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The Advent of Complex Metallurgy

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Abstract **– This study investigates the origins of extractive metallurgy in the southern Levant, particularly during the Ghassulian culture of the Chalcolithic period (circa 4700/4500–3800 BCE). It presents evidence that the production of complex alloys began earlier than previously thought. Using a novel radiocarbon sampling method focused on the production dates of metal objects, the research examines artifacts from the Naḥal Mishmar hoard and their ritual context in Israel's Judean Desert. The study highlights the evolution of long-distance trade in copper alloys, contrasting sophisticated lost-wax technique objects made from distant sources with simpler local copper tools. This reflects the technological and socio-economic complexities of early metallurgy and trade in West Asia. Recent excavations at the Chalcolithic shrine in Ein Gedi provide further insights, enhancing our understanding of Ghassulian culture's chronology and clarifying the long-discussed relationship between the Ein Gedi shrine and the Naḥal Mishmar hoard.**

Keywords: Chalcolithic metallurgy, lost wax, southern Levant, Uruk Expansion.

I. INTRODUCTION

Beyond the simple physical shaping of native copper (Cu), extractive copper pyrotechnology is thought to have originated in southeastern Europe, Anatolia, or the Iranian Highlands [1, 2]. In the southern Levant, copper metallurgy appeared during the Ghassulian culture (conventionally dated ca. 4700/4500–3800 BCE), so-named after the site of Tulaylât al-Ghassûl, Jordan, in the Chalcolithic period. While the socio-economic interpretation of metallurgy in the Ghassulian culture had been disputed for decades [3, 4], the remarkable discovery in 1961 of a hoard in a nearly inaccessible cave high on a cliff of Naḥal Mishmar in the Judean Desert, Israel, comprising 429 copper artifacts [5] (Fig. 1) marked a watershed in the study of ancient metallurgy. Together with lesser numbers of similar objects from other sites constituting the robust database of the Levant's earliest metallurgy, it clearly underscored the dichotomy between elaborate objects (maceheads, standards, crowns, etc.) cast by the sophisticated lost-wax technique of copper alloyed with varied amounts of antimony (Sb), arsenic (As), occasionally nickel (Ni) and other impurities, and simply-shaped tools (axes, adzes, chisels, etc.) cast in open molds of unalloyed, nearly pure copper [6, 7].

Fig. 1. Select objects made by the lost wax technique from the Naḥal Mishmar hoard. Collection of the Israel Antiquities Authority, Photo © The Israel Museum, with permission.

Lead isotope analysis indicated that the copper sources for the latter category originated in Feinan and, possibly, Timna in the Arabah Valley of Jordan and Israel, respectively [8] (Fig. 2). However, compositional analyses of the elaborate artifacts firmly demonstrated that they were made of cuprous-antimonious-arsenical (Fahlerz-type Cu-Sb-As) ores or ingots imported from remote sources either in Turkey, the Caucasus or Iran [8] but were clearly cast in the southern Levant [9]. Polymetallic alloys were essential for the lost wax technique because of the high melting point of pure copper (1,084 °C). The addition of Sb, As, Ni, Pb (lead), or, in later periods, Sn (tin) to create bronze lowers the melting point by several hundred degrees, reducing the viscosity of molten metal, allowing it to flow through constricted parts of the mold [10]. As all copper ore sources in the Southern Levant are monometallic, the complex foreign ores were imported. Sb and As in copper ores have been found at Arslantepe, Norşuntepe, Hassek Höyük and other Upper Euphrates sites [11, 12]. Thus, while their provenance from Eastern Anatolia has been suspected, more recent attempts to link these sources with the alloys in the Ghassulian lost wax objects have been unsuccessful [13]. In addition, these areas did not adopt the lost wax casting technique until later [10]. This technology was abandoned in the southern

Levant following the demise of the Ghassulian culture; only open-cast techniques were subsequently employed [14].

