, Cortebeeck, et al. 2023) and should be situated between ceramic and metallurgical research. Indeed, crucibles may share the basic ingredients used in domestic pottery manufacture but may often have been produced by their metallurgist users. They were typically shaped by hand and pre-fired prior to metallurgical use (Rademakers, Rehren, and Pusch 2018). Dedicated crucibles were similarly developed for glass production during the New Kingdom (e.g., Rehren and Pusch 2005).

From a metallurgical perspective, crucibles contain a wealth of information regarding melting and alloying processes. Throughout the Egyptian Bronze Age, the majority of crucibles were internally heated (i.e., air was blown onto the charcoal placed within the crucible). This resulted in a typical crucible cross-section profile consisting of a lower-fired (oxidizing) exterior ceramic part, a transitional zone of ceramic disintegration (bloating), and a vitrified zone at the crucible interior (crucible slag) (see Rademakers, Rehren, and Pusch 2018: fig. 34.5). The degree of crucible slag development differed between and within crucibles (Rademakers and Rehren 2016) as a result of heterogeneous conditions and degrees of refractoriness (i.e., the ability of a ceramic to withstand metallurgical process conditions: Freestone and Tite 1986).

The crucible slag consists of molten ceramic and inclusions from the crucible charge trapped in this vitrified layer: fuel (ash), metal (oxides), and/or minerals (fig. 5). Beyond crucible slag, a so-called dross is sometimes deposited on the crucible interior or exterior. Dross forms through the oxidation of reactive elements within the metal charge. Typically, these are residues from the smelting process (e.g., iron or manganese) accompanying raw copper (e.g., Rademakers, Verly, Delvaux, et al. 2018; Rademakers, Verly, Somaglino, and Degryse 2020) or sometimes alloy components (e.g., arsenic, tin, lead) that oxidize when (too much) air is blown directly onto the crucible charge (e.g., Rademakers, Rehren, and Voigt 2018). During casting, dross may be actively removed by the metallurgist, but (some of) it is often deposited on top of the interior crucible slag or along the crucible rim.

The analysis of crucible slag and dross informs on the composition of the crucible charge (Rademakers and Rehren 2016). Ideally, such analysis is carried out in the laboratory on cross-sections using optical microscopy and SEM-EDS. This enables a detailed reconstruction of production processes as well as an overview of the different materials used in making copper alloys. So far, the only ancient Egyptian assemblage studied this way in detail is that of New Kingdom Pi-Ramesse. This research has

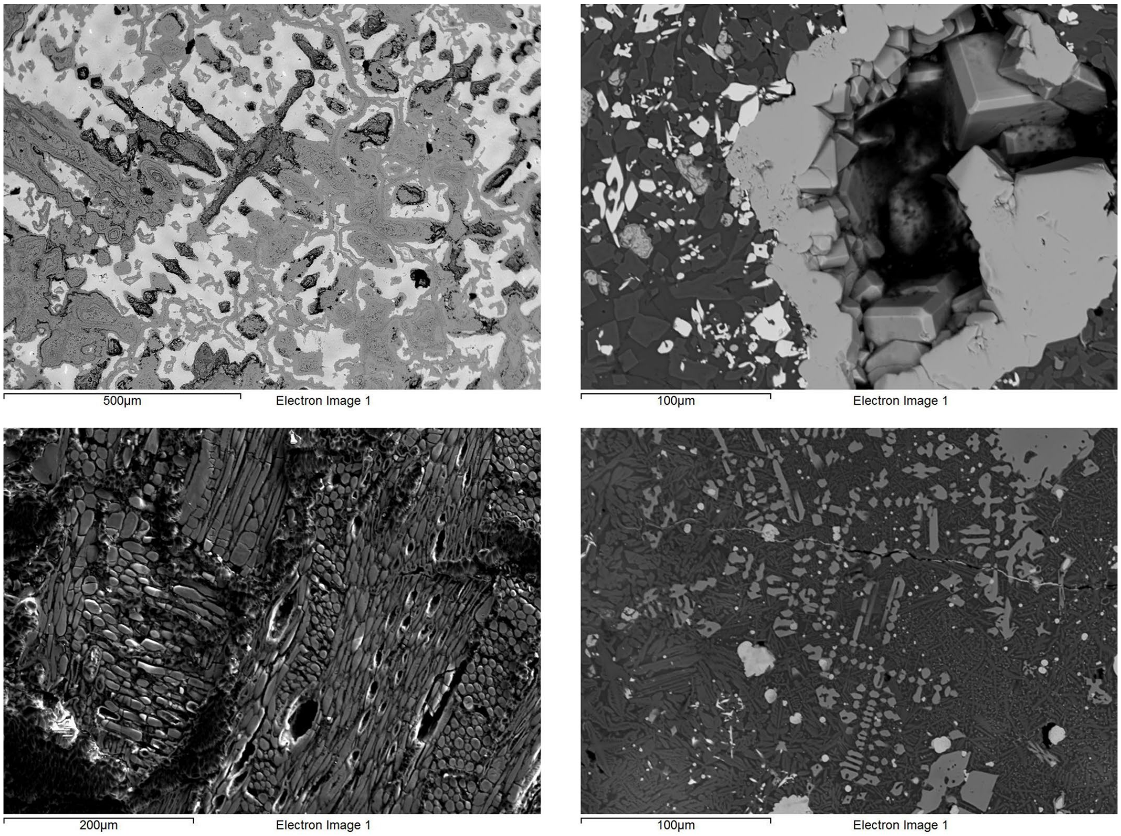

Figure 5. Scanning Electron Microscope images of crucible slag encountered in the Pi-Ramesse crucibles (further discussion in Rademakers 2015 and Rademakers, Rehren, and Pusch 2018). Top left: partially corroded tin bronze prill (dark gray: corrosion; brighter gray: metallic). Bottom left: embedded charcoal fragment. Top right: crucible slag (dark vitreous background) with metal oxides (white: tin oxide) and post-depositional corrosion products (light gray: cuprite formation in pore). Bottom right: crucible slag (dark vitreous background) with metal prills (light gray) and metal oxides (medium gray: iron-cobalt oxides).

not only shown the diversity of copper sources used in the Ramesside workshops but has also underlined the flexibility with which these were employed to create copper through recycling and active alloying. Furthermore, it has revealed that tin bronzes were produced by directly mixing copper with cassiterite (a tin oxide mineral), probably alongside copper and tin metal mixing. This practice was not previously documented in the Bronze Age for the wider region and hints at the exploitation of cassiterite deposits in the Eastern Desert (Rademakers, Rehren, and Pernicka 2017; Rademakers, Rehren, and Pusch 2018).

It is expected that similar research on crucibles from earlier periods and other sites will yield evidence for the active mixing of copper and arsenic compounds (as argued by Rademakers, Verly, Delvaux, and Degryse 2018; Rademakers, Verly, Delvaux, Vanhaecke, et al. 2021; Verly and Rademakers fc.). Indeed, arsenical copper was processed, for example, at Old Kingdom Giza and on Middle Kingdom Elephantine Island, while the copper ore minerals present at those sites contain little or no arsenic (cf. preliminary reports by Odler and Kmošek 2019, 2022, fc.). Ores processed at Middle Kingdom Ain Soukhna and Sinai were similarly poor in arsenic, producing highly pure raw copper (Abdel-Motelib et al. 2012; Rademakers, Verly, Delvaux, Vanhaecke, et al. 2021; Verly 2024). A recent study of crucibles from Kerma has shown that arsenic, either as an intermediate speiss (a pseudo-metallic smelting product) or as an arsenic-rich mineral, was intentionally alloyed with copper metal in a crucible (often along with tin) during the Middle Kerma period, proving this particular production chain for the first time (Rademakers, Verly, Cortebeeck, et al. 2023). Speiss as an alloying agent for the production of arsenical bronze was documented on Middle Kingdom Elephantine Island, with important lead concentrations besides iron and arsenic (Kmošek et al. 2024). Speiss found at el-Amarna represents a long-distance exchange commodity, raising questions regarding its value and use in a time dominated by tin bronzes (Rademakers et al. 2024). Beyond understanding how alloying practices developed over time, the documentation of these secondary processes is essential to our comprehension of how they influence the relation between elemental and LI ratio compositions of ore, raw copper, and alloys.

When assemblages can only be studied in the field, key process identifications can still be made through their macroscopic study (ideally including detailed photographic documentation and descriptions of fabrics, metal, slag, and dross deposits) and hand-held pXRF surface analysis. This enables the distinction between different copper alloys and possible contaminants and significantly aids metallurgical interpretation (Rademakers and Rehren 2016). Recent work at el-Amarna and Ain Soukhna exemplifies this approach (Rademakers fc.; Verly and Rademakers fc.).

Other key technical ceramics that are important to document include blowpipe nozzles, *tuyères*, casting molds, and furnace or hearth fragments. Their degree of vitrification and heat exposure can illustrate their specific use in the metallurgical process, and comparing their fabric selections to those of associated crucibles can inform on technological choices made upstream in the material selection process (e.g., *tuyères* at Pi-Ramesse: Rademakers 2015; Rademakers, Rehren, and Pusch 2018; *tuyères* at Tell Rehov: Yahalom-Mack 2015; ceramic mold from Aniba: Odler and Kmošek 2020: 85–86, figs. 89–97).

4.3.5 Copper alloys

The study of copper alloy objects can shed light on the final stages of production, such as casting and hot or cold working (annealing, hammering). In some cases, object manufacturing techniques can be identified without the need for object sampling, through macroscopic observations and/or non-invasive radiography (e.g., Schorsch 1988, 1992). More recently, neutron techniques have also been applied to this end (e.g., Agresti et al. 2016; Festa et al. 2018; O'Flynn et al. 2023). Evidence for joining techniques (such as riveting or soldering) or casting methods (such as bivalve mold or lost-wax casting) and secondary working (such as hammering) can often be identified this way.

In other cases, manufacturing techniques can only be identified through the study of a cross-section using optical microscopy (so-called metallography: Scott and Schwab 2019). Recent applications of this technique include the work on artifacts from various periods by Kmošek et al. (2018), Odler and Kmošek (2020, 2021), and Odler et al. (2021), who have identified the use of hot and cold working in a variety of artifact types. In addition, the study of metallographic samples has allowed for the measurement of the hardness of particular artifacts, which provides indirect information about the practical usability of the artifacts, although it does not constitute its proof (see also earlier work by Garenne-Marot 1984 and Lang 1987). Understanding artifact use may be further supported by systematic study of metalwork wear (e.g., Dolfini and Crellin 2016), which is only now being added to research approaches (Boatright 2010; Odler 2024; and remarks in Odler 2023b).

Another important strand of copper alloy analysis involves the determination of alloy constituents (major and minor elements) as well as their trace element composition and LI ratios. Alloy compositions can be identified using a variety of techniques, including surface analysis by XRF (after the removal of surface corrosion). Variations in alloy compositions over time illuminate important transitions in metallurgical technology, which can relate to innovation as well as changes in material availability as a result of local and regional economics or different metallurgical traditions in particular socio-cultural contexts. Key studies in this regard include those by Cowell (1987), Eaton and McKerrell (1976), McKerrell (1993), Philip (2006), and Riederer (1978, 1981, 1982, 1983, 1984, 1988), who analyzed the elemental composition of copper alloys in several museum collections and site assemblages. Obviously, good contextual information is crucial towards meaningful interpretation of these results, which can be a limiting factor to some museum-based studies.

To obtain a full compositional character-rization (major, minor, and trace elements, and LI ratios), a small invasive sample (< 0.1g) must be taken. A single sample can be subjected to trace element (e.g., ICP-OES, ICP-MS, NAA) as well as LI ratio (MC-ICP-MS) analysis. From these data, more detailed discussions of material provenance can be elaborated. While some work has been done in the past (e.g., Stos-Gale et al. 1995), significant advances in the understanding of copper alloy provenance in the Nile Valley were made only recently by the present authors (see Kmošek et al. 2018; Odler and Kmošek 2020; Odler et al. 2021; Rademakers, Rehren, and Pernicka 2017; Rademakers, Verly, Delvaux, et al. 2018, 2021; Rademakers, Verly, Delvaux, Vanhaecke, et al. 2021; Rademakers et al. 2022; Rademakers, Auenmüller, Spencer, et al. 2023; Rademakers et al. 2024; see also Masson-Berghoff et al. 2018; Rehren and Pernicka 2014; Schwab and Willer 2016). Still, there remains an urgent need to expand the datasets for copper alloy compositions across pharaonic history in order to understand provisioning systems in different socio-economic contexts as well as regional tendencies. Furthermore, the identification of copper alloys as colorants for glass, faience, and pigments can broaden our perspectives on their use across different crafts (e.g., Jaksch et al. 1983; Rademakers, Auenmüller, Spencer, et al. 2023; Rehren, Pusch, and Herold 2001; Schiegl, Weiner, and el Goresy 1990).

It is important to emphasize that these compositional data do not necessarily yield an absolute provenance for an individual artifact. Indeed, it may be possible to attribute a particular mining origin to a particular artifact, but this cannot always be achieved. This is because copper alloy compositions are influenced by the whole production chain underlying their manufacture. LI ratios and trace element patterns can be altered through smelting and alloying, as well as recycling practices, making it impossible to link an artifact to any one particular mining region.

Rather, the compositional data should be understood as a reflection of circulating metal stocks available to metallurgists and consumers at any given point in time (as argued for different periods by Rademakers, Rehren, and Pernicka 2017; Rademakers, Verly, Delvaux, et al. 2018; Rademakers, Verly, Delvaux, Vanhaecke, et al. 2021; Rademakers et al. 2022; Rademakers, Auenmüller, Spencer, et al. 2023; Rehren and Pusch 2012). Assuming such a broad perspective, it is possible to identify the main streams of copper arriving in the Nile Valley over time, which include relatively local sourcing of Eastern Desert and Sinai copper, but equally copper from farther away, e.g., the Arabah Valley, Cyprus, Anatolia, the Aegean, and the Arabian Peninsula, obtained through direct or indirect exchange. Furthermore, recycling practices over long time periods and across different contexts can be identified. Finally, regional stocks and compositions specific to particular primary or secondary workshops may be defined as relative provenance groups to which individual objects can be compared.

Taking into account data from research on metallurgical technology along with economic insights from wider archaeological and Egyptological studies, these compositional data play a fundamental role towards identifying dynamic production and provisioning systems along the Nile Valley.

4.4 Written and iconographic sources

Inasmuch as traditional Egyptology and archaeometallurgy can mutually benefit from the same research questions (and the examples span from Gsell 1910 to Odler 2023a), archaeometallurgy and the study of written and iconographic sources—which comprise one of the foci of traditional Egyptology—can similarly benefit.

Written and iconographic sources on the production and uses of copper and bronze objects from ancient Egypt are sparse and they focus mostly on the issues that were deemed important by the Egyptians. Moreover, their comprehensive interpretation has been complicated by the insufficient understanding of material culture and archaeometallurgy. The most obvious example is the hieroglyph Gardiner sign-list N34 (Gardiner 1969: 490). Although Jean-François Champollion had already identified this sign as a crucible (Champollion 1841: 361; see also Lepsius 1872: 91), most Egyptologists were led astray by the incorrect identification of the sign as an "ingot" by Gardiner (1969: 490). The sign N34 and its specific designs (doubled form, shapes from droplet forms, with or without projections, to lozenge shapes), however, clearly represent an image of a crucible or crucibles (Herslund 2015; Odler 2023a). An example of the use of the N34 sign from Asyut determines four names of tools with copper blades (fig. 6).

Procurement of metal took place along two main routes: either in the form of the previously mentioned expeditions organized or co-organized by the Egyptian state, or via the exchange, trade, and military looting of foreign resources (cf. also Rosińska-Balik et al. eds. 2015). Early Dynastic year-labels from the reign of Den mention malachite obtained as a result of military activity, but their interpretation is highly speculative (Tallet and Laisney 2011). For the Old Kingdom, the best information provided is from a fragment of the biographical text of an official Iny, who organized an expedition to Byblos. There is no mention of copper; only silver and lead/tin are referenced (Marcolin and Diego Espinel 2011). Documents from Early Bronze Age Ebla, in the northern Levant, further inform us: In recent years, there has been increased support for a hypothesis identifying the land of Dugurasu, mentioned in the Eblaite documents, with either Egypt or a close, intermediary region (Biga and Steinkeller 2021). And it was actually from Dugurasu—or, as some scholars presume, Egypt—that deliveries of copper were made to Ebla, as recorded in nine such documents (Biga and Steinkeller 2021: 39).

Figure 6. Model carpenter's chest of a certain Ankhef from Asyut, Tomb 9 (Middle Kingdom, Dynasty 12). The chest is inscribed for Ankhef and bears a list of tools on the right, mentioning "six axes, six adzes, six chisels, six saws."

The major Egyptian written sources from the Middle and New Kingdoms are the fragmentary Middle Kingdom Annals of Amenemhat II (Altenmüller 2015), the New Kingdom Annals of Thutmose III, and the Amarna letters (Lilyquist 1999; Hikade 2001: 100–103; Redford 2003). Despite their importance in the discussion of exchange, trade, and the role of metals, their information is at best patchy and needs to be complemented by archaeology and archaeometallurgy. The annals of Amenemhat II and Thutmose III diligently note the weight of the raw materials and count the number of artifacts brought to Egypt from different regions, with the major origin of the Middle Kingdom copper being in Lebanon, while the Levant figures again as a source in the reign of Thutmose III. Since this part of the Levant does not, in fact, have copper ores, the raw material could have been coming either from Cyprus or Anatolia, or from even more distant sources. Both annal texts also mention the plundering of metal artifacts of foreign origin that were then brought to Egypt—and which are extremely difficult to identify within the contemporaneous contexts (Odler 2023a:

551–593; a well-documented exception is the Delta site of Tell el-Dabaa, where artifacts with “foreign” forms were likely produced: Philip 2006; Prell 2020a, 2020b).

