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The Technology of Copper Alloys, Particularly Leaded Bronze, in Greece, its Colonies, and in Etruria during the Iron Age

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Ce mémoire intitulé :

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Présenté par :
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Adrian Burke, président-rapporteur
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Francine Blondé, membre du jury

Résumé

L'objet de la présente étude est le développement, l'application et la diffusion de la technologie associée à divers types d'alliages de cuivre, en particulier l'alliage du plomb-bronze, en Grèce ancienne, dans ses colonies, ainsi qu'en Étrurie. Le plomb-bronze est un mélange de diverses proportions d'étain, de cuivre et de plomb. Le consensus général chez les archéométallurgistes est que le plomb-bronze n'était pas communément utilisé en Grèce avant la période hellénistique; par conséquent, cet alliage a reçu très peu d'attention dans les documents d'archéologie. Cependant, les analyses métallographiques ont prouvé que les objets composés de plomb ajouté au bronze ont connu une distribution étendue. Ces analyses ont aussi permis de différencier la composition des alliages utilisés dans la fabrication de divers types de bronzes, une preuve tangible que les métallurgistes faisaient la distinction entre les propriétés du bronze d'étain et celles du plomb-bronze. La connaissance de leurs différentes caractéristiques de travail permettait aux travailleurs du bronze de choisir, dans bien des cas, l'alliage approprié pour une utilisation particulière.

L'influence des pratiques métallurgiques du Proche-Orient a produit des variations tant dans les formes artistiques que dans les compositions des alliages de bronze grecs durant les périodes géométrique tardive et orientalisante. L'utilisation du plomb-bronze dans des types particuliers d'objets coulés montre une tendance à la hausse à partir de la période orientalisante, culminant dans la période hellénistique tardive, lorsque le bronze à teneur élevée en plomb est devenu un alliage commun. La présente étude analyse les données métallographiques de la catégorie des objets coulés en bronze et en plomb-bronze. Elle démontre que, bien que l'utilisation du plomb-bronze n'était pas aussi commune que celle du bronze d'étain, il s'agissait néanmoins d'un mélange important d'anciennes pratiques métallurgiques. Les ères couvertes sont comprises entre les périodes géométrique et hellénistique.

Mots-clés : cuivre, étain, plomb, minerai, isotope, alliage, bronze, plomb-bronze, métal, statuette, figurine, statue, sirène, griffon, protome, chaudron, bol, anse, monnaie, trépied, fusion, four, moule, cire-perdue, fonte, métallurgie, relier, soudeur, Grèce, Étrusque, Ourartu.

Abstract

The subject of this study is the development, application and diffusion of the technology of various types of copper alloys, particularly that of leaded bronze, in ancient Greece, its colonies, and in Etruria. Leaded bronze is a mixture of tin, copper and lead in various proportions. The general consensus among archaeometallurgists is that leaded bronze was not commonly used in Greece until the Hellenistic period, and thus this alloy has not received very much attention in archaeological literature. However, metallographic analyses demonstrate that objects composed of leaded bronze had a wide distribution. The analyses also show differentiation in the composition of alloys that were used in the manufacture of various types of bronzes, a tangible indication that metalworkers distinguished between the properties of both tin bronze and leaded bronze. The knowledge of their different working characteristics is what enabled a bronzeworker to choose, in many cases, the appropriate alloy for a specific application.

The influence of Near Eastern metallurgical practices produced variations in both the artistic forms as well as alloy compositions of Greek bronzes during the Late Geometric and Orientalizing periods. The use of leaded bronze for particular types of cast objects shows an increasing tendency from the Orientalizing period onwards, culminating in the late Hellenistic period when high-lead bronze became a common alloy. This study analyzes the metallographic data of specific categories of bronze and leaded bronze cast objects, and it will demonstrate that although the use of leaded bronze was not as prevalent as that of tin bronze, it was nevertheless a significant adjunct of ancient metallurgical practices. The periods surveyed range from the Geometric to the Hellenistic periods.

Keywords : copper, tin, lead, ore, isotope, alloy, bronze, leaded-bronze, metal, statuette, figurine, statue, siren, griffin, protome, cauldron, vessel, handle, coin, tripod, smelting, furnace, mould, lost-wax, casting, metallurgy, join, solder, Greece, Etruscan, Urartu.

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To Lynda,
for her patience and support

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Introduction

The development of copper alloys, particularly that of bronze[1], can be detected in the changes of metallic composition of objects over time. According to the available metallographic analyses of bronze objects, it is quite evident that metal- workers modified alloy formulas into types that were suitable for particular applications. Bronze artifacts are commonplace at all archaeological sites in Greece, Italy and the eastern Mediterranean region from the Bronze Age onwards, but objects composed of leaded bronze, which is an alloy of tin, copper, and lead in various proportions, are not found in anywhere near the same numbers. The commentaries in archaeological literature that concern ancient metallurgy suggest that the use of leaded bronze was common in Etruria, and infer that this alloy was utilized sporadically by metal-workers in Greece and came into regular use only during the Hellenistic period. Metallographic analyses have provided evidence that objects composed of leaded bronze had a wide distribution: Etruria from the Archaic period onwards, in the Near East during the Late Geometric and Orientalizing periods, as well as in Greece from the Late Geometric to the Hellenistic periods.

The objective of this paper is to demonstrate by means of published metallographic analyses of cast bronze objects that the development, diffusion and use of leaded bronze alloys may have been more common than is currently presumed. To place this study in context, the metallurgical and casting techniques of copper alloys, as well as innovative manufacturing processes used in antiquity, will be introduced and discussed as background. The primary focus will be on small bronzes found at Greek archaeological sites, but the use of leaded bronze by the Etruscans will be briefly studied as well.

This study will endeavor to answer six main queries: 1) The metallurgical practices of Near Eastern bronze-workers apparently had a direct influence on metal working in Greece in the Late Geometric period. What evidence can be found in their metallurgical techniques that the particular alloy formulas they used, such as increases in the levels of tin in bronze, as well as leaded bronze, were adopted by Greek metalworkers?; 2) Leaded bronze was used by Near Eastern and Greek artisans. Is there a technical explanation for why they used this alloy for casting cauldron protomes and handles, as for example to

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[1] The terms bronze and tin-bronze both refer to the specific copper alloy composed of tin and copper.

facilitate their attachment to vessels through soldering, or was there some other reason why these attachments and handles were composed of different alloys than the cauldrons?; 3) In objects where the metallographic data shows deliberate addition of lead to bronze, can the data be interpreted to indicate technical innovation, or as merely the substitution of cheap lead in place of tin?; 4) The techniques of bronze working in antiquity developed and advanced through the diffusion of metallurgical techniques between regions. Did the utilization of this alloy by the Etruscans, as well as by Greek metalworkers in Magna Graecia, have any transferred influence on the alloy formulas used for casting in Greece? Did Greek metalworkers utilize leaded bronze to the same extent as the Etruscans, or does the data suggest otherwise?; 5) Bronze coins from the Greek Hellenistic period contain increasingly higher amounts of lead, and during this period the Greeks started adding more lead to cast statuettes. Is there a direct relationship in alloying techniques that can be observed between these two completely different types of objects?; 6) If leaded bronze was supposedly not generally used in Greece until the Hellenistic period, as the present archaeological literature on the topic suggests, does metallographic data support this claim?

Copper was probably the earliest metal to have been exploited in antiquity. Experimentation with the smelting of copper ores that contained arsenic resulted in arsenical copper that was harder than pure copper, while combining copper and tin ores resulted in tin-bronze. Lead ores were worked to extract the metal that was used in a variety of objects, and since silver is often associated with lead in the same deposit, the combined ores were processed chiefly to obtain the silver content, with lead as a by-product. Leaded copper was a commonly used alloy during the Bronze Age. In the Late Bronze Age and at the inception of the Iron Age, a modification of this metallic mixture that is termed a leaded bronze alloy was developed in some regions, and it was utilized for specific purposes throughout the Iron Age. There is evidence that the composition of the tin-bronze alloy used in an object was controlled to a certain degree depending upon the type of object that was to be produced, thus it is possible to differentiate between the types of artefacts made of bronze and leaded bronze alloys. Likewise, the period of an object's manufacture also appears to have some bearing on composition. For Greek, Etruscan as well as Eastern Mediterranean bronzes, there was a 'standardization' in the amount of tin used in bronze to produce an optimum working metal[2]. Analysis of the lead quantities in objects made from a leaded bronze alloy does not indicate that there was a particular standard in the composition of this alloy. Lead percentages tend to vary widely in objects from the Geometric to the Hellenistic periods, from less than 1% to over 30%. Bronze was used for weapons, tools, agricultural implements, armour, hammered and cast bronze statues both small and large-scale, cauldrons, vessels, cups, jewelry, etc. Leaded bronze is found almost exclusively in small cast objects, such as statuettes and figurines, decorative attachments and handles on cauldrons, vessel bases and in Hellenistic coins. A solder composed of tin and lead was sometimes used to attach handles and bases to cauldrons, and to repair figurines.

The topic of leaded bronze has not received very much attention in archaeological literature. Objects composed of this alloy form only a small portion of the overall larger sphere of ancient bronze work, due to a particular characteristic that made it unsuitable for the production of many types of bronzes: the low immiscibility of lead in copper that produces brittleness in the cooled metal. Leaded bronze has a tendency to tear and break up in applications where repeated and extensive hammering is required. It was therefore very rarely used for items such as bowls and cauldrons that were raised through sheet-metal forming. Metal analysis of artifacts from the Geometric to the Hellenistic periods in Greece and in Etruria demonstrate that leaded bronze was seldom used for casting weapons (other than arrowheads for extra weight), tools or armour because of this brittle quality. Its advantages over normal tin bronze are that it melts at a lower temperature, and increases the fluidity of the molten metal, which gives it an edge over tin-bronze in casting because more complex moulds can be constructed. Chasing (engraving), chiselling details and finishing are easier because the metal is softer. Statuettes and other small bronze objects were often composed of this alloy. The leaded bronze alloy thus occupies a definable niche in the development of ancient metallurgy.

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[2] Claude Rolley, *Les Bronzes Grecs*, Office du Livre S. A., Fribourg (Suisse), 1983, p. 13. Greek statuary bronzes show a surprising standardization in alloy composition: about 90% copper and close to 10% tin.

Methodology

This study of bronzes is based for the major part on a series of metallographic analyses that were conducted by Paul Craddock on various types of bronze objects in the British Museum. The results were published in the *Journal of Archaeological Science*, 1976, No. 3, and 1977, No. 4. Most of the data for the Etruscan figurines comes from another article by the same author in *Studi etruschi* 52, 1984. The data used for the sirens and griffins came from two articles in the *Bulletin de correspondance hellénique*, one authored by Éleni Magou *et al*, 1991, and the second by Georges Varoufakis *et al*, 1983. Further details and comments concerning source data are included with Graphs 1 through 8 in the text, as well as in the Catalogue annex in Tables 1 through 8. The analyses of the bronze coins are found in *The Composition of Ancient Greek Bronze Coins* by Earle R. Caley, and the data is compiled in the Bronze Coins annex. The categories of bronzes that were selected for study date from various periods, starting in the Geometric and ending in the Hellenistic: decorative attachments to bronze cauldrons, vessel handles, bronze coins, and statuettes. These object categories were selected in particular because for one they were cast, and secondly they were ones most likely to be composed of leaded bronze.

During the Bronze Age, arsenic, as well as tin, were added to copper in order to improve its poor casting properties, thus producing the first alloys. Tin became the addition of choice for a number of reasons, and it was a metal that was critical to the development of metallurgy, as well as in the manufacturing stages and forming processes in antiquity. Whereas copper and lead deposits existed in many areas in the Eastern Mediterranean, tin deposits that were available through ancient mining technology were much rarer. The extraction of metal from ore (smelting), the types of alloys that were developed, and the processes that were utilized in the manufacture of metal objects form the background to the metallographic analyses of bronzes.

When it comes to the addition of lead to bronze, questions have been raised as to whether ancient metal-workers were aware of the improvement in the casting of bronze that is produced by the addition of lead. Did they admix lead for this reason, or was it simply a means of saving on the amount of copper or more costly tin in the bronze, implying they were unaware of the alloy's characteristics?[3]. In some cases, the analyses provide good indications that bronzeworkers were familiar with its properties. Nonetheless, it would be erroneous to generally assume that lead was deliberately added to improve casting in all bronzes that show a lead content of over 1 to 2%. The percentage levels that are considered to be indicators, or benchmarks, of deliberate addition of both tin and lead in copper will be discussed.

An example of the adoption of foreign metallurgical techniques are the large bronze cauldrons and their decorative siren and handle attachments that were imported from the Near East into Greece during the Late Geometric and into the Orientalizing period. Some of the sirens and decorative figures (bullheads) have what appear to be deliberate additions of lead, sometimes in large amounts, whereas the cauldrons have very low lead[4]. It is during these periods that the Greeks apparently started using high tin levels in bronze, as well as leaded bronze for sirens, protomes and handles. I will present comparative data on Near Eastern imports and locally manufactured adaptations that were found at a number of Greek sites (the sanctuaries at Olympia, Delphi and at the Heraion on the island of Samos). The metal analyses show that the bronze-workers were aware of the properties of the two types of alloys. The amounts of tin mixed with the copper, and lead they admixed with bronze, varied according to the type of object, or part of an object, they wanted to produce[5]. I will discuss the influence of Near Eastern metallurgical techniques in Greek bronzework.

During the mid-2nd century of the Hellenistic period, Greek bronze coins abruptly exhibit increasingly higher amounts of lead, sometimes up to 30%. In what appears to be a

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[3] Noël H. Gale, "2 / Lead Isotope Studies – Sardinia and the Mediterranean: Provenance Studies of Artefacts Found in Sardinia", *Instrumentum* 23, 2006, p. 31. Similar to high lead amounts in bronzes from the British Late Bronze Age that supposedly was used to save on copper, rather than from a knowledge of improved casting properties of the alloy.

[4] G. J. Varoufakis, S. Philippakis, V. Photou, C. Rolley, "Bronzes grecs et orientaux, influences et apprentissage", *Bulletin de correspondance hellénique* 107, no. 1, 1983, pp. 121, 127.

[5] Varoufakis et al 1983, p. 128-130. The authors note that, " […] nous avons préféré laisser ouverte, sur ce point, la question de savoir si ces variations de teneur en plomb sont conscientes, ou non". They also mention that, "Mais certains groupes d'objets orientaux témoignent, de ce point de vue aussi, d'une technologie développée, qui sait adapter le travail des divers objets, ou des divereses parties d'une même objet, à leur forme ou à leur fonction." These statements are based on analyses of 79 metal samples taken from 76 bronze objects, most of which came from the site of Delphi in Greece.

simultaneous development, bronze statuettes also became highly leaded. Analyses of both types of objects will be examined and discussed, and explanations for this occurrence will be presented.

Analysis of bronze artifacts shows a differentiation between lead percentages in Etruscan and Greek statuettes that were produced during the Archaic to the Hellenistic periods. In general, according to the metallic analyses performed thus far, Greek figurines and statuettes contain lower amounts of lead. In contrast, higher lead composition and regular use of lead is noticeable in many Etruscan bronze statuettes. The Etruscans did not add lead to vessels or cauldrons (which were usually hammered from sheet metal), and since the compositions of bronze alloys that were used in manufacturing requiring either hammering or casting are very different, it demonstrates that the metal-workers were cognizant of the characteristics of different alloys[6]. I will present and compare the alloy compositions of Greek and Etruscan statuettes for the periods in question, and discuss whether or not the Etruscan practice of using leaded bronze was transferred to Greece.

This study is not an exhaustive treatment of the use of the leaded bronze alloy in Greece. This is due to the paucity of metallurgical analyses that have been performed on bronze objects from the Geometric to the Hellenistic periods in Greece[7]. Secure provenance and dating information could not be tracked down for many of the objects listed in the source articles, which narrowed the available list for study and analysis even further. Whereas a comparative study between various regions that used this alloy would have been very useful in tracking changes in alloy types over time, perhaps concurrent with historical events, sufficient analytical data to accomplish this was not available for most areas of Greece. The general conclusion found in numerous journal articles that the Greeks did not commonly use leaded bronze until the Hellenistic period appears to be based primarily on the articles written by Paul Craddock on the composition of bronze alloys in Greece in the Journal of Archaeological Science (1976-1977)[8]. In some respects, such a conclusion

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[6] P. T. Craddock, "The metallurgy and composition of Etruscan bronze", *Studi etruschi* 52, 1984, pp. 211-271.

[7] I became aware of this while researching the metal analyses, as well as through personal communication with researchers in the field of archaeometallurgy. This has resulted in a shorter paper than I had originally anticipated, because many analyzed objects had to be rejected due to unknown provenance.

[8] Personal communication with individual researchers.

is partially justified because this alloy was used more frequently in some areas than in others, and admittedly the lack of sufficient metallographic analyses is a major impediment in determining the frequency, distribution patterns, as well as the scope of its use in Greece more accurately. In my view, and in spite of problems with associating secure findspots with the objects, the existing data presents a different scenario for Greece than is currently presumed to be the case.

Chapter 1 provides the technical background on ancient metal-working: copper, tin and lead ore sources are discussed, as well as smelting practices, the various alloy types, and the fabrication and joining methods utilized in the production of bronze objects. Chapter 2 provides information on the historical background and development of alloys in Greece, with a brief discussion of metalworking in Etruria. Chapter 3 compares and discusses metallurgical analyses of various small cast bronze objects from Greece, Etruria and the Near East. The bronze objects have been placed in separate tables in the Catalogue according to their typology and period. Cauldron attachments and handles are in Tables 1 and 2. Greek statuettes are categorized in chronological order in Tables 3 through 6. Western Greek (Magna Graecia) and Etruscan bronzes are in Tables 7 and 8 respectively. The Figures annex provides visual representations of some of the bronzes. All dates are in BCE unless otherwise noted.

Chapter 1 – Technical Background of Copper Alloys

1.1 Copper, Tin and Lead Ores

Copper was probably one of the first metals to be used in the manufacture of weapons, knives, tools and agricultural implements. The earliest known use of copper dates to the Neolithic period in the 9th millennium in the regions of south-eastern Anatolia and northern Iraq. Evidence of early copper smelting from ores has been dated to the 5th millennium in southern Iran[9]. Metal alloys in the form of arsenical copper, and then tin-bronze (copper and tin), were being produced in the eastern Mediterranean by the 3rd millennium, but it was not until the 2nd millennium that tin-bronze came into common use in most areas[10]. The expansion of international trade during the Bronze Age (ca. 3000 – 1100) in the Aegean and the eastern Mediterranean not only facilitated the acquisition of metals by regions that either lacked metal resources, or possessed them in only limited quantities, but it also played a definitive role in the spread and development of metal-working technology[11].

At the end of the Bronze Age, the disruption of trade routes in the Mediterranean region and in the Near East caused a general shortage in tin supplies for a period of time to many areas. The tin-bronze that was the mainstay in the manufacture of weapons, tools, as well as artistic creations for the elite became a relatively scarce commodity. Many regions adapted to the bronze shortage by increasing their use of iron, and thus developing iron smelting and metal-forging techniques that advanced at a fairly rapid pace. With the return of the tin supply, bronze became once again the metal of choice, and it was only much later during the Iron Age that the use of iron actually outstripped bronze for the production of weapons and tools. The development of iron-working demonstrates the adaptability of the

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[9] James D. Muhly, *Copper and Tin, the Distribution of Mineral Resources and the Nature of the Metals Trade in the Bronze Age*, Transactions of the Connecticut Academy of Arts and Sciences no. 46, New Haven, Connecticut, 1973, p. 168.