Although similar elaborate artifacts had been found in lesser numbers at other Ghassulian sites, the vast majority derive from the Naḥal Mishmar hoard. That, together with the level of workmanship, led to a prestige or cultic interpretation of their possible function and of the circumstances for their being hidden in such an inaccessible location. The subsequent excavation of a Ghassulian shrine at Ein Gedi, about 12 km north of Naḥal Mishmar, led to a narrative that the hoard was comprised of the shrine's cultic paraphernalia, which was hidden in the cave at a time of crisis [15]. This hypothesis was challenged [16, 17, 18] but is still widely acknowledged and supported by some empirical reasoning [19]. Yet, regardless of the ritual association of metalworking, the current lack of an absolute date for the presumably short-lived shrine and the inconsistency of the radiocarbon (^{14}C) dates from the reed mat that enclosed the hoard [20, 21) preclude any scientifically based correlation between the hoard and the shrine within the radiometric limits of the Ghassulian culture. Moreover, whether metallurgy was limited solely to the end [17] or extended over the entire time period [21] has also been debated, not the least owing to the possibility that the radiocarbon evidence from a site where copper artifacts have been discovered may not directly indicate when they were produced, as they could have been in use for many generations. This last point is particularly significant as metal items in the Chalcolithic southern Levant were typically discovered as caches in hidden locations such as caves, burials, pits, or underground chambers [19]. As a result, the archaeological context of their discovery would usually indicate only the final stage of their lifecycle rather than their production time. Thus far, these limitations have not been seriously considered due to the absence of direct chronological indicators for the production date of alloyed prestige/cult metal artifacts or a clear locus of production. Instead, only well-dated workshops using nearly pure Arabah Valley copper [22, 23] have been found in the Beer Sheva Valley. Only a single workshop from the Jordan Valley dated to the end of the Chalcolithic period is known to have practiced the lost-wax casting technique, but it was likely recycling scrap alloyed copper objects rather than carrying out primary production [24]. The absence of the latter mode of production may be explained by its challenging visibility within the archaeological record [25].

II. METHOD

A. Dating the Naḥal Mishmar hoard

A salient but overlooked point is that the early lost wax casting process involves short-lived organic materials. If these materials were preserved, they could provide the production date that is yet missing for individual artifacts. In the Ghassulian production process, as in similar existing traditional lost wax casting technologies, a core was created using clay mixed with fine vegetal material or herbivore dung. The function of the organic material in the clay was to create pores to escape gas while it burns off partly, thus maintaining the integrity of the core. This core was coated with a mixture of beeswax and tree resin, of which the shape of the desired end-product was modeled. The mold was then made by first applying a layer of fine clay over the wax model to preserve its delicate outlines, followed by coarser layers of clay mixed with grass or sand and, finally, lime plaster mixed with coarse sand to build up the solid mold into which molten metal would be poured. Prior to that, the mold had to be heated to dry the clay and pour out the wax, leaving behind the negative of the object to be cast in this one-time mold [19].

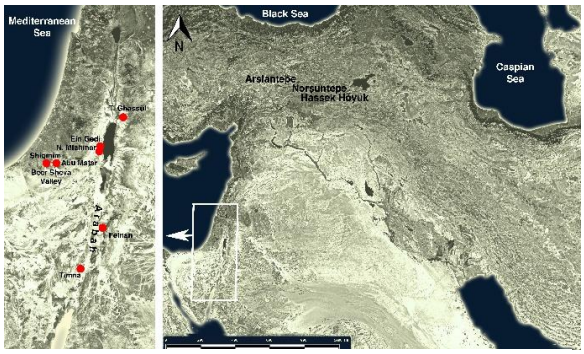


Fig. 2. Orientation map with sites mentioned in the text.

After casting the metal alloy, the clay mold was carefully chiseled off, revealing the object's exterior but typically leaving the core inside the artifact [19]. Therefore, dating the charred organic material in the core can indicate the individual production date of any artifact in which such material is found. Given the preserved charred vegetal material in the cores of many items from the Naḥal Mishmar hoard and other sites [9, 19], it was decided to initiate a research program to determine the production age for a representative selection of lost wax cast objects from the hoard utilizing Accelerator Mass Spectrometry (AMS) radiocarbon dating.

