Out of the Fiery Crucible: Egyptian Old Kingdom metallurgy

Christopher J. Davey and Peter C. Hayes

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Abstract: The evidence for Egyptian Old Kingdom metalworking is reviewed drawing upon archaeology, iconography, metallurgy, history, scientific data and process replication. The charateristics of arsenical copper are considered appropriate for making copper sheet. It is suggested that the ore was initially obtained from the southern Eastern Desert of Egypt where Pre- and Early Dynastic mines are to be found and where there may have been mining and metallurgical expertise amongst the regional nomadic people. C*haîne opératoires* are proposed for the fabrication of prestige copper vessels and for the production copper tools.

Keywords: Old Kingdom Egypt, mining and metallurgy, Pyramid Age metalworking, crucibles, arsenical copper, tomb decoration.

Introduction

The vital role that copper played in the construction of the stone pyramids of Giza and Saqqara places it at the centre of some of the most remarkable human achievements (Tallet & Lehner 2021: 68–83). It was one of several resources that were mustered and managed by a sophisticated organisation that was integral to the formation of the Egyptian state and the development of civil society (Tallet & Lehner 2021: 284–302). John Romer (2007: 169) estimated the weight of copper consumed during the construction of the Great Pyramid to have been about 290 tons. The supply of this resource and the processing of it into useful tools involved expeditions to potentially hostile non-Egyptian environments and the application of the most advanced technologies of the time.

The way Egyptians worked with copper during the Pyramid Age is depicted on the walls of at least nineteen tombs, but scholars have still not reached agreement about the processes being illustrated. Jack Ogden (2000) does not consider the images, while Andreas Hauptmann (2007: 220) suggests that they may portray smelting, although the scenes show molten metal being poured from crucibles, a smelting process that was not realised before the next millennium. Hermann Junker (1958) and Bernd Scheel (1985: 128) correctly describe the scenes to be about melting and casting, but the technological details of the process were not well understood by them.

This paper aims to explain the ancient technology and discuss its origins using archaeological evidence, iconographic images, metallurgical technology and process replication. Christopher Davey has published papers about the subject for over forty years, and with publication of Martin Odler's recent tome *Copper in Egypt* (2023), it is time to draw them together into a coherent narrative. In so doing the evidence is clarified and interpretations are revisited in the light of ongoing research, and an historical context for the development of Old Kingdom metallurgy is explored.

Figure 1: *An image of a crucible being carried by a metalworker from the Fifth Dynasty tomb of Nebemakhet at Giza, drawn by James Burton in about 1824. Note Figure 9 for a later drawing. From: J. Burton, British Library, MSS 25621 (1824-39), 87, courtesy of the British Library.*

Scholarly comment has often assumed that the metallurgical processes used during the Old Kingdom were common in other periods, but that is not necessarily

Figure 2: *The Early Dynastic crucible discovered at Elkab in 2015, field registration number E15/T3/101/1, dia. 118 mm, ht 82 mm, wt 462 g. Image: © Belgian Archaeological Mission to Elkab, used with permission.*

the case. The *chaîne opératoire* is rarely the same from one period to the next as the available resources vary, the technology develops and the political, social and economic demands and constraints alter. The evidence relied on by modern scholarship also changes. The 1824 drawing of a metalworker carrying a crucible in Figure 1, for example, was later redrawn at least twice from the tomb wall with less precision because of the deterioration of the relief itself or more casual drafting (Lepsius 1842–45: pl. 13; Hassan 1943: 140, fig. 81). Scholars relying on these later works therefore do not see the details as originally portrayed by the tomb artist.

Background

Archaeometallurgy has normally focussed on the analyses of metal artefacts and slags. However, the equipment employed in metallurgical processes, which in the ancient world was often made from ceramics that sometimes appear in the archaeological record, is also valuable evidence. Indeed, the metalworking activities depicted on the walls of Old Kingdom tombs illustrate crucibles, blowpipes, hammerstones, moulds and so on. The crucible shapes shown are especially enigmatic and are not known from more recent metalworking practice.

Complete examples of such crucibles were excavated by Lamia Al-Gailani at the Isin-Larsa Period site of Tell edh-Dhibaʻi in Baghdad, where she had discovered a remarkable coppersmith's workshop (Al-Gailani 1965; Moorey 1994: 265–68). However, the visual link with metalworking practice in Old Kingdom Egypt was not made until ten years later when Davey studied the collection (1983). Al-Gailani's publication (1965) of the workshop included a report by W. Winton of the Science Museum, London, who identified the metalworking objects from photographs supplied to him. Using photographs, rather than the objects themselves, put him at a distinct disadvantage. He did not recognize one of the earliest known broken lost-wax moulds, nor the axe head pattern and core, which were the earliest evidence for sand casting, and he proposed a crucible operating system that was not possible in the Early Bronze Age. But he did identify the blowpipe nozzle and the pot-bellows, which became the subject of further studies (Davey 1979; 1988; de Jesus 1980).

The scholarly world remained sceptical about the Tell edh-Dhibaʻi crucible shape being the same as those depicted in the Old Kingdom metalworking scenes. One of the few justifications for the scepticism was immediately offered by Laurence Garènne-Marot (1985), who drew attention to the chronological difference between Tell edh-Dhibaʻi and Old Kingdom Egypt, and the fact that no such crucibles were known from Syria, or Egypt for that matter. Only the Mesopotamian archaeologist and Ashmolean Museum keeper, Roger Moorey, took the unique Tell edh-Dhibaʻi metal workshop collection seriously, referring to it as 'by far the best identification of a workshop' (1994: 265–71).

In the spring of 2015, the Elkab excavation in Upper Egypt discovered a complete crucible, Figure 2, on the floor of a Second Dynasty building that had the shape and size of the Tell edh-Dhibaʻi crucibles, and those depicted in the Old Kingdom tomb scenes (Claes et al 2019). The unearthing of such an object in a well-defined locus in a metalworking precinct of a major Old Kingdom Egyptian town may have been expected to decide the matter. However, according to Odler 'conclusive evidence is yet to be found' to confirm that metal workshops used these crucibles as depicted (2023: 276). This paper