[10] Muhly 1973, p. 168.

[11] *Ibid.*, p. 168.

skills of metalworkers in antiquity to a new situation, and through their experimentation the development of new metallurgical techniques for different materials.

1.1.1 Copper Ores

Copper is often found in its native state, sometimes in large lumps, which can be worked and shaped without any need of refining. Other sources of copper are found in various ore types with distinctive colours: oxide (dull-red cuprite, and melaconite), carbonate (green malachite and blue azurite) and sulphurous (chalconite, chalcosite and covellite). In the eastern Mediterranean, the major deposits of sulphide ores containing copper were in Anatolia, Cyprus and Iran, and these areas do not appear to have significant deposits of oxide and carbonate ores. There were also copper ore deposits in southern Palestine, Lebanon, Midian (Arabia) and the principal deposits in Egypt are found in the Sinai peninsula[12]. Syria was a significant centre of the copper industry in the Bronze Age; the Aleppo region has numerous ore sources[13].

During the Late Bronze Age, Cyprus was a major exporter of copper. There were extensive deposits at Amathus, Soli, Karion and Tamassos, and many of these mines continued to be worked in various degrees until the Roman period[14]. An indication of the extent of copper production on Cyprus during the Late Bronze Age was produced from discoveries in two eastern Aegean shipwrecks. Excavations that were conducted by George Bass at the Late Bronze Age shipwrecks at Cape Gelidonya and at Cape Ulu Burun, both located on the south-western coast of Turkey and in close proximity to each other, revealed cargos of oxhide-shaped copper ingots and tin in various forms, as well as a variety of other goods. The Gelidonya wreck contained about 1,000 kg of copper as well as a quantity of tin oxide; the Ulu Burun ship was transporting almost ten tons of copper ingots and almost a ton of tin ingots[15]. Samples of the copper ingots were subjected to lead

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[12] Muhly 1973, p. 173; John F. Healy, *Mining and Metallurgy in the Greek and Roman World*, Thames and Hudson, London, 1978, p. 58-9; R. J. Forbes, *Studies in Ancient Technology*, Vol. 9, E. J. Brill, Leiden, Netherlands, 1972, p. 10.

[13] Forbes 1972, p. 12.

[14] Healy 1978, pp. 58-9.

[15] For descriptions of the metal finds at the Gelidonya and Ulu Burun shipwrecks, see: George F. Bass, Peter Throckmorton, Joan Du Plat Taylor, J. B. Hennessy, Alan R. Shulman, Hans-Günter Buchholz,

isotope analysis, which indicated Cyprus as the likely source of the ingots[16]. In the late Hellenistic period, copper production on Cyprus appears to have stopped, due in part to the gradual deforestation on the island caused by mining activities; production resumed again some time later in the 3rd century A.D.[17]

Copper ores in Italy are located mainly in the area of Tuscany, and there may have been copper on Elba that was associated with the island's extensive iron ore deposits[18]. The Etruscans exploited the Tuscan copper deposits between Volterra and Populonia, and at Temesa; other deposits occur in parts of Campania and Bergamo[19]. In the western Mediterranean, a number of extensive copper deposits are located in Iberia (Spain). One of the richest chalcopyrite mines is located at Rio Tinto in the north-eastern part of the Huelva district (ancient Turdetani)[20]. The extent of the exploitation of the copper deposits in Iberia prior to the Roman period is not known[21].

There are few copper deposits on mainland Greece: in the Peloponnese, east of the Taygetos range in southern Laconia (the mine was worked out sometime in the 6th century), and in the Argolid east of the Manalon range[22]. In the Laurion region of Greece, not only were there substantial deposits of silver and lead, but there are indications that copper was extracted as well, and the deposit may have been rich enough to supply Greece, the Aegean Islands, and Crete[23]. Copper and iron were mined together at Chalcis in Euboea during

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"Cape Gelidonya: A bronze Age Shipwreck", *Transactions of the American Philosophical Society*, New Series Vol. 57, no. 8, 1967, pp. 1-177. Also: George F. Bass, Donald A. Frey, Cemal Pulak, "A Late Bronze Age Shipwreck at Kas, Turkey", *The International Journal of Nautical Archaeology and Underwater Exploration*, Vol. 13, no. 4, 1984, pp. 271-279.

[16] Andreas Hauptmann, Robert Maddin, Michael Prange, "On the Structure and Composition of Copper and Tin Ingots Excavated from the Shipwreck of Uluburun", *Bulletin of the American Schools of Oriental Research*, 328, 2002, p. 2; Z. A. Stos-Gale, G. Maliotis, N. H. Gale, N. Annetts, "Lead Isotope Characteristics of the Cyprus Copper Ore Deposits Applied to Provenance Studies of Copper Oxhide Ingots, *Archaeometry* 39, no. 1, p. 107.

[17] Michail Yu Treister, *The Role of Metals in Greek History*, E. J. Brill, Netherlands, 1996, pp. 292-3.

[18] Muhly 1973, pp. 186-7. From archaeological evidence, it appears that an iron-copper trade exchange existed between Italy and Greece in the 8th – 7th centuries.

[19] Healy 1978, pp. 58-9.

[20] Muhly 1973, p. 181.

[21] Healey 1978, p. 58.

[22] Jane C. Waldbaum, *From Bronze to Iron*, Göteberg, Aström, 1978, p. 63.

[23] Treister 1996, pp. 23-4. The Laurion region is located in southern Attica. See also: Jones 1984-5, p. 106.

the Archaic and Classical periods; by the Hellenistic period, this mine was exhausted[24]. Known iron deposits were located at Boeotia, in Attica near Sounion, Phthiotis, Phokis, in Thessaly and in Thrace, and copper is found in proximity to iron at some of these mines, particularly at Mt. Othrys in Thessaly[25]. Copper ores are present in Macedonia. In the Hellenistic period, Thracian copper mines were worked at Strandzha near the coast of the Black Sea[26]. The Attalids were operating copper mines in north-western Asia Minor during the Hellenistic period: huge accumulations of slag from mines were discovered on the Biga peninsula along with Hellenistic pottery, and in the Troad, the Serçeören Köy mine in the Balekisir province was in operation[27]. At a mine in Archani (Phtiotis), large amounts of slag amounting to more than 150,000 cubic meters were found in the vicinity; the furnaces were dated through pottery evidence to the 4th – 2nd centuries. Archani may have been a metallurgical centre of major significance during the Hellenistic period[28].

Crete did not have large sources of copper, although there are many deposits that are associated in some cases with iron ore. There is evidence of copper smelting at Gournia, Malia, Vrokastro and at Phaistos. Muhly says that there are no archaeological indications that copper mines on Crete were worked during the Minoan period. The Minoans had established relations with Cyprus by Early Minoan III, and contact actually intensified during the Middle Minoan period, thus it is very possible they obtained most of their metal from copper-rich Cyprus[29]. Paul Faure presents more detailed information on the early working of copper and mineral deposits on Crete[30].

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[24] Healy 1978, pp. 57-8.
[25] Waldbaum 1978, pp. 62-3.
[26] Treister 1996, p. 290.
[27] *Ibid.*, p. 290.
[28] Treister 1996, p. 291.
[29] Muhly 1973, p. 190.
[30] Paul Faure, “Les minerais de la Crète antique”, *Revue archéologique*, Presses universitaires de France, Paris, 1966, pp. 45-78. Paul Faure conducted a general mineralogical survey of Crete from 1965 to 1966 to determine the existence and extent of the island’s mineral resources. The study uncovered nineteen geological indications of copper deposits, thirty of iron, and several of argentiferous lead, as well as small deposits of gold, ochre, and manganese. In eastern Crete, traces of malachite were situated close to Kato Zakro, and nearby the author found considerable amounts of copper and iron slag at the Minoan sites of Ano, Kato Zakro, Xerokampolina and Skinares. Faure notes that some of the rocks east of Antiskari contained between 20 – 30% copper, but that most averaged about 1%. One of the largest quarries of Minoan Crete is situated in this area, composed of a variety of metamorphic rocks such as schist, quartz, pegmatite, gneiss, granite, and andesite. Faure says that many of the vases found in tombs at Asterousia and at Mesara

Copper sources were thus located in many areas, and obtaining supplies of this important metal, particularly for the working of bronze in the areas of Greece and Crete, was accomplished fairly readily, but procuring steady imports of enough tin to alloy with the copper was an entirely different matter.

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were shaped from these rocks. In his opinion, it is highly probable that the nearby copper deposits were mined in the Minoan period. Pottery sherds dating from the Early to the Late Minoan periods are numerous in the area.

In western Crete, the areas of Phournes and Meskla contain deposits of sulphurous copper in the form of chalcopyrite, as well as nearby iron deposits. Mines recently operated in both of the areas, thus they may have been worked in antiquity as well. Faure posits that it is improbable that the Minoans did not mine the malachite deposits that are still found in the quarries at Lebena, Lasaia and close to Matalon. The artisans used coloured rocks from the quarries for vases and jewelry, and would have noticed the deposits of green-coloured malachite.

During the Early Minoan II period, Hagia Triada, Platanos and Koumasa in the Mesara region were working metal independently of Syria and Egypt. During the Early Minoan III to Middle Minoan I, Crete imported weapons of Syrian manufacture, and Cretan metalworkers exported their products to Cyprus and Gebal in Lebanon. Faure mentions a passage in an Egyptian text dated to the reign of Thutmose III (ca. 1475) that names *Keftiu* as an exporter of copper ingots. Textual research produced various interpretations of the term *Keftiu*, and most prehistorians now agree that the term refers to Crete See: Bernard A. Knapp, "Bronze Age Mediterranean Island Cultures and the Ancient Near East", *The Biblical Archaeologist* 55, no. 2, 1992, pp. 65-7. It is possible that Minoans also smelted copper ingots on Cyprus, and then transported them to Egypt as part of their trade relations with that kingdom.

A large buried deposit of copper ingots, rods and bronze blades was found in an Early Minoan sacred cave close to Arkalokhori. Analysis of some of these artifacts led to the conclusion that the copper was mined on Crete. See: Joseph Hazzidakis, "An Early Minoan Sacred Cave at Arkalokhori in Crete", *The Annual of the British School at Athens* 19, 1912/1913, p. 47. Since Arkalokhori is about 20 km from Mount Asterousia where malachite deposits are found, it is possible that the copper came from there.

Faure does not specify actual measured sizes of the copper deposits that he surveyed. He notes that several deposits are large enough to have attracted the interest of modern mining companies (in Asterousia, and in areas around the White Mountains). From archaeological evidence, the mines worked in antiquity on Crete were probably limited to surface operations, enough to supply local manufacturing needs. Mining activities were not as extensive as those seen on Cyprus and in the Laurion region of Greece. The deposits that were accessible to Cretan miners using ancient mining technology, although present in quantity in some areas, were soon exhausted. Expansion of the mines on Crete, and development of the deeper deposits occured much later during the Roman period.

1.1.2 Tin Ores

Tin is grayish-white in colour, similar to lead, and is found in two forms: cassiterite (tin oxide) and stannite. Cassiterite is often found as pebbles in placer deposits in streams. Stannite occurs in tin-bearing veins in conjunction with cassiterite, chalcopyrite and pyrite (iron)[31]. Tin was a scarce metal during the Bronze Age, and the actual sources in the eastern Mediterranean have been difficult to identify. It was not as widely available as copper, although tin ingots existed during most periods after 2000[32]. Greece, Crete, Cyprus and the Aegean islands do not have any known tin deposits, neither is there any evidence of deposits in Palestine[33]. In Syria, stream tin is found in the Adonis River east of Byblos and vein ore also occurs in the area; there may be deposits near Aleppo northwest of Beyrouth[34]. Anatolia and Egypt possessed numerous deposits of essential metal ores such as copper, iron, gold, silver, and lead, but the actual Bronze Age tin sources that were used in Anatolia are unknown. There are several known tin deposits in Anatolia: at Darmanlar (south-east of Smyrna), near Eshkishehir, in Central Anatolia and near Usak, near Kastamuni, Sivas and near Tilek. There are also several tin ore sources in the mountainous areas associated with rich copper deposits located nearby[35].

Afghanistan possesses rich mineral resources, and textual evidence suggests that this region may have been a major source of tin ore during the Bronze Age; the ore was smelted at the mine site and the metal then transported to distribution points in the eastern Mediterranean area, either at Mari or at Ugarit[36]. One of Afghanistan's tin sources is located at Kafiristan[37]. It is thought that Iran may have been a major source of the tin that was exported through Anatolia and Palestine to markets in the Aegean[38]. Tin is found at Meshed in north-eastern Iran, and in the Elburz region at Hyrkania; there may have been deposits in north-western Iran (Karadag mountains east of Tabriz) and alluvial placer

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[31] Healy 1978, p. 38.
[32] Muhly 1973, p. 246.
[33] Muhly 1973, p. 256.
[34] Forbes 1972, p. 142.
[35] Forbes 1972, p. 140, and Muhly 1973, pp. 256-7.
[36] James D. Muhly, "Sources of Tin and the Beginnings of Bronze Metallurgy", *American Journal of Archaeology* 89, no. 2, 1985, p. 281-2.
[37] Muhly 1973, p. 261.
[38] Waldbaum 1978, p. 66.

deposits have been found in streams close to Tabriz, but it has not been determined if these and other tin deposits in the region were worked during the Bronze Age[39].

Tin was worked in Spain during the Early Bronze Age, and it was being exported to the Mediterranean region before the Iron Age. Tin mines in central Gaul were operating in the Late Bronze Age; Brittany was a source of tin ca. 500[40]. Tin from Cornwall appears in international trade from ca. 500 to 43. During the Hellenistic period, tin was transported up the Loire and Garonne rivers, then overland to the Greek colony at Massilia (Marseilles)[41]. The Etruscans worked the abundant tin deposits at Cento Camerelle and at Campiglia Marittima in Tuscany[42], and it has been suggested that Italy may have been a source of tin during the Bronze Age until the Roman period[43].

According to a cuneiform text from ca. 1800 found at Tell Shemshâra in Iraqi Kurdistan, tin came from mines in southern Kurdistan; bronze spearheads of a similar date were discovered at Shemshâra, indicating that the metal-smiths of the region were familiar with tin-bronze alloying[44]. The tin fields of central Germany were exploited quite early in the initial working of bronze in the region, a development no doubt aided by the fact that copper ores are usually found nearby and are sometimes mixed with tin ore. It is not known whether international trade in tin actually existed during the Bronze Age between these northern regions and the Near East and Greece. North-south trade routes had been established during the Bronze Age, attested by the presence of amber and other northern products in southern areas[45]. Early deposits of tin ore may thus have been worked in a number of regions of the eastern Mediterranean, but small deposits and alluvial sources would have been exhausted fairly quickly. Tin may thus have been procured from a number of sources.

Locating the tin sources that would have been used during the Iron Age improves somewhat, but there are still problems apparent in localizing the actual geographical

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[39] Muhly 1973, pp. 260-1;Forbes 1972, p. 141.
[40] Forbes 1972, p. 146; Muhly 1973, p. 252.
[41] Healy 1978, p. 60.
[42] Forbes 1972, p. 166
[43] Muhly 1973, p. 256.
[44] Forbes 1972, p. 162.
[45] Forbes 1972, p. 147.

sources. During the 5th century, Athens was importing substantial quantities of tin, some of these amounts presumably to be used in the casting of large bronze statues; inscriptions that are related to the casting of the Athena Promachos list an amount of 4,000 kg as a single purchase of tin, but the tin source is not mentionned[46]. Some of the tin used for producing bronze may have been procured from Iberian sources, or from Britannia, and transported to Athens by Carthaginian traders[47].

1.1.3 Lead Ores

The most common lead ore is grayish-white galena, a sulphide ore often found with pyrite and other minerals, which contains about 80% lead[48]. Galena is frequently associated with silver ore minerals, and may itself contain silver (argentiferous lead). Lead oxide ore types are cerussite (lead carbonate), anglesite and wulfenite. Lead mines may have been worked on Sardinia[49]; in the mining region of south-eastern Turkey near the village of Alihoka, Iron Age pottery was found alongside seven furnaces and silver-lead slag heaps; lead was mined in Italy at Piombino[50]. Lead-silver ores were mined in Anatolia during the Hellenistic period, at the Isik Dag mine (Ankara province) and at Güre in north-western Anatolia[51].

In the Greek region of Attica, the area of Laurion (south of Athens) had substantial argentiferous deposits that were already known in the Mycenaean period[52]. Extraction of the rich silver and lead ores contributed in a large degree to the wealth of the Athenian city-state, and the peak of activity occurred during the 5th to 4th centuries. It has been estimated that ca. 340, smelting and processing of the ores in the Laurion region produced 26.2 tons of silver and 8.7 tons of lead annually[53]. By the end of the 4th century, the

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[46] Muhly 1985, pp. 276-7.
[47] Treister 1996, p. 259.
[48] Paul T. Craddock, *Early Metal Mining and Production*, Smithsonian Institution Press, Washington, D.C., 1995, pp. 205-6.
[49] Healy 1978, p. 38, 61.
[50] Treister 1996, p. 26.
[51] Treister 1996, p. 290.
[52] Healy 1978, p. 61. Some of the ancient mining sites are Thorikos, Agrileza and Soureza. See: Jones 1984-5, p. 106, and Hopper 1968, pp. 293-302.
[53] Treister 1996, pp. 182-3.

output of the mines had decreased significantly, but in the 3rd century mining operations had recommenced. Metals extracted in the Laurion region were being traded to other areas during the 2nd century: lead isotope analysis of Syrian and Alexandrian coins indicates that the metal came from the Laurion area. In ca. 100, a slave revolt disrupted silver extraction, and according to Strabo, the mine was exhausted at the end of the 1st century.[54]

There were argentiferous ore deposits on the islands of Keos and Siphnos, but the Siphnian mines were exhausted ca. 516[55] Thasos had silver-lead ore deposits that may have been worked as early as the 9th century, however archaeometallurgical evidence suggests that the mines were exploited as sources of metal for Thasian silver coins mainly from the second half of the 6th to the first half of the 5th century; the mines were also worked during the Hellenistic period[56]. In the Archaic period, the mines at Chalcidike in Macedonia, and mines in southern Euboea were sources of silver-lead ore[57]. Several lead bars, possibly ingots, were found at the northern Greek site of Olynthus, dated to 348[58]

1.2 Processing and Smelting Ores

The ores of copper, silver, lead, etc., contain various percentages of metal, and the ore must be mechanically processed and then smelted to extract the useable metal. After the rock fragments were extracted from the mine, they were crushed with stone pounders and hammers and the bulk of the waste materials (gangue) were mechanically separated from the metal-bearing ore fragments. The fragments were placed in mortars and pulverized, and then milled into a powder, ready for smelting. Later refinements of ore processing techniques that involved pulverizing the ore, washing out the grains through sluices, and sieving the grains into uniform sizes were utilized at silver-lead mines in the Laurion area[59].

