Monographies Instrumentum /56

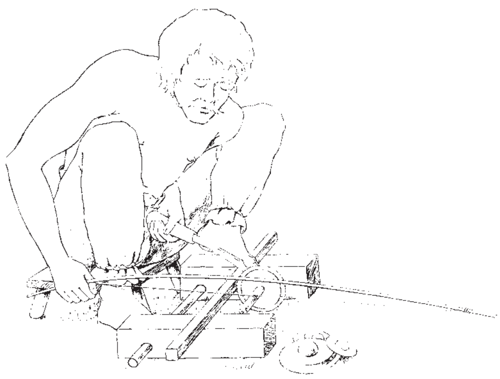
BRONZE AGE METALLURGY ON MEDITERRANEAN ISLANDS

volume in honor of Robert Maddin and Vassos Karageorgis

A. GIUMLIA-MAIR and F. LO SCHIAVO (eds.)

éditions mergoil

Monographie Instrumentum
56



Collection dirigée par
Michel Feugère

A. Giumlia-Mair and F. Lo Schiavo (eds.)

Diffusion, vente par correspondance
Editions Mergoil - 13 Rue des Peupliers - 31280 Drémil-Lafage
Tél : 0345440444 - e-mail : contact@editions-mergoil.com

ISBN: 978-2-35518-083-5
ISSN: 1278-3846

Mise en page : A. Giumlia-Mair and L. Tocco
Couverture : Editions Mergoil - Photo : Torralba-S. Antine. Ripostiglio dalla Capanna (da Lo Schiavo)
4eme de couverture : Photos : Excavation on the island of Mochlos (photo A.Giumlia-Mair) et Moule de Sidossi (photo J.-P. Antolini)

Dépôt légal Septembre 2018

Bronze Age Metallurgy on Mediterranean Islands

In honour of Robert Maddin and Vassos Karageorgis

A. Giumlia-Mair and F. Lo Schiavo eds.

Editions Mergoil
Drémil-Lafage - 2018

Bronze Age Metallurgy on Mediterranean Islands

R.M. Albanese Procelli, M.J. Becker, Ph. Betancourt, S. Cara, P. Craddock, S. Ferrence, J.I. Gil Ibarguchi, A. Giumlia-Mair, A. Hauptmann, M. Jansen, V. Kassianidou, S. Klein, T. Lachenal, F. Lo Schiavo, M.R. Manunza, C. Matzuzzi, I. Montero-Ruiz, J.D. Muhly, P. Muhly, G. Papasavvas, M. Perra, K. Pêche-Quilichini , S. Pretti, N. Rafel, A. Sanna, B. Salvà Simonet, J. Soles, P. Sureda, †R. F. Tylecote, P. Valera, A. Usai

Summary

BRONZE AGE METALLURGY IN THE MEDITERRANEAN ISLANDS
In honour of Robert Maddin and Vassos Karageorgis

(Alessandra Giumlia-Mair and Fulvia Lo Schiavo eds.)

Introduction

This work is the fruit of study and affection.

In the Eighties there was a first meeting in Cyprus, and Sardinia made its appearance in the official Conferences and in the personal discussions among scholars. This brought about a better mutual knowledge of Bronze Age Metallurgy on the two islands, and many projects, aiming to a deeper scientific understanding, were planned.
After many preliminary papers on connected topics, two major steps brought us to the present volume: *Archaeometallurgy in Sardinia from the origins to the Early Iron Age* (F. Lo Schiavo A. Giumlia-Mair, U. Sanna, R. Valera eds., *Instrumentum* 30, Monique Mergoil, Montagnac 2005), followed by *Oxhide ingots in the central Mediterranean* (F. Lo Schiavo, J. Muhly, R. Maddin, A. Giumlia-Mair eds.), Biblioteca di Antichità Cipriote 8, ICEVO-CNR, Roma 2009. Some of the Authors publishing their work in the present volume (J. Muhly, R. Maddin, V. Kassianidou, G. Papasavvas, R.M. Albanese Procelli, A. Usai, A. Hauptmann) had already worked together for the second.

Both earlier works were based on Sardinia; the second contained chapters on Sicily, Lipari and their Cypriot connections, but there was no contribution on Crete in the East and the Balearic Islands in the West, and only a short chapter on Corsica. After the necessary updating on the many new discoveries of oxhide ingots in Sardinia, we present here differently shaped copper ingots: plano-convex, flat and oval, flat and irregular, disc-shaped, truncated-cone-shaped, and many others.
Robert Maddin, who had pointed out the lack of attention to these ingots, was the initiator of this study. Meanwhile, the research extended and deepened, and the analyses of the Ballao-Funtana Coberta hoard and of the Orroli-Arrubiu ingots led to surprising results, which still have to be evaluated.

A full-scale study on bronze age moulds was long due. For the first time moulds from Sicily, Corsica and Sardinia are illustrated and catalogued in one volume. The studies also include new discoveries and preliminary studies on Sardinian “steatite”.
It is for us a privilege to present now a posthumous paper by Ronald F. Tylecote that was planned for publication many years ago, together with the paper by Marshal J. Becker.
Subjects dealt with in the concluding papers on the western Mediterranean are the metalworking tools from Sardinia (a subject already discussed in the eighties and here much broadened), Bronze Age metallurgy in the Balearic Islands (an almost unknown topic), slag smelting technology in the Mediterranean and in the West (a compendium of many years of analyses and experiments

The new astonishing discoveries at Chrisokamino and Mochlos, both on Crete, completely changed the ideas we had on the metallurgy of the island. At Chrisokamino, ores -- contrary to all previous theories -- found to have been brought to Crete from elsewhere, were reduced in a furnace completely different from anything we knew before.
At Mochlos, located just east of the Bay of Mirabello in eastern Crete, Jeffrey Soles, co-director of the Mochlos Excavation Project since 1989, and his team discovered a large amount of metal items belonging to two hoards in the same building, the House of the Metal Merchant. Among the pieces of the Foundry Hoard, just in the middle of the heap, there was a large chunk of what looks like some sort of mineral, having a very high arsenic content. This find reveals how arsenic was added to copper-based alloys as late as the Late Minoan IB period, while the study of the various objects illustrates the metallurgical habits of the local metalworkers. This study and the paper on the use of arsenic on Crete are part of a wider project on Cretan metallurgy funded by the Institute of Aegean Prehistory (INSTAP), Philadelphia PA.

The papers about Cyprus, covering the topic of mining, oxhide ingots and hoards, and population movements and transfer of metal, conclude the volume. This is certainly not the end of the story: for each section of the volume more work should be done, and more chapters should and must be added.

However, the work presented in this volume was produced and collected for the two scholars we wish to honor and who were our inspiration both from a metallurgical and an archaeological point of view

We hope that our effort will be appreciated.

Alessandra Giumlia-Mair and Fulvia Lo Schiavo

From the left: Robert Maddin, Alessandra Giumlia-Mair, James D. Muhly and Fulvia Lo Schiavo visiting the Akropolis Museum in Athens. 5th of May 2016.

Fulvia Lo Schiavo, Robert Maddin, James D. Muhly and Vassos Karageorgis in Nicosia, Cyprus, in October 2009.

Metallurgical Habits and Workshop Remains in LM IB Mochlos, East Crete

JEFFREY S. SOLES
University of North Carolina at Greensboro

ALESSANDRA R. GIUMLIA-MAIR
AGM Archeoanalisi 39021 MERANO (BZ) Italy

Abstract

This paper presents a study carried out on important finds from the House of the Metal Merchant in Mochlos, dated to the LM IB period (c. 1530-1430 BC). The characteristics of the pieces and the results of analyses carried out by XRF illustrate the habits of the metalworkers of this period and their working and finishing processes. The Foundry Hoard, from the House of the Metal Merchant, consists of a large number of pieces, vessels, tools, weapons, ingots, half-worked pieces, casting remains, and a large number of damaged objects, all collected for recycling, and partly burned and fused together.

They certainly come from a burnt workshop. The most important find is the large chunk of arsenicrich material that indicates that the copper-based alloys containing both elements, arsenic and tin, were deliberate, and presumably produced with the intention of exploiting the advantageous properties of both metals. This paper discusses the analysis data and compares them with the data from contemporary contexts.

Metallurgical Habits and Workshop Remains in LM IB Mochlos, East Crete

JEFFREY S. SOLES

ALESSANDRA R. GIUMLIA-MAIR

Introduction

A large amount of metal was found in the Late Minoan IB destruction layer at Mochlos, an important trading port throughout the Bronze Age, particularly with points to the east, including Cyprus and the Levant (Soles 2005, 2008). The metal finds are copious and mostly of excellent quality. The Neopalatial contexts yielded approximately 90 kg of bronze, over 80 kg of which (consisting of 271 objects) come from House C.3, which was identified as the House of the Metal Merchant. The next largest amount of metal comes from House C.6, with almost 7 kg of copper-based finds (23 objects), and several more were recovered from other buildings. The amount of metal used in the settlement was originally much higher, but the town was looted at the time of its destruction and a large amount of metal disappeared in the looting. The large number of metal finds in the House of the Metal Merchant (C.3) survived because the metal was hidden in two places, in a pit under the floor of a living room and at the rear of a basement storage room full of pithoi.

An important metal group for archaeometallurgical research is the one identified as a Foundry Hoard from the basement deposit in the House of the Metal Merchant, dated to the LM IB period (c. 1530-1430 BC). The group consists of a large number of tools, once employed in a metal workshop, found together with broken objects, vessels, small tools and weapons, fragments of various size of ingots, half-worked pieces, casting remains, such as spills, cuttings of sheet metal, and a large number of damaged objects, all collected for recycling. Many of these materials are partly burned and fused together, and look like the remains collected from a burned metallurgical workshop for re-melting and re-use. Metals were the most valuable materials in use at the time (with the exception of exotic imports, such as amethyst, lapis lazuli, ivory and ostrich eggs), and if a fire broke out and destroyed a workshop, the surviving metalworkers or the neighbors would have recovered the precious pieces of copper-based alloys, the finished objects and the items brought to the metalworkers for repair. Even the smallest scrap from the workshop ruins would have been salvaged. Fires must have been a common event in workshops in which open fires had to be used regularly, since wood was extensively used in Minoan buildings, particularly in the roofs. This hoard seems to consist of the kind of semi-molten and altered remains and burned objects to be expected from such a fire. It is an important testimony to the activities of a workshop of the period because it contains all materials at the disposal of the smiths before the destruction of the building by fire.