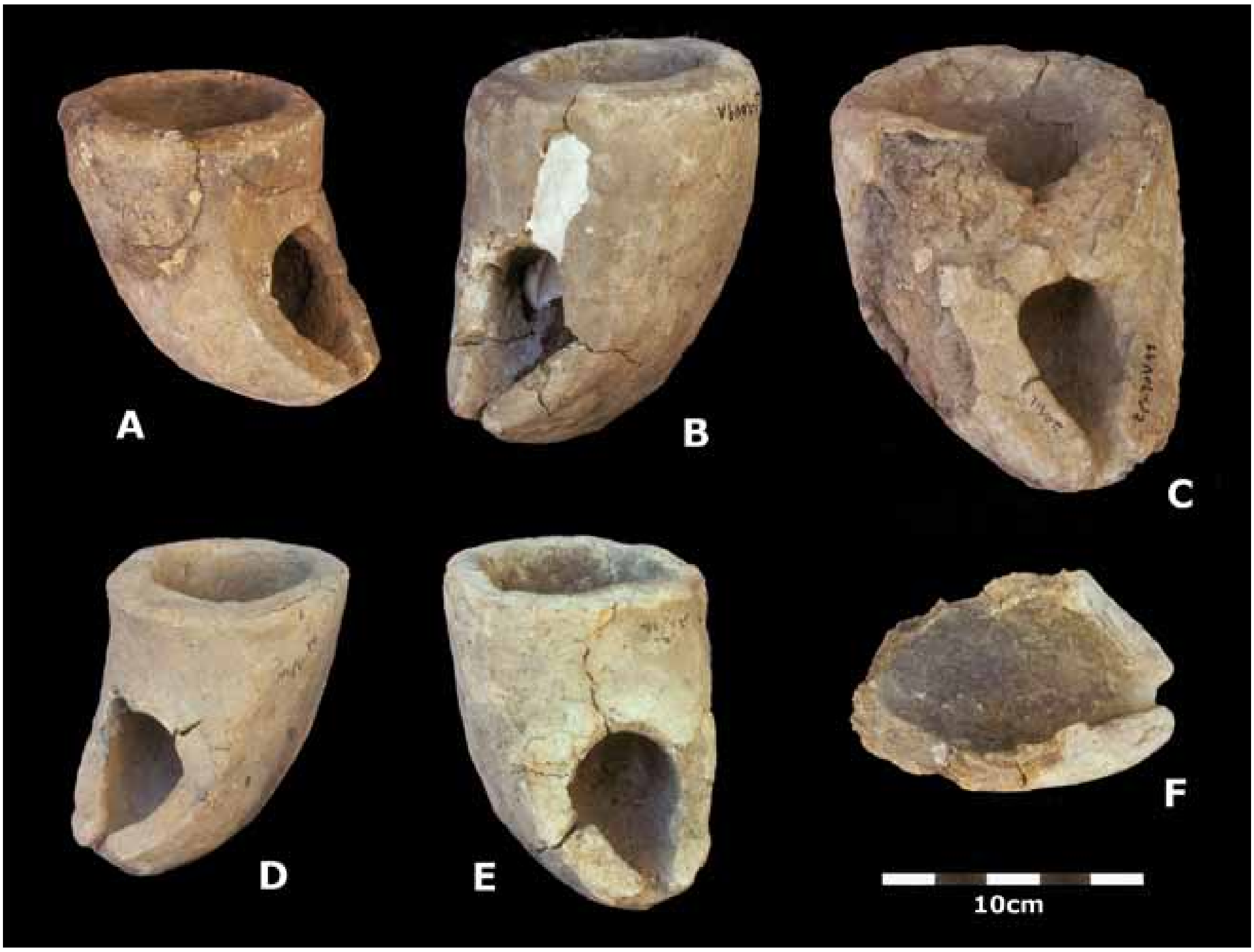

Figure 3: *The five crucibles and one crucible fragment found at Tell edh-Dhiba'i: A. 614/3 (IM65797) 100 dia. x 110 ht; B. 614/4 (IM65798) 110 dia. x 150 ht; C. 614/5 (IM65799) 130 dia. x 140 ht; D. 614/6 (IM65800) 90 dia. x 110 ht; E. 614/7 (IM65801) 100 dia. x 120 ht; F. 614/8.*

addresses the technological issues of Old Kingdom copper metalworking, while another paper will offer translations of the texts associated with the tomb metal melting scenes, to suggest that the evidence is convincing (Ockinga & Davey, In preparation). One impediment to the understanding of Old Kingdom metalworking has been the enigmatic and asymmetric shape of crucibles used at that time. A three-dimensional rendering of the Elkab crucible may be found at https://aiarch.pedestal3d.com/r/bNp8ThcV9o?studio=true.

The crucibles from Tell edh-Dhiba'i

Five complete crucibles and one fragment were discovered at the Isin-Larsa period site of Tell edh-Dhiba'i, Figure 3 (Davey 1983). The collection provides a comprehensive introduction to the fabrication, operation and life cycle of this type of crucible. While the external dimensions of the crucibles vary, the internal sizes and shapes are uniform, revealing that the crucibles were made over two similar horn-shaped armatures. Crucibles A and D appear to be unused. They are made from a coarse clay fabric levigated with straw, which was burnt out when they were fired to about 700^{o}C, producing an open and heat resistant ceramic. The thick evenly coloured ceramic section of Crucibles B and C indicates that they were made from sun-dried clay. Crucible C has 3 cm thick walls and the sloughing-off of the ceramic is a further indication that it was made from sun-dried clay. Crucible F fragment reveals that when this crucible type fails, it forms a shape that has the appearance of a broken bowl-shaped crucible.

Crucible E had been used extensively: it was very fragile and was nearing the end of its useful life. The repeated melting of copper (1080^{o}C) had produced a friable white silica-rich ceramic around its front opening and on its internal base. If it had broken, it may well have formed the shape of Crucible F fragment. Later experiments with replicas of this type of crucible confirmed that this was the normal failure pattern (Davey & Edwards 2007).

In summary, the information derived from the Tell edh-Dhiba'i crucibles was that the:

- crucibles will not retain a liquid when upright,
- seat of the fire was inside the crucible,
- crucibles were used repeatedly until they failed,
- crucibles tended to fail by breaking horizontally across the lower section,
- crucibles were made from a refractory and insulating but weak ceramic,

Figure 4: *A map of sites referred to in the paper. Map base: from Google Earth.*

- new crucibles were fired lightly to about 700°C or were made from a thicker sun-dried clay, and
- crucibles had a common internal size and shape, indicating that they were made over a horn-shaped armature.

The creation and operation of these crucibles required expertise and skilful manipulation, which must have been acquired from by a well-defined craft tradition. That tradition appears to be depicted in several Old Kingdom tomb reliefs. Davey's publication of the Tell edh-Dhiba'i collection (1983) drew specific attention to the metalworking scene from the Sixth Dynasty Tomb of Mereruka at Saqqara as an exemplar for the operation of this type of crucible.

Evidence from tomb images

From the Fourth to the Sixth Dynasties, a period of about 150 years, nineteen Egyptian tombs from Giza to Luxor are known to have images portraying metal working (Davey 2012). The scenes are not very common when compared to the large number of decorated tombs from that period. Some scholars have argued that the images were copied from a pattern book, and that there is no evidence that tomb scenes were a realistic record of contemporary Egyptian society (Malek 1999: 128). Yet, in this case the tomb artists drew crucibles of an enigmatic shape, then known only in Old Kingdom Egypt, on tomb walls once every decade or so. If these scenes were in a pattern book, they should be far more common.

The completeness and physical condition of the metalworking scenes vary. Five nearly complete series of scenes are shown in Figures 5, 9–12. The Sixth Dynasty Tomb of Mereruka, the vizier to king Teti, at Saqqara has a complete metalworking sequence, showing weighing, melting, casting and hammering, Figure 5. The sequence is left to right and begins with the weighing of the metal feedstock by a balance operator, and the recording of the result by the *Overseer of the Workshop*, *imy-r pr* (Hannig 2003: 96). Above the next three scenes are images of metal vessels illustrating the products that were to be made from the metal sheet being manufactured by the metalworkers; there is no ambiguity about the intention of the *chaîne opératoire*. It is significant that the Old Kingdom metalworking tomb scenes portray the making

Figure 5: *The metalworking scene on the East wall of Chamber A3, the Sixth Dynasty Tomb of Mereruka. Image: the author, see also Prentice Duell (1938: pls 29–33) and Naguib Kanawati et al. 2010 (pls 20–21, 74–75).*

Figure 6: *The Melting Scene, Tomb of Mereruka.*

Figure 7: *The Casting Scene.*

of metal sheet for the fabrication of prestige vessels, and not the casting of metal tools for tomb construction.

The melting scene, Figure 6, has six operators pointing their blowpipes at the front openings of two crucibles. The fire was inside the crucible, not under it. The crucibles have a profile similar to those found at Tell edh-Dhiba'i, and are in upright positions placed back-to-back with a lid on top of them. The lid retained heat within the crucibles and regulated the oxidising-reducing atmosphere in them. The operators had one hand by their mouths to cover the blowpipe orifice as they drew breath. Three operators exhaling in succession would have generated a fairly constant air stream. The disjointed portrayal of the operators' legs is probably meant to indicate that they were very close together, so that their blowpipes could be aimed directly into the crucible.

The casting scene, Figure 7, has a metalworker carrying the crucible at knee height with the aid of two wads of something like damp clay. A second metalworker pokes the hole in the front of the crucible and a stream of molten metal pours out. Some modern observers find this scene hard to believe, but other tomb scenes, Figures 9–12, depict the same practice. The crucible was made from an insulating fabric and the seat of the fire was inside at its base, so that the external temperature of the upper body of the crucible was probably less than 200^{o}C, a temperature that could be managed with the aid of insulating pads. Most representations show the crucible in profile, and the hands holding it, in front view. This convention portrayed explicitly the crucible profile and the carrying technique.