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[54] Treister 1996, p. 288-290.
[55] Treister 1996, p. 24.
[56] Treister 1996, pp. 290-1.
[57] Treister 1996, p. 26.
[58] Cynthia Jones Eiseman, “Greek Lead”, *Expedition* 22, no. 2, 1980, p. 43.
[59] Healy 1978, pp. 139-143.

Smelting an ore such as copper basically involves heating the crushed particles in a furnace on top of a layer of fuel, with an air draft supplied by either a bottom opening facing a natural air draft, or with directed air-blasts onto the fuel (charcoal) to maintain a steady high temperature, and an upper opening for the exhaust. Some of the techniques that were used in constructing kilns used for firing clay pottery were applied to building ore smelting furnaces[60], but a typical pottery kiln design could not be used for smelting, because the ore must remain in direct contact with the fuel[61].

Copper melts at 1083ºC, therefore smelting copper ore required higher temperatures than for firing clay pottery. Clay pipes, or tuyeres, were inserted through the furnace wall to which bellows were attached that provided forced air input to the ore/fuel mixture. Fuel such as charcoal provided a more intense heat than wood, and allowed more of the metal to be extracted[62]. In early shallow hearths and simple domed furnaces (Fig. 1), small depressions dug at the bottom of the hearths collected the molten copper, but large quantities could not be produced in this manner. The development of the clay-lined bowl furnace (Fig. 2), and later the shaft furnace (Fig. 3), allowed for stacking of ore and charcoal in layers. Early shaft furnaces were circular, about 15 to 40 cm in diameter. The size was limited by the necessity of sustaining a temperature of between 1100 to 1200ºC inside the furnace with the forced-air equipment that was available. With manual bellows, the maximum cross-section that can be heated to the temperature necessary to smelt the ore is about 40 cm[63]. Based on observations of traditional copper smelting that is still being practiced today in some areas, and examination of the extent of vitrification of furnace walls from fragments found at archaeological sites, a typical smelting operation in antiquity would have lasted from between 5 to 10 hours (Fig. 4)[64].

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[60] James A. Charles, “The Coming of Copper and Copper-Base Alloys and Iron: A Metallurgical Sequence”, in: Theodore A. Wertime and James D. Muhly (eds.), *The Coming of the Age of Iron*, Yale University Press, New Haven and London, 1980, p. 161.

[61] Ronald F. Tylecote, “Furnaces, Crucibles, and Slags”, in: Theodore A. Wertime and James D. Muhly (eds.), *The Coming of the Age of Iron*, Yale University Press, New Haven and London, 1980, p. 183.

[62] Healy 1978, p. 150, 159.

[63] This information about basic smelting furnace shapes and sizes is taken from observations of smelting operations in contemporary African villages and early 20th century furnaces in the Sri Lankan highlands. Craddock says they are typical of small smelting operations all over the world (Craddock 1995, pp. 169-171). Complete furnaces dating from the Bronze and Iron Ages are rarely found *in situ*, and usually only the bases are available for study.

[64] Craddock 1995, p. 201.

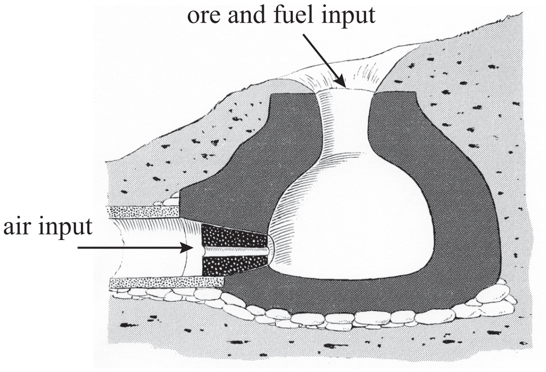

Fig. 1 – Section diagram of a dome furnace. The simple design could be built into a hillside, with air supplied by natural draught or a bellows. (Fig. 90 from Aitchison 1960, Vol. 1, with text added)

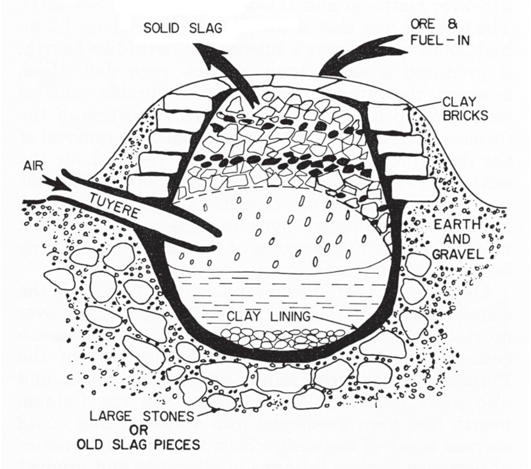

Fig. 2 – Bowl furnace. There is no chimney effect so air must be supplied by bellows. Many bowl furnaces lack a means for tapping the slag. When the melt was ready, the furnace was dismantled and the metal at the bottom was pulled out for further processing.
(Fig. 3.5, p. 29, from Rostoker and Bronson, 1990)

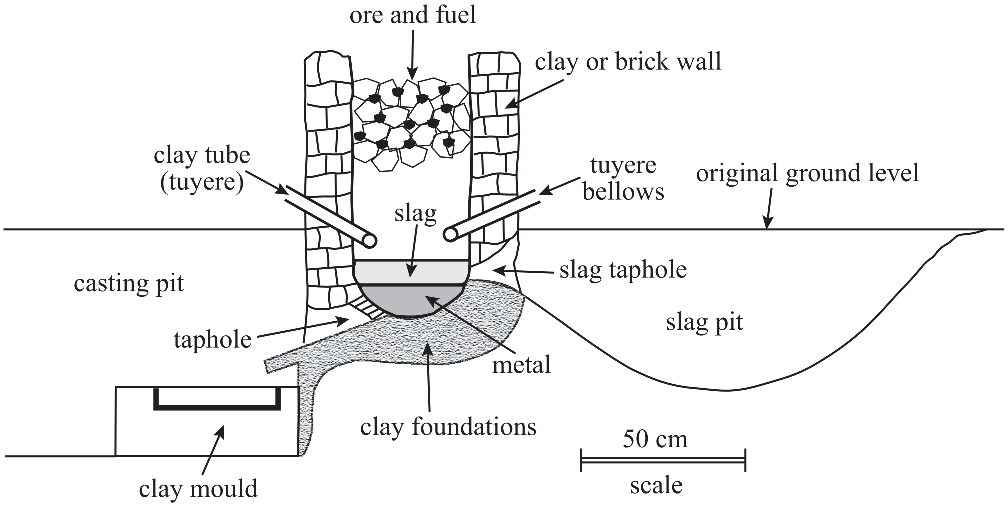

Fig. 3 – Shaft furnace for smelting copper and casting ingots.
(Illustration re-drawn from Fig. 4.2, p. 109, in Tylecote 1987)

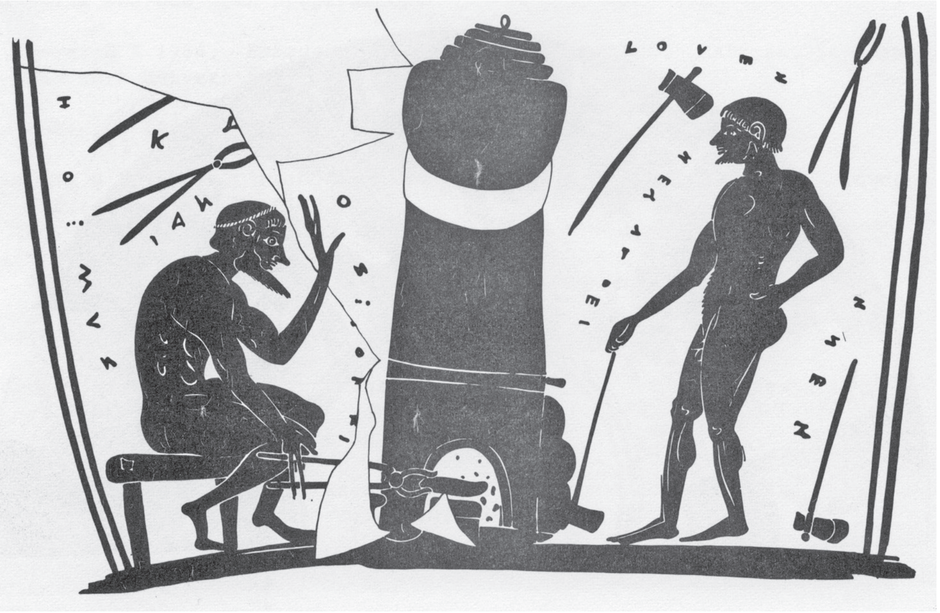

Fig. 4 – Oinochoe in the British Museum (about 500 – 475 B.C.) depicting a smith holding a lump of hot metal either on an anvil or in the mouth of a furnace. Some tools of the trade, such as hammers and pincers are also shown.
(from Oddy and Swadling 1985, fig. 3, p. 54. British Museum catalog no.: 1846.6-29.45.

Copper oxide and carbonate ores contain the highest percentages of copper and are easier to smelt than sulphurous ores. Some sulphide ores such as chalcopyrite and bornite contain copper as well as large amounts of iron. Cuprite (an oxide ore) usually contains about 89% copper, and chalconite (a sulphide ore) about 80%. An oxide ore is refined by smelting it in the presence of carbon. Impurities in the ore form a slag on the surface of the melt which can be skimmed off, or tapped out, the copper falling through the slag and accumulating at the bottom of the furnace. The copper could then be further refined with charcoal[65].

Once the smelting had finished, the furnace was tapped and the liquid contents drained off into clay moulds. Because of copper's high melting temperature, it was not practical to continuously tap (pour off) the liquid melt while smelting the ore because it would have started solidifying before filling the mould. It was feasible with lead smelting

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[65] Muhly 1973, pp. 169-171.

because of its lower melting point (327º C)[66]. When the copper ingot had solidified, the slag (melted gangue) was hammered off. Alternatively, the liquid slag could have been tapped off at the end of smelting, and the copper ingot extracted from the mould once it had solidified. This was possible because the melting point of the slag was 1150º C, whereas the melting point of copper was below 1083º C[67].

A potential problem existed with the availability of the various types of copper ores. Depending upon the geology of an area, there are usually more sulphide ores available than oxide and carbonate ores. Oxide and carbonate ores tend to be located in surface deposits, and once these are exhausted, the deeper vein ores in the form of sulphides had to be accessed. Sulphide ores were being smelted as far back as the 5th millennium in some areas, and the use of these ores expanded markedly during the Roman period[68]. Smelting copper from a sulphurous ore is technically more complex because the ore must initially be converted into a copper oxide before the copper metal can be extracted. The presence of sulphur produces a low quality copper and it must be removed. In this process, the ore is first roasted in an oxidizing atmosphere. The copper oxide can then be reduced with charcoal to produce pure copper and sulphur dioxide. Early smelting consisted of a long roast to drive off the sulphur (as sulphur dioxide) and the *matte* thus produced (a mix of copper and copper sulphide) was then reduced with charcoal. Because the initial roasting process was often incomplete, the copper *matte* was contaminated with sulphur and tended to have a dark colour ("black copper")[69]. Further refining with charcoal, fluxes, and the plunging of green twigs into the melt (escaping steam and hydrogen gas reduced the copper oxides into metal) produced a purer copper metal[70].

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[66] Healy 1978, p. 160.

[67] Tylecote 1980, p. 194.

[68] Muhly 1973, pp. 171-2.

[69] Muhly 1973, p. 172.

[70] Craddock 1995, pp. 203-4. Forbes provides a detailed description of the stages involved in the sulphide smelting process (Forbes 1972, pp. 17-21). He indicates that the procedure of placing green twigs into the melt, called "poling", may have been known to the Romans. In earlier periods, the *matte* was probably refined by simply reducing it in charcoal with blasted air. Processing copper ores containing iron sulphide required more stages in the refining process.

Copper oxhide ingots from various areas were analyzed, including the ones from the Cape Gelidonya shipwreck, and it was noted that the full-sized ingots were composed of fairly pure copper, some of almost 99% purity. See: Noel H. Gale, Zofia A. Stos-Gale, "Oxhide Copper Ingots in Crete and Cyprus and the Bronze Age Metals Trade", *The Annual of the British School at Athens* 81, 1986, p. 85.

Tin ore (cassiterite) was processed in much the same manner as copper ore. Lower heat is required in smelting tin ore (melting point of tin is 232ºC). Information on the early refining of tin comes from archaeological finds of slag hearths in Cornwall[71]. The ore was first crushed to concentrate the tin and remove the gangue, then smelted with charcoal in a low hearth or a clay-lined trench. The slag was skimmed off, and the tin removed once enough had accumulated. The subsequent introduction of an air blast increased the charge temperature and smelted the cassiterite more efficiently, but this resulted in tin being lost through absorption into the slag[72]. The later development of smelting the ore in a furnace similar to one used for copper smelting allowed for better temperature control; taps for slag and metal were incorporated into the furnace design, which consequently improved the yield of tin and its quality from a given charge[73].

The earliest examples of lead smelted from ore come from the eastern Mediterranean that date to the 6th millennium (a lead bracelet from Yarim Tepe I in northern Mesopotamia, and worked galena beads from Catal Huyuk in central Anatolia)[74]. Lead is the easiest metal to extract from its ores and separate from the gangue, as its melting point is 327.5ºC. Galena (80% lead sulphide) can be smelted in a simple hearth or in a clay-lined trench, and the drops collected for further re-melting and shaping[75]. Smelting the ore produces a crude lead which sometimes contains a certain amount of silver. The lead was de-silvered through cupellation, if it was believed that enough silver was present to warrant this extra step[76].

Cupellation was a smelting procedure that was used to extract silver from argentiferous galena ores. The quantity of silver normally present in this type of ore is usually on the order of a few ounces per ton of lead, but the ore was worked principally for its silver content and the lead was a by-product of the process[77]. The pulverized ore was placed in

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[71] Forbes 1972, p. 149.
[72] Healy 1978, pp. 177-8.
[73] Forbes 1972, p. 149; Healy 1978, p. 178.
[74] Craddock 1995, p. 125.
[75] Craddock 1995, pp. 206-7.
[76] Healy 1978, pp. 179-181. The de-silvering of lead was a simple and efficient method of silver recovery. The Greeks were able to produce a lead with only 0.02% silver, and the Romans refined this figure down to 0.01% or less (*Ibid*, p. 180).
[77] Jones 1980, p. 41.

a shallow clay plate (cupel) or in a shallow hearth, the charcoal loaded on top, and forced air maintained the temperature of the mixture above the melting point of silver (960ºC). The lead vaporized to litharge (lead oxide) and the silver was left as globules[78]. The lead was recovered by re-smelting the oxide with charcoal. At mining and smelting operations in the Laurion area, the argentiferous ore was first processed by washing to separate the ore from the gangue. After the ore had been reduced, the crude silver and the concentrated silver-lead alloy were cupelled, resulting in pure silver[79].

1.3 Copper Alloys

Because it is impossible to produce a 100% pure metal from its ore, no matter what types of smelting and refining processes are utilized, a "pure" metal can be defined as one containing impurities that do not exceed the amounts that are considered to be "characteristic of the extraction technique" that was utilized[80]. The atomic and chemical characteristics of a metal determine whether or not it can be successfully paired with other metals[81]. Additions of metal to the base, or "parent" metal such as copper, must be able to blend with it into a homogenous form when both are in a molten state, and once the metallic mixture has cooled the elements should not separate into layers[82].

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[78] Tylecote 1980, pp. 206-7.

[79] Healy 1978, pp. 157-8.

[80] Healy 1978, p. 199. As an example, Healey provides an analysis of a third millennium copper that contained 97.4% copper, 0.87% tin, 0.5% lead and more than 1% of other impurities, and indicates that it would be considered as an impure copper even though tin is present. Healey says that, "When the impurities exceed the amount inevitably present in view of the work practice of the age, the presumption is that deliberate additions have been made and the term "alloy" then becomes justifiable".

[81] A. H. Cottrell, *An Introduction to Metallurgy*, Edward Arnold Ltd., London, 1967, pp. 192-4. The solubility of one metal in another is determined by a number of factors, some of which are their relative atomic sizes, electrochemical characteristics and valency. Copper is an element that mixes extensively with many metals due to its compatibility with their atomic sizes and electrochemical factors. It dissolves well with metals such as nickel, zinc and arsenic and to a certain degree with tin and gold. Silver mixes well with zinc and gold, and to a certain extent with tin. The lead atom is very large and blends well with only a few metals, such as tin and bismuth. It is much larger in atomic size than the copper atom, and thus mixes with it in an alloy solution only to a very limited extent. See also: Albert G. Guy, *Elements of Physical Metallurgy*, Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1959, p. 142-6.

[82] Healy 1978, p. 199. Today, thousands of alloy combinations are possible, however in antiquity only a few alloys were commonly available, such as 'white gold', electrum, bronze, copper and bronze arsenic alloys, steel, brass and pewter.

An alloy often has physical properties of density, ductility, hardness, durability, plasticity and melting point that differentiate it from the characteristics of its original blending metals, and the dissimilarities in the properties of an alloy are determined by the percentage by weight of added metal(s) to the base metal. In antiquity, it was not always possible to control admixtures accurately, and alloys were often produced through either unintentional smelting of ore grains that contained more than one metal (in the case of 'white gold', because auriferous ores always contain some silver), or by deliberately smelting together two different kinds of ores (copper ore with arsenic or tin ores to make bronze, but with no control on the alloy quality). At some point, it was discovered that better control of alloy quality could be achieved by first melting the pure copper in a clay crucible with charcoal, and then adding a proportionate amount of the additional metal to the melt[83]. Over time, improved methods of controlling alloy quality were developed that involved precisely measuring out and mixing the molten metals that had first been refined from ores[84].

The use of alloys in antiquity implies that there was a technological advance wherein metalworkers, through experimentation and observation, acquired metallurgical knowledge of the interactions between copper and other elements[85]. This knowledge allowed them to intentionally alter and "improve the mechanical or other properties of pure copper" through the deliberate introduction of tin, arsenic, and lead, which were the more common additions that were utilized[86]. The questions for archaeometallurgists are these: how can this intentional addition be recognized in copper and bronze objects, and can a limit be set above which metal addition is considered to be deliberate, thus implying an advanced stage of metallurgical knowledge? The analysis of a sample taken from a copper or bronze artifact produces data on its metallic composition, either by % weight or in parts-per-million (ppm). Various types of information can be garnered about the artifact from such a metallographic study, but whether a particular percentage of a metal other than copper in the artifact can be considered to be a sign of intentional addition is not

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[83] Charles 1980, p. 170. Early crucibles were made from stone or refractory clay, which is a type of clay that melts at a high temperature (over 1600ºC). It was also used for kilns. See: Healey 1978, p. 194.

[84] Healy 1978, p. 200.

[85] E. Pernicka, F. Begemann, S. Schmitt-Strecker, A. P. Grimanis, "On the Composition and Provenance of Metal Artefacts from Poliochni on Lemnos", *Oxford Journal of Archaeology* 9 (3), 1990, p. 268.