In this paper the analyses of the finds will be discussed, interpreted and compared with the data we possess from other contemporary contexts.

The Site

The Neopalatial town of Mochlos grew rich on international trade in metals with copper brought from Cyprus, tin probably coming from the east, and silver from Lavrion, but it had the misfortune to lay in one of the major tectonic lineaments in the eastern Mediterranean Sea, the Ierapetra Fault Zone, and suffered destruction from earthquakes at various times in the Neopalatial period. A major catastrophe befell the town at the time of the Santorini eruption, the end of the LM IA period, c. 1530 BC, which caused many buildings to collapse. Perhaps as a result of this episode, much production that had been previously located in the town itself, including metalworking and pottery production, was moved to a new manufacturing center, the Artisans' Quarter, which lay on the opposite coast c. 250 m to the south (Soles 2003; Soles et al. 2017). Up to this time all production occurred in the town itself and the workshop remains found in House C.3 belonged to a shop located somewhere nearby which did not survive the LM IA destruction and removal to the Artisans' Quarter. It is likely that the LM IA event was the cause of the fire that destroyed the workshop, in which case many of the remains in the Foundry Hoard date to the end of the LM IA period although they were found in a LM IB context.

Method of Analysis

As it was not possible to take samples from the objects, a non-destructive method of analysis had to be used (see also Giumlia-Mair et al. in this volume). X-ray fluorescence spectrometry (XRF) is a well-known method (Hahn-Weinheimer et al. 1995) and has been widely employed in archaeology (cf. Lutz et al. 1996; Giumlia-Mair et al. 2015; Giumlia-Mair 2011). Before analysis all finds were first examined with various magnification devices to select the best areas for measurement. Any tool marks and wear traces, as well as corrosion phenomena, were recorded. All objects were photographed first with a normal digital camera with two macros, and then at the microscope, with different magnifications (especially x 50 and x 200).

The XRF equipment used for this research is transportable and was carried to the INSTAP Study Center for East Crete. This particular model was developed for the analysis of Cultural Heritage materials and consists of various parts that can be mounted where the equipment has to be used: the head with the X-rays source, a support with devices that control stability and position, a large transformer, a stabilizer, and a laptop computer that controls the analytical program. The head of the system is equipped with a collimator that changes the diameter of the beam as required, a laser pointer indicating the exact area to be analyzed, and a device controlling the distance from the sample. If the distance is correct (within the acceptable span of $\pm$ 0.1 mm) the program gives an audio signal.

Standards of various compositions were employed during the measurements. The ones for copper-based materials consisted of copper containing single elements (i.e. 5% Sn; 1% of As, Sn, Ag, Fe, Pb; 0.5% As, Ag, Fe respectively), and composite alloying elements (1% Sn, As, Fe, Pb in Cu; 1% As, Sn, Ag, Sb, Fe in Cu; 1% Sn, Ag, Au, As in Cu). Most of them were expressly produced in laboratory by AGM Archeoanalisi, Merano (BZ), Italy, and are as similar as possible to ancient alloys. They were routinely analyzed at the beginning of each day, whenever the equipment was switched off, and every couple of hours, to check drifts or other causes that can affect the performance. The equipment was installed in the basement of the INSTAP Study Center in which the temperature is stable and there is no danger of vibrations. Whenever the samples seemed corroded or if there were anomalous peaks, at least three measurements were taken to make sure that the data were reliable. The INSTAP conservation experts kindly removed the upper patina layer or the dirt whenever it was necessary. For more details on the analyses see also Giumlia-Mair et al. in this volume.

Past experiences showed that the analytical data compare well with the reference material. On several occasions analytical data measured both by AAS and XRF on the same samples were compared. Over 90% of the XRF results were well within + 20% of the corresponding AAS results. The calculated correlations for tin and lead, two of the most important alloying elements, range from 0.84 to 0.97.

Lead Isotope Analyses (LIA) were carried out by Zofia A. Stos-Gale (2004 and forthcoming) on some of the copper-based and lead finds from Mochlos. The LIA indicates that the copper source was Cyprus, while the lead comes from Lavrion. Only three of the ingot fragments, a vessel, and an arsenic-rich material seem to come from Lavrion.

Discussion of Results

The metal finds were analyzed by X-ray fluorescence spectrometry (XRF) for a project on all metal objects from this period excavated at Mochlos. Around 180 analyses of around 130 copper-based metal finds were carried out on all parts of the metal finds preserved at the INSTAP Center (s. Tab.2). For a better understanding of the discussion on the Foundry Hoard and on the workshop habits that can be deduced from the analyses and the examination of the various finds, it is important to present part of the data here; however, the complete analytical study on Mochlos' metalwork in all its aspects and with all relevant illustrations and drawings, will be published in a volume dedicated to Mochlos in the LM I period, *Mochlos IVA, the House of the Metal Merchant and other Buildings in the Neopalatial Town* (Soles and Giumlia-Mair forthcoming). Therefore only some of the more general data, and the table of results, which are relevant for the present study, are mentioned in this paper and discussed whenever appropriate.

Table 1

Foundry Hoard		Merchant’s Hoard		Artisans’ Quarter
		1 (half ingot)	15 kg	
2 ingots	2-5 kg	2	2-5 kg	
1 ingot	1-2 kg	8	1-2 kg	
		1	900 g – 1 kg	
		2	800-900 g	
1 ingot	700-800 g	1	700-800 g	1
1 ingot	600-700 g	3	600-700 g	1
4 ingots	500-600 g	4	500-600 g	1
4 ingots	400-500 g	2	400-500 g	

2 ingots	300-400 g	3	300-400 g	
6 ingots	200-300 g	4	200-300 g	2
4 ingots	100-200 g	6	100-200 g	10
8 ingots	50-100 g	8	50-100 g	5
8 ingots	0-50 g	30	0-50 g	4
41 ingots	17.60 kg	75	41.01 kg	24

Table 1 collects the data of all copper-based metal finds from the LM IB layer in Mochlos that have been analyzed. The objects belong to different classes of items and were produced by different techniques; therefore most kinds of alloys are represented. In the case of composite objects, such as tweezers or knives with rivets, all parts were analyzed. Corroded pieces were generally avoided. Only very few instances of corroded materials were analyzed, and only when they were of particular interest. The data collected from corroded objects can only be considered indicative and are given in *italics* in the table of results. They were not included in the groups used for statistics.

The large number of analysis results allows for a statistical treatment of the data. We can consider around 130 objects, completely analyzed in all their parts, from some 150 analyses.

Only a few Minoan materials from Crete have been analyzed up to now (Junghans et al. 1968; Renfrew 1967; Craddock 1976; Betancourt et al. 1978), and in general not many analytical data from Greece or from contemporary Mediterranean contexts exist.
The ideal comparisons for the materials from Mochlos are the metal finds from the contemporary Minoan town of Gournia, now in the University of Pennsylvania Museum of Archaeology and Anthropology (hereafter, Penn Museum) in Philadelphia (Giumlia-Mair et al. 2016). The general data from the analyses of the finds from Mochlos will be compared with those of the finds from Gournia and with the data from other contexts when appropriate.

Arsenic Content

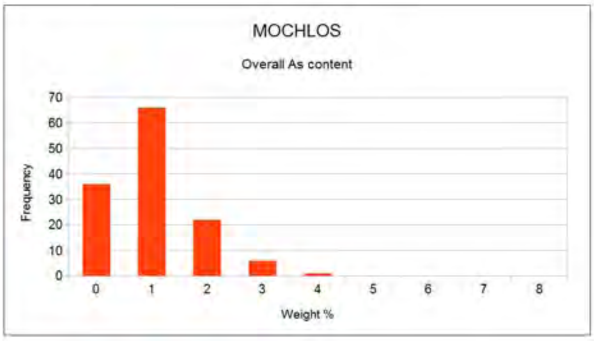
The highest arsenic content of the entire group of analyzed items was that of chisel IVA.88, with 4.3% As, but there was also an outlier with over 60% of arsenic that will be discussed below. Arsenical copper was employed since the Early Bronze Age, both in the Middle East and in Europe (Tylecote 1976; Bar-Adon 1980, 235-243; Muhly 1988, 9-11; Shalev and Northover 1993). Arsenic contents over ca. 5% render the alloy too brittle for normal employment and everyday metalwork, but in other contexts there are objects for which alloys with higher arsenic were used. All of them are special objects, such as ceremonial weapons, bells or ornaments. Besides changing the colour of the metal, arsenic also improves the sound (Hosler 1988, 330; Lechtman 1988, 356-358; Northover 1998, 117-119; Giumlia-Mair 2000, 300-301 and 305-308; 2007, 135-137; 2008, 110-117; 2009a, 155-159).

Arsenic changes the properties of copper and makes it harder when hammered, but it also changes the colour of the alloy, because of a phenomenon of inverse segregation. The presence of even 1-2% of arsenic in copper produces a silvery grey layer on cast objects (Budd, Ottaway 1991; Giumlia-Mair 2000), called "arsenic sweat." This is due to the formation of the low melting point (685°C) eutectic (copper containing 21% of arsenic) during the cooling process. The eutectic remains liquid longer than the rest of the alloy and is pushed to the surface through interdendritic filaments (or feeders) while the alloy cools down and the crystals grow. When it solidifies on the surface a silvery layer is produced. Inverse segregation can also occur with low arsenic percentages, and its aspect depends on various parameters, such as the temperature, the humidity, the cooling rate of the material used for the mold and more such variables. (see also Giumlia-Mair et al. in this volume).