The Egyptian vocabulary of metallurgy and its nuanced translation into modern languages pose several challenges. Ancient Egyptian terminology does not represent our modern scientific and mineralogical knowledge; thus translations of material identifications into modern languages must be used with caution (Harris 1961). Most problematic in this regard is a particular word for “copper.” Harris (1961) summarized earlier discussions and concluded that the ancient Egyptian word for copper was *ḥm.t*, while the metalworker was called *ḥm.tj*. These conclusions were followed by a large part of the Egyptological community. However, there is rather little direct evidence of these words for Bronze Age Egypt, copper usually being represented by logograms in various forms of the above-mentioned hieroglyph designated N34 in Gardiner’s sign-list (Gardiner 1969: 490). Recently Herslund (2015) and Odler (2023a) proposed that the word for copper should be read *bjꜣ*, a claim also made by Lalouette (1979). Odler (2023a) has clarified the issue with the argument put forth by Harris, who had mostly relied on second-hand copies of the relevant texts, especially the Pyramid Texts, and thus incorrectly identified some of the various forms of the N34 hieroglyph, which also meant “copper.” The word *bjꜣ* in itself is challenging, since it has many semantic connections, as analyzed by Graefe (1971). One of the possible translations, in addition to “copper,” is “iron.” The discussion is thus far from settled. With the exception of *bjꜣ-km*, “black copper,” produced by the addition of gold and silver to the copper alloy (Giumlia-Mair and Quirke 1997), the other names of the specific materials, e.g., *bjꜣ Sṯt*, “Asiatic copper,” are unlikely to be identified reliably without a statistically representative corpus of analyses of preserved artifacts (as argued by Odler 2023a). The word *ḥsmn* is mostly translated as “(tin) bronze,” but it is often associated only with items of conspicuous display, such as vessels, and rarely serves for the description of practical objects, such as those mentioned, for example, in the Annals of Thutmose III. The recently discovered New Kingdom notebook of Dhutmose (Hölzl, Neumann, and Demarée 2018) refers to many objects that would have been made predominantly of tin bronze as being of *bjꜣ*, “copper.” The distinction between *bjꜣ* and was apparently not well defined within the Egyptian mind and lexicon (see discussion in Odler fc.).

Apart from very brief expeditionary inscriptions, no written or iconographic sources deal with the actual mining or primary smelting of copper ore near the mining sites. Hints at such activities are present only, for example, in the stela of the expeditionary leader Khety (Gardiner 1917). There was a specific group of professionals, likely dealing with the surveying of the desert, whose ancient Egyptian title *smn.tj* is translated as “prospector” (e.g., Diego Espinel 2014), yet the ores and minerals could have been brought to Egypt by a wider range of people, not necessarily named as “prospectors” (e.g., Alù 2022). Secondary metallurgy is, however, mentioned a few times. The often-studied early Middle Kingdom stela of Irtysen (Louvre C14) refers to several craft activities. The difficult text instigated many, often diverging, translations. One of the proposals for lines 8 and 9 treats them as a description of the metallurgical process (Barbotin ed. 2005: 56–57; cf. also Fitzenreiter 2019). Reference to metallurgy appears to be likely, as it was recently noticed that the word “secret” is atypically determined by the sign N34, the metalworking crucible (Odler 2023a: 244, fig. 85). The particular deity of metalworkers was Sokar, who is described in Pyramid Text spell 669 as casting metal harpoons, and who is referred to as a “metalworker” of gods throughout the Pyramid and Coffin Texts. Furthermore, the deity Sokar is connected both to the celestial iron of meteorites and to earthly copper (Almansa-Villatoro 2019: 76), but sufficient evidence for his cult is known only from the New Kingdom (Gaballa and Kitchen 1969; Graindorge-Héreil 1994).

The subject of the painted or relief metalworking scenes in Egyptian elite tombs, particularly of the Old, Middle, and New Kingdoms, is predominantly secondary metallurgy, likely performed in workshops situated in the Nile Valley close to the centers of raw material supply and control—that is, in the royal palaces, large private households, and New Kingdom temples. Egyptian metalworking scenes are well known outside the scope of Egyptology, being the most detailed Bronze Age iconographic renderings of metalworking in the Mediterranean and beyond (Drenkhahn 1976; Garenne-Marot 1985; Scheel 1985, 1986, 1987). The challenge to understand them arises from the issue that they have been treated as the sole piece of evidence on metallurgy, disregarding ancient Egyptian norms of representation as well as ignoring material culture and archaeometallurgy. Debates center on the precision of the scenes as craft documents, rather than artistic or idealized renderings of certain key practices. Davey (2012) argues in favor of the former option, understanding them as rather precise renderings of reality by Old Kingdom artists. It is probable that tombs of elite officials imitated the motifs of similar scenes from the royal mortuary complexes, yet only a fragment of a metallurgical scene from the pyramid complex of Unas is preserved in some detail (Hassan 1938). Some aspects of metalworking represented in those scenes have, indeed, only sparse archaeological counterparts. In several Old Kingdom metalworking scenes, besides the "standard" crucibles, open, bowl-like crucibles (and/or hearths?) are depicted serving apparently similar functions (Odler 2023a: fig. 90c). Bread molds used in the context of metal processing were found at Old Kingdom sites at Giza and possibly at Buhen. In Giza, they were certainly involved in the processing of arsenical copper (Odler and Kmošek 2022). To complicate matters further, the only Old Kingdom metalworking scene with a vessel that has been identified iconographically as a bread mold has a caption "heating the gold for funerary equipment," thus connecting its use to gold processing (Hampson 2022: 187, reg. 2J, pl. 2).

The number of metalworking scenes is highest for the Old Kingdom; the complete corpus recently updated by Hampson (2022) provides a detailed study of all aspects of the scenes and their particular vocabulary (see also the online database of Linacre College, Oxford 2006). The activities depicted were associated either with royal or "private" workshops attached to high-status individuals in the royal administration. The evidence regarding metalworkers in private service is rare and unequivocal, but the existence of freelance craftspeople cannot be excluded, as they might not figure in the "official" state sources. In the First Intermediate Period and Middle Kingdom, craft activities, including metalwork and carpentry using tools equipped with metal blades, were exceptionally represented in the form of three-dimensional workshop models found in funerary contexts (Tooley 1995), while the traditional rendering of metalworking on tomb walls continued, e.g., at Thebes and Beni Hassan (Scheel 1986; for the relevant scenes in Middle Kingdom elite tombs, see also the online resource *Meketre*: https://meketre.org/themes). In the New Kingdom, such scenes were often described as being located in temple workshops (Scheel 1987): the most famous scene is from the Tomb of Rekhmira (TT 100), depicting work for the temple of Amun at Thebes (Davies 1935).

The scribal culture of ancient Egyptian society did not hold handcrafts in high esteem, and the well-known Satire of the Trades (the Teaching of Khety) can be read as an acrimonious literary version of the orderly and industrious craft scenes from tombs. Its postulated dating to the Middle or New Kingdom remains unresolved, the various preserved copies being of New Kingdom date (Helck 1970; Jäger 2004). A specific stanza on metalworkers refers likely to secondary metallurgy and copper working. The metalworkers' duty was described in the text as "task/service/servitude" (*bꜣk*). Furthermore, their fingers were described as deformed, perhaps from wielding stones as pounders and hammers, and their whole beings as smelly. This latter might be a reference to the garlic-like stench of arsenic

(Odler 2023a: 246–247, with further references on the passage), or to the general olfactory impression made by the metalworking craft and perspiring metalworkers. Verly (2017a), on the other hand, proposes that the passage might allude to the application of clay to the metallurgists' bodies as a measure of self-protection from their working conditions, particularly the high temperatures, whereas Fitzenreiter (2018: 133) posits a reference to the scars that the work leaves on the hands. The variety of interpretations of just three literary verses on metallurgy aptly illustrates the problems one encounters in attempting to understand the ancient texts.

The term for the metalworkers themselves was also written with the N34 sign, which, as noted above, was read by Harris (1961) as *ḥm.tj*. Recently, Odler (2023a: 89–96) proposed that the word for crucible, ***bḏꜣ.t***, ought to be the feminine form of the term for bread mold and for molds in general: ***bḏꜣ***. Thus the designation of the craftsperson would be ***bḏꜣ.tj***, "the one of the mold," a *nisba*-form derived from the term for crucible. *Ḥm.tj*, however, remains the dominant reading of the title among Egyptologists.

The hierarchical structure of the metalworking craft is one of the best understood for the Bronze Age Mediterranean. The earliest metalworker known, by name and social status, in the world is likely Ankhwa, represented by a statue of unknown provenance, now in the British Museum (EA171), dating to the Third Dynasty (Spencer 1980: 13). According to Drenkhahn (1976) and the reading of his titles by Kahl, Kloth, and Zimmermann (1995), Ankhwa was a metalworker (*bḏ-ms*), carpenter of *smꜣ*-ships, and property custodian of a king (on the social status of individuals with the latter title, see Bárta 1999). And since his statue was made of red Aswan granite, he could have been a rather highly positioned official. While for the Old Kingdom there are several preserved tombs of metallurgists (e.g., Moussa and Junge 1975)—all rather tiny and inconspicuous if compared to the size of the Fifth Dynasty tomb of Vizier Ptahshepses (Odler 2023a: fig. 82), one exceptionally preserving the fragments of a biographical inscription—Middle Kingdom metalworkers were named only on stelae and within expedition inscriptions (Odler 2023a: 213–248). For the New Kingdom, a few funerary stelae of copper metallurgists are known (Simpson 1985). The best source of texts pertaining to craft organization in the New Kingdom is certainly Deir el-Medina, the settlement of artisans in royal employment and their families. Evidence on its metalworkers, within their New Kingdom contexts, was recently gathered by Gabler (2018: 355-384). Moreover, craftspeople in general participated in some of the funerary rituals, especially in the "opening of the mouth" ceremony, but the evidence is comprehensive only from the New Kingdom (Fischer-Elfert 1998; Lorton 1999). Other ritual texts involving craftspeople are only fragmentarily preserved (Díaz Hernández 2014).

Old Kingdom metallurgists worked for several types of royal institutions (*pr-ꜥꜣ*, *pr-nswt*, *wꜥb.t*), but the metalworkers of the treasury (*pr-ḥḏ*) are known only from the Middle Kingdom. The inner structure of craft workshops had the typical three-fold hierarchy of overseers (*jm.jw-rꜥ*), controllers (*sḥḏ.w*/*ḫr.jw*), and the craftspeople themselves. Since the crafts were by nature hereditary, family structure was reflected in the social fabric of the crafts, and the existence of "elders" (*smsw*) of the craft is explicable within both contexts. Moreover, in Egyptian texts, the general category of craftspeople (*ḥmw.tjw*) could include metalworkers. During the Old Kingdom, the craft of metalworking might have inspired the presumed priesthood of Ptah (and Sokar) in the Memphite area, although the specific point in time when this may have occurred is hard to identify (Freier 1976).

Textual and iconographic sources rarely speak about the use of copper artifacts, although a whole range of metal objects was produced by metalworkers. In addition to goldworkers, the only other distinct group of metalworkers appearing in the sources is that of jewelry makers (on their products see, e.g., Gauthier-Laurent 1951; Wilkinson 1971; Bader 2015; Guerra, Martinón-Torres, and Quirke eds. 2023). Among the rare texts on metal artifacts is Papyrus Reisner II—a log of the copper-tool making workshop in a royal shipyard of Senusret I in early Dynasty 12 (Simpson 1965). A small part of the corpus from Deir el-Medina (Janssen 1975; Valbelle 1977) can be mentioned as similar documents. Additionally, Hölzl, Neumann, and Demarée (2018) have more recently published the "notebook" of the Deir el-Medina scribe Thutmose, containing detailed entries on operations with metal objects. Such sources provide some details about the use of copper artifacts, which are otherwise rarely preserved from the Bronze Age. Typical of all such sources is that they note information on the general class of the artifacts (e.g., axe, adze, chisel, etc.) and their weights. The interpretation of so-called non-textual markers, also mentioned, remains tentative; perhaps they denoted the ownership of tools (Andrássy 2009). Inventories inscribed on clay tablets from Old Kingdom Balat, in the Dakhla Oasis, remain unpublished, although a record of the work of a team of lumberjacks near Balat is available (Pantalacci 2010). Even though the use of axes is indirectly mentioned therein, we cannot determine whether the tools were equipped with copper or lithic blades. The question of the correct material identification applies also to iconographic sources. If the material is not specifically mentioned as copper or another metal, and if the coloration is not preserved, it is often hard to decide whether the tools and blades depicted by the ancient artists were made of metal or stone.

Due to the nature of hieroglyphic determinatives, by which words are semantically classified as belonging to certain lexicographical and conceptual groups, the tool names themselves can be established beyond doubt (Odler 2016). Connecting texts with material culture can be difficult only because of the limited preservation of either texts or iconography in very specific cases (e.g., a case of slave-branding irons: Karev 2022).

4.5 Typo-chronological studies

One of the first authors to deal with Bronze Age Egypt and its metal artifacts was none other than Swedish archaeologist and founder of typo-chronology, Oscar Montélius (1890). The earliest substantial typology of copper

Figure 7. Two First Intermediate Period or early Middle Kingdom copper-alloy battle axes, provenance unknown.

metalwork, with dating, was gathered by Petrie (1917, 1927, 1937). Although these works are now outdated, they still serve as material catalogs, alongside the early volumes of the Catalogue Général des antiquités égyptiennes du Musée du Caire on metal objects (von Bissing 1901; Bénédite 1907; Vernier 1927).

Updated studies and chronologies have been established for several categories of material culture in general, e.g.: axes (fig. 7) (Kühnert-Eggebrecht 1969; Davies 1987; Couton-Perche ed. 2021); daggers (Petschel 2011); swords (Müller and Kühn 1987; Vogel 2006; Massafra 2012); arrowheads (Huret 1990; Couton-Perche ed. 2021); harpoons (Odler and Peterková Hlouchová 2017; Czarnowicz 2018); metal parts of chariots and horse harnesses (Littauer and Crouwel 1985; Herold 1999); mirrors (fig. 8) (Vandier d'Abbadie 1972; Lilyquist 1979; Derriks 2001); leather-working tools (Schwarz 2000: 78–110); wig maintenance tools/hair curlers (Zumkley 2022); vessels (Radwan 1983; Gershuny 1985; Green 1987); statues and statuettes (fig. 9) (Roeder 1937, 1956; Hill 2004; Eckmann and Shafik 2005; Mendoza 2008; Hill and Schorsch eds. 2007); armor (Pollastrini 2017); forked staves (Cherf 1982); mast finials (Goedicke 2000); as well as wooden handles and hafts of model tools (Zöller - Engelhardt 2016; Monbaron 2021). Typo-chronological studies generally use a wealth of textual and iconographic sources to their advantage in the identification of ancient Egyptian typological categories, which are combined with archaeological definition of types. The application of more advanced computational techniques, e.g., morphometry and classificatory neural networks in typology, remains today rather limited (Odler and Dupej 2016; Gaude Fugarolas and Odler 2023). For a general overview of early Egyptian and Nubian artifact categories, see also Odler (2023a) and Czarnowicz (2021).

Only rarely is the archaeological study of metal artifacts accompanied by a thorough archaeometallurgical investigation, the main exceptions being the catalog of axes in the British Museum (Davies 1987) and the more recently published studies of collections in Brussels (Rademakers, Verly, Delvaux, et al. 2018, 2021) and Leipzig (Kmošek et al. 2018; Odler and Kmošek 2020). As already noted, such work is needed to expand the scope and utility of typo-chronological studies: the elemental composition, lead isotope ratios, and (micro-)structural data are needed for the largest possible sample of preserved artifacts. While current research suggests that the composition of an artifact will rarely (if ever) be sufficient to infer its production date (e.g., Rademakers, Verly, Delvaux, and Degryse 2021), it should be considered an essential attribute to be included in any detailed description (see, for example, Couton-Perche ed. 2021 and the contribution by Couton-Perche and Bourgarit on pages 259–267 of that volume). Beyond the similarities in artifact compositions over time (as a result of the use of similar raw sources), copper alloys could remain in the living culture much longer

Figure 8. Burial equipment of the nomarch Isi (Old Kingdom, Dynasty 6), including copper mirror disks, a razor blade, and miniature copper alloy vessels and stands, found in the central pit of the mastaba of Isi at Tell Edfu.

than, for example, organic materials, and were also recycled into new shapes and forms, which complicates their dating.

The earliest shapes of metal tools were inspired by their lithic and polished-stone counterparts—an observation made by Petrie (1917). Later, in contrast, metal-tool forms could have been rendered in flint, as is evidenced, for example, at Middle Kingdom Kahun (Petrie 1890: pl. XVI; 1891: pl. VII). The term "Bronze Age" applied to ancient Egypt and Nubia does not imply the complete abandonment of lithic tools in favor of metal implements, and as experiments by Stocks (2023) and documentation by Serotta (2023) have proven, lithic tools could have been much more effective in working hard stones, such as granite, than metal ones. Thus, while the crafting tool kits of the Bronze Age Egyptians and Nubians included metal tools, these were used mainly for precision work due to the thinness to which their blades and points could be rendered (Devaux 1999, 2000; Serotta 2023). Such tools would have been difficult to produce from stones and bones.

The debate remains inconclusive on whether the red- and white-polished ceramics from third millennium BCE Egypt, as well as the Kerma beakers from second millennium BCE Nubia, represent "cheap" imitations of metal vessels that were used only in particular contexts and thus had much higher actual value (Radwan 1983: 35; Walsh 2021; Odler 2023a: 512). The debate on the comparative value of ceramic and metal vessels can be partly addressed by studying the various known prices (Janssen 1975), but in order to comprehend the emic value system of pharaonic Egypt, we need to impartially consider the available evidence.