[86] Pernicka et al 1990, p. 268.

straightforward, because copper ores contain various percentages of other elements. The percentages that are noted as 'benchmarks' to distinguish between natural and intentional can vary between metallographic studies. As Pernicka notes in the Lemnos study, certain ores may have been selected because it was observed that the smelted product had properties that were superior to pure copper, as in the case of copper ores that contained arsenic[87]. The situation is similar with tin and lead percentages in bronze[88]. A tin content greater than 2% in bronze is usually considered to be intentional, and not a result of smelting tin ore that was sometimes naturally associated with the main copper deposit (depending upon the regional geological formations). According to Forbes, the numerical limit of 2% tin is not a "hard and fast rule"[89], and he indicates that some of the oldest Mesopotamian bronzes contain up to 4% tin, but that this was simply one of the impurities (arsenic, lead, iron) present in the copper ore that was used. Deliberate tin addition appears in Sumeria towards the end of the third millennium, in bronze artefacts with a measured tin content from 6 to 10%; bronzes from Crete and Troy at this time also exhibit an increase in tin content, rising from an early 5 – 6% to a later 8 – 11%[90].

Establishing a benchmark for deliberate metal addition for a series of bronze or copper objects found at an archaeological site would require both an initial metal analysis of the objects to determine composition percentages, as well as lead isotope analysis to locate a possible source of the raw copper ore body[91]. The study could in addition aid in

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[87] Pernicka et al 1990, pp. 268-272. Some copper ores contain arsenic in amounts up to 5%. In the analysis of Early Bronze Age artefacts from Lemnos, the authors indicate that high arsenic contents (5.9%) is some samples may simply be a result of the particular copper ore that was used, and not an intentional addition of arsenic. They state that, for the purposes of their study, a limit of 2% arsenic was established as a convenience to differentiate between 'unalloyed copper' and 'arsenical bronzes'. From observation of the histograms (Fig. 1, p. 272), it appears that most of the samples fall into this 2% limit. Interestingly, the authors set an arbitrary tin content limit at 1% to distinguish between 'unalloyed copper' and 'tin bronze', again from the histograms that indicate a gap at this value.

[88] Comments on lead 'benchmarks' are presented in the section titled "Leaded Bronze Alloys" in this paper.

[89] Forbes 1972, p, 155. In agreement with Pernicka, and contrary to Forbes, Treister takes the position that a tin content of 1% and above is intentional alloying. See: Tresiter 1996, p. 155, Note 749.

[90] Forbes 1972, p. 155. Most ancient bronzes have a tin content of between 5 and 11%. See: Healy 1978, p. 210.

[91] Igor M. Villa, "Lead isotope measurements in archeological objects", *Archaeological and Anthropological Sciences* 1, 2009, pp. 149-153. Also see: Zofia Stos-Gale, "The Origin of Metal Objects from the Early Bronze Age Site of Thermi on the Island of Lesbos", *Oxford Journal of Archaeology* 11 (2), 1992, p. 156. Every ore deposit carries a characteristic isotopic composition of lead (Pb), produced by the radioactive decay of ^{235}U into ^{207}Pb, ^{238}U into ^{206}Pb, and ^{232}Th into ^{208}Pb, as well as ^{204}Pb which is stable and not

establishing whether an object was locally manufactured or imported[92]. Ideally, at sites where leaded bronze objects are found, once the source mine is located and its copper ore content analyzed for lead composition[93], it could then be determined whether lead was deliberately added to the tin-bronze, which would indicate that the metal-worker had advanced knowledge of the special properties of this alloy. On the other hand, conducting such a study may not be practical. If recycled bronze was used to produce the object, or if scrap lead of unknown origin had been introduced into the mixture[94], then tracing the mine may be unfeasable, since it may be impossible to quantify if these procedures actually did, or did not, occur during manufacture. A one-to-one ratio comparison between the lead compositions of the ore body and the bronze artifact is useless in itself, because some of the lead would have boiled off during smelting due to its low melting temperature.

1.3.1 Arsenic-Copper Alloy

One of the first alloys to be used in antiquity was an arsenic-copper alloy. Arsenopyrite is the most common mineral containing arsenic, and it is often found either

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radiogenic. The ratios ^{208}Pb/^{204}/Pb, ^{207}Pb/^{204}/Pb, ^{206}Pb/^{204}/Pb are studied in lead isotope analysis. Smelting the ore does not alter its isotopic ratios, therefore the metal in an artefact can often be traced back to its source mine. Some mining districts that share a common geological history can have nearly the same set of Pb isotope ratios (Cyprus), but in some areas the Pb compositions can vary between various deposits in the same geographical area (Sardinia). Because mines can carry closely similar ratios, additional tests using trace element analysis of gold and silver in the artifact must then be carried out to locate the actual mine. See: Z. A. Stos-Gale, G. Maliotis, N. H. Gale, N. Annetts, "Lead Isotope Characteristics of the Cyprus Copper Ore Deposits Applied to Provenance Studies of Copper Oxhide Ingots", *Archaeometry* 39 (1), 1997, p. 84. These references also discuss the problems encountered in the provenances of objects using lead isotope analysis.

[92] Zofia Stos-Gale 1992, p. 171. Through lead isotope analysis, it was found that some of the bronze objects from this site were made from copper that did not originate in Aegean deposits, such as from the Troad and the Cyclades, and were manufactured from metal found elsewhere, possibly from Iran or Afghanistan. The author mentions that the earliest known oxhide ingots found at Aghia Triadha on Crete are also composed of a similar type of imported metal.

[93] R. Bowman, A. M. Friedman, J. Lerner, J. Milsted, "A Statistical Study of the Impurity Occurrences in Copper Ores and their Relationship to Ore Types", *Archaeometry* 17 (2), 1975, pp. 157-163. This was a study of copper ores and artifacts. Its purpose was to examine the distribution of impurities that remained in the smelted metal and in the original ores, to determine which impurities remained concentrated in the copper.

[94] N. H. Gale, "Lead Isotope Analysis Applied to Provenance Studies – A Brief Review", in: Y. Maniatis (ed.), *Archaeometry - Proceedings of the 25th International Symposium*, Elsevier Science Publishers B.V., Amsterdam, 1989, pp. 481-4

alone or associated with copper, lead, silver, and gold ores[95]. Smelting raw copper ore often produced copper that contained some arsenic, usually between 0.5 to 3% (as well as trace amounts of other elements), depending upon how much arsenic was present in the ore. Tools and implements made from arsenical copper were harder and more durable than those made from pure copper. It is known that arsenic amounts from 0.5% up to 1% improve the alloy's hardness, but brittleness is also apparent; above 1.5% the casting qualities of the alloy are improved, but brittleness and hardness increase in proportion as well[96]. Hammering a copper-arsenic alloy produces a metal with a higher strength and hardness than pure copper, and it can be cold-worked without cracking. The mechanical properties of a high arsenic object after work-hardening are comparable to those of tin-bronze[97]. Another interesting property of an arsenic-rich alloy is that it has a tendency to segregate inversely while molten, producing a silvery coating on the surface of the casting; this aspect may have contributed to the popularity of the alloy[98]. Deliberate additions of various types of arsenic ores to the copper ore during smelting are known from some areas. These additions can be recognized in objects from the Early Bronze Age of the Caucasus region, where arsenic ores were abundant, that contain percentages of arsenic as high as 10%[99].

In reviewing the description of copper-arsenic alloys thus far, a query presents itself: if this alloy could be cast, and cold-worked to harden it, why was the use of widely available arsenic ores supplanted by the much rarer tin ore? The answer may lie in the desire to control alloy quality by using tin. The ancient metal-smiths realized that tin additions from cassiterite into the copper melt produced a more consistent alloy[100]. Tin ore (stannic oxide) can be easily smelted to produce the tin metal, and the quantities of copper and tin used for producing bronze could be accurately measured. It is doubtful that arsenopyrite and other arsenic ores such as realgar (an orange or deep red mineral), and

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[95] Healy 1978, p. 42.
[96] Forbes 1972, p. 179.
[97] Charles 1980, p. 170.
[98] James D. Muhly, *Supplement to Copper and Tin: Copper and Tin, the Distribution of Mineral Resources and the Nature of the Metals Trade in the Bronze Age*, Transactions of the Connecticut Academy of Arts and Sciences no. 46, New Haven, Connecticut, 1976, p. 90.
[99] Forbes 1972, p. 179.
[100] Charles 1980, p. 177.

the bright yellow orpiment, were regularly smelted down for their pure arsenic metal content, because the technical knowledge of the metal extraction processes were not known in antiquity; another factor in favour of the switch to tin was the toxicity of arsenic, whose deleterious effects on the health of early metallurgists were well-known[101].

1.3.2 Tin-Copper Alloy – Bronze

The bronze used today may be composed of copper alloyed with various elements such as tin, antimony, phosphorous, or silicon[102] but in general terms, what is commonly termed as 'true' bronze is a mix of copper and tin. In the Early Bronze Age, when cassiterite was discovered to be a viable alternative to arsenic as an addition to previously smelted copper, the physical characteristics of the deposits were identified, and the use of cassiterite gradually supplanted arsenic; additions of arsenic to tin-bronze continued to be used for some time, most likely to obtain a silver-coloured finish on objects[103].

A number of possible ways in which tin was added to copper have been proposed. One method was to use metallic tin from an ingot; another method was a cementation process whereby stannite (tin pyrite) or cassiterite (stannic oxide) were added to the surface of the molten copper through a slag in a furnace with charcoal, and the metal thus reduced into the melted copper. Modern experimentation with furnace cementation has shown that this is efficient and easy to accomplish due to the thermodynamics of the process[104]. Early developments in bronze metallurgy, ca. 1800 – 1500, resulted in smelting cassiterite to produce the tin metal which was then added in measured amounts to the copper melt[105]. This alloy control allowed the mix to be adjusted for various purposes, whether for weapons, statues, mirrors, etc. As an example, high tin bronzes (more than 12% tin) are

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[101] Forbes 1972, pp. 177-8; Charles 1980, pp. 176-8.

[102] Personal communication with Jim Jensen of Nisse Foundry and Design. Silicon bronze (94% copper and 6% silicon) is harder than tin bronze. He avoids uing lead because of the toxicity of the fumes.

[103] Charles 1980, p. 173.

[104] Charles 1980, p. 174-5.

[105] Forbes 1972, p. 156.

too brittle to be worked into tools, but have a golden brightness that makes them suitable to be polished for use as mirrors[106].

The melting point of pure copper is 1083ºC. The molten metal is not ideal for casting because it tends to absorb gases, thereby becoming porous, and contracts upon cooling[107]. Copper mixed with 10% tin appears to have the optimum quality for the best hammered bronzes: Greek artisans were able to attain a thickness of less than 1 mm, and Roman bronze-smiths achieved 0.3 mm[108]. The quantity of tin added to copper affects the casting properties, workability, and colour of the bronze. The absorption of gases during casting is reduced, resulting in an alloy that is superior to pure copper in terms of strength and hardness that can be hammered into shape without cracking[109]. The addition of tin (melting point of 232ºC) lowers the melting point of the alloy, increasing its fluidity and thus making it easier to cast than copper: with 5% tin, the melting temperature is reduced to 1050ºC, with 10% tin to 1005ºC, and with 15% tin to 960ºC[110]. The colour of bronze varies depending upon the amount of tin it contains. Higher than optimal additions of tin produce a bronze that is harder to work with and chase, especially in the finer details, but it imparts a gold-plated appearance to the object[111]. These properties explain why bronze was preferred over copper, even though the availability of tin in antiquity was often a problem[112].

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[106] Forbes 1972, pp. 156-7. This brightness is caused by hydrogen gas in the melt forcing tin-enriched liquid to the surface during the cooling stage, producing a fine coating of a white-coloured alloy. See: Robert E. Reed-Hill, *Physical Metallurgy Principles*, D. Van Nostrand Company, Inc., Princeton, New Jersey, 1964, p. 393.

[107] Carol C. Mattusch, *Greek Bronze Statuary*, Cornell University Press, Ithaca and London, 1988, p. 13. The author notes that bronze is more cohesive than pure copper, and is thus a superior metal for hammering and casting.

[108] Rolley 1983, p. 13.

[109] Mattusch 1988, p. 13.

[110] Mattusch 1988, p. 13.

[111] Rolley 1983, p. 13. The Derveni krater contains about 15% tin.

[112] Arthur Steinberg, "Techniques of Working Bronze", in: David G. Mitten and Suzannah F. Doeringer (eds.), *Master Bronzes from the Classical World*, Philipp von Zabern, Mainz on Rhine, 1967, p. 9.

1.3.3 Lead, Leaded Copper and Leaded Bronze Alloys

Lead was a commonly used metal in antiquity, its first appearance dating back to the 4th millennium[113]. Lead deposits were found in many areas of Greece and the eastern Mediterranean, and it was a metal that was easily mined, smelted in crucibles or simple hearths, or extracted as a by-product from argentiferous ores. To list just a few examples of its utility from various sites in Greece: lead was used in the casting of small figurines[114]; lead clamps were used to repair broken pottery[115] and to hold clay stems to bowls[116]; as reinforcing bars and clamps in the construction of Greek temples, buildings, stoas, and poured lead for post supports and doors[117]; as standard weights for official or household use, as well as loom weights and in other applications requiring weights[118]; as plaques with inscriptions[119]; for seal impressions and as lead sling bullets[120]. Lead was also used as a

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[113] Jones 1980, p. 41.

[114] David Gill, Michael Vickers, “Laconian Lead Figurines: Mineral Extraction and Exchange in the Archaic Mediterranean”, *The Annual of the British School at Athens* 96, 2001, p. 229. Archaeological investigations at a number of sanctuaries in the region of Laconia have uncovered large numbers of votive lead figurines. Upwards of 100,000 were found at the sanctuary of Artemis Orthia, more than 6,000 at the Menelaion, and many more have been found from the Amykleion, the Chalkiokos, the Eleusinion and at other shrines. Outside Laconia, lead figurines have also been found at the Argive Heraion, Bassai and Phlius. The figurines that were found in the stratified deposits at the Artemis Orthia sanctuary were dated from the Spartan Geometric period (7th century) to the 3rd century. Lead isotope analysis of a few of the figurines from this shrine showed that the Laurion area was the most likely source of the lead; small percentages of silver were also noted (*Ibid*., p. 233). For full descriptions of the various types and styles of lead votives that were found at the Artemis Orthia sanctuary, see: R. M. Dawkins, J. P. Droop, Jerome Farrell, Arthur M. Woodward, G. Dickins, A. J. B. Wace, “Laconia: I.–Excavations at Sparta”, *The Annual of the British School at Athens* 14, 1907/8, pp. 1-160.

[115] Peter E. Corbett, “Attic Pottery of the Later Fifth Century from the Athenian Agora”, *Hesperia* 18, no. 4, 1949, pp. 335-6; Anastasia N. Dinsmoor, “Red-Figured Pottery from Samothrace”, *Hesperia* 61, no. 4, 1992, pp. 501-3; Homer A Thompson, “Two Centuries of Hellenistic Pottery”, *Hesperia* 3, no. 4, 1934, pp. 419, 422.

[116] S. R. Roberts, Alice Glock, “The Stoa Gutter Well: a Late Archaic Deposit in the Athenian Agora”, *Hesperia* 55, no. 1, 1986, p. 19.

[117] Homer A Thompson, “Buildings on the West Side of the Agora”, *Hesperia* 6, no. 1, 1937, pp. 8, 24, 92, 134.

[118] Gladys R. Davidson, Dorothy Burr Thompson, Homer A. Thompson, “Small Objects from the Pnyx: I”, *Hesperia Supplements* 7, 1943, pp. 27-8, 79.

[119] Davidson et al 1943, pp. 10-11. For an interesting example of a lead *defixio* with an inscribed curse found in the remains of a metalworking shop in the industrial area of Athens, see: Rodney S. Young, “An Industrial District of Ancient Athens”, *Hesperia* 20, no. 3, 1951, pp. 222-3.

[120] Davidson et al 1943, pp. 102-7.

component of bronze coins that were minted in Greece during the Hellenistic period[121]. The use of lead was particularly prevalent during the Roman period, and was used in a wide variety of applications: in bronze alloys for statues, as a replacement of terracotta for pipes, sheaths for ship hulls, for roof tiles, floors, and vat linings, and poured over iron clamps for additional strength, in paints and glassware[122].

The use of leaded copper in the production of objects is not found solely during the earlier phases of the development of alloys. Artefacts made from this alloy appear at Early Bronze Age find-sites in the Aegean area[123], but some are also found in Late Bronze Age contexts. Numerous leaded copper votive statuettes have been found on Crete that date from the Middle Minoan III (Neopalatial) to the Late Minoan III (Postpalatial) periods[124]; very few have been found from the Early Bronze Age, and those that contain lead were probably coming from the lead inclusions in copper ore[125]. An axe found at Early Bronze Age Agia Fotia was composed of 8% lead added to arsenical copper, a mixture which results in softening of the metal; the axe may have been intended for ritual or ceremonial

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[121] Homer A Thompson, “Excavations in the Athenian Agora: 1953”, *Hesperia* 23, no. 1, 1954, pp. 45-8. During field work at a six-room building located in the south-eastern corner of the Athenian Agora, a number of discs were found that resembled flans, which are disks of metal from which coins are made. Eight of the discs appear to have been severed with a chisel from a metal rod the thickness of a finger. Analysis of one of the discs showed that it was composed of 66.54% copper, 7.09% tin, and a high proportion of lead (25.63%), plus small amounts of zinc, iron and silver. The evidence that this building may have housed the Athenian mint came from a fragmentary marble inscription dated to the 5th century that was found a short distance away. The decree mentions Laurion, gold, currency exchange, and bankers. The small furnaces found in the building may have been used for the production of bronze and possibly silver and gold coins as well. This building was destroyed in 267 A.D.

[122] Jones 1980, p. 46.

[123] Helen Mangou, Panayiotis V. Ioannou, “On the Chemical Composition of Prehistoric Greek Copper-Based Artefacts from the Aegean”, *The Annual of the British School at Athens* 92, 1997, p. 65 and Table 4.

[124] Colette Verlinden, “Les statuettes anthropomorphes crétoises en bronze et en plomb, du IIIe millénaire au VIIe siècle av. J.-C.”, *Archaeologia Transatlantica IV*, L‘Université catholique de Louvain, Louvain-La-Neuve, Belgique, 1984, p. 268, Tableau des analyses de la composition du métal. In this particular study of anthropomorphic figures from Crete, metal analysis of the statuettes from these periods that were found in the Psychro grotto revealed that many had a high lead content and very little tin. Some of them contained lead in the range of 15 – 28.5%. The analysis also shows that the lead content of statuettes from Psychro and other sites on Crete dropped quite significantly during the Protogeometric and Geometric periods, as they were now made from tin bronze. Out of the ten figurines that were analyzed for these latter periods, only one example contained 3.6% lead, the rest varied between 0.14 – 1.05%, and tin quantities ranged from 1.0 – 5.9%.

[125] Helen Mangou, Panayiotis V. Ioannou, “On the Chemical Composition of Prehistoric Greek Copper-Based Artefacts from Crete”, *The Annual of the British School at Athens* 93, 1998, p. 95 and Table 3.

purposes rather than for use as a tool. From Late Bronze Age sites, only four objects contained from 2 – 3.5% lead and these were all cast. No lead was found in hammered bronze objects. It is evident that Cretan metal-workers had knowledge of the characteristics of adding lead to copper, and later to bronze, for particular applications[126].