Arsenic often occurs in copper ores and it is sometimes difficult to distinguish copper containing arsenic coming by chance from mixed ores, from deliberate alloys. Many scholars have discussed how arsenical copper alloys were produced, and in the past many thought that adding arsenic to copper was not feasible in the Bronze Age because of the physical properties of these metals and the high volatility of arsenic. However, in view of the fact that arsenical copper alloys analyzed for various projects often seemed to be correlated with the use and function of the artefacts, this opinion seemed less and less credible. In the last decade, various excavations and analyses seemed to prove that Bronze Age artisans were able to artificially produce the arsenical copper alloys needed for their products (Doonan et al.2007; Thornton et al. 2009; Rehren et al.2012) and did not just select ready smelted arsenic-rich copper.

Some very relevant and rare finds belonging to the Foundry Hoard (see below) support the hypothesis that arsenic was deliberately used to prepare alloys suitable for the specific kind of object and correlated with its employment, and that the process could be carried out and was well controlled by the ancient metalworkers. (on the problems connected with arsenic see also Giumlia-Mair et al. *Arsenic in the Network. Arsenical Copper in Minoan Crete*, in this volume).

Histogram 1 shows the frequency of arsenic in the copper-based objects from Mochlos. Most items contain around 1% As, but there are also some with higher arsenic content, up to over 4%. The contemporary copper-based finds from Gournia show similar characteristics (see Giumlia et al. 2015).

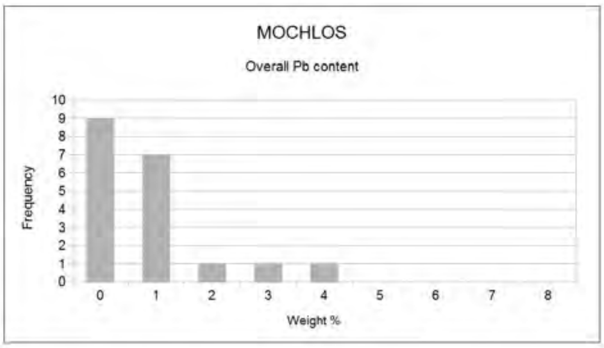


Histogram 1: Overall As content

Tin and lead content

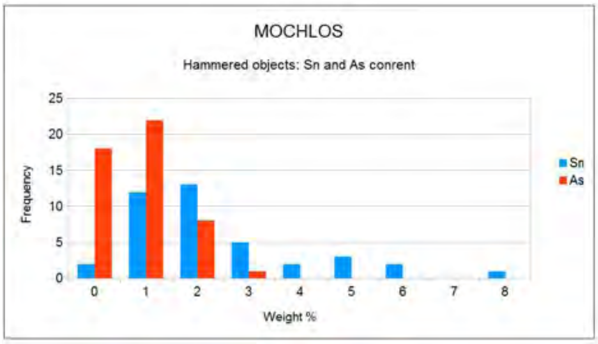
The average tin content in the 94 finds from Mochlos that contain tin is around 2.5% with a range of 0.4-8.4 % (standard deviation 1.6), while the average arsenic content in the 131 objects that contain arsenic at measurable levels is 1.5% As, range 0.2-4.3% (standard deviation 0.7). The highest Sn content was determined in knife (IVA.203) with 8.4% Sn. A bezel (IVA.254) also has a high tin content (7.2% Sn), but it is corroded and the results cannot be considered reliable. The alloy for the knife was prepared with a high tin content to obtain a good and efficient blade, and, in the case of the decorative bezel, the aim was certainly a golden colour.

The highest As percentage was 3.8%, determined in the alloy of a smaller chisel (IVA.304) and in what looks like a fragment of a mirror, but for the moment can only be defined as scrap metal (IVA.285). Around 15 objects are made of well-refined, almost pure, unalloyed copper. Some lead was determined in 19 pieces (Histogram 2), but in 9 cases the lead was only at trace level. The range of lead is 0.2-4.4% (standard deviation 1). Only a small ingot (IVA.60), with 4.4% Pb, and a cylindrical cast fragment (IVA.154) with 3.4% Pb, show higher lead contents that might be considered a deliberate addition.



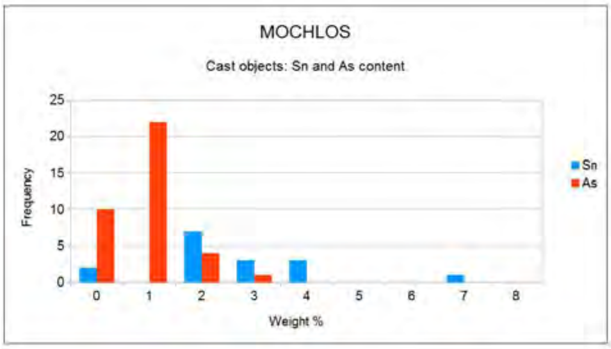
Histogram 2: Overall Pb content

In the Bronze Age lead was mostly employed sporadically, just to increase the metal quantity cheaply, as it was the cheapest, the most common and easily available metal. The addition of lead renders the alloy fragile under the hammer, and the metal becomes dull and greyish. Apparently the metal artisans at Mochlos tried to avoid lead additions and preferred good quality alloys made with well-refined copper and alloyed with arsenic and tin that could be worked by hammering.



Histogram 3: Hammered objects, Sn and As content

Histogram 3 illustrates the arsenic and tin content of hammered objects, and Histogram 4 the arsenic and tin content of castings. From the graphics it is clear that the arsenic content is similar in both groups, but also that a larger amount of tin was used for hammered pieces. The addition of tin increases the malleability of copper based alloys, so that they can be worked longer, without the need of much intermediate annealing. The results also seem to indicate that in general better refined copper was employed for hammered pieces, while for castings any metal was used.



Histogram 4: Sn and As content in castings

In the case of wrought objects the arsenic content is slightly higher, and the tin content (up to 5%) is slightly lower than in hammered pieces, but higher than in castings.

As with similar objects in other contemporary European contexts, tin - that was expensive and rare - was used carefully and with a sparing hand (cf. Junghans et al. 1960 and 1968; Craddock 1976, 98-99). The earliest additions of tin to arsenical copper are generally dated to the advanced Middle Bronze Age. Tin is first added in small quantities, and with time the amount increases to around 10%, i.e. to 8 – 12% Sn. Controlling the additions of tin to more than ± 20% was not easy. The most regular and best controlled addition of tin is found in blades (Tylecote 1976; Craddock 1976, 98; 1995, 122-135). The items from Mochlos seem to have been produced in the long transition period, when both arsenic and tin were employed. Nevertheless, the quality control of representative or decorative objects and blades is noticeable, with 6-8% of tin, while smaller blades and vessels, that had to be resistant, contain 3-5% of tin. Everyday objects and heavy tools contain 1-2% of tin.

With the exception of the ingot and the cast cylindric fragment mentioned before, the presence of lead in the alloys can be considered a simple impurity, coming from the smelting of some mixed copper ores. Most of the pieces contain lead at trace level or up to 1%, and even the objects with higher percentages only reach 4% Pb (see Histogram 2).

As Cypriot copper, indicated by LIA analyses as the source of the copper used at Mochlos, does not contain lead, it is possible that the preform IVA.60 and the fragment IVA.154 belong to a different metallurgical tradition.

Ingots

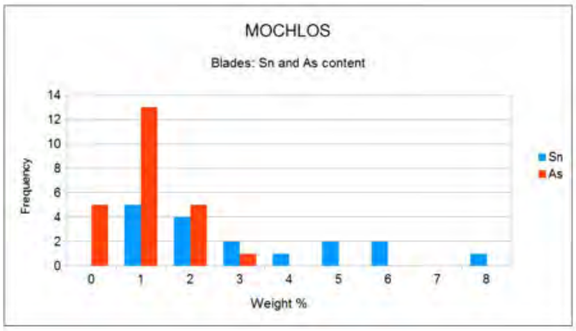
A large number of fragmentary copper ingots of oxhide type were excavated at Mochlos. Most consist of smaller pieces of various sizes and shapes. Many are irregular and amorphous; however, a large number could be attributed to oxhide ingots because of their shape and structure (cf. Giumlia-Mair 2009b). Of the 126 ingot fragments found at Mochlos, 66 come from the Merchant's Hoard, 55 from the Foundry Hoard, 34 from the Artisans' Quarter and 5 from Houses C.6 and B.4. (see Table 1) Many bear traces of chisel cuts. Only four of the fragments might perhaps come from plano-convex ingots. The largest number seem to belong to oxhide ingots of Buchholz's Type 2, with slightly curved long sides and clearly defined handles at the corners. Only five can be attributed to oxhide ingots of Buchholz's Type 1, i.e. to pillow-shaped ingots (Buchholz 1959; Bass 1967; Giumlia-Mair 2009b, 168-169).

All ingot fragments were carefully weighed multiple times, and various weight ranges could be identified. The number of ingots belonging to the weight ranges and where they were found are given in a table and discussed in the forthcoming publication on Mochlos IVA.

In the Artisans' Quarter Hoard scrap metal, spillage, crucible remains were also found, and some residues were recognized in the Merchant's Hoard too. The ingot fragments and other metal lumps were analyzed and published elsewhere in more detail (Soles and Stos-Gale, 2004, 49).

Blades

The qualitatively best alloys among those employed for the group of analyzed finds from Mochlos are the ones used for the production of blades. For this study 24 blades of different type and size were analyzed. The mean tin content in all cutting implements is 3.5% of tin, with a range of 1- 8.5% of tin (standard deviation ca. 2). The mean arsenic content is 0.4%, with a range of 0.4-3.2% of arsenic (standard deviation 0.6). In this group there were 14 daggers.



Histogram 5: Sn and As content in blades

Histogram 5, illustrates the arsenic and tin contents in all blades. 11 out of 15 larger blades contain tin percentages up to 6.4% of tin. 4 contain up to 3,2% of arsenic (mean ca. 1.7% As). 80% contain 1% of arsenic or more, with only one exception: a skinning knife (IVA.309) that is made of unalloyed copper with only traces of arsenic. On the other hand, a better quality skinning knife (IVA.202) contains 2,8% of tin and some arsenic (Fig. 1).

Fig.1: Skinning knife IVA.202

Among the blades there are interesting specimens, for example a curved blade (IVA.201) with the cutting edge on the internal side. The blade was obliquely fixed with rivets, so as to obtain a strong weapon, probably for cutting the throat of animals or thick branches of plants.