All of the scenes show crucibles being used in an upright position so, to hold a liquid, they needed a barrier near the spout, Figure 8. The depiction in the Tomb of Mereruka casting scene of a metalworker poking the crucible to dislodge the barrier and to let the molten metal discharge confirms that this was how the crucibles were used. This approach was adopted in the publication of the Tell edh-Dhiba'i workshop tools (Davey: 1983), and contrasted with the earlier tipping proposal by Winton (Al-Gailani 1965). The barrier could only partially cover the hole in the front of the crucible, as there had to be space above it to aerate the fire inside. This limited the amount of copper that could be contained in the crucible to about 50 ml, an amount that was manageable by people using blowpipes and no protective equipment. Experiments have shown that the operation of the barrier was not straightforward, but it did skim off dross and charcoal floating on the metal surface, which would otherwise have spoilt the

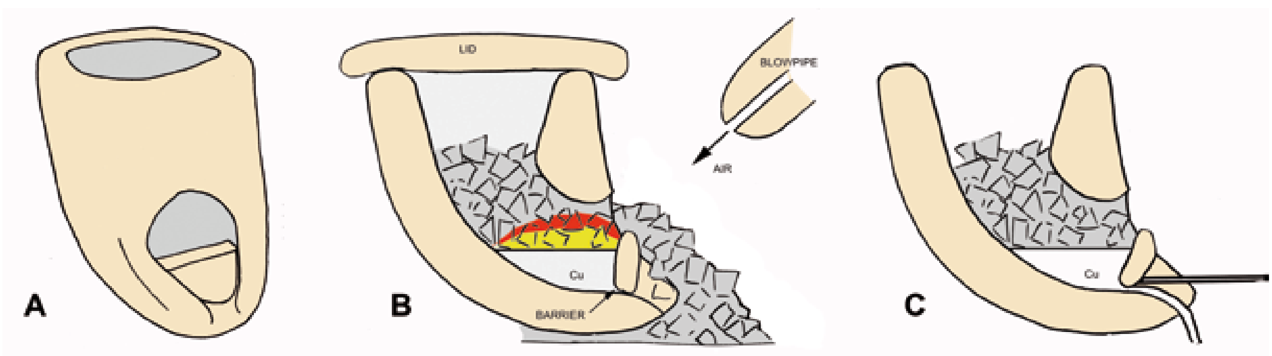

Figure 8: *A drawing of the proposed operation of an Old Kingdom crucible showing the configuration of the blowpipe, copper charge, charcoal and the barrier. A. General view, B. Melting, C. Casting.*

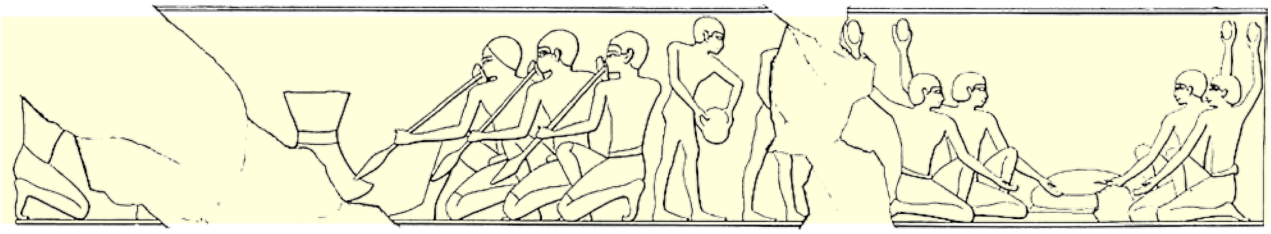

Figure 9: *The metal working scene from the Fifth Dynasty tomb of Nebemakhet at Giza, but note Figure 1. From: Lepsius (1842–45: Text 2, pl. 13).*

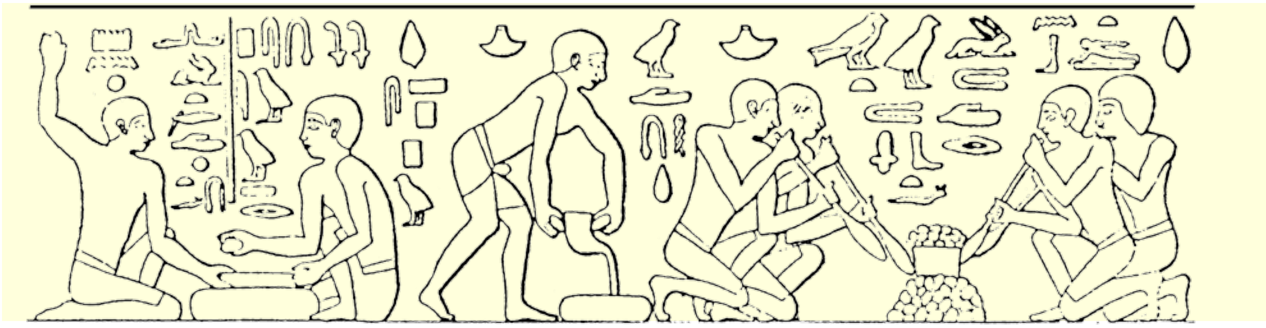

Figure 10: *The metal working scene from the Fifth Dynasty tomb of Wepemnefert at Giza. From: Hassan (1936: fig. 219).*

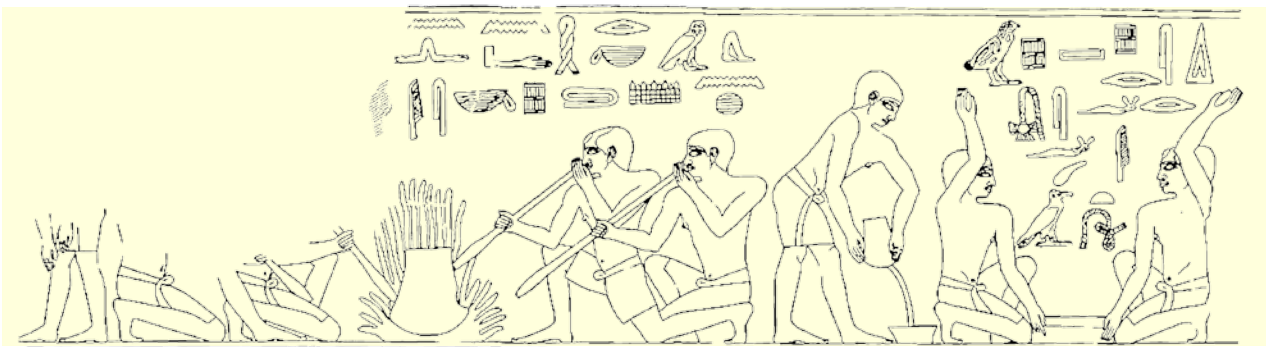

Figure 11: *The metal working scene from the Fifth Dynasty tomb of Ty at Saqqara. From: Wild (1966: fig. 173).*

Figure 12: *The metal working scene from the Sixth Dynasty tomb of Pepyankh: Heny-kem at Meir. From: Blackman and Apted (1953: pl. 16).*

casting (Davey & Edwards 2007). The crucible operating configuration at Tell edh-Dhiba'i proposed by Davey (1983: fig. 6) was devised to incorporate the pot-bellows, but subsequent research has led him to question some aspects of that reconstruction.

The tomb scenes show that the molten metal was not poured into a mould, but onto a flat surface where it flowed out and, as depicted in the fourth scene Figure 5, was hammered as it cooled to form a sheet of approximately 20 cm diameter and 1.5 mm thick. The shape of this sheet may have been the origin of the ‘drop’ hieroglyphic ideogram, X3-like, one of the two signs for copper, metalworker and crucible (Odler 2023: 78–79). The other signs were the profile of the crucible, N34, or double crucible, W13. It should be noted that the Gardiner Sign list misidentifies these signs (Junker 1958; Davey 1985; Odler 2023: 67–96).