Lead is sometimes an addition in modern bronzes[127] and it was also deliberately added to bronze in antiquity. A small amount of lead (1 to 2%) added to copper significantly increases its fluidity so that the molten metal fills the extremities of the mould more easily, permitting greater detail in the casting of complex figures[128]. The same increase in fluidity is observed when lead is added to bronze. When lead (melting point of 327ºC) is added to tin-bronze, the resulting leaded bronze alloy is rendered softer and more malleable, which simplifies and facilitates chisel work on fine details[129]. Adding successively higher amounts of lead to bronze produces slight reductions in the melting temperature, but apparently does not noticeably improve the fluidity of the molten bronze[130]. An interesting effect on the colour of the bronze metal is produced with lead amounts of 15% and higher. The bronze develops a whitish, almost silvery appearance on its surface, a colouring effect that is similar to that of adding high amounts of arsenic to copper. The whitening is caused by inverse segregation of the lead/tin rich phase upon cooling, commonly referred to as a “lead sweat”[131].

Metalworkers must have discovered early on, through their experimentation with varying the amounts of tin and lead in copper, that a leaded copper alloy with high

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[126] Mangou and Ioannou 1998, pp. 95, 100.

[127] Jean-Pierre Rama, *Le Bronze d’art et ses techniques*, Éditions H. Vial, 1988, pp. 279-80.

[128] Tamsey K. Andrews, *Bronzecasting at Geometric Period Olympia and Early Greek Metals Sources*, Ph.D. dissertation, Brandeis University, Ann Arbor, Michigan, 1994, p. 146.

[129] Rama 1988, p. 280.

[130] P. T. Craddock, A. R. Gumlia-Mair, “Problems and possibilities for provenancing bronzes by chemical composition, with special reference to Western Asia and the Mediterranean in the Early Iron Age”, in: John Curtis (ed.), *Bronzeworking Centres of Western Asia ca. 1000-539 B.C.*, Kegan Paul International, London, 1988, p. 319.

[131] Matthew J. Ponting, “East Meets West in Post-Classical Bet She’an: the Archaeometallurgy of Culture Change”, *Journal of Archaeological Science* 26, 1999, p. 1317. The lower melting point phase is squeezed to the surface of the object during solidification. Ponting mentions a technical treatise, the *Mappae Clavicula*, written in the 8th century A.D. that describes a procedure to make high lead bronze (*caldarium*) that is useful for casting, and which also produces a very white colour in the bronze. Ponting comments that the choice of this kind of alloy may have been based mostly on its aesthetic appeal.

percentages of lead was not suitable for extensive cold-working because the metal cracked and fragmented upon continuous hammering[132]. The same brittleness occurs when a high amount of lead is added to bronze, because lead is soluble in tin bronze only to a limited extent[133]. If the bronze-lead liquid metal mix is not cooled rapidly enough, the lead and copper metals segregate and isolated patches of microscopic lead globules, or "lakes", are formed throughout the metal, resulting in weakness at the lead-copper interfaces in the cast object[134]. Segregation, or incomplete homogeneity, of the metals is not a problem with a lead addition of 5% or less, and modern bronzes normally do not contain more than this amount[135]. The higher the lead content, the more brittle the bronze, and the higher its tendency to tear and crack when hammered[136]. For this reason, leaded copper and leaded bronze were never used for sheet metalwork in the production of vessels, armour, and large statues which were formed on a wooden or stone core[137], all of which required shaping the metal through repetitive hammering[138]. On the other hand, tin bronze does not have the same quality of brittleness, unless very high amounts of tin are present. The bronze can be hammered repeatedly during cold-working, a process that actually hardens the metal and thus improves its durability[139]. Metalworkers in antiquity were probably familiar with the different techniques that were required when working with either tin-bronze or leaded bronze alloys. However, determining whether the addition of lead was deliberate from

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[132] Andrews 1994, p. 146.

[133] Sabine Klein, Andreas Hauptmann, "Iron Age Leaded Tin Bronzes from Khirbet Edh-Dharih, Jordan", *Journal of Archaeological Science* 26, 1999, p. 1080. Lead is soluble only up to a certain degree in tin bronze, which limits the homogeneity of the liquid. As an example, bronze that contains 10% by weight of tin can dissolve up to 17% by weight of lead. Lead tends to collect along the grain boundaries of the copper/ tin crystals and actually acts as a lubricant that improves the fluidity of the metal. The lubricating property of leaded bronze enables the liquid metal to fill complex moulds more completely than a tin/copper mixture.

[134] M. Picon, S. Boucher, J. Condamin, "Recherches techniques sur des bronzes de Gaule Romaine", *Gallia, Fouilles et monuments archéologiques en France métropolitaine*, Tome XXIV, Fascicule 1, Centre national de la recherche scientifique, Paris, 1966, p. 192; Andrews 1994, p. 146; Staniaszek and Northover 1982, p. 273.

[135] Rama 1988, p. 280.

[136] Craddock and Gumlia-Mair 1988, p. 319.

[137] Irene Bald Romano, "Early Greek Cult Images", Ph. D. dissertation (University of Pennsylvania), Ann Arbor, Mi., 1980, p. 364-7. Many cult statues were made of hammered bronze from the Geometric period until the 7th century, at which time hollow casting became a more common technique because of the introduction of griffin head cauldron attachments. Sheet metal was hammered over a model carved from wood (sphyrelaton technique).

[138] Andrews 1994, p. 146.

[139] Andrews 1994, p. 146.

metal analyses of bronzes is not straightforward, and the data often does not provide clear answers to questions of deliberate or unintentional usage.

A major problem that arises in the study of ancient metallurgical practices concerning leaded bronze production is determining what percentage of lead can be considered to be an indicator of either a deliberate addition to improve casting, or an inadvertent component[140]. Lead ore is often associated with copper ore, and depending upon the particular deposit the copper can sometimes contain several percent of lead, so an object produced from the smelted copper ore will naturally contain lead, in some cases at levels above 2%[141]. Another aspect to consider is that the bronze object may have been produced from recycled bronze that contained lead, and scrap lead fragments at the workshop may also have been added to the melt. For these reasons, the fact that a small amount of lead in the range of 1 to 2% improves the fluidity of the metal, whether copper or bronze, cannot be taken to be the "threshold" level that would indicate deliberate addition if it is noticed in the metallic composition of an artifact. Analyses have shown that many cast bronzes contain low levels of lead, but this does not necessarily mean that the lead was deliberately added to improve casting. This brings up a question as to whether bronze-workers were generally aware of the phenomenon of improved metal liquidity through lead addition, or if it was added simply to save on more expensive tin and copper[142]. Its use in some areas may have been a combination of the two factors, and in fact it may be somewhat difficult to separate technique from convenience in some cases. The use of leaded bronze for specific purposes, such as the cauldron attachments, handles and coins that will be

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[140] Deliberate addition in alloys is discussed in Section 1.3. Lead addition is presented in more detail here.

[141] Personal communication with Zofia Stos-Gale (13/10/2011). She mentions that purification of copper metal that was smelted from ores that contained lead was not performed in Europe until the 17th – 18th centuries AD.

[142] As the discussion indicates, a lead amount above 1 to 2% in ancient bronze has often been presumed to be a deliberate addition to facilitate casting, but according to Noël H. Gale, this assumption is not entirely correct. The author indicates that the large amounts of lead found in some bronzes dating to the British Late Bronze Age may have been added in an attempt to save on the amount of more expensive copper, rather than to improve castability. See: Noël H. Gale, "2 / Lead Isotope Studies – Sardinia and the Mediterranean: Provenance Studies of Artefacts Found in Sardinia", *Instrumentum* 23, 2006, p. 31. In his analysis of Greek bronze coins, Earle Caley considers a lead percentage greater than 5% to be a deliberate addition, and that the practice of adding lead to coinage bronze was introduced because it facilitated stamping of design details on the coin surfaces. See: Earle Radcliffe Caley, *The Composition of Ancient Greek Bronze Coins*, Memoirs of the American Philosophical Society XI, Lancaster Press Inc., Lancaster, P. A., 1939, p. 134.

discussed in Chapter 3, shows familiarity with casting and other properties of this alloy due to the higher percentages of lead contained in these types of objects. But there is not a clear differentiation between the two factors where it concerns the casting of statuettes, which can contain various quantities of lead. Leaded bronze was often used in Etruria for statuettes, but its use for votive statuettes in Greece was not as prevalent, in spite of the fact that lead was commonly available in both areas. Summarizing on this particular topic, adding tin to copper already improved the fluidity of the metal, so would adding lead to the mix have produced an even greater improvement in casting properties such that it would have been noticed by ancient bronze-workers? According to the various authors who have commented on leaded bronze, the improvement in casting is quite clear.

1.4 Bronze Casting, Joining and Soldering

Bronze can be worked either by casting the molten metal into moulds, or cold-working from an ingot[143]. In casting, a negative shape of the model to be reproduced is carved into the material of the mould, which could be in stone, metal or hard clay. A simple open mould produces a piece with only one finished surface. Fastening two open moulds together, with a channel for pouring in the molten metal, produces a bivalve mould (Fig. 5) and this type was often used to make swords, axes and spears. Open and bivalve moulds could be used repeatedly if they were made of stone or metal[144]. In piece-mould casting (Fig. 6), the model to be reproduced is carved from clay or wood. Clay is then pressed onto the model surface, and when the clay mould is complete, it is cut into sections and carefully dismantled. The clay pieces are then re-assembled and heated to drive out water and volatile materials. A core is inserted for support. Molten metal is introduced into the mould through a funnel opening and allowed to cool slowly, after which the exterior mould is broken away from the solid metal object[145]. The piece is then finished through chiseling and abrasion; after casting a statuette, the fine details are tooled with a chisel[146].

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[143] Steinberg 1967, p. 9.
[144] Steinberg 1967, p. 10.
[145] Steinberg 1967, p. 10.
[146] R. Raven-Hart, “The Casting Technique of Certain Greek Bronzes”, *The Journal of Hellenistic Studies* 78, 1958, pp. 87-92. The author discusses the ‘carved look’ of many early Greek bronzes, that it is due to

The major disadvantage with this type of casting is that only one object can be produced at a time. Lost-wax casting allows fine details on the model to be reproduced more accurately, thus requiring less work in the final carving and finishing stages.

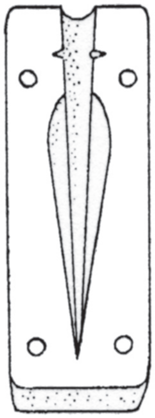

Fig. 5 – Half of a two-piece, or bivalve, mould. (Fig. 1, p. 10, Steinberg 1967)

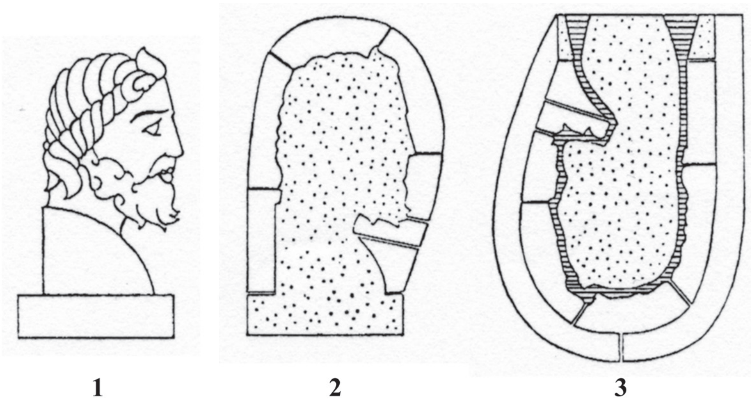

Fig. 6 – Piece Mould Casting. 1) model 2) clay mould pieces pressed onto the model surface 3) model is removed, core inserted, clay mould section reassembled and fastened together, then bronze poured into the funnel opening. (Fig. 2, p. 10, Steinberg 1967)

The lost-wax technique of casting, or *cire perdue*, may have originated in Egypt during the 3rd millennium[147]. This technique was used by the Greeks during the 7th century for both solid and hollow-casting protomes and statuettes, and a short time later it had begun to be used in the production of large Greek bronzes[148]. In solid casting, which would have been used for the production of small figures, the object was first modelled in beeswax, and then covered in a number of coats of clay. The first coat was a fine clay that acquired the details of the wax model; when this layer was dry, successive outer coats of

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casting from carved originals in hard wax such as beeswax, rather than to extensive tooling of the metal cast. His explanation is that tooling is laborious and time-intensive, and that an accidental slip of the chisel could ruin the bronze piece.

[147] Mattusch 1988, p. 44.

[148] Mattusch 1988, p. 27. It is interesting to note that the lost-wax method was already being utilized during the Geometric period of Greece for the production of small-scale bronzes, and it continued to be used from the 6th century onwards for casting large-scale Greek bronzes. Mattusch notes that the process was the only one used in Greece during the Archaic and Classical periods, and for that matter throughout later periods as well. The use of hollow casting in the production of large cast Greek bronzes was a later development, and the reason may have been due to a long-standing tradition of hammering sheet metal over sculpted models (probably in wood) in a technique called *sphyrelaton*, that may have had its origins in Egypt and which was later imported into Greece (*Ibid*, pp. 40-1, 47). See also: Romano 1980, pp. 364-7.

coarser clay were applied. When the entire mould was dry, it was heated to melt the wax, the cavity then filled through an opening with molten bronze[149].

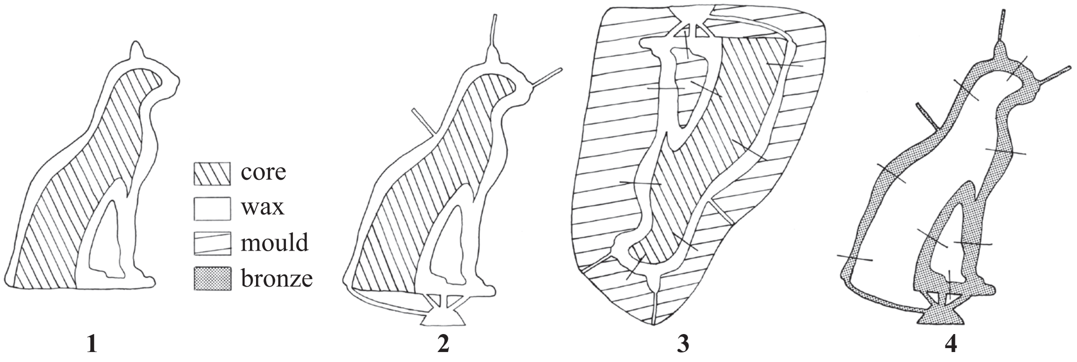

Fig. 7 – Lost-wax method for hollow casting. 1) The figure is sculpted in wax over a clay core. 2) Strips of wax are added which serve as the pouring channels (shown here underneath the figure) and as gas vents. 3) Chaplets are inserted through the wax to hold the core in place, and successive clay coats are built up over the wax figure. The assembly is heated, which solidifies the core and melts out the wax. The bronze is then poured into the top funnel. 4) When cool, the mould is broken up and the core removed. The chaplets are filed down, the pouring and gas channels removed, and the bronze object progresses to the finishing stages (chiseling, polishing, etc.)
(Fig. 2 to 5, p. 18, plus explanation of process, Rolley 1983)

Hollow casting (Fig. 7) was used for larger bronze objects because it saves on the quantity of metal used for an equivalent solid cast, and decreases the weight of the object. A clay core was constructed over a metal armature, and the beeswax model was formed and sculpted over the dried core. Both the core and the wax model were held in place with protruding pins (chaplets), and the assembly layered with successive clay coats; a funnel, channels and gates were formed through the outer clay layers for pouring in the molten bronze and to allow gases to escape. The entire assembly was then placed into a pit and packed in sand. The bronze was heated with bellows in a crucible or a shaft furnace, depending upon the quantity required; when the bronze had attained a temperature of between 1000 and 1100ºC, it was poured into the funnel opening of the mould[150]. The

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[149] Steinberg 1967, p. 11.

[150] Mattusch 1988, p. 18. The molten bronze had to be of a sufficiently high temperature so that it did not start to solidify before pouring was completed. Craddock indicates that the copper was melted first, then the tin was added. At 10% tin, the melting point of the bronze was reduced to 950ºC, and if the bronze was re-heated to about the temperature of melted copper (1083ºC), the possibility of solidification was markedly reduced. See: Craddock 1977, p. 113.

pins were filed off when the casting had cooled. Hollow casting also compensated for shrinkage (the hot melt contracting while solidifying) and possible cracking of bronze sections that were of different thickness[151]. Depending upon the structure of the bronze object that was desired, a wax model could be formed over a partial core, producing a combined solid and hollow cast[152]. Many bronzes, and especially larger statues, were cast in sections because it would have been impossible to completely fill a very large mould to all its extremities with molten bronze in only one pouring. Large quantities of molten bronze are very heavy, and dangerous to manipulate unless proper handling equipment is available. For a given quantity of the melt, the temperature and the pouring time had to be carefully monitored.

When cool, the metal sections were then joined mechanically or metallurgically. Mechanical joins were achieved by riveting, by peening (hammering and spreading) over a dowel inserted through a hole, or by forcing a dowel into a socket with a smaller diameter. Riveting was the easiest and most common method of appending small pieces to larger objects, such as handles to kraters and cauldrons, or to bind hammered sheets of bronze to form vessels[153]. More complex methods were sometimes used to attach sec-

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[151] Steinberg 1967, p. 10.

[152] Steinberg 1967, p. 11. In her book entitled *Greek Bronze Statuary*, Carol Mattusch provides a detailed description of two hollow casting methods, direct and indirect, which used the *cire perdue* technique. In both the basic solid casting and in the direct casting technique, the clay mould was destroyed because it had to be broken away from the cooled bronze object, therefore the original model was lost. A new wax copy of the original model had to be constructed if a duplicate bronze was desired. The indirect process utilizes many of the same techniques as for the direct method, the major difference being that the original model could be used to produce another set of moulds if something went wrong during the casting stage. The first step was to construct the full-sized model, usually out of clay (wax, wood or stone could also be used). A clay master mould was then produced from the model in separate joining sections (head, legs, arms, torso) and allowed to dry. Each of the master mould sections was lined with a layer of wax; the core was poured from liquid clay that adhered to the inside of the hollow wax model, usually incorporating a metal armature as a stabilizer. The master moulds were removed and the wax model extensively sculpted to produce all the finer details of the object desired. Once the sculpting of the model was completed, successive layers of clay, as in the direct process, were placed on the model, and chaplets, gates and pouring funnel were added. When casting was completed, the outer clay layer was discarded. If a duplicate of the bronze object was required, the entire process was repeated, but at least the original master moulds were available for the reproduction of an object of the same size and shape. The new wax model was worked to reproduce the same fine details as on the original. See: Mattusch 1988, pp. 16-22, 34.

[153] Steinberg 1967, p. 11.

tions[154]. Metallurgical joins of the bronze sections can be done with molten metals, but due to the fact that the surface of hot bronze oxidizes rapidly, the metals do not fuse properly with the bronze unless a flux is used[155]. Metals with a lower melting point can be used to join pieces in a method termed soft soldering (leaded joints)[156]. Soft soldering was used by the Greeks and Romans to attach handles and stems to cup bowls, but this method does not produce a join that lasts as long as when the parts are brazed[157]. Hard soldering, or brazing, requires the use of a metal that has a melting temperature close to that of bronze, which fuses with the two surfaces to be joined[158]. All of the metallurgical joins just described require the use of a flux that prevents the bronze from oxidizing too rapidly.