The thin and very long knife IVA.203 shows the highest tin content (8.4% Sn) among the analyzed pieces, and its blade was resistant and flexible, able to keep a sharp edge. Its point is neatly bent back on the blade, and the typical structure preserved in the corrosion, where the handle was fixed, suggests that the material of the handle was ivory. The point seems to have been deliberately bent, perhaps as a ritual defunctionalization. A discussion with more details on the single blades will be published elsewhere (Soles and Giumlia-Mair forthcoming).

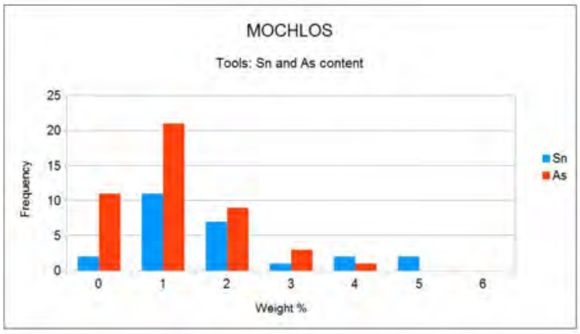
The alloys used for many of the rivets are of good quality and contain rather high arsenic and tin amounts. For example, the skinning knife (IVA.202) contains ca. 3% of tin and 1% of arsenic, but the alloy of the rivets contain around 5% of tin and 2% of arsenic. This suggests that the smiths used some metal remains kept in the workshop for the rivets.

The handle of a small "knife" (IVA.267) does not seem to ever have had a wood-, bone or ivory handle since no rivet holes are present. The composition of the alloy, with ca. 2% of tin and 1% of arsenic resembles those of tweezers, cosmetic tools and pins. This fact and the unusual shape suggest that this object might have been a kind of spatula for cosmetics.

Overall the blades compare well with those from Gournia, with the highest tin percentage (9.4% Sn) determined in one of the daggers (MS4186). The highest arsenic content (3.7% As) was determined in dagger MS4746L that also shows a shape different from those of all other examples. At Gournia too the alloys used for blades contain percentages of tin and arsenic that are higher than those determined in other classes of objects, and their copper is more carefully purified than that of other items (see also Giumlia-Mair et al in this volume).

Tools

Histogram 6, illustrating the tin and arsenic contents determined in the class of tools, shows a normal distribution of arsenic between 1 and 2 %, but there are several pieces that contain higher percentages, for example the chisel IVA.88, with up to the 4.3%. The standard deviation is 0.9%.



Histogram 6: Sn and As content in tools

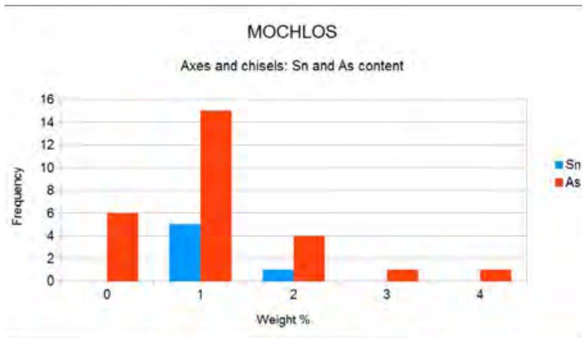
The tin employed in tools shows a normal distribution at around 1-2%, with some pieces containing higher amounts of tin. The tool with the highest tin content is the trident, with over 5% of tin; however, this is a special object with a particular significance and cannot be considered a simple tool (see Soles 2007; 2008, 152-154, figs. 7, 8). The object with the next highest tin content is a pair of tongs (IVA.218, IVA.219) with around 4% of tin and over 1% of arsenic. However, we also must bear in mind that XRF is a surface analysis and that we are measuring metal that was buried for millennia in a seaside environment; therefore, various alteration phenomena took place. This means that possibly the original tin content was higher than can be determined now with a surface analysis.

It is quite clear that for special items - larger tools and tools that needed to be sturdy and resistant - more tin and most probably more arsenic were added to the copper than for simple everyday tools.

Smaller tools, such as needles, pins and awls, tend in general to contain lower arsenic (range 0.4 – 2.5% As, mean 1.3%, standard deviation 0.9) and tin (range 0.8- 2.9% Sn, mean 1.99%, standard deviation 0.7). Larger and smaller tools should therefore be discussed separately and, whenever the number of objects makes it possible, single groups of similar items can be evaluated and compared with the finds from Gournia or with the few contemporary objects belonging to large museum collections that have been analyzed in the past.

Axes

The largest class of objects of this period excavated at Mochlos is that of the axes. It is important to note that none of these heavy tools contains tin. The group of 13 cast axes is not sufficient for statistics, Histogram 7 is therefore only a graphic way of illustrating the results, but it is useful as it gives a clear idea of the composition of these items for which a copper-based alloy containing arsenic was used. It shows the rather controlled and limited arsenic content of the axes, which only reaches up to 3%. For such large objects that had to be tough, keep the edge of the blade and withstand shock, this was the most appropriate arsenic content, because with higher percentages of arsenic the alloy would have been too brittle.



Histogram 7: Sn and As content in axes and chisels

The earliest axes must be the two examples (IVA.2, IVA.3; Fig. 2), found in a cavity under a wall, most probably deposited as a foundation offering. Interestingly, in the case of the smaller example, the blade was hardened by hammering and seems to have been used, because traces of wear are visible. The edge might have been flattened on purpose. The larger axe was left in as-cast condition and does not show any traces of working or hardening of the blade, but one of the blades shows a large and very straight fracture, parallel to the sharp edge, which might have been produced by striking it sideways on a stone slab. This piece seems to have been in contact with wood, possibly the handle of the other axe. Its patina bears traces of wood fibres. Both pieces are made of arsenical copper, with 1-2% of arsenic.

Fig. 2: The earliest axes from Mochlos (IVA.2, IVA.3)

The large Merchant's Hoard contains nine axes of different sizes. All give the impression of being new and unfinished. In all cases one of the blades was worked by hammering (and we can hypothesize that they were repeatedly annealed), but the other blade was left in as-cast condition. Possibly the idea behind this was to demonstrate to potential buyers that the blade could be hardened and sharpened, but leaving them the choice of shaping the tool as they required.

Fig. 3: The axes from the Merchant Hoard. In all examples one blade is hammered, the second is left in as-cast condition

This was done for instance with the iron bars from Khorsabad, Assyria (8th century BCE), with one pointed and one flattened end. The bars could be worked to become picks or other agricultural tools as the customer wished (Giumlia-Mair and Maddin, 2004, 48-50, fig.10). The pointed tip was hardened by tempering, while the other was flat, and showed that the iron was malleable and well refined. The idea behind having one part hardened and the other still malleable, seems to be the same as in the case of the half worked axes from Mochlos.

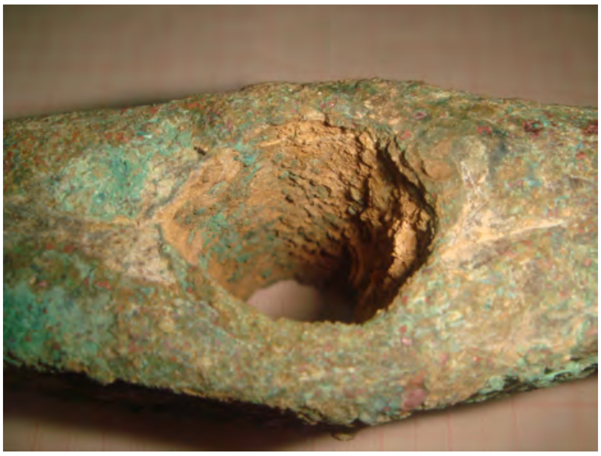


Fig.4: Detail of axe IVA.212, showing deepened shrinkage grooves

Fig. 5: Detail of axe IVA.212, showing the flat surface on the opposite side

The axes were cast in moulds that must have been open at the top because there are noticeable traces of metal shrinkage on one side of the blade that must have been caused by the fast cooling of the molten metal exposed to the air. The shrinkage grooves were then mostly deepened to make place for the nail that had to keep the axe head in place (Fig. 4). The opposite side is always smooth, flat and without any trace of shrinkage (Fig. 5).

The axes are made of arsenical copper. The range is 0.4% - 2.6% As, with a mean of 1.4% As. It has to be noted that the range is rather narrow and only one axe (IVA.210) contains a low amount (0.4%) of arsenic. The artisans who produced them were clearly able to control the composition of the tools they produced.

For such heavy axes, employed to cut and work wood, a large amount of metal was used. Their production required noticeable care and attention. This is evident in the care their alloys were prepared, but also because of how their surfaces and even the inside of the shaft-holes were finished. This suggests that they were expensive and were certainly considered prestigious objects.

Only two axes (IVA.211, IVA.216) contain some low traces of tin, but it is clear that this was not a deliberate addition in these cases since low tin traces have no influence on the properties of the tools. Possibly some scrap metal was added to the copper employed for their production.

Not many axes from Crete or the Aegean in general have been analyzed, and only a few comparisons exist. The two similar and chronologically comparable axes MS 4188 and MS 4189 from Gournia, recently analyzed (Giumlia-Mair et al. 2015) belonging to the Gournia collection in the Penn Museum in Philadelphia, show a similar composition.

Some double axes were also analyzed in the past, including some examples among the Greek Bronze Age objects published by Renfrew (1967), Junghans et al. (1968) and Craddock (1976). The earlier examples mostly contain around 1% or more of arsenic, but their date is not certain.

Craddock (1976, 99) analyzed six double axes dated to the Greek Middle Bronze Age. Four of them contained 3.7-6.6 % of tin and two were made of arsenical copper with an arsenic content comparable to that of the axes from Mochlos; however, the date and the provenance of the objects is not indicated, and they might also be of later date or come from areas where tin was employed in an earlier period.
For instance, we know that tin had already been employed in the Early Bronze Age on Syros and in Troy (Branigan 1974).

In the group of large tools from Mochlos the adze (IVA.221) must also be mentioned. Its composition with 2.6% of arsenic can be compared to that of the double axes.

This tool was probably employed in agriculture for digging or perhaps for quarrying soft stone.