Large blades of tools and weapons, mirror disks and handles (see figs. 7 and 8), and vessel surfaces can bear inscriptions (fig. 10), identifying the titles and names of the probable owners of the artifacts themselves. In the case of metal tool blades, some of the inscriptions refer to work divisions—that is, Old Kingdom phylae. Thus the tools appear to have been "state-"owned and issued for specific tasks (Roth 1991: 122–124; Odler 2023a: 361–362), while problems of specific ownership of particular tools were also subjects of mention (e.g., Gutgesell 1984; Davies 1993). The inscriptions could have been incised rather faintly, leaving only their remnants preserved just below the corrosion layers. The utmost caution is required in any cleaning or restoration of copper objects, but it can be rewarded by the uncovering of new prosopographical information, for example on vessels (Cressent and Raimon 2016). It is likely that many inscriptions, especially those recovered in early excavations, have been missed on corroded or fragmentary metal objects that were not sufficiently studied or conserved, or were too extensively cleaned; moreover, the inscriptions themselves could have been rather inconspicuous (Whitehouse 1987). Such inscriptions can also provide chronological information, which is otherwise hard to establish on specific metal objects.

Figure 9. Late Middle Kingdom statuette of a woman, provenance unknown.

Figure 10. Brazier or censer inscribed with the name of the First Intermediate Period king Meryibra Khety, from Meir.

Nevertheless, since inscriptions increase the art-market value of ancient objects, some suspicious renderings of "ancient" inscriptions on genuine metal objects could have been produced in modern times (cf. Odler 2016: 34–35). The distinction of genuine inscriptions from fake ones would require detailed study of all inscribed objects coming from documented archaeological contexts.

5. *Copper Alloy Objects*

5.1 Use of finished objects: Contexts and dating

To date, most of the important contexts with preserved artifacts from throughout the Egyptian Chalcolithic and Bronze Age have been cemeteries, e.g.: Predynastic Naqada (Petrie and Quibell 1895); Kafr Hassan Dawood (Rowland 2014); Dynasty 1 Saqqara, Tomb 3471 (Emery 1949); Dynasty 2 Abydos, Tomb of King Khasekhemwy (Petrie 1901b, 1901a); Dynasty 3 Beyt Khallaf (Garstang 1903); the Old Kingdom (Odler 2016); First Intermediate Period and early Middle Kingdom cemeteries south of Asyut (Brunton 1927, 1937, 1948); Middle Kingdom and Second Intermediate Period Tell el-Dabaa with clearly foreign metalwork of non-Egyptian forms (Philip 2006); Dynasty 17 Western Thebes (von Bissing 1900; Miniaci and Lacovara 2022; and especially Morris 2022); and Dynasty 18 Theban elite burials (Smith 1992) (fig. 11). The reader may notice here references to rather early works, since these have rarely been replaced by more recent systematic publications. Today one finds that the material from a single site is often dispersed throughout the world and its museums. For many of the pieces, fresh documentation would be helpful, as each museum collection may contain unique pieces, due to the rare preservation of copper metalwork in general.

The ancient value of copper-based artifacts tends to be downplayed by some scholars, but as an apt illustration of their scarcity, the Dynasty 18 cemetery of Fadrus 185 in Lower Nubia can be cited. Out of 715 burials, more than 90 percent were undisturbed, being sealed under a layer of gravel. Only about 8

Figure 11. Early New Kingdom battle-axe with haft, Asasif, Courtyard of Tomb CC 41, Pit 2, Burial D 3 (found in coffin).

percent of the structures contained copper-based items or had a tomb size wherein copper-based objects could be expected (Säve-Söderbergh and Troy 1991a: 212–225).

Miniature versions of actual tools found in funerary contexts are often characterized as "models," but this assumption has never been based on a systematic study of the physical and chemical properties of the artifacts themselves and their metalwork wear. While there exist clear artifact groupings of small blades, cut out of metal sheets or hammered into shapes, especially from the Old Kingdom tombs (Odler 2016, 2023b), there are also objects from other eras, predominantly the Predynastic and Early Dynastic Periods, that are sufficiently large to serve as practical objects, e.g., those found at the above-mentioned sites of Kafr Hassan Dawood, Naqada, and Saqqara. Moreover, some specific crafts involved precious wood, precious stones, and ivory, and they would have required small, practical tools. Such tools might be known from settlement contexts, e.g., from Old Kingdom Giza (Odler et al. 2021). Further archaeometallurgical study of such artifacts, however, is required to provide arguments for their practical "usability."

Since the Middle Kingdom, model tool blades of copper were also included in the foundation deposits of temples dedicated to deities or deceased kings (fig. 12). Additionally present were small rectangular "bricks" or "ingots" of various materials, including copper (Weinstein 1974). Vessels, models, miniatures, and miniaturized versions are treated as distinct categories, depending on their practical usability as containers for liquids and other substances (Arias Kytnarová, Jirásková, and Odler 2018; see also Allen 2006).

Tell el-Dabaa is one of the rare settlement sites with a substantial number of metal finds preserved (Philip 2006), in addition to New Kingdom el-Amarna (Frankfort and Pendlebury 1933; Pendlebury 1951; Stevens and Dolling eds. 2012) and Predynastic Tell el-Farkha (Czarnowicz 2012). Settlement finds tend to be otherwise rather fragile, fragmented, and small in size, as the inhabitants leaving a site intentionally would take any recyclable objects with them, as they apparently did, for example, at Old Kingdom Giza (Kromer 1978; Odler and Kmošek 2019, 2022).

Temple furniture of metal is another rare occurrence in archaeological contexts, as these artifacts would have been either removed or looted anciently. A comparison with the textual and iconographic evidence demonstrates that the same types of metal furniture were used in both funerary and temple contexts (Odler 2017). It is fascinating to observe that many forms of the temple ritual tools, originating early in pharaonic history, were used down to the first millennium BCE (Green 1987).

Figure 12. Reconstruction of a foundation deposit from the temple of Hatshepsut at Deir el-Bahri, containing several model tools with copper alloy blades.

Workshop sites, such as the one documented at Dynasty 19 Pi-Ramesse, demonstrate that a combination of materials was used and processed, and copper alloys were only one of the materials employed for particular craft activities (Prell 2011). Metal tools, for example, are conspicuously absent from mining sites and metal processing workshops, where stone tools were largely used. Yet finds of (fragments of) copper alloy chisels (e.g., Arnold 1991; Goyon 2004: 378–393; Petrie 1917) illustrate their use in at least some of these contexts, and our underestimation thereof due to (ancient) practices of careful curation and recycling.

Highly problematic is the issue of the "ethnic" identification of material culture. The most numerous artifacts found in Egypt are considered to be "Egyptian," while the majority of objects documented in Nubia tend to be described as "Nubian," belonging either to A-Group, C-Group, or Kerma populations. However, molds, for example, for late Middle Kingdom "Egyptian" lugged axe blades were uncovered not only at the Egyptian site of Kahun but also at the Delta site of Tell el-Dabaa, and in Nubia, at Aniba and Buhen (Odler 2023a: 288). It is impossible to reconstruct the specific "ethnic" identity of the craftspeople involved in the production of these "Egyptian" artifact forms. Similarly, all the Lower Nubian artifacts made of copper tend to be perceived as imports from Egypt (Roy 2011; R. Klemm, D. Klemm, and Murr 2019: 37). So far, we do not have sufficient information on the Nubian copper ore sources to distinguish local production, but some particular artifacts appear to be locally produced (Odler 2023a: 331). Semi-nomadic groups, similar to the A-Group or C-Group, appear to have produced metal artifacts, and metallurgy is not a craft solely practiced by sedentary populations (Anfinset 2010).

Without understanding the underlying technology of these artifacts, it is doubtful whether typology alone can provide sufficient evidence to integrate metal artifacts into current debates of a more theoretical nature, e.g., about their material agency or cultural involvements within society. Conversely, theoretical archaeology tends to remind us that categories employed in material science do not immediately reveal what actually "happened" to artifacts (e.g., the history of their whereabouts over time and the actions performed on them), nor the perceived identity/identities of the people who produced and used them (Matić 2020: 4–5). In order to understand the past, the integrated study of metal artifacts using the widest possible range of methods is necessary. Thus far, only a fraction of all known metal objects have been analyzed (fig.13).

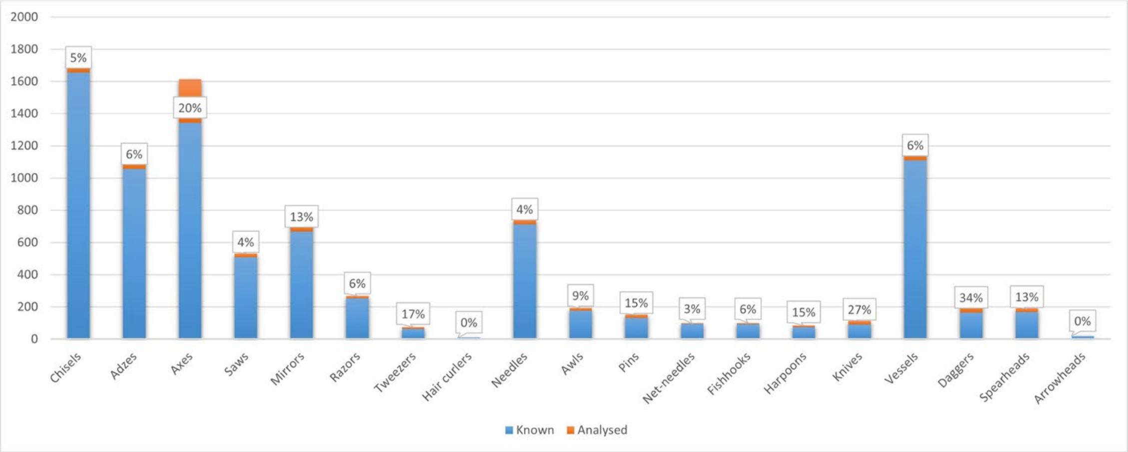

Figure 13. Number of known copper alloy artifacts and model metal artifacts from the Egyptian and Lower Nubian Chalcolithic Period and Early and Middle Bronze Age, with a percentage of the archaeometallurgically analyzed objects indicated.

Figure 14. Mirror of the Chief of the Southern Tens Reniseneb (Middle Kingdom, Dynasty 12–13), Asasif, Pit Tomb CC 25 (found on chest of mummy).

Figure 15. A weight in the shape of a bull's head (New Kingdom, Dynasty 18), provenance unknown. It weighs 181.41 grams, thus two New Kingdom copper deben

5.2 The value of copper (alloys)

In ancient Egypt metal objects were weighed and compared to weight standards. The weight of metal objects given in the written sources also represented their transactional value, that is, in transactions the price of an object equaled its weight (Janssen 1975). Exceptional in this regard were the uniquely produced objects of conspicuous display—such as, for example, luxury versions of weapons, vessels, and mirrors (fig. 14), comprising combinations of metals and materials—whose value was likely higher. But even New Kingdom tomb robbers focused on the weight of metal objects as a measure of the value of stolen goods (Peet 1930).

Metal objects were associated with weighing, for which the earliest evidence is provided by tomb paintings in the Dynasty 3 tomb of Hesyra at Saqqara (Quibell 1913). The earliest undoubted weighing stone is datable to Dynasty 2 and was found at Buto (von der Way 1997: 171–172, pl. 70: 9). Inscribed on the stone is the earliest known text with the hieroglyphic sign S21 of a *deben*-ring ◎; the unit of 29 grams is used, likely indicating a copper *deben* (Odler 2023a: 155–210). The existence of copper *deben*, with a value of c. 28 grams, has been identified for the Middle Kingdom (Vercoutter 1977). It would be a doubled weight of the "small," or "golden," deben of 13–15 grams (Cour-Marty 1997). Thus, it seems that for the earlier period of Egyptian history, this system of doubled "big" copper *deben* and "small" gold *deben* worked on the state level, although the discussion on the interpretation of Bronze Age Egyptian weighing stones is far from settled (Rahmstorf 2022: 373–397). In the New Kingdom, the fundamental unit of copper *deben* was tripled and weighed 90–95 grams (fig. 15), divided into smaller units of 10 *qedet* (kite) (Janssen 1975: 101–111; but see Graefe 1999).

The comparative value of different metals can be identified only rarely in written sources. Based on values mentioned in texts, a ratio of 1:100 can be averaged for the New Kingdom value of a silver unit to a copper unit (Černý 1954; see also Johnsen 2018). There is no earlier evidence that would enable us to compare the relative value of copper to either silver or gold. However, in the Second Intermediate Period Juridical Stela from Karnak, the debt of 60 gold deben consisted of "gold, copper, grain, and clothes"; thus the gold value unit included other items (Lacau 1949).

Due to their "costly" production and special materiality, metal objects were considered valuable goods. The literary work The Dialogue of Ipuwer and the Lord of All states that the ownership of a mirror was an attribute of higher social status: "she who glimpsed her face in the water is the owner of a mirror" (Enmarch 2008: 140). More broadly, the nomarchs and officials of the First Intermediate Period and early Middle Kingdom stressed copper as one of the important items of their personal property (Morenz 2010: 80; Odler 2023a: 186–190).

Papyrus CG 65739 contains the protocol of a lawsuit relating to slave trade (Gardiner 1935; Mrsich 1995). It is a significant and almost unique document, shedding light on the purchase and ownership of slaves in the New Kingdom. Moreover, it provides one of the few pieces of evidence of the ratio between the values of copper and silver, with the latter being used as the unit of value to set market prices. In this papyrus, a woman called Irytnefret states that she has legally purchased a Syrian slave in exchange for a series of goods that are carefully listed, together with their equivalent price in silver. These goods include pieces of clothing that belonged to her and were likely of her own making, or made at her workshop. The remaining goods, almost half of the slave's total value, include bronze or copper items that she claims to have purchased or obtained, perhaps as loans, from certain people who are named so as to verify the authenticity of the statement. The difficulty lies in deciding whether Irytnefret has purchased those copper or bronze goods prior to purchasing the slave, or whether it is a loan that has been arranged at the time of purchase. In this case, it is assumed that she incurs a debt with the people who, like the woman Tutuia, have provided her with the goods that allow her to purchase the slave (cf. Janssen 1994). But the conclusion can be made that metal objects could represent a significant part of real-world transactions. For a theoretical and practical exploration of the broader topic of value in the New Kingdom, cf. Cooney (2007).

One of the underlying arguments of Janssen's (1975) work is that we are able to study the transactions and abstract use of "values" only for New Kingdom Egypt.

Abstract thinking was for Janssen unimaginable in "the early stages of Egyptian culture" (Janssen 1975: 104). However, for a complex society to work and build large and complex structures, some common denominators and units must exist. The closer study of texts about copper and artifacts made of copper indicates the existence of "abstraction," units, and valuations for the early periods of Egyptian history, as argued by Odler (2023a). Without some common ground, also in the handling of copper, the complex societies of Bronze Age Egypt, and Nubia, would have been unable to accomplish what we are currently uncovering and studying.

Bibliographic Notes

For examples of the archaeological survey of mining sites and workshops near them, see: Abdel-Motelib et al. 2012; Abdel Tawab et al. 1990; Castel and Mathieu 1992; Castel and Pouit 1997; Castel et al. 1996; Castel et al. 1998; Harrell and Mohamed 2020; D. Klemm and R. Klemm 2008; R. Klemm and D. Klemm 2013; Rothenberg 1970; Rothenberg et al. 1998; Shaw et al. 2010; and Tratsaert 2012. On metalworking workshops with copper processing, see: Balat (Jeuthe 2012); Buhen (Davey 1985; Davey, Santarelli, and Rehren 2021; Emery and Kirwan 1935; Emery, Smith, and Millard 1979; O'Connor 2014); Edfu (Moeller and Marouard 2018; Martinet 2021); Elephantine (Kopp 2006: 33; Odler and Kmošek fc.; Kmošek et al. 2024); Elkab (Claes, Davey, and Hendrickx 2019; Davey and Hayes 2023); Giza (Lehner 2002: 38; Odler and Kmošek 2019, 2022; Saleh 1974); Kerma (Bonnet 2004; Rademakers et al. 2022; Rademakers, Verly, Cortebeeck, et al. 2023); Maadi (Rizkana and Seeher 1989: 13–18; Hauptmann 2017); Pi-Ramesse (Pusch 1990; Rademakers, Rehren, and Pernicka 2017; Rademakers, Rehren, and Pusch 2018); el-Amarna (Eccleston and Kemp 2008; Nicholson 2007; Rademakers fc.); Tell el-Dabaa (Philip 2006); Ain Soukhna (Abd el-Raziq et al. 2011; Verly 2024; Verly et al. 2021; and currently under study by Verly et al.); Dangeil (Rademakers, Mongiatti, and Anderson fc.); and Serabit el-Khadim and Wadi Maghara (e.g., Davey 1985). For examples of ingot finds, see: Abusir (Odler 2023a: 283, fig. 110; Odler and Kmošek 2021); Maadi (Rizkana and Seeher 1989: 13–18); Pi-Ramesse (Rademakers, Rehren, and Pernicka 2017: 56); and Tell el-Dabaa (Philip 2006). For examples of crucible finds, see: Amara West (under study by Rademakers and Auenmüller; for some preliminary information, see Rademakers, Auenmüller, Spencer, et al. 2023); Badari (Davey 1985); Balat (Jeuthe 2012); Berenike (Oller Guzmán 2020); Buhen (Davey 1985; Davey, Santarelli, and Rehren 2021; Emery and Kirwan 1935; Emery, Smith, and Millard 1979); Buto (Ballet and Mazou 2018; Téreygeol and Mazou 2019); Edfu (Moeller and Marouard 2018); Elephantine (Kopp 2006: 33, fig. 12; Odler and Kmošek fc.; Kmošek et al. 2024); Elkab (Claes, Davey, and Hendrickx 2019); el-Quleila (for gold: Hassan, van Wetering, and Tassie 2021); Giza (Odler and Kmošek 2019, 2022); Karnak (Durand 2015); Kerma (Bonnet 2004; Rademakers, Verly, Cortebeeck, et al. 2023); Marsa Matruh and Zawiyet Umm el-Rakham (Hulin 2009); Qau (Davey 1985); Thebes (Ptolemaic: Scheel 1988); Pi-Ramesse (Pusch 1990; Rademakers, Rehren, and Pernicka 2017; Rademakers, Rehren, and Pusch 2018); el-Amarna (Eccleston and Kemp 2008; Nicholson 2007; Rademakers fc.); Tell el-Dabaa (Philip 2006); Ain Soukhna (Abd el-Raziq et al. 2011; Marouard 2020; Verly 2024; and currently under study by Verly and Rademakers); Dangeil (Rademakers, Mongiatti, and Anderson fc.); and Serabit el-Khadim and Wadi Maghara (e.g., Davey 1985). For examples of casting mold finds, see: Aniba (Odler and Kmošek 2020: 80–86, figs. 89–97); Askut (Smith 1991: 115, fig. 7a); Buhen (Emery, Smith, and Millard 1979; O'Connor 2014); Kahun (Odler 2023a: 273, fig. 103); Tell el-Dabaa (Philip 2006); Serabit el-Khadim (Beit-Arieh 1985, 1987); and Qubbet el-Hawa (Auenmüller, Verly, and Rademakers 2019; Fitzenreiter et al. 2014; Fitzenreiter, Willer, and Auenmüller 2016; Verly et al. 2022). For copper artifacts, see the relevant works cited above in Section 5: *Copper Alloy Objects*.