None of the metalworking depictions are identical, however it is possible to identify consistencies and to explain most variations, Figures 9–12. All metal working scenes show that the blowpipes were directed at the front of the crucible to ventilate the seat of the fire above the metal charge inside the crucible, not under it. All scenes have two or three blowpipe operators. Some of the scenes show the crucible being carried and the molten metal being discharged from about knee height onto a flat surface, where it was hammered into a sheet.

The differences in the depictions from one tomb to another are also significant. The ‘furnace’ in Nebemakhet, Figure 9, is comprised of two back-to-back crucibles similar to that of Mereruka, except that the cover has a different shape, which is not dissimilar to an inverted Clayton ring (Bobrowski & Mączyńska 2020) (https://artsandculture.google.com/asset/a-desert-enigma-clayton-rings/-QGps3wj7Ps5IA). The Wepemnefert scene, Figure 10, shows the crucibles surrounded by charcoal. This depicts what an observer would have seen, and is a *Realistic* style, rather than the *Technical* or *Didactic* style found in the tombs of Mereruka and Nebemakhet, where the coals were stripped away to reveal the back-to-back crucibles that formed the furnace (Davey 2012: 95). The furnace in the tomb of Ty, Figure 11, has what appears to be flames coming from the crucibles. This is a third style of depiction, which may be called *Naturalistic* because it conveyed the atmosphere of the environment; in this case the ‘flames’ indicate that the crucibles were radiating heat, not that the fire was under the crucible. Many later metal working scenes adopt the Naturalistic style.

The scene in the tomb of Pepyankh, Figure 12, shows quite a different shape of crucible. It is proposed that this crucible was made from sun-dried clay and, like the sun-dried clay crucibles at Tell edh-Dhiba‘i, it had an internal shape like most Mereruka-shaped crucibles, but it was bulkier. Such a design had advantages but was less portable. This is a Realistic style of depiction. The portrayal of the metal workers hammering is also notable. Both Realistic style scenes, Wepemnefert and Pepyankh, depict one person with the hammering hand-held high while the other person was about to strike the metal, showing that they were operating reciprocally, taking it in turns to strike. This is in contrast to the Technical style in the tombs of Mereruka and Nebemakhet, which show all foundrymen with their hammering hands above their heads, indicating the hammering stroke was the maximum possible extent.

To explain the rationale behind the use of a crucible that would not normally retain a liquid, it was proposed that the primary function of the crucibles was the refining of slag-rich copper concentrate that derived from the low-temperature and inefficient smelting process used at that time (Davey 2018). John Merkel (1983; 1990) explored this aspect of metallurgy in a New Kingdom context. However, the absence of slag in the crucibles from Elkab and Tell edh-Dhiba‘i indicates that these crucibles were not used for slag-rich copper. Instead, it seems that the hole in the front of the crucible enabled the process to be monitored so that casting could be carried out as soon as the metal melted, thus conserving charcoal by not generating unecessary heat, and minimising the oxidation of copper and the loss of useful impurities such as arsenic.

A metalworker image and statue

A sketch from the burial chamber of the Fifth or Sixth Dynasty Tomb of Ka-em-ankh in the West Field at Giza provides more evidence, Figure 13 (Junker 1940: 72–75, pl.10: PM III/[2]131–33; G4561). It depicts a single metalworker with a blowpipe ventilating an upright crucible that appears to have a ‘Mereruka’ shape (Davey 2009: 42, fig. 4; 2012: fig. 6). The blowpipe is directed toward the front of the crucible, which according to the accompanying inscription contained copper. The simple outline conveys the appearance, atmosphere and energy of the scene. The figure was drawn from a three-quarter view, which contrasts with the traditional frontal and profile views of Old Kingdom Egyptian art. This image would not have appeared in a pattern book and reveals that the tomb artists were skilful draftsmen who had the capacity to draw from the reality that they knew.

***Figure 13:** An ancient sketch of a metalworker in the Fifth or Sixth Dynasty Tomb of Ka-em-ankh at Giza. From: Junker (1940: 72–75, pl. 10).*

Figure 14*: The small servant statue of a metalworker in the University of Chicago's Institute for the Study of Ancient Cultures Museum, OIM 10631, ht 110 mm, l. 100 mm, w. 50 mm. Courtesy of the Institute for the Study of Ancient Cultures, The University of Chicago.*

The collection of late Fifth or Sixth Dynasty servant statues probably from Giza and now at the University of Chicago's Institute for the Study of Ancient Cultures contains a small statue of a metalworker (Davey 2009). The collection was acquired in 1920 and published by James H. Breasted jnr (1948). The metalworker is operating a blowpipe, which is directed at the front opening of a 'Mereruka' shape crucible, Figure 14. The small statue is painted and shows the area around the tip of the blowpipe, which is almost inside the crucible, to be bright red, indicating that it was hot, Figure 15. The statue provides a 3D representation of the 'Mereruka' shape crucible and operator.

It is significant that the statue portrays the crucible to be tilted backward. From the time that these crucibles were first encountered by Al-Gailani and Winton, this was deemed to be the logical way to use them. However, all depictions of the crucible, other than this statue, show the crucible being used in an upright position. It was therefore suggested that the tomb scenes show the melting of copper for the fabrication of prestige vessels, while the small statue represents the common way that Old Kingdom metalworkers melted copper and recycled copper to produce tools (Davey 2009). Hundreds of tonnes of copper were cast and recast into tools and the most efficient way to do that was to use the 'Mereruka' style crucible, which concentrated the heat, conserved charcoal, and facilitated the pouring of the molten metal. It was also suggested that this form of crucible developed into the shape that is well known from the First Intermediate Period and Middle Kingdom, where the hole in the front was retained, but the base was formed into a bowl, Figure 19 Crucibles D–F, so the crucible could retain a liquid (Davey: 2009).

Figure 15: *Crucible detail of the small servant statue of a metalworker, OIM 10631. Courtesy of the Institute for the Study of Ancient Cultures, The University of Chicago.*

Egyptian Old Kingdom crucibles: Elkab and Elephantine

In the spring of 2015, the excavation at Elkab in Upper Egypt sponsored by the Belgian Archaeological Mission of the Royal Museums of Art and History in Brussels, discovered a complete crucible of the shape and size of the Tell edh-Dhiba'i crucibles and those depicted in the Old Kingdom tomb scenes, Figures 2 & 19 Crucible A. It was discovered upside down on the floor of a Second Dynasty building with a collection of other objects (Claes et al. 2019). The crucible had been used and was still operable when it was left where it was found nearly five thousand years later. Radiocarbon dates of associated material between 2850 and 2536 BC confirm the Second Dynasty date. It is not clear why the crucible was not retrieved from the debris of the collapsed building, as it was a valuable piece of equipment for metalworkers.

The crucible has fragments of copper on the base, indicating that it had been used in an upright position as portrayed in the tomb scenes. It has no slag or vitrified ceramic inside it.

***Figure 16:** Smelter feed from Elkab. The sample consists of green malachite in a quartz host rock with a brown mineral formed from decomposed pyrite-arsenopyrite. Courtesy of the Belgian Archaeological Mission to Elkab, used with permission.*

The assemblage found with the crucible included a stone pounder (E15/T3/102), a small cup (E15/T3/100/1), a Clayton disk (E15/F-06), a fossilized aurochs axis vertebra (E15/T3/99), an oval ceramic vessel (E15/T3/97/1) and a quartz pebble, which together with the metalworking context are significant (Claes et al. 2019: 36 fig. 8). The Clayton disk may have been a lid for the crucible used to regulate the oxidising-reducing conditions in the crucible. These objects are well-known from the Western Desert and Western Sudan, where there is little or no metallurgy, so it is unlikely that there was a long-term dedicated relationship between the two object types (Riemer & Kuper 2000; Claes et al. 2019: note 27). It is interesting that a Clayton disk was also found at Elephantine (Kopp 2006: pl. 29 no. 459). The vertebra may have been used as a support for the crucible. Also found in the vicinity of the building containing the assemblage were small chunks of malachite, possibly smelter feedstock, Figure 16, and a copper-slag piece of smelter product, Figure 17. These offer potentially important analyses.