Fig. 6: Adze (IVA.221) contains 2.6% As

The ceremonial double axe (IVA.61) is made of a rather thin hammered sheet of unalloyed copper with only traces of arsenic and belongs to the group of finds employed for ritual or ceremonial activities, which have very different characteristics.

As the previous discussion of analytical data indicates, arsenical copper without any tin was the preferred alloy in the case of heavy tools. Arsenical copper can be shaped and hardened by hammering, and the metalworkers could obtain a good cutting edge. This kind of alloy could also be more easily cast then unalloyed copper because the presence of arsenic lowers the melting point and renders the metal less viscous, with fewer bubbles and casting faults.

Chisels

Among the large tools found at Mochlos there is also a group of 12 chisels of different shape and size, employed most probably for working different materials, such as for example copper-based alloys, wood, antler, bone, ivory and precious metals.

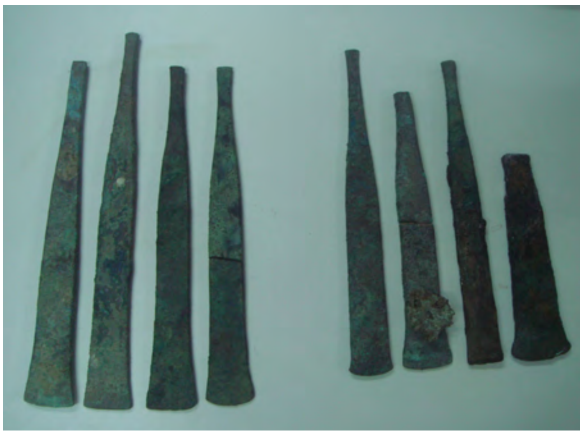


Fig. 7: A choice of large chisels from Mochlos

Two different kinds of chisels were recovered from the Foundry Hoard. Both seem to have been in a fire, but are in very good condition. Nevertheless, in this case the analysis data must be considered only indicative and semiquantitative because the fire seems to have altered the original composition. The analysis of the larger (IVA.88) of the two chisels showed an arsenic content over 4%. This amount is still acceptable for this period, but it is perhaps significant that this is the highest arsenic content determined in the entire group.

In the case of the second, shorter chisel the analysis determined over 60 % of arsenic. The analysis was repeated several times on various areas, always with roughly the same result. There is no doubt that this high arsenic concentration is limited to the surface because a tool with this composition would have shattered under the hammer, and this chisel had been worked by hammering.

The known instances of objects with very high arsenic belonging to the Maikop Culture (Ravich, Ryndina 1995) are all cast, without any further finishing, and the composition choice was due to the wish of obtaining a beautiful silvery metal, but not a functional object. Such alloys were present in Crete in the EM I period too: for example, the dagger HNM4658 from Hagia Photia (Davaras and Betancourt 2004, 9–10, fig. 9:2A.50) contains 23% of arsenic and, still now, shows a slight, but recognizable, silvery sheen on the surface of the blade (Giumlia-Mair and Ferrence 2017; Giumlia-Mair et al. in this volume).

Fig. 8: The four chisels come from the same mould but were differently wrought and finished

The high arsenic content of the chisel from Mochlos must be due to a fire and to the contact with a large piece of shapeless material with a very high arsenic content, found among the objects of the Foundry Hoard, which will be discussed below.

An interesting detail that demonstrates how the smiths of the time were working is given by the 6 large chisels in the Merchant's Hoard. Four of them come from the same mould, but have different compositions (Sn range 1.3-2%; As range 0.2-1.2%), and must have been cast by using different batches of metal. This is not surprising because the mould was probably only one, and even if the smith had to produce four pieces in one day, keeping the large amount of metal in molten status necessary for four heavy chisels would have been too time consuming, difficult and expensive in terms of fuel and manpower. The width and thickness of the four chisels in the central part are identical (Fig. 8), while the heel and the blade, which were wrought and hardened, show different shapes and proportions (Fig. 9).

Chisel IVA.189 has a different shape and comes from a different mould, but its composition is broadly similar to that of the other chisels. This clearly illustrates the skill of the metalworkers who were able to keep the composition under control in spite of the high volatility of arsenic.

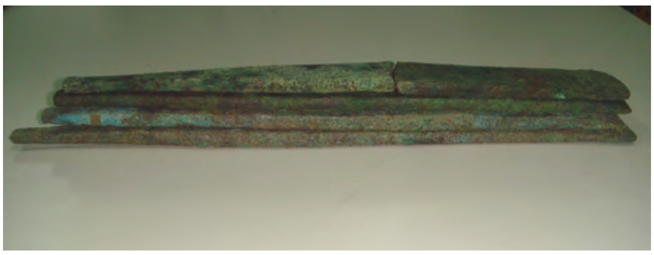


Fig. 9: The four chisels have an identical central part, but heel and blade have different proportions and dimensions.

The large chisel IVA.186 is the only example that does not contain tin, but in this case the arsenic content was enhanced to 2.6%, certainly to counterbalance the absence of tin.

The smaller chisels IVA.191 with 0.7% As; IVA.190 with 1.9% As and IVA.304 with 3.8% As, all do not contain any tin. The high arsenic of this last piece increases the hardness and helps to keep an efficient blade, useful, for instance, for working organic materials such as antler, bone and ivory.

The five chisels from Gournia (MS4178; MS4180; MS4181; MS4182; MS4199) represent an excellent comparison. The two largest examples MS4181 and MS4182, for cutting wood, are well worked and made of copper containing 2.9 and 3.9% of arsenic, respectively. The very high arsenic content is similar to that of the larger chisels from Mochlos, but also the other examples regularly contain around 1.3-1.5% of tin. Two of the smaller examples from Gournia, the thin and very long MS4178 and MS4199 do contain, however, a noticeable amount of tin (1.8 and 2.7% of tin, respectively). The tin was probably added to render these especially long tools more resistant. The medium sized, elongated MS4180 is made of very well purified, unalloyed copper. With proper annealing stages between the hammering phases unalloyed copper becomes very hard and is also more corrosion resistant than alloyed copper. The Bronze Age chisels from Greece, published by Junghans et al. (1968), Renfrew (1967) and Craddock (1976) mostly contain comparable arsenic, but much higher tin contents up to almost 10%. Regrettably the exact dates of these chisels are not specified, so that it is rather difficult to draw a comparison.

Not all tools analyzed for the Mochlos project up to now can be mentioned here: there are saws, a drill, a rasp, tongs and several smaller tools. The composition of the larger tools is roughly comparable to that of the chisels, while most of the smaller tools are of unalloyed copper. Only one contains 2.3% of tin and two more are of arsenical copper (with more than 1% As). These results also compare well with the analytical results of the objects from Gournia (Giumlia-Mair et al. 2015).The group of analyzed metal finds from Mochlos comprises a large number of extremely interesting vessel remains, decorative objects, etc., but only a few can be discussed here. Some important pieces, such as the trident, found buried as foundation deposit under the floor of the Ceremonial Building B2, together with the only tin ingot discovered in Crete, has been published elsewhere (Soles 2007), and the tin ingot is at the moment under study.

A further piece that gave fascinating results and insights into the metallurgy of the period is the sistrum IVA.183. Its parts were made of different alloys. The cast handle contains ca. 2 % of tin and arsenic, the arch is of unalloyed copper, while the mobile rods inserted into the arch are made of copper containing ca. 5% tin, and ca. 8% silver and the disks contain ca. 5% tin and silver. The silver additions and the higher tin in the parts that rattled and gave the timbre to the sound, when the sistrum was shaken, produced a better, more pleasant and silvery sound. A detailed discussion is published elsewhere (Soles and Giumlia-Mair 2011, and forthcoming).

Nevertheless, the most interesting finds from the metallurgical point of view are certainly the workshop remains of the Foundry Hoard.

Workshop Remains

The Foundry Hoard from House C.3 collects the kind of remains, which would be salvaged from the area of a workshop destroyed by fire. In detail, it consists of several tools, scrap metal and what looks like a hoarded metal reserve with various pieces of copper ingots. Most of these materials bear the traces of a strong fire. Beside ingots and tools there are broken objects of all sorts, including some weapons, strips wrapped around themselves, fragmentary pieces and working remains, such as spills, metal cuttings and even a casting funnel. Destruction by fire was not a rare event in ancient workshops, in buildings partially made of wood and other organic materials, and several instances dated to various periods are known (cf. Giumlia-Mair 1998a; b; 2014).

The hoard gives us a perfect snapshot of the materials employed in a Minoan foundry, as it preserves all items that were in use in the workshop before the fire. The impression is that the merchant who lived in House C.3 obtained the valuable remains of the burned workshop by some means, and kept them for recycling in the basement of the house. This means that we cannot be completely sure that the Foundry Hoard originated from Mochlos, but it is very probable, as metal workshops have been identified in the Artisans' Quarter in front of the ancient Mochlos peninsula (Soles 2003).

Fig.10: Casting funnel from the Foundry Hoard IVA.64, broken in two pieces

A casting funnel from the Foundry Hoard (IVA.64), which represents the surplus metal poured into a large mould up to the brim of the empty space left by the burned wax in the clay, was cut away after the casting. Very clearly it was kept for recycling, it contains 4.5% of tin and 1.8% of arsenic, and must have been used in the production of a fairly large object that had to be resistant and could be hardened by hammering. It shows a large bubble at the top and two more bubbles at the other end, all produced by the gases escaping from the liquefied metal when it was poured (Fig. 11).

Fig.11: Detail of broken casting funnel IVA.64, showing the bubbles produced by gases during casting

Among the finds there are also some preforms, i.e. a kind of small ingots ready to be worked by hammering. Their composition is somewhat irregular: the alloy was probably prepared as required by the kind of object for which the ingot was planned.

Fig. 12: Three, apparently new, strip bundles

The strips and strip bundles (Fig. 12) with multiple strips wrapped around themselves are made of well-purified copper. The strips, which are often quite long, were cut from large and thin sheets. They seem to be the production of skilled metalworkers that sold them to smaller or less specialized workshops or artisans that were not able to produce them. We cannot know if the bundles were made at Mochlos, but quite a few, apparently new, bundles were found, while for instance only bits and pieces of strips have been recovered at Gournia. This suggests that possibly one of the local workshops at Mochlos specialized in this production.