References

Abdel-Motelib, Ali, Michael Bode, Rita Hartmann, Ulrich Hartung, Andreas Hauptmann, and Kristina Pfeiffer
2012 Archaeometallurgical expeditions to the Sinai Peninsula and the Eastern Desert of Egypt (2006, 2008). *Metalla* 19, pp. 3–59.

Abd el-Rahman, Y., A. A. Surour, A. H. W. El Manawi, M. Rifai, Ali Abdel Motelib, W. K. Ali, and A. M. El Dougdoug
2013 Ancient mining and smelting activities in the Wadi Abu Gerida area, central Eastern Desert, Egypt: Preliminary results. *Archaeometry* 55, pp. 1067–1087.

Abd el-Raziq, Mahmoud, Georges Castel, Pierre Tallet, and Philippe Fluzin
2011 *Ayn Soukhna II: Les ateliers métallurgiques du Moyen Empire*. Fouilles de l'Institut français d'archéologie orientale 66. Cairo: Institut Français d'Archéologie Orientale.

Abd el-Raziq, Mahmoud, Georges Castel, Pierre Tallet, and Victor Ghica
2002 *Les inscriptions d'Ayn Soukhna*. Photographs by Jean-François Gout. Mémoires publiés par les membres de l'Institut français d'archéologie orientale 122. Cairo: Institut Français d'Archéologie Orientale.

Abdel Tawab, M., Georges Castel, Georges Pouit, and Pascale Ballet
1990 Archéo-géologie des anciennes mines de cuivre et d'or des régions El-Urf/Mongul-Sud et Dara-Ouest. *Bulletin de l'Institut français d'archéologie orientale* 90, pp. 359–364.

Afia, M. S.
2006a *Mining in Egypt, past and present: Volume I*. Osra Library (in Arabic).
2006b *Mining in Egypt, past and present: Volume II*. Osra Library (in Arabic).
2006c *Mining in Egypt, past and present: Volume III*. Osra Library (in Arabic).

Afify, A. M., R. A. Osman, H. A. Wanas, and T. M. Khater
2022 Mineralogical and geochemical studies of copper mineralization in the Paleozoic sedimentary section in southwestern Sinai, Egypt. *Ore Geology Reviews* 147: No. 104994.

Agresti, Juri, Iacopo Osticioli, Maria Cristina Guidotti, Nikolay Kardjilov, and Salvatore Siano
2016 Non-invasive archaeometallurgical approach to the investigations of bronze figurines using neutron, laser, and X-ray techniques. *Microchemical Journal* 124, pp. 765–774.

Allen, Susan
2006 Miniature and model vessels in ancient Egypt. In *The Old Kingdom Art and Archaeology*, ed. Miroslav Bárta, pp. 19–24. Prague: Czech Institute of Egyptology, Faculty of Arts, Charles University.

Almansa-Villatoro, M. Victoria
2019 The cultural indexicality of the N41 sign for ***bjꜣ***: The metal of the sky and the sky of metal. *The Journal of Egyptian Archaeology* 105(1), pp. 73–81.

Altenmüller, Hartwig
2015 *Zwei Annalenfragmente aus dem frühen Mittleren Reich*. Studien zur altägyptischen Kultur Beihefte 16. Hamburg: Buske.

Alù, Cristina
2022 Some remarks on the *sḫ.tjw* and their overseers: The multiple meanings of *sḫ.t* and the social identity of the marsh-dwellers. In *The world of Middle Kingdom III: Contributions on archaeology, art, religion, and written sources*, ed. Wolfram Grajetzki and Gianluca Miniaci, pp. 1–7. London: Golden House.

Andrássy, Petra
2009 Symbols in the Reisner Papyri. In *Non-textual marking systems, writing and pseudo script from prehistory to modern times*, Lingua Aegyptia, Studia – Monographica 8, ed. Petra Andrássy, Julia Budka, and Frank Kammerzell, pp. 113–122. Göttingen: Widmaier.

Anfinset, Nils
2010 *Metal, nomads and culture contact: The Middle East and North Africa*. Approaches to Anthropological Archaeology. Oakville, CT: Equinox.

Arias Kytnarová, Katarína, Lucie Jirásková, and Martin Odler
2018 Old Kingdom model and miniature vessels from Giza. In *Proceedings of the 5th International Congress for Young Egyptologists, Vienna, September 2015*, Contributions to the Archaeology of Egypt, Nubia and the Levant 6, ed. Andrea Kahlbacher and Elisa Priglinger, pp. 15–29. Vienna: Austrian Academy of Sciences.

Arnold, Dieter

1991 *Building in Egypt: Pharaonic stone masonry*. Oxford: Oxford University Press.

Auenmüller, Johannes

fc. a In great demand: The production and deposition of bronze Osiris figures in 1st millennium BCE Egypt and beyond. In *Crafting for the god(s): Dynamics of cult, craft production, and socio-technological identities*, Orientalische Religionen in der Antike, ed. Vanessa Workman, Laura Gonnermann, and Shira Albaz. Tübingen: Mohr Siebeck.

fc. b Gussmodelle und Gussformen: Technologien zwischen Einmaligkeit und (Re)Produktion. In *KunstModell: Modelle im Alten Ägypten*, ed. Heike Wilde et al. Berlin: Kadmos.

Auenmüller, Johannes, Georges Verly, and Frederik W. Rademakers

2019 Bronze casting artefacts from Qubbet el-Hawa: Moulds, materials, and experimental methods. In *Studies in experimental archaeometallurgy: Methodological reflections from non-ferrous metallurgies*, ed. Georges Verly, Frederik W. Rademakers, and Florian Téreygeol, pp. 141–163. Dremil-Lafage: Éditions Mergoil.

Bachmann, Hans-Gert

1980 Early copper smelting techniques in Sinai and Negev as deduced from slag investigations. In *Scientific studies in early mining and extractive metallurgy*, ed. Paul T. Craddock, pp. 103–134. London: British Museum.

1982 *The identification of slags from archaeological sites*. London: Institute of Archaeology.

Bader, Bettina

2015 Disc-shaped ornaments of the early Middle Kingdom. *Bulletin of the Egyptological Seminar* 19, pp. 117–130.

Ballet, Pascale, and Loïc Mazou

2018 Buto II: The Late period. *Egyptian Archaeology* 53, pp. 33–36.

Barbotin, Christophe, ed.

2005 *La voix des hiéroglyphes: Promenade au Département des antiquités égyptiennes du Musée du Louvre*. Paris: Institut Khéops.

Bárta, Miroslav

1999 The title "Property Custodian of the King" during Old Kingdom Egypt. *Zeitschrift für Ägyptische Sprache und Altertumskunde* 126(2), pp. 79–89.

Bayley, Justine, David Dungworth, and Sarah Paynter

2001 *Centre for Archaeology guidelines: Archaeometallurgy*. Swindon: English Heritage Publications.

Beit-Arieh, Itzhaq

1982 New discoveries at Serâbît el-Khâdîm. *The Biblical Archaeologist* 45(1), pp. 13–18.

1985 *Serâbît El-Khâdim: New metallurgical and chronological aspects*. Levant 17(1), pp. 89–116.

1987 Canaanites and Egyptians at Serabit el-Khadim. In *Egypt, Israel, Sinai: Archaeological and historical relationships in the Biblical period*, ed. Anson F. Rainey, pp. 57–67. Tel Aviv: Tel Aviv University.

2003 *Archaeology of Sinai: The Ophir Expedition*. Sonia and Marco Nadler Institute of Archaeology Series Monograph 21. Tel Aviv: Emery and Claire Yass Publications in Archaeology.

Bénédite, Georges

1907 *Catalogue général des antiquités égyptiennes du Musée du Caire: Nos. 44001–44102: Miroirs.* Cairo: Institut Français d'Archéologie Orientale.

Ben-Yosef, Erez

2018 The Central Timna Valley Project: Research design and preliminary results. In *Mining for copper: Essays in memory of Professor Beno Rothenberg*, ed. Erez Ben-Yosef, pp. 28–63. Tel Aviv: Tel Aviv University.

Biga, Maria Giovanna, and Piotr Steinkeller

2021 In search of Dugurasu. *Journal of Cuneiform Studies* 73, pp. 9–70.

Boatright, Daniel

2010 Battlefield remains? The interpretation of weaponry in Bronze Age Egypt and the Levant. *Archaeological Review from Cambridge* 25, pp. 99–121.

Bonnet, Charles

2004 *Le temple principal de la ville de Kerma et son quartier religieux*. Paris: Éditions Errance.

Brady, Barry H. G., and Edwin T. Brown

2004 *Rock mechanics for underground mining*. Amsterdam: Kluwer Academic Publishers.

Brunton, Guy
1927 *Qau and Badari I*. British School of Archaeology in Egypt and Egyptian Research Account, Twenty-Ninth Year. London: Bernard Quaritch.
1937 *Mostagedda and the Tasian Culture: British Museum Expedition to Middle Egypt, First and Second Years.* London: Bernard Quaritch.
1948 *Matmar: British Museum Expedition to Middle Egypt 1929 – 1931*. London: Bernard Quaritch.
Brunton, Guy, and Gertrude Caton-Thompson
1928 *The Badarian civilisation and Predynastic remains near Badari*. Publications of the British School of Archaeology in Egypt and Egyptian Research Account: 30th Year. London: Bernard Quaritch.
Castel, Georges, Eva Christiana Köhler, Bernard Mathieu, and Georges Pouit
1998 Les mines du ouadi Um Balad (désert Oriental). *Bulletin de l'Institut français d'archéologie orientale* 98, pp. 57–87.
Castel, Georges, and Bernard Mathieu
1992 Les mines de cuivre du Ouadi Dara: Rapport préliminaire sur les travaux de la saison 1991. *Bulletin de l'Institut français d'archéologie orientale* 92, pp. 51–65.
Castel, Georges, Bernard Mathieu, G. Pouit, M. El Hawari, G. Shaaban, H. Hellal, T. Abdallah, and A. Ossama
1996 Wadi Dara copper mines. In *Proceedings of the First International Conference on Ancient Egyptian Mining and Metallurgy and Conservation of Metallic Artifacts*, ed. F. A. Esmael, pp. 15–31. Cairo: Ministry of Culture.
Castel, Georges, and Georges Pouit
1997 Anciennes mines métalliques dans la partie Nord du désert oriental d'Égypte. *Archéo-Nil* 7, pp. 101–112.
Castel, Georges, and Georges Soukiassian
1989 *Gebel el-Zeit I: Les mines de galène (Égypte - II^e^ millénaire av. J.-C.)*. Fouilles de l'Institut français d'archéologie orientale 35. Cairo: Institut Français d'Archéologie Orientale.
Cech, Brigitte, Thilo Rehren, and Abdelrahman Ali Mohamed
2018 *The quarries of Meroe, Sudan*. Doha, Qatar: Hamad bin Khalifa University Press.
Černý, Jaroslav
1954 Prices and wages in Egypt in the Ramesside Period. *Journal of World History* 1(4), pp. 903–921.
Champollion, Jean-François
1841 *Dictionnaire égyptien en écriture hiéroglyphique*. Paris: Firmin Didot Frères.
Cherf, William J.
1982 The function of the Egyptian forked staff and the forked bronze butt: A proposal. *Zeitschrift für Ägyptische Sprache und Altertumskunde* 109, pp. 86–97.
Claes, Wouter, Christopher J. Davey, and Stan Hendrickx
2019 An Early Dynastic crucible from the settlement of Elkab (Upper Egypt). *The Journal of Egyptian Archaeology* 105(1), pp. 29–42.
Cooney, Kathlyn M.
2007 *The cost of death: The social and economic value of ancient Egyptian funerary art in the Ramesside Period.* Egyptologische Uitgaven 22. Leiden: Peeters.
Cooper, Julien Charles
2020 *Toponymy on the periphery: Placenames of the Eastern Desert, Red Sea, and South Sinai in Egyptian documents from the Early Dynastic until the end of the New Kingdom*. Probleme der Ägyptologie 39. Leiden and Boston: Brill.
Cour-Marty, Marguerite Annie
1997 Les poids inscrits de l'Ancien Empire. In *Études sur l'Ancien Empire et la nécropole de Saqqâra dédiées à Jean-Philippe Lauer*, Orientalia Monspeliensia 9/1, ed. Catherine Berger and Bernard Mathieu, pp. 129–145. Montpellier: Université Paul Valéry-Montpellier III.
Couton-Perche, Nathalie (ed.)
2021 *Les armes de l'Égypte ancienne: La collection du musée du Louvre*. Paris: Éditions Khéops.
Couton-Perche, Nathalie, and David Bourgarit
2021 Métal. In *Les armes de l'Égypte ancienne: La collection du musée du Louvre*, ed. Nathalie Couton-Perche, pp. 259–267. Paris: Éditions Khéops.
Cowell, Michael R.
1987 Scientific appendix I: Chemical analysis. In *Catalogue of Egyptian antiquities in the British Museum VII: Axes*, ed. Vivian Davies, pp. 96–118. London: British Museum Press.

Craddock, Paul T.
2010 *Early metal mining and production*. London: Archetype Publications.
2014a Refractories: Ceramics with a purpose. *The Old Potter's Almanack* 18(2), pp. 9–20.
2014b Refractories with a purpose II: Ceramics for casting. *The Old Potter's Almanack* 19(1), pp. 2–17.
Cressent, Mélanie, and Aymeric Raimon
2016 Inscriptions in the name of Governor Neby revealed by the restoration of miniature metal vases. *Sudan & Nubia* 20, pp. 28–34.
Czarnowicz, Marcin
2012 Copper tools. In *Tell el-Farkha I: Excavations 1998 – 2011*, ed. Marek Chłodnicki, Krzysztof Ciałowicz, and Agnieszka Mączyńska, pp. 345–355. Poznań: Archaeological Museum; Krakow: Institute of Archaeology, Jagiellonian University.
2018 Examples of copper harpoons of Naqada culture in the eastern Nile Delta area. In *Mining for copper: Essays in memory of Professor Beno Rothenberg*, ed. Erez Ben-Yosef, pp. 527–538. Tel Aviv: Tel Aviv University.
2021 *Copper in early Egypt*. Krakow: Profil-Archeo Publishing House.
Davey, Christopher J.
1985 Crucibles in the Petrie Collection and hieroglyphic ideograms for metal. *The Journal of Egyptian Archaeology* 71, pp. 142–148.
2001- The excavation technology used in the cow catacombs of the Sacred Animal Necropolis, North Saqqara, Egypt. *Buried History* 37-38 (2001 – 2002), pp. 15–24.
2012 Old Kingdom metallurgy in Memphite tomb images. In *Ancient Memphis: "Enduring is the perfection": Proceedings of the international conference held at Macquarie University, Sydney, on August 14 – 15, 2008*, Orientalia Lovaniensia Analecta 214, ed. Linda Evans, pp. 85–108. Leuven: Peeters.
2021 Ancient pot-bellows: A review forty years on. *Bulletin of the American Schools of Oriental Research* 385, pp. 201–218.
Davey, Christopher J., and Peter Hayes
2023 Out of the fiery crucible: Egyptian Old Kingdom metallurgy. *Buried History: The Journal of the Australian Institute of Archaeology* 59, pp. 11–28.
Davey, Christopher J., Brunella Santarelli, and Thilo Rehren
2021 Egyptian Middle Kingdom copper: Analysis of a crucible from Buhen in the Petrie Museum. *Journal of Archaeological Science: Reports* 36: No. 102859.
Davies, Benedict G.
1993 O. Berlin P. 11239 and the coppersmiths at Deir el-Medina. *Göttinger Miszellen* 137, pp. 39–47.
Davies, Norman de Garis
1935 *Paintings from the tomb of Rekh-mi-Rēʻ at Thebes*. Metropolitan Museum of Art Egyptian Expedition, Vol. 10. New York: Plantin Press.
Davies, W. Vivian
1987 *Catalogue of Egyptian antiquities in the British Museum 7: Tools and weapons 1: Axes*. London: British Museum Publications.
Debono, Fernand
1951 Expédition archéologique royale au désert oriental (Keft-Kosseir): Rapport préliminaire sur la campagne 1949. *Annales du Service des Antiquités de l'Égypte* 51, pp. 59–91.
Derriks, Claire
2001 *Les miroirs cariatides Égyptiens en bronze: Typologie, chronologie et symbolique*. Münchner Ägyptologische Studien 51. Mainz: Philipp von Zabern.
Devaux, Judith
1999 Nature du métal employé pour les outils des sculpteurs égyptiens. *Revue d'Égyptologie* 50, pp. 275–277
2000 Définition de quelques caractéristiques techniques de la statuaire de pierre dure en Égypte ancienne. *Revue d'Égyptologie* 51, pp. 39–53.
Díaz Hernández, Roberto A.
2014 *Der Ramesseumspapyrus E: Ein Ritualbuch für Bestattungen aus dem Mittleren Reich*. Göttinger Miszellen, Beihefte 15. Göttingen: Seminar für Ägyptologie und Koptologie.
Diego Espinel, Andrés
2014 Surveyors, guides and other officials in the Egyptian and Nubian deserts: Epigraphic and historical remarks on some Old Kingdom graffiti. *Revue d'Égyptologie* 65, pp. 29–48.