Due to the loose, friable nature of ceramic cores in lost-wax-cast objects, samples could be collected by merely inserting a metal spatula or a jeweler's chisel into the tube or shaft of the artifact and breaking off a small piece. We used a chrome-vanadium spatula and a glass funnel placed on top of an Eppendorf test tube to extract the samples. After extracting each sample, the spatula and fennel were wiped, washed in acetone, and dried. The Eppendorf vials containing the samples were each sealed in a plastic bag and brought to the Centre for Isotope Research at the University of Groningen.

In Groningen, the samples from the Naḥal Mishmar

cores were subjected to chemical pretreatment according to the ABA procedure [26, 27]. The quoted measurement uncertainties arise from counting statistics, the analytical performance of the AMS, and variations due to sample consistency and pretreatment. The radiocarbon (^{14}C) ages were calibrated against IntCal20 [28] using the OxCal program, version 4.4 [29].

B. Dating the Ein Gedi shrine

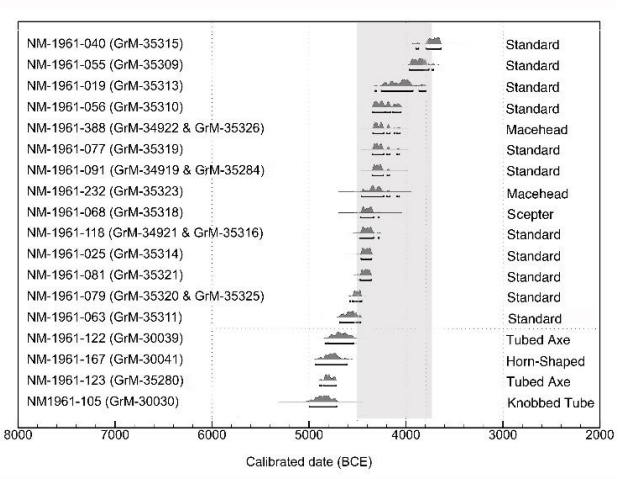
Renewed excavations were conducted at the Ghassulian shrine at Ein Gedi (Figure 3) to better determine the chronology of the alleged short-lived occupation of the shrine, initially identified during the excavations of 1961-1962 [15], which was established. The goal was to use modern techniques, unavailable during the original excavations, to find additional remains and gain deeper insights into the site's history and function. This may help us compare the dates obtained from the Naḥal Mishmar hoard and determine whether the two sites could be related chronologically, making the ritual association of the hoard feasible and exploring the implications of that determination. Additionally, on-site laboratories and microarchaeological techniques were used to detect in situ remnants of otherwise imperceptible pyrotechnological and other micro-artifact debris [25].

III. RESULTS

A. The Naḥal Mishmar hoard

Short-lived organic samples (microscopically identified as grass or herbivore dung [9]) from the ceramic cores of select alloyed copper objects of the Naḥal Mishmar hoard yielded 20 radiocarbon dates. The 2-sigma calibrated ^{14}C date distributions appear in Table 1.

Table 1. 2-sigma calibrated ^{14}C distributions of selected alloyed copper implements from the Naḥal Mishmar hoard.



The results reveal that the lost wax technique was employed to cast elaborate items from ca. 4700 to 3800 BCE. The timeframe of these distributions covers the entire known radiometric duration of the Ghassulian culture and offers proof that the hoard consists of artifacts produced over an extended period but was deposited in the cave at the end of the Ghassulian culture.

B. Dating the Ein Gedi shrine

During the October 2021 season of the renewed excavations at the Ghassulian shrine of Ein Gedi, Unit 20 was uncovered at the northwest corner of the previously excavated Building A. This new unit was determined to be stratigraphically superimposed by the foundation of that building and possessed a pit that was dug into the natural conglomerate upon which the complex was established. The pit was covered with large stones plastered with mud, and the building's walls were constructed on top of this cover. This pit contained twigs, seeds of wheat and barley, and chaste tree fruit, which were charred green (E. Weiss, pers. comm), along with an indicative Ghassulian ceramic cornet (horn-shaped vessel typical of the Ghassulian culture). Five samples of the short-lived charred twigs were submitted to the Centre for Isotope Research at the University of Groningen for radiocarbon dating.