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[154] Gisela M. A. Richter, "A Bronze Eros", *American Journal of Archaeology* 47 (4), 1943, p. 370. A hollow cast Hellenistic period life-size Eros statue was cast in several pieces, and the joins are visible from the inside. A dovetail join was used to attach the separately cast wing to the shoulder, and a hole in the shoulder once held a rivet where the left arm was fastened.

[155] Steinberg 1967, p. 11. Modern methods of soft soldering and brazing metals utilize various types of fluxes that minimize surface oxidation and allow the hot metal solder to flow and "wet" the solid surfaces. It is not known what types of fluxes were used in ancient Greece or elsewhere in the eastern Mediterranean region when performing metallurgical joins, although it is possible that tallow or some kind of animal fat may have been used. Surface oxidation was not a problem when joining sections of iron, because the iron oxide on the surface flaked off while the sections to be welded together were hammered at a red heat. Bronze sections cannot be welded because the metal becomes very brittle near its melting temperature, and breaks apart when hammered. For this reason, welding copper or brass is not possible either. See: Maryon 1949, pp. 103-4.

[156] Steinberg 1967, p. 11.

[157] Maryon 1949, p. 113. In "The Histories", Herodotus describes what appears to be an early example of brazing: "After bringing the war with Miletus to an end, Alyattes died, having reigned for fifty-seven years. He was the second of his family to send a present to Delphi, for in return for the recovery of his health he gave a large silver bowl, and a salver of welded iron – the most remarkable of all the offerings at Delphi. It was the work of Glaucus of Chios, the inventor of the art of welding." (Herodotus, Book 1, 25) Alyattes was the ruler of Lydia from 609 to 560. It is not clear what type of 'welding' Herodotus actually refers to, but he may be describing a new type of soldering. According to Maryon, there was no word in the Greek language to differentiate between soldering and brazing. Pausanias, in his "Description of Greece", provides more details: "Of the offerings sent by the Lydian kings I found nothing remaining except the iron stand of the bowl of Alyattes. This is the work of Glaucus the Chian, the man who discovered how to weld iron. Each plate of the stand is fastened to another, not by bolts or rivets, but by welding, which is the only thing that fastens and holds together the iron." (Pausanias Book 10, 16.1) Also see: Maryon 1949, p. 111.

[158] Increasing the percentage of tin mixed with copper lowers the melting point of the bronze. With 10% tin the melting point of the resulting bronze is lowered to 1020ºC. At 30% tin, the melting point is about 730ºC. It can thus be seen that cast bronze sections could be brazed without too much difficulty if the tin percentages were high, and that an alloy composed of a high level of tin would be a good brazing material to join the sections. Maryon comments that it is not known where and when the brazing technique for joining was first discovered, but that the Etruscans and the Romans were able to make brazed joints See: Maryon 1949, pp. 108-9, Fig. 16. He uses an example of an Etruscan bronze pail from the 4th century. The body and the base were raised from a single sheet of bronze, with no evidence of a join. A stamped moulding with two

Numerous bronze objects that were cast in sections exhibit evidence of soldering, but the type of solder that was used for the majority of objects is not known. In one particular case, an Archaic period Greek bronze footbath, silver solder was used to attach bronze sections together. This was possible because the tripod base, the handles, and the bowl were all cast. The casting of the bowl itself is unusual, because bowls were typically produced from hammered sheet bronze. The high heat involved in hard silver soldering (brazing) would not have damaged the walls of this particular bowl[159].

Besides soldering, another method of joining two sections was to place them in a mould separated by a space in between them, and then pouring molten metal into the space and over the edges of the sections until they were fused. The result was a solid mass of metal, which was then filed down. Pressure welding (heating near to melting point and then hammering) was used to join sections of iron, however bronze cannot be welded because it is brittle when red-hot and shatters when hammered[160]. Fusion welding may have been a workable option if the pieces were of the same physical size. They would have been placed in contact over a charcoal fire and heated to near the melting point, and molten bronze poured over the join. But this would not have worked when attempting to attach a thick handle to a thin-walled bowl. The wall of the bowl and the handle would reach melting temperature at different rates, and there would have been a risk of damaging the bowl.

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lugs were brazed to the rim of the pail. The brazing material is a copper alloy of an undetermined percentage of tin (or zinc) (*Ibid*, p. 112). As a side note, archaeological evidence from Ur dating to the 4th millennium shows that brazing was used for working silver and gold, and other examples of early brazing of these two metals were also found in Greece, Crete, Etruria, Persia and in Egypt (*Ibid*, p. 111). It is difficult to determine whether ancient metallurgists utilized brazing as a general technique in the manufacture of copper and bronze objects, and how widely this technique was implemented, because it is not always possible to conduct extensive analyses on artifacts that are located in museums. The patina, or surface colour, would be damaged during the analysis (*Ibid*, p. 111). From the textual evidence of Herodotus and Pausanias, it appears that the brazing of bronze was being practiced during the Archaic period in Greece. It seems highly unlikely that metalworkers who were experienced with brazing gold and silver would not have adapted this technique to copper and bronze as well.

[159] Milne, Marjorie J., "A Greek Footbath in the Metropolitan Museum of Art", *American Journal of Archaeology* 48 (1), 1944, pp. 26. According to the style of the low tripod-shaped lion-footed base, the bowl was dated to ca. 525 – 425. The bowl wall is thicker than one typically made from sheet bronze, and the author indicates that casting so large a bowl (50cm in diameter without the handles) would have required a high order of technical proficiency. All the sections were brazed using hard silver solder.

[160] Steinberg 1967, pp. 11-12.

The technique that was used, whether a form of soldering or running hot liquid metal, to join separate pieces together depended upon the location of the join and of course which method was best suited to the job at hand. Bronze is malleable and can be cold-worked, but if it is hammered too much it tends to harden and become brittle[161]. Annealing, or re-heating of the metal to a red heat, softens it so that it can be hammered again. Repetitive hammering and annealing actually improves the strength and ductility of bronze; a vessel could thus be shaped from an ingot of bronze through repeated annealing and hammering[162].

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[161] Steinberg 1967, p. 13.
[162] Steinberg 1967, p. 13.

Chapter 2 – Historical Background and Influences on the Development of Bronze and Leaded Bronze Alloys

2.1 Late Bronze Age

The metallurgy of bronze, as well as metal working and forming, had advanced to a considerable degree by the Late Bronze Age. Arsenical copper had been replaced by tin bronze, which became the main copper alloy used in Greece and Crete. According to the analyses of numerous artifacts found at archaeological sites in these regions, the knowledge of varying tin percentages according to the type of object, and the shaping work necessary to produce it, was common in many areas[163]. Objects were produced through hammering and annealing, as well as by mould casting. The addition of lead to bronze to facilitate casting was used in areas such as Mycenae[164]. However, for some reason, leaded bronze was not generally used on mainland Greece during this period. On Crete, analysis of artefacts found during excavations at the Unexplored Mansion in Knossos revealed that the optimum tin percentage of 10%, which balances hardness against brittleness, was utilized for chisels, punches, gravers and tracing needles; spearheads had a consistently high tin content[165]. Low tin in the range of 5 – 6% was used for hinges to maintain malleability. A few vessel fragments had tin amounts in the range of 12 – 22%. Lead was present in

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[163] Helen Mangou, Panayiotis V. Ioannou, "On the Chemical Composition of Prehistoric Greek Copper-Based Artefacts from Mainland Greece", *The Annual of the British School at Athens* 94, 1999, pp. 81-100. Analysis of Late Bronze Age objects (1550 – 1050) from Achaia, the Argolid, Attica, and Magnesea exhibited tin percentages that varied between 4% to 15% (p. 95, Tables 4A – 4E). The bronze objects in these areas were found to contain less than 1% lead. A few bronze objects, such as from Patras (Achaia), contained what appear to be deliberate additions of lead: a brooch handle (3.05%) and a spearhead (4.73%).

[164] Mangou and Ioannou 1999, p. 95, Table 4A. At the House of Mycenae, the three legs of tripod A contained 3.07/3.58/4.04% lead respectively; the vessel body contained no lead. The legs of Tripod B37 contained 0.22/6.20/6.69% lead. A double-edged axe contained 4.8% lead; other axes contained lead amounts from 1.72% down to traces.

[165] H. W. Catling, R. E. Jones, "Analyses of Copper and Bronze Artefacts from the Unexplored Mansion, Knossos", *Archaeometry* 19, 1977, pp. 57-66. The metal artefacts belong to the later period of Minoan metalwork, just before the final destruction of Knossos in the early 14th century. There is mention of low tin contents for tools such as an axe and a knife, which must have been work-hardened to fulfill their purposes. High-impact tools such as punches and chisels have consistent tin amounts of 8.5 – 10.5%. There is no mention in the article of any analysis of cast statuettes.

small amounts of less than 1%. Analyses of artefacts found at the Sellopoulo Tomb 4 near Knossos produced comparable results[166].

2.2 Protogeometric and Geometric Periods

At the end of the Bronze Age, the disruption of trade routes in the Mediterranean region and in the Near East caused a general shortage in the supply of tin. Greece was dependant upon international trade for imports of tin and copper, as well as precious metals such as gold. Tin was scarce in mainland Greece from about 1025 until the mid-10th century, and because of problems with the procurement of tin, bronze also became a rare commodity[167]. In contrast, bronze did not disappear from Crete during this same period, probably due to Crete's continuous contacts with Cyprus, and neither was the site of Lefkandi on Euboea as isolated as mainland Greece was from sources of metal[168]. Iron became more commonly used on mainland Greece, perhaps as a reaction to the penury of bronze[169]. At Greek sanctuaries such as Olympia, lead was often used as a substitute for tin in the manufacture of tripods[170]. Metal goods in graves began increasing during the Protogeometric period, and by 900 the Geometric pottery style made its first appearance in Athens[171]. Early Geometric graves in Athens have produced a wide array of iron objects (spearheads, knives, and a Naue Type II sword), which would indicate that the development of smelting and working iron had by this time advanced to a considerable degree

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[166] H. W. Catling, R. E. Jones, "Sellopoulo Tomb 4", *The Annual of the British School at Athens* 71, 1976, pp. 21-23. Fourteen various objects were analyzed, dating to the Late Minoan II – early IIIA period. The majority contained between 5.5 and 16% tin. Lead was present in one object at less than 1%. An oinochoe contained from 16 – 20% tin, and it is surmised that such a high amount of tin was added for aesthetic purposes to lighten the colour of the bronze.

[167] Rolley 1983, p. 14.

[168] Rolley 1983, p. 51.

[169] A. M. Snodgrass, *The Dark Age of Greece*, Edinburgh University Press, Edinburgh, 1971, pp. 237-8.

[170] Rolley notes that the substitution of lead for tin is also seen in western and central Europe at this time. See: Rolley 1983, p. 14.

[171] J. N. Coldstream, *Geometric Greece*, Metheun & Co., London, 1979, p. 25.

in some regions[172]. The working of bronze was in operation at Lefkandi[173]. The evidence from the rich graves in both Athens and at Lefkandi point to an increase in material prosperity by the mid-9th century[174] There was a resurgence in trade with the Levantine area, particularly with Cyprus. A bronze bowl that was found in a male grave at the Kerameikos cemetery in Athens is considered to be a Levantine import, because a similar bowl located at the sanctuary of Idalion on Cyprus bears an almost identical decorative style. This suggests that Phoenician craftsmen produced both objects at their colony (Idalion) on Cyprus, and were exporting goods to Greece[175].

Bronze cauldrons with ring-handles were very popular as votive objects in Greece during the Geometric period. The supporting tripod legs were usually cast and then riveted to the vat. Large vessel assemblies were placed in sanctuaries as dedications. Some of these bronze cauldrons were up to 1.2 m in diameter, and bronze leg supports for the larger cauldrons were almost 2 m high; smaller round bronze vessels were used in male cremations[176]. The decorative elements on the tripods became more elaborate from the second half of the 9th century. These included figures of bullheads, birds, and horses that were mounted above the handles[177]. Numerous small bronze figurines formed in a rudimentary style imitative of the male and animal figures found on Dipylon terracotta kraters were also produced in large numbers. Athens became a main centre for hammered bronze-work such as tripods and ring handles[178].

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[172] Coldstream 1979, pp. 30-3. Macedonia was a major iron-working region at this time. The Protogeometric finds at the cemetery site of Vergina consisted of numerous iron weapons in male burials (20 swords of which almost all are of the Naue Type II, spearheads, arrowheads, daggers and knives). Many high-quality ornamental bronzes were found in the female graves, which would indicate that bronze was readily available in Macedonia. See: Anthony M. Snodgrass, "Iron and Early Metallurgy in the Mediterranean", in: Wertime, Theodore A, Muhly, James D, (Eds.), *The Coming of the Age of Iron*, Yale University Press, New Haven and London, 1980, pp. 350-1, and Snodgrass 1971, pp. 253-5. Snodgrass mentions that the bronze objects, particularly the spectacle-fibula, have a Balkan connection, and therefore bronze was coming to Macedonia from regions other than the eastern Mediterranean. See: Snodgrass 1971, pp. 254-6.

[173] Coldstream 1979, p. 70. Coldstream indicates that the bronze foundry at the settlement of Lefkandi (region of Euboea) was in operation around 900. Bronze was being imported from Cyprus, which meant that tin was available in some areas at this time See: Coldstream 1979, p. 52.

[174] Coldstream 1979, p. 55.

[175] Coldstream 1979, pp. 59-60.

[176] Coldstream 1979, pp. 126-7.

[177] Rolley 1983, p. 52-3. Smaller-scale tripods were offered as votive objects by the general population and many of these have been found at the Olympia sanctuary.

[178] Coldstream 1979, pp. 128-9.

A definite change over time in the types of alloys that were used in the manufacture of the supporting tripod legs and handles can be observed at the sanctuary of Olympia[179]. Metal analysis of early Geometric period cult objects at Olympia (beginning in the second half of the 9th century) indicated that leaded copper was used in the manufacture of solid cast tripods[180], and that the addition of lead was deliberate. When more tin became available at Olympia through renewed trade contacts with the Near East during the second half of the 8th century (Late Geometric), large tripods made of tin bronze went into production[181]. The tripod legs were hammered out of sheet-metal and riveted together, and although their period of manufacture overlapped with that of the traditional cast tripods, they contained very little lead[182]. In a study of tripods at Olympia, it was found that tin began to be used in appreciable amounts after the second half of the 8th century. Out of 10 tripods analyzed for this period, 7 contained more than 1% tin, with the average at 4.4%. Analysis of earlier tripods dating from the late 9th century to the second half of the 8th century showed less than 1% tin[183].

If some of the bronze-smiths at Olympia continued using leaded copper for cast tripods, they may have been aware of the technical advantages of this alloy in the casting process. An unanswered question is why the bronze-smiths added such low amounts

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[179] Kyrieleis 1990, p. 22. Olympia was an important panhellenic sanctuary, and artisanal production of many regions of Greece and the Near East were brought there. Metalworkers from areas such as the Argive, Attica, Delphi, Samos and Corinth produced objects at their workshops near the sanctuary. Phoenicians brought in goods from the Near East. Thus the bronze work at Olympia cannot be considered to be strictly the production of local artisans. See also: Coldstream 1979, pp. 133.

[180] Andrews 1994, pp. 138, 145-6, 149. Lead percentages of up to 2.15% were alloyed with copper. The tin percentages were very low.

[181] Andrews 1994, p. 177, 192. Andrews proposes that, from the large numbers of votives and spectacle fibulae found at the site, metal was widely available at Olympia from the 9th century, and may have in fact been imported from sources in Italy, Macedonia and the Balkans. This statement brings up a question concerning the use of lead. If tin was imported to Olympia in this period, then the use of leaded copper for cast tripod legs cannot be satisfactorily explained, other than as an alloying technique that dates to an earlier period when tin was in short supply, and which continued as traditional practice among some bronze-casters (my comment).

[182] Concerning hammered sheet metalwork, Craddock notes that "Thus the universal absence of lead from sheet metalwork has nothing to do with culture or typology, it is just a metallurgical fact of life." See: Craddock 1988, p. 319. (and see note above, my comment).

[183] Varoufakis et al 1983, p. 118 and Appendice II. Four of the bronzes from the later period are noted as tripod legs by Andrews. See also: Andrews 1994, pp. 140-1. The lead percentages of the Olympian tripods were not included in this study. The figures are my calculations.

of lead that are coincidental with the optimum level of lead required to improve fluidity (2%), and not higher amounts since lead was common and cheap while tin was in short supply[184]. It is significant that the use of leaded copper did not continue into later periods at Olympia once the tin supply had been re-established. The bronzesmiths probably noticed that if the tripod legs were cast from leaded copper, they could not be worked or shaped to any great extent because of the inherent brittleness factor of this alloy. A finer finish could be achieved through hammering. This readily explains why tin bronze superseded leaded copper, due to its superior forming properties and resilience to repeated hammering during the shaping process. Tin bronze is also a stronger alloy than leaded copper, and its use for tripods legs would have made them more capable of supporting heavier cauldrons. Tripod dedications had disappeared at the sanctuary of Olympia by the end of the 7th century to be replaced by dedications of armour such as greaves. Tripods continued to be placed in sanctuaries on Delos during the Archaic period; at Delphi and Athens they acquired an elitist status and were used mostly as symbols of state[185]. As a side note to the tripods, the few analyses that have been conducted on Olympian votive figurines that date from the 8th to the early 7th centuries indicate that they were made of either copper or tin bronze, but that there was no preferred alloy standard in the tin/copper percentages; the amounts of lead were on the order of 1% or less[186].

The large tripods at the Delphi sanctuary demonstrate the same trend over time as those at Olympia when it comes to the use of tin, however the use of lead generally appears to remain at low percentages. In the Protogeometric and early Geometric periods, lead was often added to cast tripods and tin levels were very low (less then 4%). When tin became more available during the Late Geometric, tin levels rose and hammered and riveted bronze tripods became the norm. These changes in the composition of alloys was confirmed through studies conducted of bronze tripods at Delphi and they demonstrate a

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[184] Andrews 1994, pp. 138-9, 145. Lead in the cast tripods was not an accident and was added out of “craft experience”, because the hammered tripods exhibit only trace amounts of lead. It has been previously noted (Chapter 1, this paper) that the addition of more than 2% of lead to copper does not markedly improve the alloy. The fact that the cast tripods at Olympia do not contain more than the minimum amount necessary to increase fluidity may be coincidental, but it is nonetheless difficult to explain why the bronze-workers did not increase the lead amounts. See also previous notes on metal supplies at Olympia.

[185] Treister 1996, pp. 129-31.

[186] Andrews 1994, p. 150. Geometric period figurines contained anywhere from 4% to 12% tin. Andrews does not indicate whether the figurines were cast, or hammered out of sheet metal.

definite trend in the increases of tin percentages[187]. From the late 9th century to the second half of the 8th century, only 11 out of 20 tripods (foot, handles and vat) contain more than 1% tin (average of 3.9%) and 6 contain more than 1% lead (average 1.45%). From the second half of the 8th century and onwards, 13 out of 16 tripods (foot, handles and vat) contain significantly more tin with an average of 4.5%; 6 out of 16 contain more than 1% lead, with an average of 1.9%[188]. Of the 36 tripod sections that were analyzed, only four feet contained what could be considered to be deliberate additions of lead: early examples at 1.81% and 2.27%, later ones at 2.36% and 3.96%, if the inclusion of 2% and more of lead is considered to be the threshold level (see Section 1.3.3)[189]. There is no clear differentiation in the quantities of lead that were used for the tripod supporting feet and handles, but lead is almost completely absent from all five hammered tripods that were analyzed from the later period, which closely correlates with the data on hammered tripods from Olympia.