The so-called blanks are quite interesting too: they are short curved rods with traces of metal shrinking inside the bend and a thickness of around 5 mm. The shrinkage suggests that they were cast in a simple open mould, and they seem to have been employed in the production of small items, such as awls or pins. The shrinkage lines can still be recognized along the shaft (Giumlia-Mair et al. 2015) of several small objects manufactured from this kind of small blank. At Mochlos there is only one blank (IVA.79; Fig. 13), while at Gournia a large group was recovered.

Fig. 13: Blank (IVA. 79) from Mochlos. The shrinkage line is visible on the internal part of the curve. Such small blanks were employed in the production of small objects, like for instance pins or awls.

The composition of the blanks seems to depend on the kind of the object for which they were cast. Simple open molds of the kind used for the production of the blank were also found in the Artisans' Quarter of Mochlos and demonstrate that these small semi-worked items were produced there as well.

A further interesting piece is a small fragment of crucible reddened by fire. The microscope examination of the clay-based fabric showed that fragments of shell had been mixed with the clay to render the crucible more refractory and fire resistant (Fig. 14).

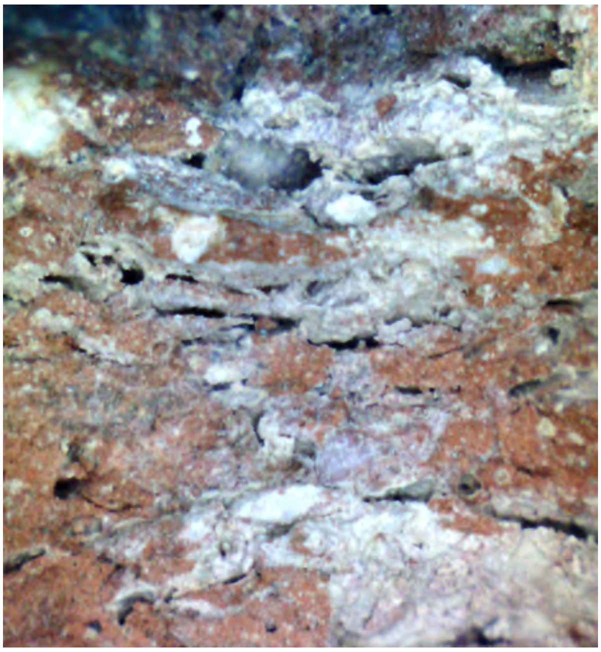


Fig. 14: Fabric of crucible: clay mixed with shell fragments

As the shell fragments are still recognizable and almost intact, it seems that the mixture employed for this item was not efficient enough and the crucible broke rather early, so that some of the pieces of shell still survive.

Fig. 15: Fragment of arsenic-rich material mixed with workshop remains, detached from the larger chunk. On the right side the remains of a chisel can be recognized.

From the metallurgical point of view, the most important find in Mochlos is the large chunk of arsenic-rich material from the Foundry Hoard (Fig.15). As mentioned above, the hoard consists of the remains recovered from a burned metal workshop, including tools, metal objects and metal stock, such as ingot fragments and broken objects for recycling. The large piece of arsenic-rich material was clearly part of the foundry supply because it was found in a heap with the metal pieces. Several years ago, a similar material was excavated at Poros Katsambas, an Early Minoan site on the Cretan northern coast, where also tuyeres, slagged crucibles, slag and dross, metal artifacts, an ingot and "a mineral resembling iron pan," were recovered (Doonan et al. 2007). The mineral contained 52.8% Fe; 39% As and no detectable Cu, and it was identified as löllingite, i.e. as an iron arsenide mineral ($Fe As_2$). The residual metal prills inside the crucibles were also analyzed: they contained up to 52% arsenic, while the slag on the crucibles' walls contained up to 23% arsenic. The researchers suggested that the crucibles had been used to add arsenic to copper by mixing löllingite and molten metal (Doonan et al. 2007, 112). Only a couple of years later a German team excavated the site of Arisman (4^{th} - 3^{rd} Millennium BCE) in Iran, and identified a complex process with two types of slag. The first, grey slag, came from the smelting of copper ores, but the second, brown slag, came from the production of speiss, i.e. a man-made iron-arsenic alloy (FeAs), from arsenopyrite (Thornton et al. 2009; Rehren et al. 2012). Arsenopyrite could not be used as arsenic addition to copper ores because it would have formed a matte with the sulphur, so it had to be smelted to speiss first. The iron present in the speiss would oxidise, when the speiss was added to the molten copper, and thus protected the arsenic from oxidation. The same happened when casting the obtained arsenical copper: as long as there was some iron in the molten copper the arsenic would not volatilize (Thornton et al 2009; Rehren et al. 2012). In this way the addition of arsenic to the copper could be controlled.

In their paper on Arisman, Thornton et al. (2009, 310) also discussed the "arsenic mineral" found at Poros Katsambas and asserted that the published composition of the material found at Poros Katsambas was consistent with speiss, a man-made compound, and not with löllingite, a mineral found in nature.

The material found at Mochlos seems to be a speiss too and testifies to the circulation of this material and its employment in metallurgical workshops still in this period, LM IB, when we would have expected the use of bronze. As discussed above, most of the objects analyzed contain at least 1% of arsenic, and there are quite a few that contain higher arsenic percentages, up to 4%. Most of the objects made of copper alloys containing tin, also contain some arsenic, and therefore they still belong to the long period of transition between the use of arsenical copper and bronze.

It is important to underline that, up to now, it was supposed that the reason for the presence of arsenic in copper alloys containing tin was due to the simple recycling of arsenical copper, to which the expensive tin was added. The identification of speiss at Mochlos in the Late Minoan IB period now indicates that the copper-based alloys containing both elements, arsenic and tin, were deliberate and produced presumably with the intention of exploiting the advantageous properties of both metals, and certainly to avoid using higher amounts of expensive imported tin. (compare also Giumlia-Mair et al. in this volume).

Conclusions

The Foundry Hoard consists of materials that the local merchants were interested in and kept for recycling, but it also represents a unique and extremely important instance of workshop remains of this period because, together with the analytical data collected from the entire corpus of copper-based items of this period, it allows us to reconstruct the habits of the metalworkers and the ways of production of specific items, such as for example chisels and axes. In particular, the large chunk of speiss reveals unexpected workshop habits in the Late Minoan IB period and reveals the form in which arsenic was added to copper, and the fact that the presence of arsenic in the finds was deliberate and not just due to recycling.

Acknowledgements
We wish to thank Stephania Chlouveraki, Head of the W.D.E. Coulson Conservation Laboratory, and Kathy Hall, Senior Conservator at the Study Center for their help: they kindly cleaned the objects before analysis.

All photos and histograms by A. Giumlia-Mair

Bibliography

Bar-Adon P., 1980, The Cave of the Treasure. The Finds from the Caves in Nahal Mishmar, Israel Exploration Society, Jerusalem.

Bass G.F., 1967, Cape Gelydonia: a Bronze Age Shipwreck, Transactions of the American Philosophical Society, N.S. 57/8, Philadelphia.

Betancourt P.P, Wheeler T.S., Maddin R. and Muhly J.D. 1978. Metallurgy at Gournia, Museum Applied Science Center for Archaeology Journal (MASCA)1, 7–8.

Buchholz H.G., 1959, Keftiubarren und Erzhandel im zweiten vorchristlichen Jahrtausend, Prähistorische Zeitschrift 37, 1-40.

Budd P., Ottaway B.S., 1991, The properties of arsenical copper alloys: implications for the development of Eneolithic metallurgy, Archaeological Sciences 1989, Budd P., Chapman B., Jackson C., Janaway R., Ottaway B. eds., Proceedings of the Conference on the Application of Scientific Techniques to Archaeology, Bradford, Oxbow Monographs 9, Oxford, 132-142.

Craddock P.T., 1976, The Composition of the Copper Alloys used by the Greek, Etruscan and Roman Civilizations, 1. The Greeks before the Archaic Period, Journal of Archaeological Science 3, 93-113.

Craddock P.T., 1995, Early Metal Mining and Production, Edinburgh University Press, Edinburgh.

Davaras, C. and Betancourt, P.P., 2004, *The Hagia Photia Cemetery* I: *The Tomb Groups and Architecture* (Prehistory Monographs 14), INSTAP Academic Press, Philadelphia.

Doonan R.C.P., Day P.M., Dimopoulou-Rethemiotaki N., 2007, Lame Excuses for Emerging Complexity in Early Bronze Age Crete: the metallurgical Finds from Poros Katsambas and their Context, in Day P.M. and Doonan R.C.P. eds., Metallurgy in the Early Bronze Age, Oxbow Books, Oxford, 98-122.

Giumlia-Mair A., 1998a, Studi tecnici sui bronzi dall'officina dei Ciastjei, in: Paola Cassola Guida, Silvia Pettarin, Gabriella Petrucci, Alessandra Giumlia-Mair, Pozzuolo del Friuli, II, 2, La prima età del ferro nel settore meridionale del castelliere. Le attività produttive ed i resti faunistici, 181-230.

Giumlia-Mair A., 1998b, Iron Age Metal Workshops in the Eastern Alpine Area, Metallurgica Antiqua, Festschrift Maddin/Bachmann, Der Anschnitt, Beiheft 8, Bochum, 45-55.

Giumlia-Mair A., 2007, Arsenical copper in the Iron Age, in: Proceedings of the International Conference on Surface Modification Technologies SMT21, Paris 24-26 September 2007, Valar Docs, 131-142.

Giumlia-Mair A., 2008, The Metal of the Moon Goddess, in Alessandra Giumlia-Mair ed., Proceedings of the Session "Arts and Surfaces" SMT21 Paris, 24-26 September 2007, Surface Engineering, March 2008, Vol. 24, Nr. 2, 110-117.

Giumlia-Mair A., 2009a, Ancient metallurgical traditions and connections around the Caput Adriae, Journal of Mining and Metallurgy 45 B (2), 141-222.