Dolfini, Andrea

2014 Early metallurgy in the central Mediterranean. In *Archaeometallurgy in global perspective*, ed. Benjamin W. Roberts and Christopher P. Thornton, pp. 473–506. New York: Springer.

Dolfini, Andrea, and Rachel J. Crellin

2016 Metalwork wear analysis: The loss of innocence. *Journal of Archaeological Science* 66, pp. 78–87.

Drenkhahn, Rosemarie

1976 *Die Handwerker und ihre Tätigkeiten im alten Ägypten*. Ägyptologische Abhandlungen 31. Wiesbaden: Harrassowitz.

Durand, Benjamin

2015 Un four métallurgique d'époque ptolémaïque dans les annexes du temple de Ptah à Karnak. *Cahiers de Karnak* 15, pp. 181–188.

Eaton, E. R., and Hugh McKerrell

1976 Near eastern alloying and some textual evidence for the early use of arsenical copper. *World Archaeology* 8, pp. 169–191.

Eccleston, Mark A. J.

2008 Metalworking at Amarna: A preliminary report. *Bulletin of the Australian Centre for Egyptology* 19, pp. 29–48.

Eccleston, Mark A. J., and Barry J. Kemp

2008 Metalworking and crucibles. In *Busy lives at Amarna: Excavations at Grid 12 in the Main City*, ed. B. J. Kemp and A. K. Stevens, pp. 419–453. London: Egypt Exploration Society.

Eckmann, Christian, and Saherr Shafik

2005 *"Leben dem Horus Pepi": Restaurierung und technologische Untersuchung der Metallskulpturen des Pharao Pepi I. aus Hierakonpolis*. Römisch-Germanisches Zentralmuseum Monographien 59. Mainz: Habelt.

Eichler, Eckhard

1993 *Untersuchungen zum Expeditionswesen des ägyptischen Alten Reiches*. Göttinger Orientforschungen 4.26. Wiesbaden: Harrassowitz.

El Gayar, El Sayed, and M. P. Jones

1989a A possible source of copper ore fragments found at the Old Kingdom town of Buhen. *Journal of Egyptian Archaeology* 75, pp. 31–40.

1989b Old Kingdom copper smelting artifacts from Buhen in Upper Egypt. *Historical Metallurgy* 23, pp. 16–24.

Emery, Walter Bryan

1949 *Great tombs of the First Dynasty I*. Cairo: Government Press.

Emery, Walter Bryan, and Lawrence P. Kirwan

1935 The excavations and survey between Wadi Es-Sebua and Adindan, 1929 – 1931. Cairo: Government Press.

Emery, Walter Bryan, Harry S. Smith, and A. Millard

1979 *The fortress of Buhen: The archaeological report*. Egypt Exploration Society Excavation Memoir 49. London: Egypt Exploration Society.

Enmarch, Roland

2008 *A world upturned: Commentary on and analysis of The Dialogue of Ipuwer and the Lord of All*. A British Academy Postdoctoral Fellowship Monograph. Oxford: Oxford University Press.

Festa, Giulia, Triestino Minniti, Laura Arcidiacono, Matilde Borla, Daniela Di Martino, Federica Facchetti, Enrico Ferraris, Valentina Turina, Winfried Kockelmann, Joe Kelleher, Roberto Senesi, Christian Greco, and Carla Andreani

2018 Egyptian grave goods of Kha and Merit studied by neutron and gamma techniques. *Angewandte Chemie International Edition* 57, No. 7375.

Fischer-Elfert, Hans-Werner

1998 *Die Vision von der Statue im Stein: Studien zum altägyptischen Mundöffnungsritual*. Schriften der Philosophisch-Historischen Klasse der Heidelberger Akademie der Wissenschaften 5. Heidelberg: Universitätsverlag C. Winter.

Fitzenreiter, Martin

2018 *Allerhand Kleinigkeiten*. Internet-Beiträge zur Ägyptologie und Sudanarchäologie 20. London: Golden House.

2019 Schon wieder Stele Louvre C 14 des Irtisen. *Göttinger Miszellen* 257, pp. 49-61.

Fitzenreiter, Martin, Christian E. Loeben, Dietrich Raue, and Uta Wallenstein (eds.)

2014 *Gegossene Götter: Metallhandwerk und Massenproduktion im alten Ägypten*. Rahden/Westfalen: Verlag Marie Leidorf.

Fitzenreiter, Martin, Frank Willer, and Johannes Auenmüller

2016 *Materialien einer Gusswerkstatt von der Qubbet el-Hawa*. Bonner Aegyptiaca. Berlin: EB Verlag.

Frankfort, Henri, and John D. S. Pendlebury

1933 *The city of Akhenaten, Part II: The North Suburb and the Desert Altars: The excavations at Tell El Amarna during the seasons 1926 – 1932*. Excavation Memoir 40. London: Egypt Exploration Society.

Freestone, Ian C., and Mike S. Tite

1986 Refractories in the ancient and preindustrial world. In *High-technology ceramics: Past, present, and future: The nature of innovation and change in ceramic technology*, ed. W. D. Kingery and E. Lense, pp. 35–63. Westerville, OH: American Ceramic Society.

Freier, Elke

1976 Zu den sogenannten Hohenpriestern des Ptah von Memphis im Alten Reich. *Altorientalische Forschungen* 4, pp. 5–34.

Gaballa, Gaballa A., and Kenneth A. Kitchen

1969 The festival of Sokar. *Orientalia* 38, pp. 1–76.

Gabler, Kathrin

2018 *Who's who around Deir El-Medina: Untersuchungen zur Organisation, Prosopographie und Entwicklung des Versorgungspersonals für die Arbeitersiedlung und das Tal der Könige*. Egyptologische Uitgaven 31. Leiden: Peeters.

Gardiner, Alan Henderson

1917 The tomb of a much-travelled Theban official. *The Journal of Egyptian Archaeology* 4(1), pp. 28–38.

1935 A lawsuit arising from the purchase of two slaves. *The Journal of Egyptian Archaeology* 21(2), pp. 140–146.

1969 *Egyptian grammar: Being an introduction to the study of hieroglyphs*. Third edition. Oxford: Oxford University Press.

Garenne-Marot, Laurence

1984 Le cuivre en Égypte pharaonique: Sources et métallurgie. *Paléorient* 10(1), pp. 97–126.

1985 Le travail du cuivre dans l'Égypte pharaonique d'après les peintures et les bas-reliefs. *Paléorient* 11(1), pp. 85–100.

Garland, Herbert, and Charles Olden Bannister

1927 *Ancient Egyptian metallurgy*. London: Charles Griffin & Co.

Garstang, John

1903 *Mahasna and Bet Khallaf*. British School of Archaeology in Egypt and Egyptian Research Account, 7th year. London: Bernard Quaritch.

Gaude Fugarolas, Daniel, and Martin Odler

2023 Whose tools are these? An artificial neural network applied to the classification of the Old Kingdom Egyptian chisels. *Asian and African Studies* 32(2), pp. 137–162.

Gauthier-Laurent, Madeleine

1951 Couronnes d'orfèvrerie à bandeau de soutien de l'Ancien Empire. *Revue d'Égyptologie* 8, pp. 79–90.

Gershuny, Lilly

1985 *Bronze vessels from Israel and Jordan*. Prähistorische Bronzefunde, Abteilung II, Bd. 7. Munich: C. H. Beck.

Giumlia-Mair, Alessandra, and Stephen Quirke

1997 Black copper in Bronze Age Egypt. *Revue d'Égyptologie* 48, pp. 95–108.

Goedicke, Hans

2000 An ancient naval finial of the Middle Kingdom. *Ägypten und Levante* 10, pp. 77–81.

Goyon, Jean Claude

2004 *La construction pharaonique du moyen empire à l'époque gréco-romaine: Contexte et principes technologiques*. Paris: Picard.

Graefe, Erhart

1971 *Untersuchungen zur Wortfamilie* **bjꜣ-**. Ph.D. dissertation: Köln: Philosophische Fakultät der Universität zu Köln.

1999 Über die Goldmenge des Alten Ägypten und die Beraubung der thebanischen Königsgräber. *Zeitschrift für ägyptische Sprache und Altertumskunde* 126, pp. 19–40.

Graindorge-Héreil, Catherine

1994 *Le dieu Sokar à Thèbes au Nouvel Empire*. Göttinger Orientforschungen 28. Wiesbaden: Harrassowitz.

Green, Christine Insley

1987 *The temple furniture from the sacred animal necropolis at North Saqqâra, 1964 – 1976*. Excavation Memoir 53. London: Egypt Exploration Society.

Gsell, Martin

1910 *Eisen, Kupfer und Bronze bei den alten Ägyptern: Archäologisch-metallurgische Abhandlung*. Karlsruhe: G. Braun.

Guerra, Maria Filomena, Marcos Martinón-Torres, and Stephen Quirke (eds.)

2023 *Ancient Egyptian gold: Archaeology and science in jewellery (3500 – 1000 BC)*. Cambridge: McDonald Institute for Archaeological Research.

Gutgesell, Manfred

1984 Ostrakon Göttingen AE 15. *Zeitschrift für ägyptische Sprache und Altertumskunde* 111, pp. 3–6.

Hampson, Michelle

2022 *"Make it according to plan": Workshop scenes in Egyptian tombs of the Old Kingdom*. BAR International Series 3083. Oxford: BAR Publishing.

Harrell, James A., and Abdelrahman A. Mohamed

2020 Exploitation of geological resources: Ancient mines and quarries in Nubia. In *The Oxford handbook of ancient Nubia*, ed. G. Emberling and B. B. Williams, pp. 955–974. Oxford: Oxford University Press.

Harrell, James A., and Per Storemyr

2009 Ancient Egyptian quarries: An illustrated overview. In *QuarryScapes: Ancient stone quarry landscapes in the Eastern Mediterranean*, ed. N. Abu-Jaber, E. G. Bloxam, P. Degryse, and T. Heldal, pp. 7–50. Oslo: Geological Survey of Norway.

Harris, John R.

1961 *Lexicographical studies in ancient Egyptian minerals*. Berlin: Akademie-Verlag.

Hassan, Fekri A., Joris van Wetering, and Geoffrey J. Tassie

2021 Late Protodynastic – Early Dynastic cemetery at el-Quleila North (Kh.2B), Naqada region, Upper Egypt. In *Egypt at its origins 6: Proceedings of the Sixth International Conference "Origin of the State: Predynastic and Early Dynastic Egypt," Vienna (Austria), 10th – 15th September 2017*, Orientalia Lovaniensia Analecta 303, ed. E. C. Köhler, F. Junge, N. Kuch, and A. -K. Jeske, pp. 253–274. Leuven: Peeters.

Hassan, Selim

1938 Excavations at Saqqara. *Annales du Service des Antiquités de l'Égypte* 38, pp. 503–521.

Hauptmann, Andreas

2007 *The archaeometallurgy of copper: Evidence from Faynan, Jordan*. New York: Springer.

2017 Copper and ores from elsewhere and the question of metallurgy at Maadi. In *Predynastic Maadi in context: The research of the Italian expedition revisited (1977 – 1986)*, Studi di preistoria orientale 4, ed. Jade Bajeot, pp. 145–155. Rome: Dipartimento di Scienze dell'Antichità, Sapienza Università di Roma.

2020 *Archaeometallurgy: Materials science aspects*. New York: Springer.

Helck, Wolfgang

1970 *Die Lehre des* **Dwꜣ-Ḫtjj**: *Teil 1*. Kleine ägyptische Texte 3. Wiesbaden: Harrassowitz.

Herold, Anja

1998 Gegossen - Geschmiedet – Tordiert: Zur Herstellung von bronzenen Trensen in der Ramses-Stadt Piramesse/Ägypten. *Metalla* 5(1), pp. 3–21.

1999 *Streitwagentechnologie in der Ramses-Stadt: Bronze an Pferd und Wagen*. Forschungen in der Ramses-Stadt 2. Mainz: Philipp von Zabern.

Herslund, Ole

2015 On the pictorial meaning of the drop-shaped hieroglyph for "copper" from the Archaic Period to the Middle Kingdom. In *Lotus and laurel: Studies on Egyptian language and religion in honour of Paul John Frandsen*, CNI Publications 39, ed. Rune Nyord and Kim Ryholt, pp. 103–120. Copenhagen: Museum Tusculanum Press.

Hikade, Thomas

2001 *Das Expeditionswesen im ägyptischen Neuen Reich: Ein Beitrag zu Rohstoffversorgung und Außenhandel*. Studien zur Archäologie und Geschichte Altägyptens 21. Heidelberg: Heidelberger Orientverlag.

Hill, Marsha

2004 *Royal bronze statuary from ancient Egypt: With special attention to the kneeling pose*. Egyptological Memoirs 3. Leiden: Brill.

Hill, Marsha, and Deborah Schorsch (eds.)
2007 *Gifts for the gods: Images from Egyptian temples*. New York: Metropolitan Museum of Art.
Hodgkinson, Anna K.
2018 *Technology and urbanism in Late Bronze Age Egypt*. Oxford Studies in Egyptian Archaeology. Oxford: Oxford University Press.
Hofmann, Inge
1967 *Die Kulturen des Niltals von Assuan bis Sennar vom Mesolithikum bis zum Ende der christlichen Epoche*. Monographien zur Völkerkunde 4. Hamburg: De Gruyter & Co.
Hölzl, Regina, Michael Neumann, and Robert J. Demarée
2018 *The notebook of Dhutmose: P. Vienna ÄS 10321*. Probleme der Ägyptologie 37. Leiden: Brill.
Hulin, Linda
2009 Pragmatic technology and the Libyan Bronze Age. *Journal of Ancient Egyptian Interconnections* 1, pp. 18–21.
Huret, Thierry
1990 Les pointes de flèches métalliques en Égypte ancienne: Essai de typologie. *Cahiers de recherches de l'Institut de papyrologie et d'Égyptologie de Lille* 12, pp. 57-66.
Hussein, Abdel Aziz A., and M. A. el Sharkawi
1990 Mineral deposits. In *The geology of Egypt*, ed. R. Said, pp. 511–566. Rotterdam: Balkema.
Jäger, Stephan
2004 *Altägyptische Berufstypologien*. Lingua Aegyptia – Studia Monographica 4. Göttingen: Widmaier.
Jaksch, Heiner, Wilfried Seipel, Karl Ludwig Weiner, and Ahmed el Goresy
1983 Egyptian blue – cuprorivaite: A window to ancient Egyptian technology. *Naturwissenschaften* 70, pp. 525–535.
Janssen, Jac. J.
1975 *Commodity prices from the Ramesside Period: An economic study of the village of necropolis workmen at Thebes*. Leiden: Brill.
1994 Debts and credit in the New Kingdom. *Journal of Egyptian Archaeology* 80, pp. 129–136.
Jeuthe, Clara
2012 *Balat X: Ein Werkstattkomplex im Palast der 1. Zwischenzeit in Ayn Asil*. Cairo: Institut Français d'Archéologie Orientale.
Johnsen, Daniel
2018 *The relative value and role of copper within an Egyptian New Kingdom economic context, using production, trade, and use of copper as indicators of copper's value*. MA thesis. Cairo: American University in Cairo.
Kahl, Jochem, Nicole Kloth, and Ursula Zimmermann
1995 *Die Inschriften der 3. Dynastie: Eine Bestandsaufnahme*. Ägyptologische Abhandlungen 56. Wiesbaden: Harrassowitz.
Karev, Ella
2022 "Mark them with my mark": Human branding in Egypt. *The Journal of Egyptian Archaeology* 108, pp. 191–203.
Kelany, Adel
2015 Fire-setting in ancient quarries: Ancient sources, new evidence and experiments. In *From the Delta to the cataract: Studies dedicated to Mohamed el-Bialy*, ed. A. Jiménez-Serrano and C. von Pilgrim, pp. 88–97. Leiden: Brill.
Klemm, Dietrich D., and Rosemarie Klemm
2008 Mining in ancient Egypt and Nubia. In *Encyclopaedia of the history of science, technology, and medicine in non-western cultures*, ed. H. Selin, pp. 1685–1698. Berlin: Springer.
Klemm, Rosemarie
1998 Neue Expeditionsinschriften aus der Ostwüste Oberägyptens. Teil 1: Geländekundliche Analyse der Inschriftenvorkommen in Wadi Dungash und Wadi Umm Hode. *Mitteilungen des Deutschen Archäologischen Instituts, Abteilung Kairo* 54, pp. 237–249.
Klemm, Rosemarie, and Dietrich D. Klemm
2008 *Stones and quarries in ancient Egypt*. London: British Museum Press.
2013 *Gold and gold mining in ancient Egypt and Nubia: Geoarchaeology of the ancient gold mining sites in the Egyptian and Sudanese eastern deserts*. Berlin: Springer.