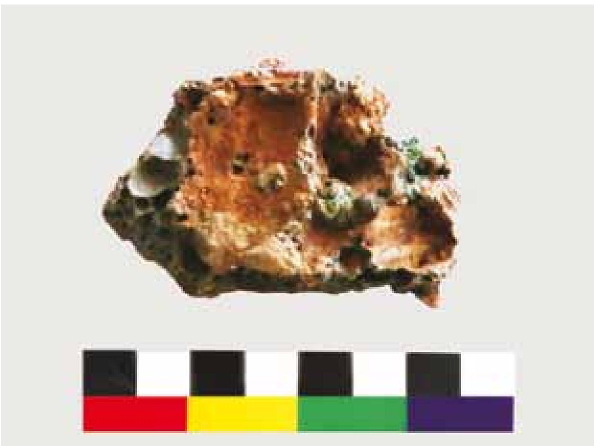

***Figure 17:** Smelter product from Elkab. Prills of copper encased in slag. This would have been ground up to separate the copper from the gangue. Courtesy of the Belgian Archaeological Mission to Elkab, used with permission.*

The German Archaeological Institute excavations at Elephantine discovered a crucible fragment in a First Dynasty industrial context, Figure 18 (Kopp 2006: 32, fig. 12). Although comparatively large, it does conform to the profile of a broken 'Mereruka' crucible type, Figures 18 & 19 Crucible B. Indeed, when publishing it, Peter Kopp referenced the Mereruka metalworking scene. Odler's description of it as an open bowl crucible fragment is incorrect (2023: 269). This find is important because it reveals that the technology later depicted in Old Kingdom tombs was in the Nile Valley from the beginning of Dynastic Egypt. It also raises the possibility that metalworking may have influenced the unification of Egypt.

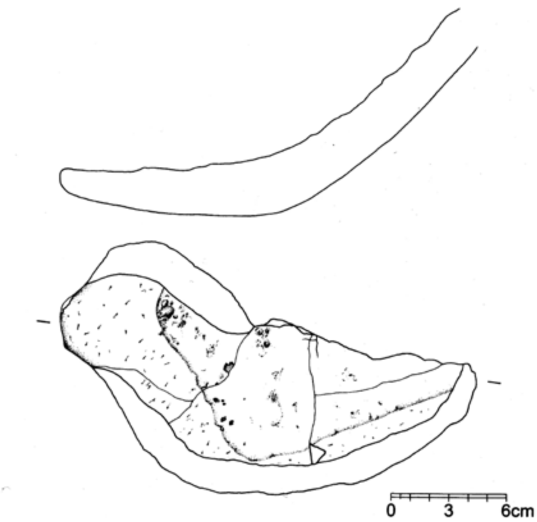

***Figure 18:** The First Dynasty crucible fragment found at Elephantine. From Kopp (2006: fig. 12).*

Process replication

Two series of experiments using replicas of Mereruka style crucibles and copper were conducted, the first at the Royal Melbourne Institute of Technology and the second at the Australian Institute of Archaeology (Davey & Edwards 2007). The crucibles were made by shaping a sheet of clay over a horn-shaped pattern, Figure 20.

The first series of experiments failed to operate the crucible effectively. The barrier became welded to the body of the crucible, revealing the importance of using refractory clays that do not vitrify easily, and to conduct

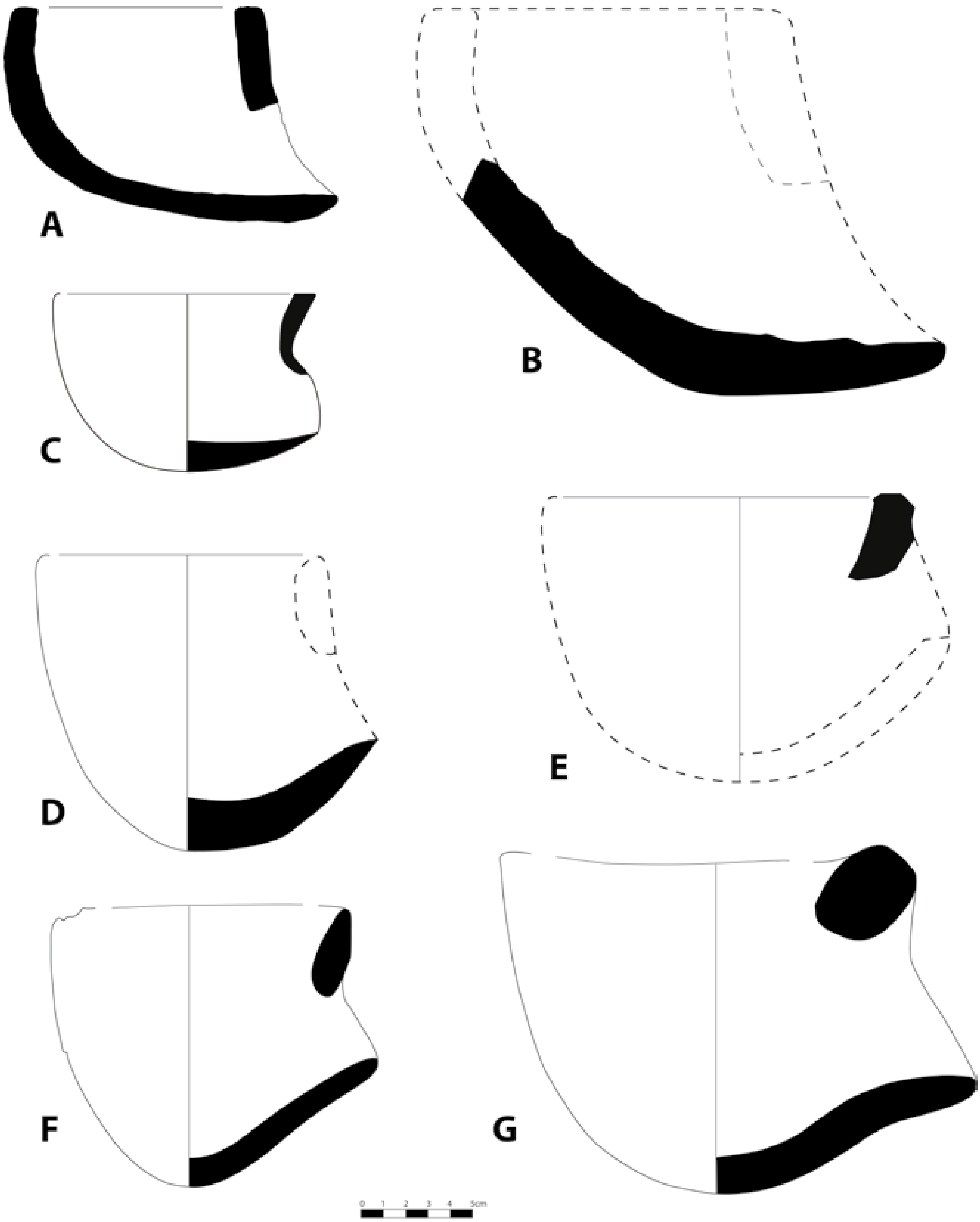

Figure 19: *A number of different crucible shapes showing the change from the Old Kingdom through to the Middle Kingdom. Crucibles A, B and C required a barrier to enable to the crucible to retain a liquid. Crucibles from the First Intermediate Period and after (D, E, F, and G) could retain a liquid without a stopper. A. Elkab E15/T3/101/1, after Claes et al (2019: Fig. 2); B. Elephantine, after Kopp (2006: fig. 12; reconstruction C.J. Davey); C. Buhen, UC 188.2, after Emery and Kirwan (1935: pl. 14.xxii); D. Buhen, UC 21748, (drawing: C.J. Davey); E. Ayn Soukhna Crucible no. 4, after Abd el-Raziq et al (2011: fig. 133); F. Badari, UC 18146, after Davey (1985b: fig. 1.5); G. Serâbîṭ el-Khâdim, Sinai, UC 8901, after Davey (1985b: fig. 1.6).*

Figure 20: *The forming of the crucible using a horn-shaped pattern. From Davey and Edwards (2007).*

the melting quickly to limit the propagation of heat throughout the crucible. Attempts to remove the barrier broke the crucible forming the shape of the Tell edh-Dhiba'i crucible fragment F, Figure 3.