Giumlia-Mair A., 2009b, The hoard under the *alpha* II hut on the Acropolis of Lipari: a metallurgical study, in: Lo Schiavo F., Muhly J.D., Maddin R., Giumlia-Mair A. eds., Oxhide Ingots in the Central Mediterranean, A.G. Leventis Foundation, CNR – Istituto di Studi sulle Civiltà dell'Egeo e del Vicino Oriente, Roma, 166-214.

Giumlia-Mair A., 2011, Composition of the Mochlos Sistrum, Appendix to: Soles J., The Mochlos Sistrum and its origins, in: Metallurgy: Understanding How, Learning Why: Studies in Honor of James D. Muhly, Betancourt P.P.; Ferrence S.C., Prehistory Monographs, INSTAP Press, Philadelphia, 131-144.

Giumlia-Mair A., 2014, Analisi di materiali metallici dallo scavo di Fiesole, Piazza Garibaldi, in Daldelli G. e Lo Schiavo F. eds., L'amore per l'antico. Dal Tirreno all'Adriatico, dalla Preistoria al Medioevo e oltre. Studi di Antichità in ricordo di Giuliano de Marinis, Vol.1 – 2, Scienze e Lettere dal 1919 Srl, Roma, 209-220.

Giumlia-Mair A., Maddin R., 2004, The Origins of Iron, in: The Civilisation of Iron, W. Nicodemi ed., Olivares, Milan, 35-62.

Giumlia-Mair A., Ferrence S.C., forthcoming, Analysis of Cretan Metalwork, in "Latest Results and Examination Methodologies of Pre- and protohistoric Metals and Other Inorganic Materials", Proceedings of the 1st International Scientific Conference of the UISPP Commission on Archaeometry of Pre- and Protohistoric Inorganic Artifacts, Materials and Technologies, 14th October 2016, Miskolc, Hungary.

Giumlia-Mair, A., Ferrence, S.C. and Betancourt, P. P., 2015, *Metallurgy of the copper-based objects from Gournia, East Crete*, Proceedings of the 3rd International Conference "Archaeometallurgy in Europe III", June 29-July 1, 2011, Hauptmann, A. and Modarressi-Tehrani, D., eds., Deutsches Bergbau-Museum, Bochum, 145-154.

Hahn-Weinheimer P., Hirner A., Weber-Diefenbach K., 1995, Röntgenfluoreszenz-analytische Methoden – Grundlagen und praktische Anwendung in den Geo-, Material- und Umweltwissenschaften, Vieweg Verlag, Braunschweig Wiesbaden.

Hosler D., 1988, The Metallurgy of Ancient West Mexico, in: The Beginnings of the Use of Metals and Alloys, R. Maddin ed., MIT Press, Cambridge Mass., 328-343.

Junghans S., Sangmeister E., Schröder M., 1960 and 1968, Studien zu den Anfängen der Metallurgie, Mann Verlag, Berlin.

Lechtman H., 1988, Traditions and Styles in Central Andean Metalworking, in The Beginnings of the Use of Metals and Alloys, R. Maddin ed., MIT Press, Cambridge Mass., 344-378.

Lutz J., Pernicka E., 1996, EDXRF analysis of ancient copper alloys, Archaeometry, 38, 2, 313-323.

Ravich I.G., Ryndina N.V., 1995, Early Copper-Arsenic Alloys and the problems of their Use in the Bronze Age of the North Caucasus, Bulletin of the Metals Museum 23, Sendai, 1-18.

Rehren Th., Boscher L., Pernicka E., 2012, Large scale smelting of speiss and arsenical copper at Early Bronze Age Arisman, Iran, Journal of Archaeological Science 39, 1717-1727.

Renfrew C., 1967, Cycladic metallurgy and the Aegean Early Bronze Age, American Journal of Archaeology 71, 1-20.

Shalev S., Northover J.P., 1993, The metallurgy of the Nahal Mishmar hoard reconsidered, Archaeometry 35, 35-47.

Soles J.S., 2003. *Mochlos IA. Period III. Neopalatial Settlement on the Coast: The Artisans' Quarter and the Farmhouse at Chalinomouri. The Sites*, INSTAP Academic Press, Philadelphia.

Soles J.S., 2005, From Ugarit to Mochlos - Remnants of an Ancient Voyage, in Laffineur R. and Greco E., eds., *EMPORIA: Aegeans in the Central and Eastern Mediterranean*, (*Aegaeum* 25), Liège, 429–439.

Soles J.S., 2007, "Saevus Tridens," in Betancourt P.P., Nelson M. C., Williams H. eds., Krinoi kai Limenes, Studies in honour of Joseph and Maria Shaw, INSTAP Academic Press, Philadelphia, 251-255.

Soles J.S., 2008. Metal Hoards from LM IB Mochlos, Crete, in I. Tzachili, ed., *Weights in Context. Aegean Metallurgy in the Bronze Age*, Athens, 143–156.

Soles J.S., and Stos-Gale Z.A., 2004, The Metal Finds and their geological Sources, in Mochlos IC – Period III. Neopalatial Settlement on the Coast: The Artisans' Quarter and the Farmhouse at Chalinomouri. The Small Finds, INSTAP Academic Press, 45-60.

Soles S.J., 2011, The Mochlos Sistrum and Its Origins, with an appendix by A. Giumlia-Mair, in: Ph. P. Betancourt and S. C. Ferrence eds., Metallurgy: Understanding How, Learning whY – Studies in Honor of James D. Muhly, INSTAP Academic Press, Philadelphia, 133-146.

Soles J.S., F. McCoy and R. Suka, 2017, Evidence for Three Earthquakes at Mochlos in the Neopalatial Period, ca. 1700-1430 BC, in S. Jusseret and M. Sintubin eds., Minoan Earthquakes. Breaking the myth through interdisciplinarity, Leuven University Press, Leuven, 307-325

Soles J.S., Giumlia-Mair A., forthcoming, Metal Objects, Materials and Sources, with a contribution by Stos-Gale Z., in J.S. Soles and C. Davaras, eds., *Mochlos IVA. Period III: The House of the Metal Merchant and other Buildings in the Neopalatial Settlement*, INSTAP Press, Philadelphia.

Stefan L., Giumlia-Mair A., Degasperi N., Bellintani P., 2017, The Iron Age bronze workshop of „el Vato", Trento, Italy, in A. Giumlia-Mair ed., Aspects of Ancient Metallurgy, Special Number of Materials and Manufacturing Processes, 1-9. www.tandfonline.com/lmmp

Stos-Gale Z., forthcoming, The Origin of Copper Metal found in the Mochlos Settlement, contribution to Soles J.S., Giumlia-Mair A., "Metal Objects, Materials and Sources", in J.S. Soles and C. Davaras, eds., *Mochlos IVA. Period III: The House of the Metal Merchant and other Buildings in the Neopalatial Settlement*, INSTAP Press, Philadelphia.

Tylecote R.F., 1976, A History of Metallurgy, The Metals Society, London.

MOCHLOS Tab.2

OBJECT AND PART		Cu	Sn	As	Pb	Sb	Mn	Ni	Fe	Co	Zn	Ag	Au
axe	IVA. 3	97		1,8		0,4	tr.		0,4				
axe	IVA. 3	97		1,9		0,5			0,4			tr.	
axe	IVA. 2	98		1,1					0,3				
sheet metal	IVA. 1	97	1,2	1,6		0,2	tr.		0,4				
sheet metal	IVA. 1	97	1,4	1,5		0,3			0,3				
axe	IVA. 210	98		0,4		0,2			1,1			tr.	
axe	IVA. 209	97		0,7	0,6	0,4			0,7				
axe	IVA. 211	98	tr.	0,9					0,6				
axe	IVA. 212	97		1,7		tr.			0,5				tr.
axe	IVA. 213	97		1,8	0,4	0,2			0,8			tr.	
axe	IVA. 214	98		1,3	tr.	0,3			0,3			tr.	
axe	IVA. 214	98		1,4		0,2			0,5			tr.	
axe	IVA. 215	98		0,7	tr.	tr.			0,5	tr.			
axe	IVA. 216	98	tr.	1,2		tr.			0,3			tr.	