Klemm, Rosemarie, Dietrich D. Klemm, and Andreas Murr
2019 Geologically induced raw materials stimulating the development of Nubian culture. In *Handbook of ancient Nubia*, ed. Dietrich Raue, pp. 15–38. Berlin: De Gruyter.
Kmošek, Jiři, Martin Odler, Marek Fikrle, and Yulia V. Kochergina
2018 Invisible connections: Early Dynastic and Old Kingdom Egyptian metalwork in the Egyptian Museum of Leipzig University. *Journal of Archaeological Science* 96, pp. 191–207.
Kmošek, Jiři, Martin Odler, Peter Kopp, and Johanna Sigl
2024 "Production of arsenical bronze using speiss on the Elephantine Island (Aswan, Egypt) during the Middle Kingdom (Middle Bronze Age)." Poster presented at the 6th International Conference "Archaeometallurgy in Europe," Falun (Sweden), 11th – 14th June 2024.
Kopp, Peter
2006 *Elephantine XXXII: Die Siedlung der Naqadazeit*. Archäologische Veröffentlichungen des Deutschen Archäologischen Instituts, Abteilung Kairo 118. Mainz: Philipp von Zabern.
Kromer, Karl
1978 *Siedlungsfunde aus dem frühen Alten Reich in Giseh: Österreichische Ausgrabungen 1971 – 1975*. Denkschriften/Österreichische Akademie der Wissenschaften, Philosophisch-Historische Klasse 136. Vienna: Verlag der Österreichischen Akademie der Wissenschaften.
Kühnert-Eggebrecht, Eva
1969 *Die Axt als Waffe und Werkzeug im alten Ägypten*. Münchner Ägyptologische Studien 15. Berlin: Hessling.
Lacau, Pierre
1949 *Une stèle juridique de Karnak*. Supplément aux Annales du Service des Antiquités de l'Égypte 13. Cairo: Imprimerie de l'Institut Français d'Archéologie Orientale.
Lalouette, Claire
1979 Le "firmament de cuivre": Contribution à l'étude du mot *bi͗ꜣ*. *Bulletin de l'Institut français d'archéologie orientale* 79, pp. 333–353.
Lang, Janet R. S.
1987 Scientific appendix II: Metallurgical examination. In *Catalogue of Egyptian antiquities in the British Museum VII: Axes*, ed. W. V. Davies, pp. 96–118. London: British Museum Press.
Lehner, Mark
2002 The Pyramid Age settlement of the Southern Mount at Giza. *Journal of the American Research Center in Egypt* 39, pp. 27–74.
Lepsius, Carl Richard
1872 *Die Metalle in den Aegyptischen Inschriften*. Abhandlungen der Königlichen Akademie der Wissenschaften zu Berlin 1871. Berlin: Königliche Akademie der Wissenschaften.
Levy, Thomas Evan, Erez Ben-Yosef, and Mohammad Najjar
2018 Intensive surveys, large-scale excavation strategies and Iron Age industrial metallurgy in Faynan, Jordan: Fairy tales don't come true. In *Mining for copper: Essays in memory of Professor Beno Rothenberg*, ed. Erez Ben-Yosef, pp. 244–258. Tel Aviv: Tel Aviv University.
Lilyquist, Christine
1979 *Ancient Egyptian mirrors: From the earliest times through the Middle Kingdom*. Münchner Ägyptologische Studien 27. Munich: Deutscher Kunstverlag.
1999 The objects mentioned in the texts. In *Royal gifts in the Late Bronze Age, fourteenth to thirteenth centuries BCE: Selected texts recording gifts to royal personages*. Transcriptions and translations by Zipora Cochavi-Rainey. Beer-Sheva Studies by the Department of the Bible and Ancient Near East 13, ed. Schmuel Ahituv, pp. 211–218. Beer-Sheva: Ben-Gurion University of the Negev Press.
Linacre College, Oxford
2006 *Oxford expedition to Egypt: Scene-details database*: https://doi.org/10.5284/1000009.
Littauer, M. A., and J. H. Crouwel
1985 *Chariots and related equipment from the tomb of Tutʿankhamūn*. Tut'ankhamūn's Tomb Series 8. Oxford: Griffith Institute.
Lorton, David
1999 The theology of cult statues in ancient Egypt. In *Born in heaven, made on earth: The making of the cult image in the ancient Near East*, ed. Michael B. Dick, pp. 123–210. Winona Lake: Eisenbrauns.
Lucas, Alfred
1926 *Ancient Egyptian materials and industries*. First edition. London: Edward Arnold.

1962 *Ancient Egyptian materials and industries*. Fourth edition, revised and enlarged by John R. Harris. London: Edward Arnold.

Maddin, Robert, Tamara Stech, James D. Muhly, and Edward Brovarski

1984 Old Kingdom models from the tomb of Impy: Metallurgical studies. *The Journal of Egyptian Archaeology* 70, pp. 33–41.

Malainey, M. E.

2011 *A consumer's guide to archaeological science: Analytical techniques*. New York: Springer.

Manzo, Andrea

2016 Weapons, ideology and identity at Kerma (Upper Nubia, 2500 – 1500 BC). *Annali Sezione Orientale* 76, pp. 3–29.

Marcolin, Michele, and Andrés Diego Espinel

2011 The Sixth Dynasty biographic inscription of Iny: More pieces to the puzzle. In *Abusir and Saqqara in the year 2010*, Volume 2, ed. Miroslav Bárta, Filip Coppens, and Jaromír Krejčí, pp. 570–615. Prague: Czech Institute of Egyptology, Charles University.

Maréchal, Jean R.

1957 Les outils égyptiens en cuivre. *Métaux corrosion industries (Saint Germain en Laye)* 32, pp. 132–133.

Marouard, Grégory

2020 Étude du dépotoir de creusets du Moyen Empire du secteur G8-G10. In *Ayn Soukhna IV: Le matériel des galeries-magasins*, ed. Georges Castel and Pierre Tallet, pp. 427–447. Cairo: Institut Français d'Archéologie Orientale.

Martinet, Émilie

2021 Le processus d'émergence des élites provinciales dotées de monuments inscrites à la lueur des récentes découvertes réalisées à Tell Edfou (V^e^ - VI^e^ dynasties). *Revue d'Égyptologie* 71, pp. 45–70.

Massafra, Angela

2012 *Le* harpai *nel Vicino Oriente antico: cronologia e distribuzione*. Studies on the Archaeology of Palestine & Transjordan 9. Rome: La Sapienza Expedition to Palestine & Jordan.

Masson-Berghoff, Aurélia, Ernst Pernicka, Duncan Hook, and Andrew Meek

2018 (Re)sources: Origins of metals in Late Period Egypt. *Journal of Archaeological Science: Reports* 21, pp. 318–339.

Matić, Uroš

2020 *Ethnic identities in the land of the pharaohs*. Past and Present Approaches in Egyptology. Cambridge: Cambridge University Press.

McKerrell, Hugh

1993 Results of radio-isotope non-dispersive X-ray fluorescence analysis of Predynastic Egyptian copper. In *Catalogue of the Predynastic Egyptian collection in the Ashmolean Museum*, ed. Joan Crowfoot Payne, p. 256. Oxford: Oxford University Press.

Meketre

2009 *Meketre: The online repository for Middle Kingdom scenes*. Vienna: University of Vienna, Faculty of Historical and Cultural Studies. https://meketre.org/themes.

Mendoza, Barbara

2008 *Bronze priests of ancient Egypt from the Middle Kingdom to the Graeco-Roman Period*. BAR International Series 1866. Oxford: Archaeopress.

Miniaci, Gianluca, and Peter Lacovara (eds.)

2022 *The treasure of the Egyptian Queen Ahhotep and international relations at the turn of the Middle Bronze Age (1600 –1500 BCE)*. Middle Kingdom Studies 11. London: Golden House Publications.

Moeller, Nadine, and Gregory Marouard

2018 The development of two early urban centres in Upper Egypt during the 3rd millennium BC. In *From microcosm to macrocosm: Individual households and cities in ancient Egypt and Nubia*, ed. Julia Budka and Johannes Auenmüller, pp. 29–58. Leiden: Sidestone.

Monbaron, Noémie

2021 Scies et archets: Sur deux types de manches d'outils à la VI^e^ dynastie. In *Dans les pas d'Imhotep: Mélanges offerts à Audran Labrousse*, ed. Rémi Legros, pp. 103–112. Leuven: Peeters.

Montélius, Oscar

1890 L'âge du bronze en Égypte. *L'Anthropologie* 1(1), pp. 27–48.

Moorey, Peter Roger Stuart

1999 *Ancient Mesopotamian materials and industries: The archaeological evidence*. Winona Lake, IN: Eisenbrauns.

Morenz, Ludwig D.
2010 *Die Zeit der Regionen im Spiegel der Gebelein-Region: Kulturgeschichtliche Re-konstruktionen*. Probleme der Ägyptologie 27. Leiden and Boston: Brill.
2019 *Sinai und Alphabetschrift: Die frühesten alphabetischen Inschriften und ihr kanaanäisch-ägyptischer Entstehungshorizont im Zweiten Jahrtausend v. Chr*. Studia Sinaitica 3. Berlin: EB Verlag.

Morris, Ellen
2022 Daggers and axes for the queen: Considering Ahhotep's weapons in their cultural context. In *The treasure of the Egyptian queen Ahhotep and international relations at the turn of the Middle Bronze Age (1600 – 1500 BCE)*, ed. Peter Lacovara and Gianluca Miniaci, pp. 165–186. London: Golden House.

Moussa, Ahmed M., and Friedrich Junge
1975 *Two tombs of craftsmen: Old Kingdom tombs at the causeway of King Unas at Saqqara*. Archäologische Veröffentlichungen, Deutsches Archäologisches Institut, Abteilung Kairo 9. Mainz: Philipp von Zabern.

Mrsich, Tycho
1995 Erenofres Verteidigung. In *Gedenkschrift für Winfried Barta: ḥtp dj n ḥzj*, Münchener Ägyptologische Untersuchungen 4, ed. Dieter Kessler and Regine Schulz, pp. 291–310. Frankfurt am Main: Peter Lang.

Müller, Hans Wolfgang, and Hermann Kühn
1987 *Der Waffenfund von Balâṭa-Sichem und die Sichelschwerter*. Abhandlungen/Bayerische Akademie der Wissenschaften, Philosophisch-Historische Klasse, n. F., Heft 97. Münich: Verlag der Bayerischen Akademie der Wissenschaften; C. H. Beck.

Mumford, Gregory
2006 Tell Ras Budran (Site 345): Defining Egypt's eastern frontier and mining operations in south Sinai during the late Old Kingdom (early EB IV/MB I). *Bulletin of the American Schools of Oriental Research* 342, pp. 13–67.

Murillo-Barroso, Mercedes, Marcos Martinón-Torres, M. Dolores Camalich Massieu, Dimas Martín Socas, and Fernando Molina González
2017 Early metallurgy in SE Iberia: The workshop of Las Pilas (Mojácar, Almería, Spain). *Archaeological and Anthropological Sciences* 9, pp. 1539–1569.

Nicholson, Paul T.
2007 *Brilliant things for Akhenaten: The production of glass, vitreous materials and pottery at Amarna Site O45*.1. London: Egypt Exploration Society.
2010 Kilns and firing structures. In *UCLA Encyclopedia of Egyptology*, ed. Willeke Wendrich. Los Angeles: http://digital2.library.ucla.edu/viewItem.do?ark=21198/zz0025sr24.

O'Connor, David B.
2014 *The Old Kingdom town at Buhen*. Egypt Exploration Society Excavation Memoir 106. London: Egypt Exploration Society.

Odler, Martin
2016 *Old Kingdom copper tools and model tools*. With contributions by Jiří Kmošek, Ján Dupej, Katarína Arias Kytnarová, Lucie Jirásková, Veronika Dulíková, Tereza Jamborová, Šárka Msallamová, Kateřina Šálková, and Martina Kmoníčková. Archaeopress Egyptology 14. Oxford: Archaeopress.
2017 For the temples, for the burial chambers: Sixth Dynasty copper vessel assemblages. In *Abusir and Saqqara in the year 2015*, ed. Miroslav Bárta, Filip Coppens, and Jaromír Krejčí, pp. 293–315. Prague: Czech Institute of Egyptology, Charles University.
2023a *Copper in ancient Egypt: Before, during and after the Pyramid Age (c. 4000 – 1600 BC)*. Culture and History of the Ancient Near East 132. Leiden: Brill.
2023b Größer ist nicht immer besser: Kupferwerkzeuge und ihre Modelle im Alten Ägypten. In *Modelle im Alten Ägypten: Objekte des Wissens*, ed. Susanne Deicher, Heike Wilde, Mansour Elnoubi Mansour, and Saleh Mohamed Abdel Moaty, pp. 305–324. Berlin: Kadmos.
2024 Dispelling the myths about ancient Egyptian copper tools. *Egyptian Archaeology* 64, pp. 9–14.
fc. What type of bronze was ancient Egyptian *ḥsmn*? In *Proceedings of the conference "Minerals in ancient Egypt, from Naqada to Alexandria," October 3 – 4, 2022*, ed. Christine Karlshausen and Thierry de Putter. Brussels, Belgium: Palace of the Academies.

Odler, Martin, and Ján Dupej
2016 Morphometrical and statistical case study of Old Kingdom adze blades. In *Old Kingdom copper tools and model tools* (with contributions by Jiří Kmošek, Ján Dupej, Katarína Arias Kytnarová, Lucie Jirásková,

Veronika Dulíková, Tereza Jamborová, Šárka Msallamová, Kateřina Šálková, and Martina Kmoníčková), Archaeopress Egyptology 14, pp. 248–260. Oxford: Archaeopress.

Odler, Martin, and Jiří Kmošek

2019 Copper at Giza: The latest news. *Aeragram* 20(2), pp. 11–17.

2020 *Invisible connections: An archaeometallurgical analysis of the Bronze Age metalwork from the Egyptian Museum of the University of Leipzig*. (With chapters by Katarína Arias, Veronika Dulíková, and Lucie Jirásková.) Archaeopress Egyptology 31. Oxford: Archaeopress.

2021 Old Kingdom copper at Abusir: First archaeometallurgical data. In *Abusir and Saqqara in the Year 2020*, ed. Miroslav Bárta, Filip Coppens, and Jaromír Krejčí, pp. 141–157. Prague: Czech Institute of Egyptology, Faculty of Arts, Charles University.

2022 Copper at Giza: Analyses tell stories. *Aeragram* 23(1–2), pp. 12–17.

fc. An introduction to the realities of metalworking on the Elephantine Island in the late Middle Kingdom. In *Excavating the extra-ordinary 2: Challenges and merits of working with small finds: Proceedings of the international workshop at Johannes Gutenberg University Mainz, 25 – 26 November 2022*, ed. Monika Zöller-Engelhardt, Andrea Kilian, and Alexander Pruß. Heidelberg: Propylaeum.

Odler, Martin, Jiří Kmošek, Marek Fikrle, and Yulia V. E. Kochergina

2021 Arsenical copper tools of Old Kingdom Giza craftsmen: First data. *Journal of Archaeological Science: Reports* 36: No. 102868.

Odler, Martin, and Marie Peterková Hlouchová

2017 "May you receive that favourite harpoon of yours...": Old Kingdom spears/harpoons and their contexts of use. *Studien zur altägyptischen Kultur* 46, pp. 191–222.

O'Flynn, Daniel, Anna Fedrigo, Laura Perucchetti, and Aurélia Masson-Berghoff

2023 Neutron tomography of sealed copper alloy animal coffins from ancient Egypt. *Scientific Reports* 13: No. 4582.

Ogden, Jack

2000 Metals. In *Ancient Egyptian materials and technology*, ed. Paul T. Nicholson and Ian Shaw, pp. 148–176. Cambridge: Cambridge University Press.

Oller Guzmán, Joan

2020 New evidence of metallurgical production during the Ptolemaic Period in the ancient harbor of Berenike (Eastern Desert) in Egypt. *Polish Archaeology in the Mediterranean* 29, pp. 109–125.

Ottaway, Barbara S.

2001 Innovation, production and specialization in early prehistoric copper metallurgy. *European Journal of Archaeology* 4, pp. 87–112.

Pantalacci, Laure

2010 Organisation et contrôle du travail dans la province oasite à la fin de l'Ancien Empire: Le cas des grands chantiers de construction à Balat. In *L'organisation du travail en Égypte ancienne et en Mésopotamie: Colloque AIDEA, Nice 4 – 5 octobre 2004*, ed. Bernadette Menu, pp. 139–153. Cairo: Institut Français d'Archéologie Orientale.

Peet, Thomas Eric

1930 *The great tomb-robberies of the Twentieth Egyptian Dynasty: Being a critical study, with translations and commentaries, of the papyri in which these are recorded.* Oxford: Clarendon Press.

Pendlebury, John Devitt Stringfellow

1951 *The city of Akhenaten, Part III: The Central City and the official quarters: The excavations at Tell El-Amarna during the season 1926 – 1927 and 1931 – 1936.* Excavation Memoir 44. London: Egypt Exploration Society.

Petrie, William Matthew Flinders

1890 *Kahun, Gurob, and Hawara*. London: Kegan Paul, Trench, Trübner, and Co.

1891 *Illahun, Kahun and Gurob: 1889–90*. London: David Nutt.

1901a *The royal tombs of the earliest dynasties, Part II: Extra plates.* Special extra publication of the Egypt Exploration Fund. London: Kegan Paul, Trench, Trübner & Co., B. Quaritch, Asher & Co.

1901b *The royal tombs of the 1st Dynasty, Part II.* Nineteenth Memoir of the Egypt Exploration Fund. London: Kegan Paul, Trench, Trübner & Co., B. Quaritch, Asher & Co.

1906 *Researches in Sinai*. London: John Murray.

1917 *Tools and weapons: Illustrated by the Egyptian Collection in University College, London, and 2000 outlines from other sources.* British School of Archaeology in Egypt and Egyptian Research Account 30. London: Bernard Quaritch.