The second series was conducted with a faster and more focussed jet of air and the use of cow dung to secure the barrier, Figure 21. A stream of air was supplied mechanically through a nozzle and the internal temperature was measured by a thermocouple. The copper charge was melted and poured out after the barrier was dislodged.

The time-temperature graph is significant, Figure 22. Charcoal was an excellent fuel, raising the temperature to 900°C after about eight minutes. It then drifted for twenty-two minutes, before rising to 1100°C, where it again levelled out. The crucible had been previously fired to 900°C, completing all ceramic reactions associated with that temperature range. So when it was heated up to that point it did not absorb very much heat, however, as the temperature rose above 900°C the crucible ceramic required a significant amount of heat to drive a reaction involving the dehydroxification of the clay. This is an endothermic reaction, and once completed in the ceramic adjacent to the metal charge, the temperature rose quickly again until it reached the melting point of copper (1085°C). The reaction in the ceramic is irreversible, so that when the crucible was used again, it did not need the extra heat associated the reaction in the ceramic. Ancient crucibles that had been 'broken-in', so to speak, required much less heat and were therefore reused until they disintegrated. They were valuable pieces of equipment for metalworkers, with whom they were always to be found, so that their shape became the hieroglyphic ideogram for copper, crucible and metalworker. Some of the tomb scene inscriptions state that the crucible is new in the context of the need for increased effort from the blowpipe operators.

Figure 21: *The experimental set-up showing the blowpipe nozzle directed into the crucible over the barrier with the thermocouple displaying a temperature of 1140°C. From Davey and Edwards (2007).*

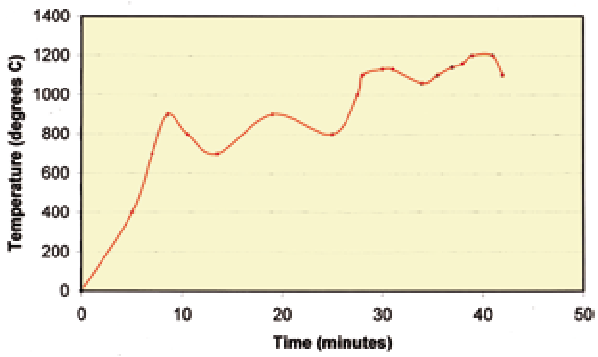

Figure 22: *The graph of the temperature in the crucible during the firing. From Davey and Edwards (2007).*

The historical context

The earliest known copper artefacts in Egypt come from the site of Maadi, located in the southern suburbs of Cairo. Quantities of malachite, copper objects and ingots were found in an archaeological context dated by radiocarbon to 3,800–3,400BC (Rizkana & Seeher 1989: 13–18; Hauptmann 2017; Odler 2023: 119, 265–67). Analyses, overseen by Hauptmann, revealed that the copper ingots at Maadi were very pure, having little arsenic, and could have come from orebodies in the Wadi Arabah at Wadi Faynan, Timna or Wadi Amram, or in south-western Sinai (Hauptmann 2017: 154). Kristina Pfeiffer (2013: 321–23) has described casting moulds from the Chalcolithic settlement of Tell Hujayrat al-Ghuzlan, near Aqaba in the Wadi Arabah, which had a shape that could have produced the ingots found at Maadi revealing a potential link between the two places. At the time there were wide ranging contacts between Egypt and the southern Levant (Klimscha 2011).

The ingot-mould link between Maadi and Tell Hujayrat al-Ghuzlan does not necessarily mean that there was a direct relationship between the sites, although that seems likely (Hartung 2013: 185), but it does show a potential link between Egypt and the technology used in the southern Levant. Pfeiffer (2013: 308) found that crucibles used at Tell Hujayrat al-Ghuzlan, Tell al-Magass, Wadi Fidan 4 and Abu Matar had a range of sizes, and consisted of flat round bowls with sockets to facilitate their manipulation with rods. No crucibles of this shape have been found in Egypt, nor is there any evidence of Mereruka shape crucibles in the southern Levant in the fourth millennium.

Ulrich Hartung (2013: 187) suggests that it was the more extensive trade connections at the start of the Early Bronze Age that facilitated the transfer of technologies, such as metal processing and the potter's wheel, to Egypt. Anfinset (2010:167) sees a dramatic change in Egyptian copper usage associated with Nubia at that time. David Wengrow's assessment that 'there is no direct evidence of metallurgical knowledge in Egypt until the later fourth millennium' (2006: 32) continues to hold true. He notes that in the southern Levant metallurgical industries restructured at the beginning of the Early Bronze Age with a separation of mining and manufacturing processes (Wengrow 2006: 39), but does not speculate on the reasons for the reorganisation, which may have been driven by increasing production, the economics of fuel and manpower, and issues of control and security. Despite this, there is no apparent metallurgical technology link between Lower Egypt and the southern Levant at the beginning of the Old Kingdom.

Egypt's involvement with metals also appears to have been restructured at this time. To envisage what happened it is necessary to review the copper working *chaîne opératoire*. During the third and fourth millennia it seems that smelting was conducted at comparatively low temperatures. Experiments have shown that at the Middle Kingdom harbour and smelting facilities of Ayn Soukhna on the Red Sea coast, smelting was probably conducted at about 900^{o}C, using a combination of green wood and donkey dung as a fuel, and natural ventilation (Verly et al 2021), so it is unlikely that smelting was carried out at higher temperatures in the Old Kingdom and before. Smelting produced prills of copper encased in slag, as shown in Figure 17, that needed to be crushed to separate the more dense copper grains from the less dense slag with wet gravity separation. The process produced no chunks of slag and would appear to have been 'slagless' smelting, something that scholars have puzzled about (Hauptmann 2007: 149). The lack of slag for the third millennium and before has limited the study of early smelting.

The granular copper was then melted, refined and cast using a crucible in the manner illustrated in Figure 8. Any impurities floating on the surface of the molten metal would have been held back during the cast by the barrier. Crushing the ore in preparation for smelting was probably part of the mining process used at that time, but after that all activities could be conducted elsewhere. As production increased, it would have been advantageous to relocate processes requiring fuel and manpower to centres of population. The Mereruka style crucibles at Elephantine and Elkab and the evidence of smelting at Elkab, would indicate that smelting was established in the Nile Valley by the Second Dynasty.

Arsenical copper

Not only did the operating structure of metal production change, but also the metal itself. The prevalence of arsenical copper in Old Kingdom Egypt has long been recognised (Goresy et al 1995). Odler (2023: 5, 303–8) found that arsenical copper occurs at nearly all Egyptian sites, metal weapons tended to have less arsenic than vessels, while mirrors had more. The copper being used at the time must have either come from orebodies that also contained arsenic, or arsenic was added during processing. Alternatively, arsenic may have been added in the form of orpiment or realgar during melting and casting (Coghlan 1951: 79). Both pigments were known in Egypt, but their use in the Old Kingdom has not been confirmed (Lee & Quirke 2000). In ancient Near Eastern studies, an arsenic content of over 5% is deemed to indicate a deliberate addition (De Ryck et al. 2005: 266), but Odler (2023: 304) argued that the lack of arsenic in the copper orebodies he identified to have been mined by Egyptians meant that the amount was much less for Egypt. However, as this was an early stage of metallurgical development, alloying is less likely to have been practiced. Instead, it is probable that ores from different locations were selected because they were known to deliver products with desirable properties or to have had advantages in processing.

The reasons for the use of arsenical copper rather than pure copper appear to be both aesthetic and practical (Chen 2021). Arsenic gives a silver lustre to copper, which would otherwise be reddish in colour, making it a luxury fashion item in many ancient Near Eastern cultures, including Egypt. Mirrors made from polished copper-arsenic alloys typically contained over 5% arsenic. Arsenical copper also has mechanical properties superior to pure copper (Charles 1967).