OBJECT AND PART		Cu	Sn	As	Pb	Sb	Mn	Ni	Fe	Co	Zn	Ag	Au
axe	IVA. 217	97		1,8		0,2			0,4				
dagger	IVA. 196	92	6,4	1,7		0,3			0,3				
dagger	IVA. 196	92	6,4	1,8		tr.			0,4				
dagger	IVA. 198	95	2,3	2,2		0,2			0,4				
dagger rivet	IVA. 198	96		1,6	0,8	0,3	tr.		0,7			0,2	
dagger	IVA. 200	96		3,2		tr.			0,5				
dagger	IVA. 192	97		1,8		0,8			0,3			tr.	
dagger rivet 1	IVA. 192	97		0,9		1,2			0,4				
dagger rivet 2	IVA. 192	98		0,8	tr.	0,2			0,3			0,2	
dagger rivet 3	IVA. 192	98		1,2					0,5			tr.	
dagger	IVA. 194	94	1,6	2,4	1,4				0,2				
dagger rivet 1	IVA. 194	95		2,3	1,7	tr.			0,6			0,3	
dagger rivet 2	IVA. 194	96	tr.	2,4	1,3	tr.			0,4			tr.	
dagger rivet 3	IVA. 194	96	tr.	2,1	1,3	tr.			0,6			0,2	
dagger	IVA. 193	91	5,7	2,5	0,7	0,2			0,4				
dagger rivet 1	IVA. 193	94	2,3	1,2	0,6	0,3			1,5	tr.	tr.		
dagger rivet 2	IVA. 193	93	2,4	1,7	0,9	tr.			1,3				
dagger rivet 3	IVA. 193	94	1,9	1,9	0,6	0,2			1,2				
dagger blade	IVA. 195	94	3,2	1,8		0,2			0,3				
dagger	IVA. 192	97		1,9		0,8			0,4			tr.	
dagger	IVA. 197	94	3,5	1,8					0,3			0,2	
skinning knife	IVA. 202	95	2,8	0,8	tr.	0,2			0,6			0,2	
rivet 1	IVA. 202	92	5,2	1,6					0,4			0,3	
rivet 3	IVA. 202	92	4,9	2,1	tr.				0,5			tr.	
knife	IVA. 199	92	5,3	1,5		0,2			0,7			tr.	
rivet 1	IVA. 199	92	5,1	1,7		0,3			0,4			tr.	
rivet 2	IVA. 199	92	4,6	1,5		tr.			1,2			tr.	
curved blade	IVA. 201	93	4,2	1,8		0,2			0,3				
knife	IVA. 203	88	8,4	2,3		0,3			0,2				
rivet 1	IVA. 203	95	1,7	3,1	tr.	tr.			0,4			tr.	
rivet 2	IVA. 203	95	1,4	2,8					0,5				
knife	IVA. 85	97		1,6		tr.			1,1		tr.	0,3	
knife rivet 1	IVA. 85	95	1,2	1,5		tr.	tr.	tr.	1,4			0,2	
knife rivet 2	IVA. 85	96	0,4	0,7					2,3	tr.			
knife fragment	IVA. 286	95	2,3	1,2	tr.	0,2			0,4				
small knife cosmetic	IVA. 267	96	1,9	0,8		tr.			0,3				
knife fragment	IVA. 302	97		1,9	tr.	0,7			0,4				
knife rivet	IVA. 302	97	1,1	1,4					0,6				
small triangular knife	IVA. 303	98		1,6		0,3			0,3			tr.	
small chisel	IVA. 304	95		3,8	0,2				0,2				
awl	IVA. 305	96		2,5		0,4			0,5			0,3	
file	IVA. 208	95	1,8	2,1				tr.	0,3			tr.	
Chisel-shaped tool	IVA. 191	98		0,7			tr.		0,2		0,4		
Chisel-sh tool, "sleeve"	IVA. 191	96	tr.	2,2	tr.	0,2		tr.	1,2		tr.		
Chisel-sh tool, "sleeve"	IVA. 191	96		2,3		0,2			1,1			tr.	
Ch-sh tool, c funnel	IVA. 191	96		2,3	tr.	0,2	tr.	tr.	1,2		tr.	tr.	
rasp	IVA. 90	94	2,1	1,2		0,5	tr.		1,3				
bowl	IVA. 225	94	5,6			tr.				tr.			
bowl w Ag rivets, handle	IVA. 224	94	3,7	0,9		0,4			0,4			0,5	
bowl w Ag rivets, bowl	IVA. 224	95	3,4	tr.		0,3			0,5			tr.	
bowl w Ag r, bowl bis	IVA. 224	95	3,6	0,9		0,3			0,5			tr.	
bowl w Ag rivets, rivet	IVA. 224	95	3,5	0,5		tr.	tr.		0,6			0,2	
chisel	IVA. 187	98	1,3	tr.		0,3			0,2			0,2	
chisel	IVA. 188	97	1,8	1,1		0,2			0,2			0,3	
chisel	IVA. 185	96	2	1,2		0,3			0,4			0,2	
hisel	IVA. 186	97		2,6					0,3			0,2	
chisel	IVA. 189	96	2,1	1,3		0,2			0,2				
mirror	IVA. 285	91	1,7	3,8	2,2				0,6			0,3	

OBJECT AND PART		Cu	Sn	As	Pb	Sb	Mn	Ni	Fe	Co	Zn	Ag	Au
chisel	IVA. 88	93		4,3					2,7				
small chisel	IVA.	97	1,6	0,5		0,3			0,4			0,2	
metal blob	IVA.	93	2,7	1,7		0,3			1,3			0,3	
adze	IVA. 221	95		2,6		tr.			1,9	tr.			
balance pan 1	IVA. 222	99				tr.			0,5			tr.	
balance pan 2	IVA. 223	99		tr.		tr.			0,4				
tweezers fragment	IVA. 157	94	4,9	tr.		0,3			0,5				
tripod leg	IVA. 158	95	1,4	1,9		tr.	0,2	tr.	0,7				
bezel	IVA. 254	*90*	*7,2*		*1,5*				*1,2*			*tr,*	
preform	IVA. 270	92	3,8	1,4		0,5			1,9				
preform	IVA. 270	92	4,2	1,1		tr.			2,2				
hook-shaped pin	IVA. 205	96	2,5	tr.		0,2			0,4			0,2	
needle	IVA. 273	96	2,3	0,4	tr.	0,5	tr.		0,2	tr.		0,2	
needle	IVA. 255	98		0,9		tr.			0,3			tr.	
needle	IVA. 178	98		1,3					0,5			tr.	
strip	IVA. 263	99		tr.					0,8			tr.	
curved strip	IVA. 318	95	2,2	1,8		0,4		tr.	0,2			0,3	
cup fragments	IVA. 155	95	4,1	tr.	tr.	0,5			0,2				
fish hook	IVA. 258	98	1,2	tr.	tr.	0,2		tr.	0,4	tr.			
strip	IVA. 241	99		0,2		0,4	0,2		0,2	tr.			
strip	IVA. 240	99		0,3		0,3			tr.			tr.	
strip	IVA. 245	100							tr.				
strip	IVA. 65	99		0,3								tr.	
strip	IVA. 66	99	tr.	0,6					0,3				
preform	IVA. 60	91	2,7	1,7	4,4			tr.	0,4			0,2	
blank	IVA. 79	97	1,3	1,2		tr.	tr.		0,3				
strip	IVA. 68	96	2,6	0,9		0,3	tr.	tr.	0,4	tr.			
sheet metal	IVA. 72	97		2,1					0,3			tr.	
casting funnel	IVA. 64	92	4,5	1,8					0,7		0,5		
hook-shaped pin	IVA. 56	97	1,8	tr.		0,2			0,3		0,6	tr.	
hook-shaped pin	IVA. 7	94	2,9	2,5		tr.	tr.		0,4	tr.			
needle	IVA. 180	99		0,4		tr.	tr.		0,4			tr.	
chisel or wedge	IVA. 190	97		1,9		tr.	tr.		0,5			0,2	
tongs	IVA. 220	97	1,2	0,8		0,4	tr.	tr.	0,3			tr.	
drill or chisel	IVA. 207	98		1,1		tr.	tr.		0,3	tr.		tr.	
handle	IVA. 153	95	2,1	1,3	0,8	0,4		tr.	0,5				
cauldron wall	IVA. 153	*96*	*0,6*	*1,4*	*tr.*	*tr.*		*tr.*	*1,2*	*tr.*	*0,8*		
rivet	IVA. 153	96	1,3	0,8		tr.	tr.		0,9	tr.	0,7		
double axe fragm	IVA. 61	99		tr.		tr.		tr.	0,3	tr.			
saw	IVA. 204	96	2,7	0,5		0,3	tr.		0,3				
saw	IVA. 47	97	1,6	1,2		tr.	tr.		0,2			tr,	
saw	IVA. 48	98	1,4	tr.	tr.	0,2			0,3				
saw	IVA. 49	95	0,9	1,3	1,7	tr.		tr,	0,4			tr.	
knife	IVA. 52	93	2,2	1,4				tr.	1,9		0,4	0,2	
knife	IVA. 52	94	2,1	1,5		tr.	0,2		2,1		0,2	tr.	
dagger ribbed point	IVA. 51	97	1,8	0,9	tr.	tr.			0,3	tr.		tr.	
knife	IVA. 85	97	1,1	0,7		0,3	tr.		0,2				
knife, rivet	IVA. 85	97	1,2	0,8					0,5			tr.	
knife fragment	IVA. 50	95	1,7	2,3			tr.		0,3			tr.	
knife frg, upper rivet	IVA. 50	97		2,5			tr.		0,4			tr.	
pin	IVA. 57	98	0,8	tr.		0,2	0,2		0,2	tr.			
balance pan	IVA. 55	97	1,1	0,7				tr.	0,4	tr.			
balance pan	IVA. 54	96	tr.	1,2					2,3			tr.	
tongs	IVA. 219	93	4,4	1,3			tr.		0,8	tr.			
tongs	IVA. 218	94	3,9	1,5			tr.		0,4	tr.			
hook-sh pin	IVA. 206	91	2,4				tr.	tr.	0,3	tr.		6,3	tr.
cosmetic tool	IVA. 259	96	2,1	1,2		tr.		tr.	0,2			tr.	
cosm tool rivet	IVA. 259	97	1,5	tr.				tr.	0,8				

OBJECT AND PART		Cu	Sn	As	Pb	Sb	Mn	Ni	Fe	Co	Zn	Ag	Au
trident	CA 427	92	5	2,6	tr.	0,2	tr.		0,3			tr.	
trident	CA 427	91	5,3	3,1	tr.	0,2	tr.		0,3				
trident	CA 428	91	5,1	3,2	tr.		tr.		0,3				
chisel	IVA. 184	97	1,4	1,2					0,3				
ring	IVA.	98		0,9		0,2			0,2			0,2	
ring	IVA. 317	94	3,3	tr.	1,7		tr.		0,4	tr.		0,2	
ring	IVA.	97		1,2	tr.	0,4			0,4			0,5	
handle	IVA. 59	95	2,5	1,3		0,2	tr.	tr.	0,6			0,4	
handle rivet	IVA. 59	95	2,1	1,7		tr			0,9			tr.	
cylindrical handle frg	IVA. 154	90	3,8	1,8	3,4		0,3	tr.	0,4	tr.		0,2	
sistrum arch	IVA. 183	97		0,9		tr.			1,5	tr.		tr.	
sistrum scarab	IVA. 183	94	2,3	1,9		tr.		tr.	0,8			tr.	
sistrum dolphin	IVA. 183	94	2,2	1,9		tr.			0,9			tr.	
sistrum handle	IVA. 183	95	2,2	1,8		tr.			0,8			tr.	
miniature ingot	IVA. 177	98		0,6		0,2		tr.	1,7				
preform	IVA. 175	98	tr.	0,6		tr.	0,2		1,3				
preform	IVA. 118	97	0,5	0,5		tr.			0,9	0,5			
skinning knife	IVA. 309	98		0,4		0,3	tr.	tr.	0,6	tr.		0,2	
oval applique	IVA. 310	98		0,7		0,2		tr.	0,3			tr.	