The Ein Gedi samples contained approximately 65% carbon, a typical composition for cultigens. This consistency supports the supposition that the charred sample materials did not undergo significant mixing with other materials. The graphite samples contained around 2 mg of carbon, similar to the calibration and reference standards used in the same AMS batches for these measurements. This ensures reliable calibration and verification of the results.

The Ein Gedi samples were measured and divided into two different batches. The reported uncertainties in the results account for variations in the analysis of carbon isotopes observed between subsamples of the same material (which share homogeneous isotope composition and similar size). These variations arise from chemical pre-treatment, combustion, and isotope measurement differences.

The short-lived twigs were used for five AMS radiocarbon dates, providing an average calibrated ^{14}C age of 4250 BCE. This is a tentative terminus post quem for the shrine's foundation.

IV. DISCUSSION

The results of this study offer the opportunity to gain novel insight into a long-standing debate about the emergence of complex metallurgy and its impact on socioeconomic developments in the Fertile Crescent region. A primary outcome is that attempting to determine the age of technological advancements in metal production based mainly on the archaeological context of the finished artifacts may be misleading, as metal items may have very

long life spans. Thus, the significance of the artifacts sampled from the Naḥal Mishmar hoard lies in providing dates indicative of a continuous production history spanning nearly a millennium (Table 1). The earliest dates in this sequence precede the records considered so far to represent the earliest use of the lost wax technique from Varna, Bulgaria, and Mehrgarh, Baluchistan [30, 31]. However, since the ages of the latter examples were determined based on the depositional contexts of the artifacts, it is uncertain whether the earliest objects in the Naḥal Mishmar hoard indeed predate them. Therefore, it is important to differentiate between historical conclusions drawn from the direct dating of production (such as smelting or melting slags, crucible fragments, and casting molds or cores) and indirect dating based on the depositional context of the finished object. Furthermore, when it comes to the lost-wax technique, it may be challenging to identify in situ evidence of production, as these traces may be invisible to field archaeologists lacking the aid of on-site laboratories.

Based on the available data from direct dating of Ghassulian metallurgy, the assumption that there were two coexisting technologies, the lost wax casting of alloyed copper and the open casting of unalloyed copper, can now be challenged. That conjecture was based on indirect dating, resulting from finding items of both technologies together in caches, pits, or caves, including that of the Naḥal Mishmar hoard. All Beer Sheva Valley area sites, such as Abu Matar, Horvat Beter, Shiqmim and additional sites in this region, have provided direct evidence for the smelting and melting of pure copper from Arabah Valley ores. This evidence includes ores, slag, crucibles, and tuyères [22, 23], providing direct dating for this technology at ca. 4200–3800 BC [32, 33]. This close grouping of dates, obtained from production contexts at similar sites, only partially overlaps the dates obtained in the present study from the direct dating of the lost wax artifacts from the Naḥal Mishmar hoard, as shown in Table 1. The shift to simpler production of open casting using local ores from the Arabah Valley occurred approximately 500 years after the first production of intricate items using the lost wax technique. The reasons for the emergence of less sophisticated technology during the last four centuries of the Ghassulian culture are unclear. However, it may be linked to the simplification of pyrotechnology. After an elaborate and prestigious introduction, the practices of earlier pyrotechnology may have become trivial. Copper artifacts from both methods were buried in caches, in the Naḥal Mishmar hoard and elsewhere. During the Early Bronze Age, approximately 3700–2000 BCE, copper was produced through open casting using local ore sources found near the mines, particularly from Feinan in the Arabah Valley [34]. This method differed from the earlier Ghassulian production technique, where copper ores were transported from Feinan to the habitation sites in the Beer Sheva Valley for processing.

This chronological difference raises several questions. What could have led to the supply of ores from Turkey, the Caucasus, or Iran to the southern Levant from around 4700 to the beginning of the 4th millennium BCE? These imports could be connected to earlier contacts during the Neolithic period and the transfer of exotic minerals, such as obsidian, from Anatolia to the southern Levant [35]. However, the circumstances that led to the innovation of the lost wax technique in the southern Levant using alloyed ores from remote areas are a mystery. Our direct dating of the objects from the Naḥal Mishmar hoard shows that this technology persisted for almost a millennium. The approximately 600 Ghassulian copper artifacts that exist today, most of which are made using the lost wax technique [21], would suggest roughly a production rate of less than one item per year.