Experiments have investigated the processing of copper-arsenic ores. Paul Budd (1993) described experiments by a colleague, Richard Thomas, in which malachite and weathered sulphides containing arsenic were smelted at temperatures as low as 700^{o}C to produce arsenical copper. The experiments also showed that, with an increase in smelting temperature, arsenic diffusion into the copper increased. Smelting under 900^{o}C produced copper with 1–2% arsenic, but when temperatures approached 1000^{o}C, arsenic concentration in the copper could rise to over 5%. Heather Lechtmann and Sabine Klein also conducted co-smelting experiments with copper sulpharsenide ores, and showed that the process was uncomplicated and could be carried out without roasting and fluxes (Lechtman 1999). These experiments illustrate how arsenical copper objects could have been produced without alloying.

A number of comments can be made in relation to the metallurgical processes taking place during the refining and casting of the copper arsenic alloys obtained from the previously smelted ore.

Margrit Junk (2003: 21) drew attention to the copper-arsenic equilibrium phase diagram, which shows that the temperatures at which the metal is completely liquid (liquidus) depend on the bulk composition of the alloy and, for the range of compositions relevant to arsenical copper used in Old Kingdom in Egypt, decrease with increasing arsenic concentration. The solubility of arsenic in the solid copper phase also increases as the temperature decreases. As a result of these properties, the castability of the Cu-As alloy is increased relative to pure copper since the range of temperatures at which the alloy is fully liquid is extended to lower temperatures. This means the liquid metal is present at these lower temperatures and will continue to flow and spread to greater distances on casting before solidification is complete. Further, under the rapid, non-equilibrium cooling conditions encountered in this application, although the instantaneous arsenic concentration of the solid formed increases as the temperature decreases, there is insufficient time for the previously formed solid to completely equilibrate to the new conditions. In effect, less arsenic is present in the solids than predicted from the thermodynamic equilibrium. These non-equilibrium cooling conditions mean that the liquid ahead of the moving solid/liquid interface becomes progressively enriched with arsenic as solidification proceeds and the temperature for complete solidification is further lowered. In the case of copper – arsenic alloys, depending on the initial alloy composition and the cooling conditions, the liquid phase may still be present as low as the eutectic temperature at 685°C with the liquid composition of approximately 21wt% As and result in the formation of the solid Cu_3As phase in addition to the copper metal (Shishin and Jak 2018). The rejection of excess arsenic into the liquid phase will also lead to what is termed 'constitutional undercooling' and the growth of the solid metal phase in the form of cored dendritic (tree-like) structures as solidification proceeds. These microstructures are exemplified in the samples of cast Cu-As alloys produced in the studies by Junk (2003), Modlinger (2018) and Sabatini (2020).

Solidification of the alloy takes place progressively as heat is extracted from the melt and progresses in directions directly opposite to the heat flow. The first solids will form as the liquid contacts the cold solid mould surface. The bulk of the melt would at this time still be liquid and able to flow. The process depicted in the tomb images shows the molten metal is poured onto a flat mould surface. The extent to which the charge spreads over the mould surface will depend principally on the temperature of the liquid metal on casting, the bulk composition of the alloy and the horizontal momentum imparted to the fluid as it is released from the crucible. Clearly, the greater the area over which a given mass of molten metal is spread the thinner will be the cast sheet produced and the saving in the amount of the mechanical work required to prepare the metal sheet. The Egyptian metalworkers performed all tasks manually by hammering, and so even small benefits from using arsenical copper would have been most advantageous.

The combustion of charcoal provides the heat to melt the copper-arsenic alloy charge. The presence of excess charcoal in the crucible is also beneficial, since this reduces the effective oxygen activity and the concentration of oxygen dissolved in the liquid metal, thereby lowering the probability of formation of metal oxide inclusions in the material when casting. These inclusions are undesirable, since they reduce the strength of the final product and potentially influence the quality of the surface finish attainable: both factors would be important for the production of sheet materials, in particular alloy mirrors. The presence of the reducing conditions in the crucible would also reduce the production of arsenic oxide in the gas released in the process reducing the impact on the health of the metalworkers.

Old Kingdom copper sources

Knowing the sources of the Old Kingdom's copper arsenic ores may help locate the origin of the Mereruka crucible type. Finding the origin of the arsenical copper used during the Old Kingdom is, however, problematic according to Odler (2023: 151):-

> *The study of provenance suffers from the lack of data on ore bodies in Egypt and Sudan. The Sinai Peninsula is best represented, but the geologically rich Eastern Desert woefully lacks substantial data.*

Odler (2023: 106) is dismayed that the surveys of the Eastern Desert in 2006 and 2008 by a joint Egyptian-German team only collected eleven ore samples from the region, none of which contained significant arsenic (Abdel-Motelib et al. 2012). In particular, Odler concentrates on the mining area of Wadi Dara as a possible source of arsenical copper, although the ore sample taken from the area by the Egyptian-German team did not contain significant arsenic. Archaeological work in the Wadi Dara in 1989–1996 is yet to be published (Odler 2023: 109–14). Preliminary reports indicate that the mines, crushing facilities, furnaces and huts are substantial, and that there are many metalworking related artefacts dating from the Naqada III and Early Dynastic periods onward (Grimal 1993: 482–88; 1994: 423–34; 1996: 570–72). Earlier archaeological work at Wadi Dara was reported by Georges Castel et al (1993). There was also significant Old Kingdom copper mining at nearby Wadi Umm Balad and Wadi el-Urf (Castel et al. 1998; Klemm & Klemm 2013: 56–68). The areas are geographically and chronologically appropriate to be associated with Old Kingdom metalworking technology, but arsenic is not reported to be in the ores, although surveying has not been comprehensive.

Figure 23: *The Higalig mine area looking north. The arrows indicate the line of the gold-malachite-sulphide bearing quartz reef, which runs east-west and was mined from the surface. Image: Google Earth 13-9-2023.*

A recent study by Frederik Rademakers and colleagues (2018) of lead isotope data for copper artefacts from the Royal Museums of Art and History, Brussels, and dating to the period before the Sixth Dynasty, found that there was continuity of copper supply from the Sinai and Eastern Desert. However, the joint Egyptian-German team also collected many ore samples from ancient mining areas on the Sinai Peninsula and found that they were also non-arsenic bearing (Abdel-Motelib et al. 2012). Only Wadi Tar in south-eastern Sinai is known to have copper-arsenic minerals, but the region has no evidence of prehistoric mining or of an Egyptian presence, indicating that it was outside their sphere of influence (Hauptmann 2017: 154; Odler 2023: 116). Tallet has found that Egyptian exploitation of Sinai copper deposits can be firmly dated to the beginning of the Fifth Dynasty at Wadi Kharig and Bir Nasb (Tallet 2018; Tallet & Lehner 2021: 71).

Significant arsenic is not present in copper ores from deposits in the southern Levant, such as Faynan and Timna (Hauptmann 2007: 296). The Chalcolithic Nahal Mishmar hoard contained tools made from pure copper, probably mined in the southern Levant, but the ceremonial objects were made from Cu-As-Ni alloys, suggesting that metal types were selected for aesthetic reasons. Lead isotope analysis of ten mace-heads showed that seven of them were cast from copper mined at Ergani Maden in southern Turkey, while the other three were made from copper mined in Oman (Hauptmann 2007: 30, 300). While this demonstrates that long-range trade routes existed for special copper ores, it does not provide a common source of ore for Egypt's Old Kingdom copper industry.

To Egypt's south, copper orebodies in Sudan are not well characterised. A recent study of Middle Kingdom copper objects from the site of Kerma found that they contained significant arsenic and tin (Rademakers et al 2022), but the lead isotope analyses were compatible with the south-western Sinai ore deposits rather than Sudan. These studies have been hampered by the lack of lead isotope data for orebodies in Egypt and Sudan.