A study of alloys used in tripods that were found on Mount Ida on Crete indicate a similarity with tripod alloys on mainland Greece[190]. According to the description of the sources of the samples used for analysis, the production period of tripods with riveted vats was very short on Crete, starting in about 800 and ending some fifty years later. Analyses of a series of tripod feet and handles indicated that tin percentages were rather low, from traces to a high of 3.76%. Lead percentages ranged from 0.67 to 2.16%. There is no clear correlation in the percentages that shows more lead being used for handles than for the feet, because the alloy compositions are dispersed in a random manner.

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[187] Varoufakis et al 1983, p. 118 and Appendice I.

[188] Treister 1996, p. 156. I have re-calculated the percentage figures for lead from Varoufakis et al 1983. There are no metal analyses of tripod legs in this article.

[189] It would have been interesting to have had lead isotope analysis figures for these tripods to assess the location of the source copper ores and what percentage of lead makes up the ore body. This would not in itself provide an answer to the question of deliberate lead addition, since it is unknown how much scrap metal of indeterminate alloy composition may have been used for the tripods, how much lead was associated with the tin ore, etc.

[190] Éléni Magou, S. Philippakis, Claude Rolley "Trépieds géométriques de bronze, Analyses complémentaires", *Bulletin de correspondance hellénique* 110 (1), 1986, p. 130, 135 (Trépieds crétois, Musée d'Héracleion).

2.3 The Influences of Near Eastern Metallurgy in Greece from the Late Geometric Period into the Orientalizing Period

Tin became available in larger quantities in Greece when trade was re-established with the Near East in the mid-8th century. Objects that were imported from North Syria and Urartu (East Anatolia), particularly bronze cauldrons with bronze handle-attachments in the form of sirens and bullheads, with griffin protomes as cast decorative attachments on the rims[191], contained on average about 10% tin. Many of these attachments also contained lead, but in low amounts. The alloying techniques imported by Near Eastern metalworkers who immigrated to Greece may have had a direct influence on the amount of tin that was used in locally manufactured Greek orientalizing bronzes, which rose to comparable levels. Nevertheless, some newly established workshops in Greece continued to produce traditional tripods where the supporting legs were riveted to the vat and which contained from 3 to 5% tin[192]. From the archaeological evidence found at Greek sanctuaries in Samos, Argos, Delphi and Olympia during the Orientalizing period, many Greek artisans who were imitating Near Eastern figural motifs also adopted the bronze alloy compositions that were being used by Near Eastern bronze-workers[193]. The increased tin levels in Greek bronzes could be partially explained by the easier access to tin during this period, but the adoption of Near Eastern metalworking techniques, and the use of different alloy compositions according to the object being manufactured, are all factors that attest this influence.

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[191] The siren is a creature with a human head and torso, with the wings and tail of a bird. There is usually a ring in the back for the insertion of a free-swinging loop handle. ‘Siren’ is a general term because some of these protomes are males with beards, while other are female. They were mounted on the cauldron rim, facing the inside of the vessel. See: Oscar W. Muscarella, “The Oriental Origin of Siren Cauldron Attachments”, *Hesperia* 31 (4), 1962, p. 317. The griffin protome is a composite of a half-lion, and a half-eagle with an open beak. The head and neck portion was used as a decorative rim attachment; earlier versions of the griffin protome are found in Mycenaean art. See: David G. Mitten, “Two Griffin Protomes”, *Acquisition (Fogg Art Museum)* 1964, p. 11. The word protome comes from the Greek ϖροτομή, and is an adornment in the shape of an animal head or a human bust.

[192] Rolley 1983, p. 14. Rolley mentions that whereas Near Eastern bronze-workers used high amounts of tin, Greek bronzes are very low in tin up to the mid-8th century. The low amounts of tin would indicate that older bronze, perhaps Mycenaean bronze which contained tin, was being recycled. See also: Varoufakis et al 1983, p. 127.

[193] Mattusch 1988, p. 35.

Fig. 8 – Tripod cauldron from Olympia, 9th century. Height 65 cm. Feet and handles are cast and riveted to the hammered bronze cauldron. (Fig. 29, p. 54 in Rolley 1983; Olympia Museum inv. no.: B 1240)

Fig. 9 – Tripod cauldron from Salamis, Cyprus, late 8th century. Total height 1.25 m. Local imitation of North Syrian models. The four bearded sirens are hammered, the eight griffins are cast. The hammered cauldron is made from two metal sheets.
(Fig. 51, p. 71 in Rolley 1983; Archaeological Museum of Nicosia)

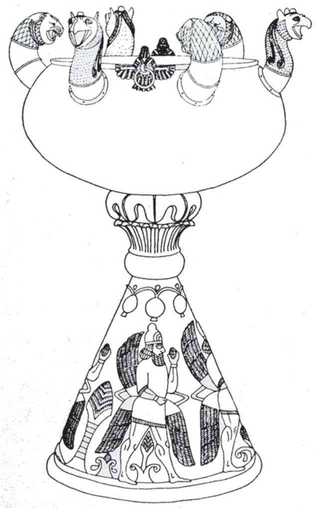

Fig. 10 – Reconstruction of a bronze cauldron with conical stand from Olympia, early 7th century.
Lip diameter about 65 cm.
(Fig. 46, p. 67 in Boardman 1980)

A number of comments by Claude Rolley on the topic of tin-bronze alloys of the Orientalizing period provide explanations of the Near Eastern influence. He says that bronze-workers in the Near East were familiar with various types of bronze alloys early on. During the Bronze Age, major tin sources that probably existed in Iran or Afghanistan were being exploited, and the processed ore exported to metal-working ateliers in Near Eastern regions. Bronze-workers must have experimented with varying the proportions of copper and tin to make bronze, and also the amounts of lead to be added to the bronze according to the type of object, and the process by which it was manufactured (either hammered or cast). The individual parts of an object, such as the head, arms, and base of a statue, as well as cauldron attachments, etc., were also manufactured with various alloy compositions. The conclusion reached by Rolley is that the Greeks acquired specialized metallurgical knowledge from the East during the Orientalizing period, and that the practice of adding large quantities of tin in the making of bronze was a component of this transfer of knowledge. He says that analysis of a number of bronze objects that were produced in Greece during the period prior to the renewal of Eastern trade contacts show an overall lower tin content[194].

Soon after the influx of Near Eastern bronze work, the traditional Greek tripod cauldron was replaced by imitations of the Eastern oriental types, which consisted of a round bronze cauldron that was placed upon either a conical stand or on a rod tripod support (Figures 8, 9 and 10)[195]. The elaborate attachments (sirens) with ring handles, and long-necked griffin protomes were mounted in pairs or sets of four, and were usually affixed to the cauldrons with metal rivets. The siren protome may have originated in Assyria, and their shape and designs probably derived from representations of the god Assur[196]. Cauldrons and siren attachments had a widespread distribution. Sirens were found in tombs and sanctuaries on mainland Greece at Athens, Delphi, Ptoon, Olympia, and Argos; in Etruria at the sites of Palaestrina and Vetulonia; on the islands of Delos, Samos, Cyprus and Rhodes. Earlier versions, as well as concurrent examples, were found at the site of

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[194] Varoufakis et al 1983, pp. 127-8. The lower tin content of bronzes was apparent during the Protogeometric and Geometric periods when there was a general penury of tin in Greece. Tin levels during the Late Bronze Age were higher, and were comparable to tin levels that were used during the Orientalizing period.

[195] Coldtream 1979, pp. 128-9; Mattusch 1988, p. 35.

[196] D. C. Romano, V. C. Pigott, “A Bronze Siren Cauldron Attachment from Bryn Athyn”, *Masca Journal* 2 (4), 1983, p. 124, 126.

Toprak Kale in Urartu (Eastern Anatolia) and at Gordion, which was the Phrygian capital in Central Anatolia[197]. At excavation sites, some sirens and griffin protomes were found still attached to cauldrons or parts thereof, but the majority have been unearthed as either separate complete pieces or in fragments.

There is a noticeable development in the technical aspects of metal-working used to produce the protomes. The griffin protomes were usually less than 30 cm high, and early ones were made of hammered sheet bronze[198]. At the same time, while the early Greek Orientalizing protomes were hammered and the details traced with a small hammer and chisel, the imported Near Eastern attachments were usually cast and the details incised[199]. In later Greek types the griffin heads are hollow-cast and attached to hammered necks, and in a further development both the heads and necks are hollow-cast in one piece. Hollow casting was used for large protomes because of the impracticality of solid-casting a heavy metal object that was to be attached to the thin metal rim of a cauldron. The griffins also evolve from their earlier squat proportions to a more elongated and serpentine shape[200]. In Greece, the peak of the manufacture of protomes that were attached to tripod cauldrons appears to have occurred during the first half of the 7th century, at the height of the Orientalizing period. Their number diminished quite significantly at the sanctuary of Olympia by the first quarter of the 6th century (beginning of the Archaic period).

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[197] Muscarella 1962, pp. 317-8. The author states that about three-quarters of the total number were found in Greece and Italy, and that “25% of those found in Greece are clearly Greek in style, whereas the remainder found in Greece, those from Italy, and the ones from Gordion and Urartu form another group.”

[198] Mattusch 1988, p. 36. The 30 cm height of the griffin protomes is an average figure, but some protomes were exceptionally large. Three hollow-cast griffin protomes, that scholars agree have their origin at Olympia in the 7th century, were estimated to have originally measured from between 0.65 m and 0.8 m high, and appear to have been worked to be of the same size. The entire monument, including the base and the massive cauldron, is thought to have stood from 4.6 m to 5.6 m high. See: Mattusch 1990, pp. 552, 557-8.

[199] Boardman 1980, p. 81.

[200] Mattusch 1988, p. 36. A group of hollow griffins, dated to the second quarter of the 7th century, that were found at the Heraion on the island of Samos appear to have been cast in piece moulds by the indirect lost-wax process, which shows that this technique was already known by this time, and was used to produce duplicate forms from an original model (Mattusch 1988: 36). It is evident that during the 7th century, Greek bronze-workers were familiar with the direct and indirect lost-wax processes in the casting of hollow protomes and statuettes (*Ibid*. p. 47). See also: Mitten 1964, p. 14. Slender, snake-like protomes were found on Samos.

At this same time, the quantity of these items that were being produced at the Heraion sanctuary on Samos actually increased[201]. Samos was a major centre of artistic bronze-working in the 7th century[202]. Samian artisans set up a workshop at the sanctuary of Zeus at Olympia, and adapted the cauldron with its protome and siren attachments from Argive craftsmen[203]. By the mid-7th century, they were producing large hollow-cast griffin protomes rather than sphyrelata (hammered bronze on wooden cores) which was the technique current in Greece at that time[204]. Casting enabled the reproduction of finer and more elaborate details on the object than was possible through hammering sheet metal into shape. The smaller griffin protomes that were found at the Heraion sanctuary were essentially leaded bronzes containing over 10% lead. The lead was presumably added for aesthetic reasons to differentiate their colour from that of the cauldrons[205].

In spite of their widespread use as decorative attachments, the exact place of origin of the griffin protome is not known. The figures of sirens mounted on cauldrons that were imported from the Near East are differentiated from those that were of local Greek manufacture by their facial characteristics (Figures 11 and 12)[206], but this is not the case with the griffins[207].

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[201] Treister 1996, pp. 129-31.

[202] Helmut Kyrieleis, “Samos and Some Aspects of Archaic Greek Bronze Casting”, in: Marion True, Jerry Podany (eds.), *Small Bronze Sculpture from the Ancient World: papers delivered at a symposium held at the J. Paul Getty Museum, March 16-19, 1989*, The J. Paul Getty Museum, Malibu, 1990, pp. 19-23. Some 200 griffin protomes have been uncovered at the Heraion sanctuary on Samos.

[203] Treister 1996, pp. 68-9. It was common for craftsmen to travel to various regions to ply their trades and work on contract. See: Mattusch 1988, p. 62, and Treister 1996, pp. 86-92. It is thought that Achaeans from the Peloponnesus region established colonies in the Aegean islands during the migrations at the end of the Bronze Age, one of which was Samos. See: Sarah B. Pomeroy, Stanley M. Burstein, Walter Donlan, Jennifer Tolbert Roberts, *Ancient Greece, a Political, Social, and Cultural History*, Oxford University Press, New York, 1999, p. 44.

[204] Mattusch 1988, p. 36; Treister 1996, p. 69.

[205] Cauldrons usually contained very little or no lead. Their colour would have been reddish compared with the protomes. For further details on Samian protomes, see section on attachments in Chapter 3.

[206] Rolley 1983, pp. 72-4. For a figural comparison of an oriental and a Greek imitation of a siren attachment, see Coldtream 1979, p. 364, Fig. 115. See also: Muscarella 1962, p. 318, for physical comparisons of the two types. Larger versions are in the Figures section of this paper.

[207] The problem is compounded by questions concerning the precise area of manufacture of the tripod cauldrons, as well as the siren attachments that were imported from the Near East. Their production centre was located either in North Syria or in Urartu, both of which had metal-working industries at this time. See: Romano and Pigott 1983, p. 126; Coldstream 1979, p. 365; Muscarella 1962, pp. 320-1. Barnett argued that the siren attachments and open-mouthed griffins that were found at Toprak Kale in Urartu were definitely

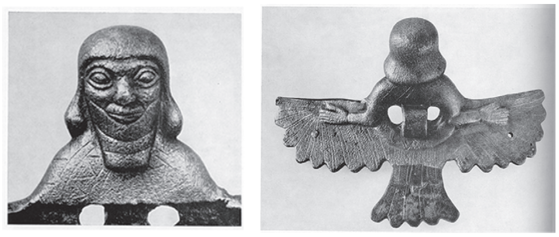

Fig. 11 – Oriental siren from Olympia.
Bust 6.2 cm high, wingspan 19.5 cm.
(Tafel 8 in Herrmann 1966, *Olymp. Forsch* VI)

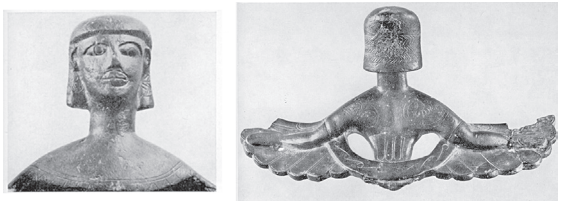

Fig. 12 – Greek siren from Delphi, ca. 700.
Wingspan 17.5 cm.
(Tafel 35 in Herrmann 1966, *Olymp. Forsch* VI)

This subject has created a great deal of controversy, therefore a short discussion on the research that has been conducted, and opinions of various authors is presented here. A clarification of the origins of the sirens and griffins would also shed some light on the use of the leaded bronze alloy by the Greeks in the Orientalizing Period, and whether its use can be directly attributed to a Near Eastern influence on Greek metallurgy[208]. Very few examples of a griffin protome have been found in the Near East, although antecedent motifs bear some similarities. One example came from Gordion, as well as a lion figure protome from the Urartian site of Karmir Blur, and they are all hollow-cast whereas early Greek examples are hammered[209]. An imitation of a Near Eastern style was found on a cauldron with eight protomes from Salamis on Cyprus, (Fig. 9) and on this cauldron the sirens are hammered and the griffins are cast[210]. According to Coldstream, the griffin and lion attachments from Greece and Etruria (Barberini cauldron) are most likely Greek adaptations based on Oriental types, which were then attached to imported Oriental caul-

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manufactured locally, and not in North Syria. He does not indicate if these items were cast or hammered. See: R. D. Barnett, "The Excavations of the British Museum at Toprak Kale near Van", *Iraq* 12 (1), 1950, p. 39. Rodney Young indicates that although the general opinion has tilted in favour of North Syria as the major manufacturing source, this area was itself influenced by Late Hittite, Assyrian and Canaanite styles, and thus the North Syrian 'style' may be an amalgam of decorative and iconographic inputs from various sources, not to mention regional tastes for particular designs. See: Rodney S. Young, "A Bronze Bowl in Philadelphia", *Journal of Near Eastern Studies* 26 (3), 1967, pp. 153-4.

[208] See also Section 3.1.1 for details on alloy compositions that were transferred from the Near East to Greece, and on metal analyses of sirens and griffins.

[209] Coldstream 1979, p. 365. Coldstream does not include a mention of the griffins at Toprak Kale in Urartu.

[210] Rolley 1983, p. 74. See also: John Boardman, *The Greeks Overseas*, Thames and Hudson Ltd., London, 1980, p. 81.

drons[211]. He also indicates that the griffin and lion heads on the Barberini cauldron are very similar to the compact North Syrian figures that are typically seen on monumental sculpture, and which may have served as the basic models that were modified for local tastes[212]. A dabo-relief found at Ankara contained a "representation of a griffin-headed beast", and another set of reliefs from Sakcegözü showed griffin-men. Their similarities to Greek griffin protomes are unmistakable: open mouth, quadruped's ears, spiral curl on the neck and a knob on top of the head[213]. The problem, according to Muscarella, is that the Ankara figure cannot be taken as the Phrygian prototype for the Greek griffin because the actual date of the slab is unknown, and it may be North Syrian. The Sakcegözü reliefs were dated to the latter 8th century, which is earlier than the Greek protomes. The spiral curl on the neck is also a common motif in North Syrian iconography, thus Muscarella proposes that the relationship between Oriental and Greek griffins is to be found in the region of North Syria[214]. But due to the fact that almost no griffin protomes were found in the Near East, or even in North Syria, it was proposed that Greeks adopted the griffin motif from North Syrian art and transformed it into an object that was placed on cauldron rims; large numbers of bronze griffin protomes have been found on Samos, and perhaps this area was the origin of these protomes[215].

The influences of Near Eastern artistic motifs such as sphinxes, sirens, lions, etc., as well as metalworking techniques, on the stylistics and types of objects that Greek craftsmen imitated and reproduced for local tastes are unmistakable. It has been suggested that Near Eastern craftsmen who specialized in these luxury goods may have immigrated to Greece and produced imitations of Oriental motifs for local tastes, passing on their techniques to Greek metalworkers[216].

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[211] Coldstream 1979, p. 365.
[212] Coldstream 1979, p. 365. This implies that there were two distinctly separate areas (and workshops) involved in the production of the griffin protome cauldrons.
[213] Muscarella 1962, p. 319.
[214] Muscarella 1962, p. 320.
[215] Muscarella 1962, p. 320. See also: Varoufakis *et al* 1983, p. 122. Muscarella's article dates to 1962, but the article by Varoufakis from 1983 mentions that opinion is still divided as to the workshops that produced the cast Oriental sirens and hammered griffins, namely between Urartu and North Syria. A more recent article by Magou *et al* 1991, p. 566, says that there is still no unanimity concerning the Oriental hammered griffins, but that general opinion leans in favour of a Near Eastern origin.
[216] Maurits van Loon, "The Place of Urartu in First-Millennium B.C. Trade", *Iraq* 39 (2), 1977, p. 231.