1927 *Objects of daily use: With over 1800 figures from University College, London*. British School of Archaeology in Egypt and Egyptian Research Account 42. London: Bernard Quaritch.

1937 *Stone and metal vases*. British School of Archaeology in Egypt and Egyptian Research Account 59. London: Bernard Quaritch.

Petrie, William Matthew Flinders, and James Edward Quibell

1895 *Naqada and Ballas*. British School of Archaeology in Egypt and Egyptian Research Account 1. London: Bernard Quaritch.

Petschel, Susanne

2011 *Den Dolch betreffend: Typologie der Stichwaffen in Ägypten von der prädynastischen Zeit bis zur 3. Zwischenzeit.* Philippika – Marburger altertumskundliche Abhandlungen 36. Wiesbaden: Harrassowitz.

Pfeiffer, Kristina

2013 *Neue Untersuchungen zur Archäometallurgie des Sinai: Die Entwicklungsgeschichte der Innovation "Kupfermetallurgie."* Rahden/Westfalen: Leidorf.

Philip, Graham

2006 *Tell El-Dab'a XV: Metalwork and metalworking evidence of the Late Middle Kingdom and the Second Intermediate Period*. Untersuchungen der Zweigstelle Kairo des Österreichischen Archäologischen Institutes 26. Vienna: Verlag der Österreichischen Akademie der Wissenschaften.

Pollard, A. Mark, and Carl Heron

2008 *Archaeological chemistry*. Cambridge: The Royal Society of Chemistry.

Pollastrini, Alberto Maria

2017 Some remarks on the Egyptian reception of foreign military technology during the 18th Dynasty: A brief survey of the armour. In *Proceedings of the XIth International Congress of Egyptologists, Florence Egyptian Museum, Florence, 23 – 30 August 2015*, Archaeopress Egyptology 19, ed. Gloria Rosati and Maria Cristina Guidotti, pp. 513 – 518. Oxford: Archaeopress.

Prell, Silvia

2011 *Einblicke in die Werkstätten der Residenz: Die Stein- und Metallwerkzeuge des Grabungsplatzes Q I*. Die Grabungen des Pelizaeus-Museums Hildesheim in Qantir-Pi-Ramesse, Forschungen in der Ramses-Stadt 8. Hildesheim: Gerstenberg.

2020a "Buckle up and fasten that belt!" Metal belts in the Early and Middle Bronze Age. *Ägypten und Levante* 29, pp. 302–329.

2020b Hard to pin down: Clothing pins in the eastern Delta of Egypt and their diffusion in the Middle Bronze Age. *Ägypten und Levante* 30, pp. 495–533.

Price, T. D., and J. H. Burton

2012 *An introduction to archaeological chemistry*. New York: Springer.

Pusch, Edgar B.

1990 Metallverarbeitende Werkstätten der frühen Ramessidenzeit in Qantir-Piramesse/Nord: Ein Zwischenbericht. *Ägypten und Levante* 1, pp. 75–113.

1994 Divergierende Verfahren der Metallverarbeitung in Theben und Qantir? Bemerkungen zur Konstruktion und Technik. *Ägypten und Levante* 4, pp. 145–170.

Quibell, James Edward

1913 *Excavations at Saqqara (1911-12): The tomb of Hesy*. Cairo: Institut Français d'Archéologie Orientale.

Rademakers, Frederik W.

2015 *Into the crucible: Methodological approaches to reconstructing crucible metallurgy, from New Kingdom Egypt to Late Roman Thrace*. Unpublished Ph.D. dissertation: University College London. http://discovery.ucl.ac.uk/id/eprint/1469615

fc. Copper alloy production at Amarna: Evidence from M50.14–16. In *Working in the suburbs: The study of archaeological and material remains at domestic workshop site M50.14–16 at Amarna*, ed. Anna K. Hodgkinson. London: Egypt Exploration Society.

Rademakers, Frederik W., Johannes Auenmüller, Neal Spencer, Kate Fulcher, Manuela Lehmann, Frank Vanhaecke, and Patrick Degryse

2023 Metals and pigments at Amara West: Cross-craft perspectives on practices and provisioning in New Kingdom Nubia. *Journal of Archaeological Science* 153: No. 105766.

Rademakers, Frederik W., Aude Mongiatti, and Julie Anderson

fc. Crucible technology at Dangeil: New insights into Kushite copper alloy metallurgy.

Rademakers, Frederik W., and Thilo Rehren

2016 Seeing the forest for the trees: Assessing technological variability in ancient metallurgical crucible assemblages. *Journal of Archaeological Science: Reports* 7, pp. 588–596.

Rademakers, Frederik W., Thilo Rehren, and Ernst Pernicka

2017 Copper for the pharaoh: Identifying multiple metal sources for Ramesses' workshops from bronze and crucible remains. *Journal of Archaeological Science* 80, pp. 50–73.

Rademakers, Frederik W., Thilo Rehren, and Edgar B. Pusch

2018 Bronze production in Pi-Ramesse: Alloying technology and material use. In *Mining for copper: Essays in memory of Professor Beno Rothenberg*, ed. Erez Ben-Yosef, pp. 503–525. Tel Aviv: University of Tel Aviv.

Rademakers, Frederik W., Thilo Rehren, and Mary M. Voigt

2018 Bronze metallurgy in the Late Phrygian settlement of Gordion, Turkey. *Archaeological and Anthropological Sciences* 10, pp. 1645–1672.

Rademakers, Frederik W., Marie Vandenbeusch, Elvira Vassilieva, Frank Vanhaecke, and Patrick Degryse

2024 Speiss at Amarna (Egypt, c. 1353 – 1336 BCE) – Exotic anachronism or cherished commodity? *Journal of Archaeological Science* 170: No. 106043.

Rademakers, Frederik W., Georges Verly, Kylie Cortebeeck, Patrick Degryse, Charles Bonnet, and Séverine Marchi

2023 Alloying copper, arsenic and tin: The first crucible evidence from Kerma. *Sudan & Nubia* 27, pp. 2–23.

Rademakers, Frederik W., Georges Verly, Patrick Degryse, Frank Vanhaecke, Séverine Marchi, and Charles Bonnet

2022 Copper at ancient Kerma: A diachronic investigation of alloys and raw materials. *Advances in Archaeomaterials* 3, pp. 1–18.

Rademakers, Frederik W., Georges Verly, Luc Delvaux, and Patrick Degryse

2018 Copper for the afterlife in Predynastic to Old Kingdom Egypt: Provenance characterization by chemical and lead isotope analysis (RMAH Collection, Belgium). *Journal of Archaeological Science* 96, pp. 175–190.

2021 Provenance reinterpretation of some early Egyptian copper alloy artefacts. *Journal of Archaeological Science: Reports* 38: No. 103095.

Rademakers, Frederik W., Georges Verly, Luc Delvaux, Frank Vanhaecke, and Patrick Degryse

2021 From desert ores to Middle Kingdom copper: Elemental and lead isotope data from the RMAH Collection, Belgium. *Archaeological and Anthropological Sciences* 13: No. 100.

Rademakers, Frederik W., Georges Verly, Claire Somaglino, and Patrick Degryse

2020 Geochemical changes during Egyptian copper smelting? An experimental approach to the Ayn Soukhna process and broader implications for archaeometallurgy. *Journal of Archaeological Science* 122: No. 105223.

Rademakers, Frederik W., Georges Verly, Florian Téreygeol, and Johannes Auenmüller

2021 Contributions of experimental archaeology to excavation and material studies. *Journal of Archaeological Science: Reports* 38: No. 103036.

Radwan, Ali

1983 *Die Kupfer- und Bronzegefäße Ägyptens*. Prähistorische Bronzefunde, Abteilung II, Bd. 2. Munich: C. H. Beck.

Rahmstorf, Lorenz

2022 *Studien zu Gewichtsmetrologie und Kulturkontakt im 3. Jahrtausend v. Chr.* Universitätsforschungen zur prähistorischen Archäologie 379. Bonn: Rudolf Habelt.

Redford, Donald B.

2003 *The wars in Syria and Palestine of Thutmose III*. Culture and History of the Ancient Near East 16. Leiden: Brill.

Rehren, Thilo, Katja Broschat, Myrto Georgakopoulou, and Stavroula Golfomitsou

2022 Die naturwissenschaftlichen Untersuchungen. In *Tutanchamuns Mumienmaske: Chronographie einer Ikone*, ed. Katja Broschat and Christian Eckmann, pp. 147–194. Mainz: Römisch-Germanisches Zentralmuseum.

Rehren, Thilo, and Ernst Pernicka

2014 First data on the nature and origin of the metalwork from Tell el-Farkha. In *The Nile Delta as a centre of cultural interactions between Upper Egypt and the southern Levant in the 4th millennium BC*, Studies in African

Archaeology 13, ed. Agnieszka Mączyńska, pp. 237–252. Poznań: Poznań Archaeological Museum, Poland.

Rehren, Thilo, and Edgar B. Pusch

2005 Late Bronze Age glass production at Qantir-Piramesses, Egypt. *Science* 308, pp. 1756–1758.

2012 Alloying and resource management in New Kingdom Egypt: The bronze industry at Qantir-Pi-Ramesse and its relationship to Egyptian copper sources. In *Eastern Mediterranean metallurgy and metalwork in the second millennium BC: A conference in honour of James D. Muhly, Nicosia, 10th – 11th October 2009*, ed. Vasiliki Kassianidou and George Papasavvas, pp. 215–221. Oxford: Oxbow Books.

Rehren, Thilo, Edgar B. Pusch, and Anja Herold

2001 Qantir-Piramesses and the organisation of the Egyptian glass industry. In *The social context of technological change: Egypt and the Near East, 1650 – 1550 BC*, ed. Andrew J. Shortland, pp. 223–238. Oxford: Oxbow Books.

Reisner, George Andrew

1923 *Excavations at Kerma II: Parts IV-V*, Vol. 5/6. Harvard African Studies. Cambridge, MA: Peabody Museum of Harvard University.

Riederer, Josef

1978 Die naturwissenschaftliche Untersuchung der Bronzen des Ägyptischen Museums Preußischer Kulturbesitz in Berlin. *Berliner Beiträge zur Archäometrie* 3, pp. 5–42.

1981 Metal analysis of Egyptian bronzes. *Revue d'Archéométrie* 1 (Actes du XXe symposium international d'archéométrie Paris 26 – 29 mars 1980, Volume III), pp. 239–243.

1982 Die naturwissenschaftliche Untersuchung der Bronzen der Staatlichen Sammlung Ägyptischer Kunst in München. *Berliner Beiträge zur Archäometrie* 7, pp. 5–34.

1983 Metallanalysen der ägyptischen Statuetten des Kestner-Museums, Hannover. *Berliner Beiträge zur Archäometrie* 8, pp. 5–17.

1984 Die naturwissenschaftliche Untersuchung der ägyptischen Bronzen des Pelizaeus-Museums in Hildesheim. *Berliner Beiträge zur Archäometrie* 9, pp. 5–16.

1988 Metallanalysen ägyptischer Bronzestatuetten aus deutschen Museen. *Berliner Beiträge zur Archäometrie* 10, pp. 5–20.

Rizkana, Ibrahim, and Jürgen Seeher

1989 *Maadi III: The non-lithic small finds and the structural remains of the Predynastic settlement*. Archäologische Veröffentlichungen des Deutschen Archäologischen Instituts, Abteilung Kairo 80. Mainz: Philipp von Zabern.

Roberts, Benjamin W., and Christopher P. Thornton (eds.)

2014 *Archaeometallurgy in global perspective: Methods and syntheses*. New York: Springer.

Roeder, Günther

1937 *Ägyptische Bronzewerke*. Pelizaeus-Museum zu Hildesheim: Wissenschaftliche Veröffentlichung 3. Glückstadt: J. J. Augustin.

1956 *Ägyptische Bronzefiguren*. Mitteilungen aus der Ägyptischen Sammlung 6. Berlin: Staatliche Museen zu Berlin.

Roman, Itzhak

1990 Copper ingots. In *The ancient metallurgy of copper: Archaeology-Experiment-Theory (Researches in the Arabah 1959 – 84, v. 2)*, ed. Beno Rothenberg, pp. 176–181. London: The Institute for Archaeo-Metallurgical Studies.

Rosińska-Balik, Karolina, Agnieszka Ochał-Czarnowicz, Marcin Czarnowicz, and Joanna Dębowska-Ludwin (eds.)

2015 *Copper and trade in the south-eastern Mediterranean: Trade routes of the Near East in Antiquity*. BAR International Series 2753. Oxford: Archaeopress.

Roth, Ann Macy

1991 *Egyptian phyles in the Old Kingdom: The evolution of a system of social organization*. Studies in Ancient Oriental Civilization 48. Chicago: Oriental Institute of the University of Chicago.

Rothenberg, Beno

1970 An archaeological survey of South Sinai: First season 1967/1968, preliminary report. *Palestine Exploration Quarterly* 102, pp. 4–29.

1987 Pharaonic copper mines in South Sinai. *Institute of Archaeo-Metallurgical Studies* 10-11, pp. 1–7.

Rothenberg, Beno (ed.)
1990 *The ancient metallurgy of copper: Archaeology-experiment-theory: Researches in the Arabah 1959-84, Vol. 2*. London: The Institute for Archaeo-Metallurgical Studies.

Rothenberg, Beno, C. Tim Shaw, Fekri A. Hassan, and Abdel Aziz A. Hussein
1998 Reconnaissance survey of ancient mining and metallurgy in the Mersa Alam region, Eastern Desert of Egypt. *Institute of Archaeo-Metallurgical Studies* 20, pp. 4–9.

Rowland, Joanne M.
2014 Interregional exchange: The evidence from Kafr Hassan Dawood, East Delta. In *The Nile Delta as a centre of cultural interactions between Upper Egypt and the Southern Levant in the 4th millennium BC*, ed. Agnieszka Mączyńska, pp. 269–297. Poznań: Poznań Archaeological Museum.

Roy, Jane
2011 *The politics of trade: Egypt and Lower Nubia in the 4th millennium BC*. Culture and History of the Ancient Near East 47. Leiden: Brill.

Saleh, A. -A.
1974 Excavations around Mycerinus pyramid complex. *Mitteilungen des Deutschen Archäologischen Instituts, Abteilung Kairo* 30, pp. 131–154.

Salem, S. M., S. A. Arafa, T. M. Ramadan, and E. S. A. El Gammal
2013 Exploration of copper deposits in Wadi El Regeita area, Southern Sinai, Egypt, with contribution of remote sensing and geophysical data. *Arabian Journal of Geosciences* 6, pp. 321–335.

Säve-Söderbergh, Torgny, and Lana Troy
1991a *New Kingdom pharaonic sites: The finds and the sites: Text*. The Scandinavian Joint Expedition to Sudanese Nubia, Volume 5:2. Uppsala: The Scandinavian Joint Expedition to Sudanese Nubia.
1991b *New Kingdom pharaonic sites: The finds and the sites: Lists and plates*. The Scandinavian Joint Expedition to Sudanese Nubia, Volume 5:3. Uppsala: The Scandinavian Joint Expedition to Sudanese Nubia.

Scheel, Bernd
1985 Studien zum Metallhandwerk im Alten Ägypten I: Handlungen und Beischriften in den Bildprogrammen der Gräber des Alten Reiches. *Studien zur altägyptischen Kultur* 12, pp. 117–177.
1986 Studien zum Metallhandwerk im Alten Ägypten II: Handlungen und Beischriften in den Bildprogrammen der Gräber des Mittleren Reiches. *Studien zur altägyptischen Kultur* 13, pp. 181–205.
1987 Studien zum Metallhandwerk im Alten Ägypten III: Handlungen und Beischriften in den Bildprogrammen der Gräber des Neuen Reiches und der Spätzeit. *Studien zur altägyptischen Kultur* 14, pp. 247–264.
1988 Fundobjekte einer ptolemäerzeitlichen Metallverarbeitungsstätte in Theben und Vergleichsfunde anderer vorderorientalischer Ausgrabungsplätze. *Studien zur altägyptischen Kultur* 15, pp. 243–254.

Schiegl, Solveig, Karl Ludwig Weiner, and Ahmed el Goresy
1990 Zusammensetzung und Provenienz von Blau- und Grünpigmenten in Altägyptischen Wandmalereien: Ein Beitrag zur exakten Chronologie der Bronzetechnologie in Altägypten. *Erzmetall* 43, pp. 265–272.

Schorsch, Deborah
1988 Technical examinations of ancient Egyptian theriomorphic hollow cast bronzes: Some case studies. In *Conservation of ancient Egyptian materials*, ed. Sarah C. Watkins and Carol E. Brown, pp. 41–50. London: UKIC Archaeology Section.
1992 Copper ewers of Early Dynastic and Old Kingdom Egypt: An investigation of the art of smithing in antiquity. *Mitteilungen des Deutschen Archäologischen Instituts, Abteilung Kairo* 48, pp. 145–159.

Schwab, Roland, and Frank Willer
2016 Die Zusammensetzung und mögliche Herkunft der Gusslegierungen. In *Materialien einer Gusswerkstatt von der Qubbet el-Hawa*, ed. Martin Fitzenreiter, Frank Willer, and Johannes Auenmüller, pp. 71–81. Berlin: EB Verlag.

Schwarz, Stephanie
2000 *Altägyptisches Lederhandwerk*. Europäische Hochschulschriften. Reihe XXVIII, Kunstgeschichte 365. Frankfurt am Main: Peter Lang.

Scott, David A.
1991 *Metallography and microstructure of ancient and historic metals*. Malibu, CA: The J. Paul Getty Trust.

Scott, David A., and Roland Schwab
2019 *Metallography in archaeology and art*. Berlin and New York: Springer.

Serotta, Anna
2023 Reading tool marks on Egyptian stone sculpture. *Rivista del Museo Egizio* 7, pp. 69–92.