Sulphide mineralisation is commonly found in association with gold in the Eastern Desert, and was sometimes identified by Rosemarie and Dietrich Klemm (2013: 146) to be arsenopyrite. With the support of geological colleagues, Odler has proposed this to be the likely source of the arsenic in Old Kingdom tools (Odler et al. 2021). Klemm and Klemm identified four Pre- and Early Dynastic mining areas in the Eastern Desert, Wadi el-Urf (Wadi Dara) in the north, Abu Mureiwat east of Qena, Bokari east of Elkab and Higalig east of Kom Ombo (2013: 603, fig. 7.1).

Higalig is the oldest mining area dating to the beginning of the third millennium, Figure 23. As it was not subject to later mining, Klemm & Klemm (2013: 268–70) deemed it to be the Pre- and Early Dynastic mine type site. An east-west quartz vein contained free gold, layers of malachite, and 'brown iron hydroxide stains, which derive from decomposition of pyrite and chalcopyrite' (2013: 270). Klemm & Klemm (2013: 146) do not normally distinguish between iron pyrite and arsenopyrite as their appearance is similar, so this is probably the source of the Old Kingdom's earliest arsenical copper ore. The Bokari mining area is about 70 km north of Higalig. It also has quartz reefs containing gold, malachite and pyrites that were mined in the Early Dynastic and Old Kingdom periods (Klemm & Klemm 2013: 183–84).

The earliest mining at Higalig and Bokari was carried out by pounding the quartz and host rock with heavy stone hammers. The smelter feed from Elkab, Figure 16, shows that the ore was broken up but not pulverised by the mining method. Klemm & Klemm (2013: 5) describe the mine openings to be smooth walled, which may indicate that a groove was first mined in the country rock (i.e. rock native to the area), and then the narrow mineralised quartz reef was broken toward it. Alternatively, they may have pulverized the ore to make a face to work to within the quartz reef. While pieces of ore would have been separated by hand-picking, finely crushed material could have been treated by wet gravity separation; the heavies, free gold, would have settled out first, thereafter the middlings, all other heavy minerals including malachite and the sulphides, would have settled next.

No dwellings were apparent near the Higalig Pre- and Early Dynastic mining area, leading Klemm & Klemm (2013: 6) to conclude that the prospecting and mining were carried out by tent-dwelling nomadic groups. The discovery of the two oldest Egyptian crucibles at Elephantine and Elkab, directly west of Bokari and Higalig, make this southernmost region of Upper Egypt a likely place for the earliest development of Egypt's copper and gold industries.

The origin of the technology is less clear. If Klemm & Klemm are correct about the presence of nomadic prospectors and miners in the Eastern Desert, they may be the origin of the expertise, although Anfinset (2010: 200) deems them to have been 'middlemen'. Miners have always been itinerant and there are traditions that ancient nomadic groups, such as the Ishmaelites, were miners. Erez Ben-Yosef argues that in a later period at Timna, nomadic people were the miners and metalworkers (Ben-Yosef et al. 2017; Ben-Yosef 2020).

These earliest Egyptian copper deposits also contained gold, and it may have been the gold that was the initial focus of mining. As free gold needs no processing other than comminution and wet separation, it is probable that gold was also melted in Mereruka style crucibles. Fifth Dynasty images on the Unas Causeway at Saqqara (Smith 1942: fig. 8) depicts Mereruka shape crucibles and the accompanying texts make it clear that it was gold being melted. The Tomb of Serfka at Sheikh Said (Davies 1901: pl. 4) also shows the melting of gold. The origin of the crucible may therefore be associated with gold rather than copper.

Not all Old Kingdom copper contained significant amounts of arsenic. The data prepared by Odler (2023: Tables 35 & 36) show that there is a similar chronological and geographical quantitative occurrence of pure copper and arsenical copper artefacts from the Naqada Period until the Second Intermediate Period. Without knowing the details of this data and the reliability of the analyses, it is not possible to comment further. It seems that Mereruka crucibles were used for all copper compositions.

The Mereruka shape crucible was used in Egypt from at least the First Dynasty (*c.* 3000 BC), as evidenced by the fragment found at Elephantine, and they are not depicted in tomb images after the Sixth Dynasty (*c.* 2250 BC). Many scholars (e.g. Odler 2023: 277) confuse these crucibles (Figure 19 A–C) with later crucibles that could retain a liquid because of their bowl-shaped bases (Figure 19 D–G). The functions of the two types seem to be different. The Mereruka shape crucible was used to cast arsenical copper into sheets for the fabrication of prestige vessels, and to melt recycled copper, and maybe gold, for casting tools. The later crucibles with bowl-shaped bases may also have been used to melt copper, but the study of one such crucible from Buhen found that it was used for high-temperature smelting (Davey et al. 2021).

While the Mereruka shape crucibles cease to be used in Egypt at the end of the Old Kingdom, they do appear in Sinai during the Middle Bronze Age, 2000–1550 BC (Beit-Arieh 1985), and of course they were used in Mesopotamia during the Isin-Larsa period, *c.* 1800 BC, for melting tin-bronze. Once archaeologists become familiar with the enigmatic shape, these crucibles may be found to have a much broader domain.

Concluding comments

The proposed *chaîne opératoire* of Pre- and Early Dynastic and Old Kingdom Egyptian metalworking differs depending on the product, whether it be prestige metal vessels or tools. For prestige metal vessels:

- mining, malachite and arsenopyrite, initially at Higalig or Bokari, then elsewhere in the Eastern Desert,
- crushing, if necessary, and hand-picking to separate gold and copper-arsenic ores,
- wet gravity separation, of the fines to produce gold and malachite-sulphide concentrate,
- smelting, copper-arsenic ore and malachite-sulphide concentrate, initially in holes in the ground and later in furnaces using wood and animal dung as fuel,
- comminution, of the smelt product and wet gravity separation to produce copper-arsenic alloy granules,
- melting, the copper-arsenic alloy granules in Mereruka shape crucibles using charcoal as fuel,
- casting, arsenical copper onto a flat surface to produce a metal sheet,
- hammering, the sheet to be 1–1.5 mm thick,
- fabricating, vessels mechanically from the sheet metal using annealing, welding on, etc.

The proposed *chaîne opératoire* for tools is the same as for producing prestige vessels, except that it was often copper, rather than arsenical copper, that was treated and:

- mining, malachite in the Eastern Desert, at sites including at Wadi Dara, and later in Sinai,
- casting, into open moulds,
- mechanical forming, sharpening, and work-hardening of tool blades.

Given the lack of reliable data, these suggested sequences are tentative until:

- Eastern Desert orebodies are characterised by mineralogical and lead isotope analyses,
- More Old Kingdom copper vessels and tools are studied using metallography and quantitative analytical methods,
- Egyptian gold technology is clarified, and
- Egyptian crucible ceramics are analysed using microscopy and SEM.

Mereruka shape crucibles were used because they allowed the melt to be observed so that casting could be carried out promptly, minimising arsenic and copper oxidation, and charcoal usage. They could also be manipulated manually with the aid of insulating pads.

Arsenical copper ores were selected for prestige vessels because the refined alloy produced objects with silver-gold colours and reflective surfaces. The alloy was also easier to process because it melted at lower temperatures and flowed more freely to form sheet metal.

The origin of the Mereruka shape crucible is unclear. Their earliest occurrence is during the First Dynasty in Upper Egypt and they do not appear in the southern Levant and Sinai until much later. Their association with Clayton disks in the Nile Valley is not replicated in the Western Desert where Clayton disks are common, but crucibles are not. Nubia remains a possible source of the Mereruka crucible technology.

The development of Egyptian metalworking in the Old and Middle Kingdoms is becoming increasingly understood from research on Ayn Soukhna, Buhen and sites in Western Sinai. This study has drawn attention to the probability that Egypt's earliest indigenous metallurgy began in Upper Egypt with local copper-arsenic resources and the application of technologies not known from the southern Levant, but maybe acquired from nomadic prospectors from Nubia with possible contacts further afield in Africa or south Asia.

Christopher J. Davey
Honorary Fellow, University of Melbourne
Executive Director, Australian Institute of Archaeology

Peter C. Hayes
Emeritus Professor, The University of Queensland
Pyrometallurgy Innovation Centre (PYROSEARCH)

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