Given this conclusion, the extensive time span represented by the Naḥal Mishmar hoard—which includes earlier artifacts that are unique to it—suggests that its production dates extend back two centuries prior to the conventional transition into the Ghassulian culture around 4500 CalBC. This evidence suggests that the hoard likely represents a communal and sacred collection gathered over many centuries by a highly exclusive elite group or clan. Starting around 4500 CalBC, with the widespread distribution of the Ghassulian culture, the production of these artifacts underwent a process of standardization and simplification. This shift resulted in the creation of primarily simple maceheads, as well as a smaller number of standards and scepters. Furthermore, there was some leakage of these items to other contemporary sites, which may have also served to display the prestige of local elites.

It seems that by the end of the Chalcolithic period, much of the Ghassulian copper was no longer in use and was deposited in hidden locations, as demonstrated by the near absence of evidence for the recycling of these alloys in subsequent Early Bronze Age metals [36]. Possibly, owing to the decline of the Ghassulian culture, copper artifacts of the two technologies were cached together in pits and caves. The new dates for establishing the shrine in Ein Gedi suggest that the cultic connotation of copper production, primarily the Naḥal Mishmar hoard, is probable. If, indeed, the shrine was established around 4250 BCE and survived for a few centuries, as we assume now based on as yet unpublished results of the ongoing excavations at the site, its abandonment may be linked with the deposition of the hoard at the end of the Ghassulian culture. However, the direct dating of objects from the hoard indicates that by the time the shrine was established, the lost wax casting of alloyed copper objects, including a significant part of the Naḥal Mishmar hoard, had already been practiced for several centuries. It is possible that ritually significant copper artifacts were gathered in this distant shrine, and with the decline of the Ghassulian culture, they were brought for ritual burial in the cave that had been frequented for several centuries,

leading to the evident accumulation of pottery sherds of diverse origins [16].

The findings lead to another more salient question: why was the age-old tradition of lost wax casting replaced by the more straightforward method of open casting using unalloyed copper from local sources? This shift could be linked to the depletion of Cu-Sb-As ores at their distant sources. This compelled the Ghassulian coppersmiths to gradually utilize lower-quality local copper ore unsuitable for lost wax casting. Our direct dating indicates that this transition occurred progressively, during the last centuries of Ghassulian culture, towards the beginning of the 4th millennium BCE. The reasons for this change in the source area of such copper ores, particularly in the Taurus Mountains, Anatolia, and Iran in the Late Chalcolithic period, are unknown. This process did not occur overnight; it likely developed over a few centuries, affecting various aspects at different times. As alloyed copper ores suitable for lost wax production became increasingly scarce in the southern Levant, artisans began utilizing local copper mineral sources in the arid regions of the Arabah Valley. They also had to develop smelting methods in the nearby semi-arid areas of the Beer Sheva Valley, the nearest location to the Arabah Valley that could support agricultural-based subsistence strategies. In this production mode, the ores were brought to these sites for the entire process, from smelting to casting [22, 23]. Therefore, the settlement of the Beersheva Valley marks a late stage of Chalcolithic occupation. As the local copper minerals lacked the necessary qualities for lost-wax casting, production shifted to open casting of available pure copper. This technology continued into the Early Bronze Age in this region. While some infiltration of ores was still maintained during the late 4th millennium BC [37], the impact of these processes led to a cessation of the lost-wax technique until much later historical periods. As alloyed copper ores suitable for lost wax production became increasingly scarce in the southern Levant, artisans began utilizing local copper mineral sources in the arid regions of the Arabah Valley. They also had to develop smelting methods in the nearby semi-arid areas of the Beersheva Valley, the nearest location to the Arabah Valley that could support agricultural-based subsistence strategies. In this production mode, the ores were brought to these sites for the entire process, from smelting to casting [22, 23]. Therefore, the settlement of the Beersheva Valley marks a late stage of Chalcolithic occupation. As the local copper minerals lacked the necessary qualities for lost-wax casting, production shifted to open casting of available pure copper, a technology that continued into the Early Bronze Age in this region.

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