Seyfried, Karl-Joachim

1981 *Beiträge zu den Expeditionen des Mittleren Reiches in die Ost-Wüste*. Hildesheimer Ägyptologische Beiträge 15. Hildesheim: Gerstenberg.

Shaw, C. Tim, and Şevket Durucan

2008 A study of mining methods and ventilation during the Egyptian period at the mines of Timna. In *Ancient mining in Turkey and the Eastern Mediterranean*, ed. Ü. Yalçin, H. Özbal, and A. G. Paşamehmetoğlu, pp. 435–464. Ankara: Atılım University.

Shaw, Ian

1998 Exploiting the desert frontier: The logistics and politics of ancient Egyptian mining expeditions. In *Social approaches to an industrial past: The archaeology and anthropology of mining*, ed. A. B. Knapp, V. C. Pigott, and E. W. Herbert, pp. 242–258. London: Routledge.

Shaw, Ian, Elizabeth Bloxam, Tom Heldal, and Per Storemyr

2010 Quarrying and landscape at Gebel El-Asr in the Old and Middle Kingdoms. In *Recent discoveries and latest researches in Egyptology: Proceedings of the First Neapolitan Congress of Egyptology, June 18th – 20th 2008*, ed. Francesco Raffaele, Massimiliano Nuzzolo, and Ilaria Incordino, pp. 293–312. Wiesbaden: Harrassowitz.

Simpson, William Kelly

1965 *Papyrus Reisner II: Accounts of the dockyard workshop at This in the reign of Sesostris I: Transcription and commentary*. Boston: Museum of Fine Arts.

1985 A stela of the chief coppersmith Ahmose. In *Mélanges offerts à Jean Vercoutter*, ed. Francis Geus and Florence Thill, pp. 312–316. Paris: Éditions Recherche sur les Civilisations.

Smith, Stuart Tyson

1991 Askut and the role of the Second Cataract forts. *Journal of the American Research Center in Egypt* 28, pp. 107–132.

1992 Intact tombs of the 17th and 18th dynasties from Thebes and the New Kingdom burial system. *Mitteilungen des Deutschen Archäologischen Instituts, Abteilung Kairo* 48, pp. 193–231.

Spencer, Allan Jeffrey

1980 *Early Dynastic objects*. Catalogue of Egyptian Antiquities in the British Museum 5. London: British Museum Press.

Stevens, Anna, and Wendy Dolling (eds.)

2012 *Akhenaten's workers: The Amarna Stone Village Survey, 2005 – 2009, Vol. 1: The survey, excavations and architecture*. Excavation Memoir 100. London: Egypt Exploration Society.

Stevens, Anna, and Mark Eccleston

2007 Craft production and technology. In *The Egyptian world*, ed. Toby Wilkinson, pp. 146–159. London: Routledge.

Stocks, Denys A.

2023 *Experiments in Egyptian archaeology: Stoneworking technology in ancient Egypt*. London: Routledge.

Stos-Gale, Zofia, Noel Gale, and Judy Houghton

1995 The origins of Egyptian copper: Lead-isotope analysis of metals from el-Amarna. In *Egypt, the Aegean and the Levant: Interconnections in the second millennium BC*, ed. W. Vivian Davies and Louise Schofield, pp. 127–135. London: British Museum Press.

Tallet, Pierre

2012 *La zone minière pharaonique du Sud-Sinaï I: Catalogue complémentaire des inscriptions du Sinaï*. Cairo: Institut Français d'Archéologie Orientale.

2015 *La zone minière pharaonique du Sud-Sinaï II: Les inscriptions pré- et protodynastiques du Ouadi ʿAmeyra*. Cairo: Institut Français d'Archéologie Orientale.

2016- D'Ayn Soukhna à la péninsule du Sinaï: Le mode opératoire des expéditions égyptiennes à la fin de la XIIe dynastie. In *Sésostris III et la fin du Moyen Empire*, CRIPEL 31 (2016 – 2017), ed. Guillemette Andreu-Lanoë and Fleur Morfoisse, with the collaboration of Nicolas Leroux, pp. 179–198. Lille: Université de Lille, SHS.

2018 *La zone minière pharaonique du Sud-Sinaï III: Les expéditions égyptiennes dans la zone minière du Sud-Sinaï du prédynastique à la fin de la XXe dynastie*. Cairo: Institut Français d'Archéologie Orientale.

Tallet, Pierre, Georges Castel, and Philippe Fluzin

2011 Metallurgical sites of South Sinai (Egypt) in the pharaonic era: New discoveries. *Paléorient* 37(2), pp. 79–89.

Tallet, Pierre, and Damien Laisney

2011 Iry-Hor et Narmer au Sud-Sinaï (Ouadi ʻAmeyra): Un complément à la chronologie des expéditions minières égyptiennes. *Bulletin de l'Institut français d'archéologie orientale* 112, pp. 381–398.

Téreygeol, Florian, and Loïc Mazou

2019 Les creusets métallurgiques de l'antiquité tardive à Bouto: Une expérimentation autour de l'adaptation de l'objet et de son usage à la matière disponible. In *Studies in experimental archaeometallurgy: Methodological reflections from non-ferrous metallurgies*, ed. G. Verly, F. W. Rademakers, and F. Téreygeol, pp. 165–179. Dremil-Lafage: Éditions Mergoil.

Tooley, Angela M. J.

1995 *Egyptian models and scenes*. Shire Egyptology 22. Risborough: Shire Publishers.

Tratsaert, Barbara J. M.

2012 Roman gold mining in the Eastern Desert: The mining settlement in Wadi Bakariya. In *The history of the peoples of the Eastern Desert*, ed. Hans Barnard and Kim Duistermaat, pp. 245–255. Los Angeles: Cotsen Institute of Archaeology, University of California, Los Angeles.

Tylecote, Robert F., and John F. Merkel

1985 Experimental smelting techniques: Achievements and future. In *Furnaces and smelting technology in antiquity*, ed. P. T. Craddock and M. J. Hughes, pp. 3–20. London: British Museum Press.

Valbelle, Dominique

1977 *Catalogue des poids à inscriptions hiératiques de Deir el-Médineh nos 5001–5423*. Documents de fouilles de l'Institut français d'archéologie orientale 16. Cairo: Institut Français d'Archéologie Orientale.

Van der Perre, Athena

2015 Quarry marks of the Amarna Period: The limestone quarries of Dayr Abū Hinnis. In *Non-textual marking systems in ancient Egypt (and elsewhere)*, ed. Julia Budka, Frank Kammerzell, and Sławomir Rzepka, pp. 69–80. Hamburg: Widmaier.

Vandier d'Abbadie, Jeanne

1972 *Catalogue des objets de toilette égyptien*. Paris: Éditions des Musées Nationaux.

Vercoutter, Jean

1977 Les poids de Mirgissa et le "standard-cuivre" au Moyen Empire. In *Ägypten und Kusch: Fritz Hintze zum 60. Geburtstag*, ed. Erika Endesfelder, Karl Heinz Priese, Walter Friedrich Reineke, and Steffen Wenig, pp. 437–445. Berlin: Akademie Verlag.

Verly, Georges

2017a Khety or the Satire of Trades, mud and experimental archaeology: The use of mud as protection by metallurgists in pharaonic Egypt. *Göttinger Miszellen* 252, pp. 135–144.

2017b The smelting furnaces of Ayn Soukhna: The excavations of 2013, 2014 and 2015. In *Archaeometallurgy in Europe IV*, ed. I. Montero Ruiz and A. Perea, pp. 143–157. Madrid: Consejo Superior de Investigaciones Cientificas.

2024 *Les chaînes opératoires métallurgiques du cuivre, spécifiques à Ayn Soukhna Ancien/Moyen Empire. Alliage volontaire d'arsenic*. Unpublished Ph.D. dissertation: Paris: Lettres Sorbonne Université.

Verly, Georges, Johannes Auenmüller, Lux Delvaux, and Frederik W. Rademakers

2022 Re-membering Osiris: Late Period casting moulds and Osirian ritual. *Bulletin de l'Institut français d'archéologie orientale* 122, pp. 541–571.

Verly, Georges, and Alexandre Longelin

2019 Méthodologie en archéologie expérimentale. In *Studies in experimental archaeometallurgy: Methodological reflections from non-ferrous metallurgies*, ed. Georges Verly, Frederik W. Rademakers, and Florian Téreygeol, pp. 13–33. Dremil-Lafage: Éditions Mergoil.

Verly, Georges, and Frederik W. Rademakers

fc. Métallurgie des alliages cuivreux à Ayn Soukhna: Méthodologie de recherche et perspectives. In *Ayn Soukhna V: Études sur la zone d'habitat et d'activités artisanales du site (1): Rapport archéologique*, ed. Claire Somaglino, Georges Castel, and Pierre Tallet. Cairo: Institut Français d'Archéologie Orientale.

Verly, Georges, Frederik W. Rademakers, Séverine Marchi, and Charles Bonnet

2020 Le four en croix de Kerma revisité. In *PCR paléométallurgies et expérimentations: Rapport intermédiaire 2020*, ed. Florian Téreygeol, pp. 142–154. Belfort: CNRS, Institut de Recherches sur les Archéomatériaux, UMR 5060, Laboratoire Métallurgies et Cultures.

Verly, Georges, Frederik W. Rademakers, Claire Somaglino, Pierre Tallet, Luc Delvaux, and Patrick Degryse

2021 The *chaîne opératoire* of Middle Kingdom smelting batteries and the problem of fuel: Excavation, experimental and analytical studies on ancient Egyptian metallurgy. *Journal of Archaeological Science: Reports* 37: No. 102708.

Verly, Georges, Frederik W. Rademakers, Athena Van der Perre, and Erez Ben-Yosef

2019 The missing link between New Kingdom chisels and chisel marks: From documentation to reproduction. In *Studies in experimental archaeometallurgy: Methodological approaches from non-ferrous metallurgies*, ed. Georges Verly, Frederik W. Rademakers, and Florian Téreygeol, pp. 117–140. Dremil-Lafage: Éditions Mergoil.

Vernier, Émile

1927 *Catalogue général des antiquités égyptiennes du Musée du Caire: Nos 52001–53855: Bijoux et orfèvreries*. Cairo: Institut Français d'Archéologie Orientale.

Vogel, Carola

2006 Hieb- und stichfest? Überlegungen zur Typologie des Sichelschwertes im Neuen Reich. In *In Pharaos Staat: Festschrift für Rolf Gundlach zum 75. Geburtstag*, ed. Dirk Bröckelmann and Andrea Klug, pp. 271–286. Wiesbaden: Harrassowitz.

von Bissing, Friedrich Wilhelm

1900 *Ein thebanischer Grabfund aus dem Anfang des Neuen Reichs*. Berlin: Duncker.

1901 *Catalogue général des antiquités égyptiennes du Musée du Caire: Nos. 3426–3587: Metallgefäße*. Vienna: Holzhausen.

von der Way, Thomas

1997 *Tell el-Faraʿîn – Buto 1: Ergebnisse zum frühen Kontext: Kampagnen der Jahre 1983 – 1989*. Archäologische Veröffentlichungen des Deutschen Archäologischen Instituts, Abteilung Kairo 83. Mainz: Philipp von Zabern.

Wainwright, Gerald Avery

1943 Egyptian bronze-making. *Antiquity* 17, pp. 96–98.

Walsh, Carl

2021 Skeuomorphism in Kerma metal vessels. *Sudan & Nubia* 25, pp. 243–251.

Weinstein, James Morris

1974 *Foundation deposits in ancient Egypt*. Ph.D. dissertation in Oriental Studies: Philadelphia: University of Pennsylvania.

Whitehouse, Helen

1987 King Den in Oxford. *Oxford Journal of Archaeology* 6(2), pp. 257–267.

Wilkinson, Alix

1971 *Ancient Egyptian jewellery*. London: Methuen.

Yahalom-Mack, Naama

2015 Egyptian bronzeworking practices in Late Bronze Age Canaan. *Bulletin of the American Schools of Oriental Research* 374, pp. 103–114.

Yahalom-Mack, Naama, Ehud Galili, Irina Segal, Adi Eliyahu-Behar, Elisabetta Boaretto, Sana Shilstein, and Israel Finkelstein

2014 New insights into Levantine copper trade: Analysis of ingots from the Bronze and Iron Ages in Israel. *Journal of Archaeological Science* 45, pp. 159–177.

Zöller-Engelhardt, Monika

2016 Wooden models, tools and weapons. In *Asyut, Tomb III: Objects*, The Asyut Project: Vol. 3, ed. Jochem Kahl, pp. 1–171. Wiesbaden: Harrassowitz.

Zumkley, Kira

2022 An unknown ancient Egyptian tool (for wig maintenance?). In *Beautiful bodies: Gender and corporeal aesthetics in the past*, ed. Uroš Matić, pp. 69–118. Oxford: Oxbow.

Image Credits

Figure 1. Location of some of the most important sites mentioned in the text, mapped on a background from Natural Earth in qGIS. (Map by Martin Odler.)

Figure 2. Example of a Middle Kingdom smelting workshop at Ain Soukhna. The closed workshop space, internally divided in two, contains four column-shaped furnaces used for copper smelting (F88-89-90-91), constructed in sandstone with an internal lining (Verly 2024). (Photogrammetry: © Georges Verly, Mission Ayn Soukhna.)

Figure 3. Front and side views of two examples of copper processed in the Ramesside workshops at Pi-Ramesse. At top: a fragment of an oxhide ingot made of raw Cypriot copper. At bottom: a copper scrap intentionally folded and wrapped in textile for later recycling (cf. Rademakers, Rehren, and Pernicka 2017; Rademakers, Rehren, and Pusch 2018). (Photographs by Axel Krause, courtesy of the Qantir-Piramesse Project [Projekt Ramsesstadt].)

Figure 4. Side and front exterior views of two Middle Kingdom crucible types of varying size. At top: a vessel used for arsenical copper processing, 7.4 cm wide, 8.8 cm long, 7.4 cm high. At bottom: a vessel used for raw copper melting, 11.8 cm wide, 13.3 cm long, 14.8 cm high (Verly 2024). (Photographs © Georges Verly, Mission Ayn Soukhna.)

Figure 5. Scanning Electron Microscope images of crucible slag encountered in the Pi-Ramesse crucibles (further discussion in Rademakers 2015 and Rademakers, Rehren, and Pusch 2018). Top left: partially corroded tin bronze prill (dark gray: corrosion; brighter gray: metallic). Bottom left: embedded charcoal fragment. Top right: crucible slag (dark vitreous background) with metal oxides (white: tin oxide) and post-depositional corrosion products (light gray: cuprite formation in pore). Bottom right: crucible slag (dark vitreous background) with metal prills (light gray) and metal oxides (medium gray: iron-cobalt oxides). (Micrographs by Frederik W. Rademakers.)

Figure 6. Model carpenter's chest of a certain Ankhef from Asyut, Tomb 9 (Middle Kingdom, Dynasty 12). The chest is inscribed for Ankhef and bears a list of tools on the right, mentioning "six axes, six adzes, six chisels, six saws." Metropolitan Museum of Art, New York, Edward S. Harkness Gift, 1917, acc. no. 17.9.31. (Photograph: public domain.)

Figure 7. Two First Intermediate Period or early Middle Kingdom copper-alloy battle axes, provenance unknown. Metropolitan Museum of Art, New York, Edward S. Harkness Gift, 1926, acc. nos. 26.9.16 and 26.9.17a–e. (Photograph: public domain.)

Figure 8. Burial equipment of the nomarch Isi (Old Kingdom, Dynasty 6), including copper mirror disks, a razor blade, and miniature copper alloy vessels and stands, found in the central pit of the mastaba of Isi at Tell Edfu. (Photograph © 1979 Musée du Louvre/Maurice et Pierre Chuzeville.)

Figure 9. Late Middle Kingdom statuette of a woman, provenance unknown, Louvre, E 16267. (Photograph © 2002 Musée du Louvre/Christian Décamps.)

Figure 10. Brazier or censer inscribed with the name of the First Intermediate Period king Meryibra Khety, from Meir(?), Louvre E 10501. (Photograph © 2002 Musée du Louvre/Christian Décamps.)

Figure 11. Early New Kingdom battle-axe with haft, Asasif, Courtyard of Tomb CC 41, Pit 2, Burial D 3 (found in coffin). Metropolitan Museum of Art, New York, Rogers Fund, 1916, acc. no. 16.10.403a–c. (Photograph: public domain.)

Figure12. Reconstruction of a foundation deposit from the temple of Hatshepsut at Deir el-Bahri, containing several model tools with copper alloy blades. Metropolitan Museum of Art, New York, Rogers Fund, 1925, acc. no. 25.3.39. (Photograph: public domain.)

Figure 13. Number of known copper alloy artifacts and model metal artifacts from the Egyptian and Lower Nubian Chalcolithic Period and Early and Middle Bronze Age, with a percentage of the archaeometallurgically analyzed objects indicated. (Graph after Odler fc.: Figure 9.)

Figure 14. Mirror of the Chief of the Southern Tens Reniseneb (Middle Kingdom, Dynasty 12–13), Asasif, Pit Tomb CC 25 (found on chest of mummy). Metropolitan Museum of Art, New York, Purchase, Edward S. Harkness Gift, 1926, acc. no. 26.7.1351. (Photograph: public domain.)

Figure 15. A weight in the shape of a bull's head (New Kingdom, Dynasty 18), provenance unknown. It weighs 181.41 grams, thus two New Kingdom copper *deben*. Metropolitan Museum of Art, New York, Purchase, Lila Acheson Wallace Gift, 1968, acc. no. 68.139.2. (Photograph: public domain.)

---

[*] In this overview, the first two authors contributed to the text equally. The research of Martin Odler was carried out as part of the UKRI-funded EgypToolWear-Metalwork Wear Analysis of the *Ancient Egyptian Tools* project, a Horizon Europe Guarantee (originally Marie Skłodowska-Curie Fellowship), project reference no. EP/X026434/1.