The type and styles of bronze work found on Crete during the Late Geometric and Orientalizing Periods are quite different from those found on mainland Greece during these periods. The bronze cauldrons with sirens incorporating ring handles and with their griffin protomes that were so prevalent in Greece, Etruria and Cyprus have not been found on Crete[217]. Sites which date from the first half of the 7th century, such as Afrati in south-central Crete, have produced imitations in clay and stone of North Syrian bronze objects, such as stone oil bowls fed by lion-head spouts, and low cauldrons with griffin heads reproduced in clay. The use of different media to imitate Near Eastern bronze work may have resulted from the arrival of foreigners who perhaps had an influence on the techniques of local craftspeople[218]. North Syrian metalworkers with a particular expertise in beaten metalwork may have arrived on Crete in the late 9th century. Their work is seen in some of the cult objects, such as bronze tympanums and conical shields with animal-head bosses that have been found at the Idaean Cave site. The recognizable craftwork of these objects, with their particular Near Eastern styles that had been modified to incorporate local and regional religious iconography, have been found elsewhere on Crete as well as at sites on Delphi, Dodona and Miletus[219]. The decorative motifs became increasingly more similar to those from mainland Greece from the 8th to the first half of the 7th century[220].

2.4 Archaic Period

It has often been argued that the major impetus for Greek colonization from the 8th to the 6th centuries in the western Mediterranean was the search for new sources of primary metals such as gold, iron ore, copper and tin, however there may have been other determining factors, such as a lack of arable land, overpopulation, or droughts caused by climate change, and thus a direct link cannot be made between the increasing commerce in metals and expanding colonization[221]. Nonetheless, it is not coincidental that many Greek

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[217] Boardman 1980, p. 80.

[218] Boardman 1980, p. 74.

[219] Boardman 1980, p. 72.

[220] Boardman 1980, p. 74.

[221] Treister 1996, pp. 146-7, and pp. 176-181. Greeks were trading overseas for metals well before the period of colonization. In comparison, the Phoenicians had long-established trade areas in silver-rich regions of Iberia and Etruria as purely commercial interests. Phoenician colonization started only after Phoenicia was

colonies were founded in regions which possessed rich mineral resources. This is particularly noticeable with the Phocaeans who conducted colonizing ventures in areas that provided ready access to metals. They founded Massilia (present-day Marseilles) ca. 600 as a port at the mouth of the Rhône River, which was the end of the tin route that ran from Armorica (Brittany and areas between the Loire and the Seine rivers) and southern England. Alalia was near Etruscan iron and other metal deposits; Emporion was founded in 575, on the coast near northern Iberian mining areas that were rich in silver and tin[222]. The Phocaeans were also in regular contact with the port of Tartessos (southern Iberia) that was located in a particularly metal-rich area. Communication and trade between the colonies and the founding cities in eastern Greece were most likely maintained by the Phocaeans, but some scholars believe that Greek goods were transported to these western colonies by Phoenician traders, who also had interests in the mineral resources of Iberia[223]. The Greeks had trade contacts not only with the Near Eastern regions of Syria, the Levant and Urartu, but with the inhabitants of Italy as well. Traders from Greece had been conducting commercial relations with Etrurian and Campanian natives in Italy long before the first Greek colonies were established in these areas.

From analysis of Greek bronze objects from the 8th to the 6th centuries (Geometric to Archaic Periods), one surprising aspect of the increased and easier access to tin is that there was no corresponding sharp increase in the tin percentages that were used to make bronze[224]. Late Bronze Age and Geometric statuettes averaged 7.4% tin. Tin usage rose slightly in the Archaic Period, with statuettes still averaging about 7.4%, but a wider variety of bronze objects were being manufactured, such as mirrors (average 9.9%), decorative bronzes (8.9%) and vessels (8.5%)[225]. Archaic Greek bronzeworkers used similar tin percentages in their bronzes as Etrurian and Iberian metal-workers, and they adhered to

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conquered by the Assyrians in 737 and it lasted into the first decades of the 6th century, thus economic and political pressure from Assyria and Babylon were the major determining factors (*Ibid*, p. 180).

[222] Treister 1996, p. 148.

[223] Treister 1996, pp. 148-150. Some scholars believe that overseas trade during the 7th century was conducted mostly by the Phoenicians. Pre-colonial trade goods could have been transported by either the Etruscans, Phoenicians or the Greeks, because there is no evidence of pre-colonial Phocaean materials in these regions.

[224] Treister 1996, p. 155 and p. 157.

[225] Treister 1996, pp. 155-6. See also: Craddock 1976 and 1977 for tables of metal analyses.

the formulas that they had been using for some time for mixing bronze alloys as far as tin quantities were concerned[226].

Greek artisans started producing large-scale sculptures in stone and marble during the Archaic Period, and it is thought that the Greeks learned the techniques of casting large-scale bronzes from Egyptian artisans[227]. Some of these techniques, which were familiar to Greek bronzeworkers, involved the direct and indirect lost-wax casting processes (hollow cast) which they were using to make smaller-scale bronzes, such as griffin protomes and statuettes. Smaller-scale bronzes could be solid cast, but larger bronzes posed too many technical problems for solid casting to be practical, mostly because of the uncertainty that the molten bronze would remain liquid long enough to reach all extremities of a large mould[228]. The principle of piece-casting was known in Greece as well. The heads and necks of large cauldron griffins were often cast in separate sections using hollow casting and then pieced together using rivets, or a form of fusion welding could also be used to join the pieces. But the production of large bronze statuary required that they be cast in many sections due to the sheer weight of the metal. Numerous moulds had to be constructed from life-size or larger stone or wood models; iron armature systems were designed and built for use as bracing for the mould walls. It is probable that improvements in melting techniques as well as in the construction of furnaces were developed in order to produce the larger volumes of molten bronze that would have been required for this type of statuary. According to the ancient writer Diodorus, the first Greek productions of large-scale bronzes that utilized the new Egyptian techniques occurred on Samos[229]. The earliest archaeological evidence of larger-scale statuary comes from Olympia and Athens[230].

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[226] Treister 1996, pp. 156-7. A detailed breakdown of alloy compositions in statuettes and figurines from the Geometric to the Hellenistic periods are discussed in Chapter 3 of this paper.

[227] Carol C. Mattusch, *Classical Bronzes – the Art and Craft of Greek and Roman Statuary*, Cornell University Press, New York, 1996, pp. 8-9. The Egyptians already had considerable experience in the casting of large-scale bronze statuary, an art form which supposedly made a great impression upon the Greeks who lived at their trading colony at Naukratis in the Nile Delta (ca. 650).

[228] Mattusch 1988, p. 47. The addition of a small amount of lead would have increased the fluidity of the bronze, and raising the temperature of the melt would have also aided in maintaining the melt fluid for a longer period of time. Lead was usually not a deliberate addition to alloy mixtures used for casting large statuary in Greece.

[229] Mattusch 1988, p. 46; Treister 1996, p. 68.

[230] Mattusch 1988, pp. 53-4. Fragments of a large kouros, estimated to be 0.5 m high, were found at Olympia and dated to the first half of the 6th century. It consisted of the thighs and partial legs. A find at the Athenian

One interesting example of the types of variations in alloy mixtures that were used for different sections of large-scale castings was found in a statue that is thought to be a representation of Zeus, the so-called “Ugento god”[231]. The statue itself is 86.78% copper, 8.47% tin, and 3.58% lead. The narrow rectangular base has 4.68% tin and 19.58% lead, the lead undoubtedly added for stability. The statue was attached to the base with lead dowels. A bunch of grapes that were found in the same area as the statue were composed of a tin/lead alloy (6.09 / 90.76%) as well as 2.06% silver, and there was also evidence that the grapes had originally been gilded with gold.

With easier access to tin and other metals on the rise in the Archaic Period, Greek metal-workers were evidently experimenting with alloy compositions for particular applications, although in general they adhered to specific formulas for statues[232]. In addition to the advances in metallurgical and working techniques that were used for casting large bronze statuary, the numbers of votives such as bronze figurines that were placed as dedications at temples and sanctuaries were increasing. Through colonization and trade, the Greeks had regular contacts with metal-workers in other regions and the various types of objects that were manufactured in foreign workshops. Itinerant craftsmen dispersed their techniques in the working of metals and other materials throughout the Mediterranean area[233]. And continuing on the trend that started during the Orientalizing period, variations in alloying techniques that were used for particular purposes would undoubtedly have been adopted into Greek artisanal metalworking. Greek metal-workers set up shops in eastern areas as well as in Etruria, and foreign metal smiths also set up their workshops on mainland Greece as well as in Greek colonies in Magna Graecia.

Agora of clay investment moulds indicated that a bronze kouros, measuring about 1.0 m high, was cast there sometime in the mid-6th century.

[231] Mattusch 1988, pp. 14-5, 68-71. This statue was found in 1961 in Ugento, Italy, and was dated ca. 530 to the early 5th century. It measures 0.71 m tall.

[232] Mattusch 1988, p. 14.

[233] Treister 1996, pp. 86-92.

2.5 Classical and Hellenistic Periods

By the Classical Period, Greek artisans had advanced in their technical knowledge and were producing a variety of bronze designs. Life-size bronzes and huge bronze statuary hollow-cast in sections[234], as well as portrait bronzes were being executed by specialized bronze-casters for placement at temples. At the same time, the practice of offering small votive statuettes at temples and sanctuaries, which had been a common practice during the Geometric and Archaic Periods, almost ceased after 450[235]. Large statuary from this period, such as the Piraeus collection of four large bronze statues, exhibit alloy compositions that were the "standard" mixture commonly used in Greece[236]. The Apollo (1.91 m) has been dated from 530 – 450 based on its stylistic and technical aspects and thus could be Archaic. The other statues are Classical Period works: the Athena (2.35 m) and the large Artemis (1.94 m) were dated to the 4th century based on stylistic similarities with marbles of the same period, and the smaller Artemis (1.55 m) was tentatively dated to the 4th century, although it could be Hellenistic. The Apollo, the Athena and the large Artemis contain very little lead, with copper averaging 88%, tin 10.3%, and lead 1%[237].

Although the degree of accuracy to which Greek bronzeworkers calculated their alloy compositions in actual practice is unknown, an inscription that was found in Eleusis, dated to the last third of the 4th century, provided material specifications that were to be followed for the manufacture of bronze poloi and empolia[238]. The bronze was to be composed of eleven parts Cypriot copper and one part tin (91.67% copper, 8.33% tin). It can be seen that these figures are fairly close to the alloy composition of the Piraeus statues. Another example of probable specifications for alloy composition came from several fragmentary inscriptions on stele that were found in northern Athens, dated between 421 – 415. They provided details about the manufacture of two very large bronze statues,

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[234] Mattusch 1988, p. 167-9. The sculptor Phidias specialized in the production of colossal statuary in marble and bronze. His bronze Athena that stood in the Acropolis has been estimated to have been over 15 m high.

[235] Treister 1996, p. 197. The author mentions that this decline in production is quite noticeable in museum collections, where Archaic statuettes outnumber Classical ones by almost ten to one.

[236] Mattusch 1988, p. 129. These four large statues were discovered at Piraeus, the port city of Athens, in 1959. They were part of a group of bronzes and marbles that were found in an ancient warehouse.

[237] Mattusch 1996, pp. 135-7.

[238] Mattusch 1988, p. 14. The poloi and empolia were used for columns of the Philonian Stoa, and set up on the front of the Telesterion temple site. See also: Healey 1978, p. 210.

now lost (Hephaistos and Athena) and their supports to be installed at the Hephaisteion in Athens[239]. The partial inscriptions detailed many aspects of the work that was to be performed, and included purchases of amounts of copper (or bronze), tin and lead. It is thought that the lead was used for the large supporting dowels for the assemblies. Researchers who have studied the metal requisitions list, of which only part has survived, have determined that the composition of a decorative bronze support, or *anthemon*, would have been about 88 – 87.5% copper and 9.9 – 12% tin, which is the ideal working composition of bronze[240]. Due to the fact that the inscriptions are incomplete, it was not possible to obtain an accurate idea as to what quantities of the metal acquisitions were actually destined for the statues themselves, since the amounts mentioned would not have been sufficient to manufacture statues of the purported size as well as their supports[241].

The tin percentages used in the Classical period for vessels, mirrors and statuettes as a whole averaged 8.5%[242]. Statuettes tended to contain more lead than vessels or mirror discs. As was the norm during the Archaic and in previous periods, vessels were raised from unleaded sheet bronze, although if scrap bronze was utilized in some cases then lead may have entered the mix. Analyses of Classical vessels showed very low lead values, with average tin values of about 8.9%[243]. Their handles contained substantially more lead. Mirrors were composed of two sections, the mirror disc and the caryatid figure handle. The mirror discs were usually composed of high-tin bronze that produced a lighter colour and improved the surface reflecting qualities once polished[244]. The presence of lead in a disc is not an indicator of deliberate addition in most cases, but comes from the copper

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[239] Evelyn B. Harrison, “Alkamenes’ Sculptures for the Hephaisteion: Part I, the Cult Statues”, *American Journal of Archaeology* 81 (2), 1977, pp. 139-145. The statues are estimated to have been more than twice life-size. It is thought that the anthemon itself weighed over 400 kg. (*Ibid*, p. 144). See also: Homer A. Thompson, R. E. Wycherley, “The Agora of Athens: The History, Shape and Uses of an Ancient City Center”, *The Athenian Agora*, Vol. 14, The Agora of Athens: The History, Shape and Uses of an Ancient City Center (1972), American School of Classical Studies at Athens, pp. 145-6.

[240] Harrison 1977, p. 144.

[241] Harrison 1977, p. 143.

[242] Treister 1996, p. 156. It should be mentioned here that the figure of 8.5% is an average for 86 objects. (Chapter 3 of this paper discusses alloy types of statuettes in more detail and includes their provenance.)

[243] Craddock 1977, p. 106-7.

[244] Lenore O. Keene Congdon, “Metallic Analyses of Three Greek Caryatid Mirrors”, *American Journal of Archaeology* 71 (2), 1967, p. 149. Analyses of mirrors by Craddock showed tin levels from 5.4 to 12.3%. See: Craddock 1977, p. 107.

and tin ores which contained some percentage of lead[245]. However the decorative caryatids of mirrors often contained substantial additions of lead because they functioned as mirror supports, so it stands to reason that lead would have been a common alloy component. Analyses of Etruscan mirrors from the 4th to the 3rd centuries showed even higher tin percentages than for Greek mirrors, between 12.54 to 15.39%, with only traces of lead[246].

During the early Hellenistic Period, the alloy compositions that were used for vessels and large bronze statuary were generally similar to those used in the Archaic and Classical Periods. Starting in the mid-2nd century, preferences in the types of materials that were used for the manufacture of statuary changed, and marble was used more often than bronze for statuary[247]. There are also clear alterations in the alloy compositions that were used for certain types of bronzes. In particular, the use of leaded bronze became much more prevalent than in the previous periods. Mirrors contained more lead on average, and the reason may have been the use of an ancient technique called tinning which was used to "re-surface" the mirror discs[248], and thus the addition of lead would not have been a factor in the reduction of mirror reflectiveness. The metallic composition of coinage also changed dramatically in the Hellenistic period. Classical and early Hellenistic bronze coins averaged about 10% tin with less than 2% lead. During the 2nd quarter of the 2nd century there was an interruption in tin supplies reaching the eastern Mediterranean, and this is reflected in the metal composition of coins[249]. By the second half of the 2nd century, lead proportions had reached 26% with less than 6% tin.

Analyses of bronze statuettes shows that many were highly leaded. Public dedications of statues were replaced by private ones in the Hellenistic period; portraits and

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[245] Craddock 1977, p. 107. Analyses of three mirrors from Camirus dated to the 5th century show a lead content from 3 – 8% . The lead may have been added to save on tin, but it would have reduced the reflecting properties of the alloy and made polishing much more difficult.

[246] Carlo Panseri, Massimo Leoni, "The Manufacturing Techniques of Etruscan Mirrors", *Studies in Conservation* 3 (2), 1957, pp. 51, 54.

[247] Treister 1996, p. 327.

[248] Panseri and Leoni 1957, p. 58. The mirror disc was heated and tin was melted directly onto the surface. The tin diffused into the bronze and produced a white-silvery colour with a very hard surface (speculum). This technique was found in objects from many areas, and its use may date back to 2000 B.C. See: Craddock 1984, p. 231.

[249] Treister 1996, p. 358; Caley 1939, p. 124.

decorative sculpture in parks and palaces was common[250]. Statuettes became popular again during the Late Hellenistic period, but most were now commissioned by the wealthy as decorations for their residences. Their function became more decorative rather than votive, although evidence of their placement in sanctuaries has been noted in some areas[251]. The size of these figures increased as well, and they were usually copies of well-known statuary that had been produced by prominent ateliers such as those of Lysippos and Polyclitus.

Specialization in the various fields of metal-working had started in the Classical Period, but it was typical of the Hellenistic Period, as was the formation of guilds and associations. More advanced developments in the techniques of casting bronze sculptures required the construction of casting pits whose interior walls were tiled, rather than the typical sand pits, and these were built by professionals who specialized in the area of furnace design and construction[252]. Contracts and production of items such as bronze statuary were divided between specialists in wax modelling, casting, finishing, and final installation who often operated out of different centres, although these workshops were usually not distant from each other[253]. Roman power and its influence on economics in the Mediterranean was on the ascendancy, and Roman clients created a high demand for various products from bronze utensils to sculptures. This burgeoning market meant that Greek workshops could concentrate on servicing particular market sectors, and it is possible that a rudimentary form of assembly-line production existed in Greece to fabricate as many reproductions as were required. The technique of indirect casting was developed to facilitate the serial casting of identical metal articles, whether they were vessels, statues or busts[254].

The new city building programs that had been initiated by Alexander the Great, and which continued into the Hellenistic period, not only contributed to employment opportunities for itinerant craftsmen as well as metalworking establishments, they also placed an increasingly heavy demand on all types of utilitarian and precious metals[255].

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[250] Treister 1996, p. 327.

[251] Treister 1996, p. 327-8. A bronze figure of a strategist dated to the early 3rd century was found at Dodona.

[252] Treister 1996, p. 329. Two similar casting pits that were located in the workshop of Eubulos were constructed by a professional mason.

[253] Treister 1996, p. 328-9.

[254] Treister 1996, p. 330-1. This technique was common by the late 2nd century.

[255] Treister 1996, pp. 331-2.

The proliferation of temples and the taste for statuary by elite clients as an expression of wealth also contributed to the heavy demand for bronzes of all types, and the procurement of sufficient tin to satisfy this demand may have been a problem.

In summary, bronze alloy compositions changed noticeably during the Hellenistic Period, and the major contributing factor was the low price of lead compared with tin[256]. Tin continued to be available through increased mining activities in regions such as Iberia, southern England, Brittany, and Tuscany[257], but it remained a relatively expensive metal compared with lead. As a result, lead became an increasingly common substitute for tin in bronze, and tin percentages in the alloy gradually decreased[258]. The interruptions in supplies of crucial metals such as tin due to wars, depletions of metal deposits, and political changes that influenced the control of shipping routes all contributed to increased usage of leaded bronze[259]. However temporary some of these influences were on the availability of metal supplies in general, the increases in silver mining activities produced copious quantities of lead for distribution on international markets. Excavations at numerous shipwrecks dated to the Hellenistic period have found evidence that lead ingots and bars were a common part of mixed cargoes on vessels[260].

2.6 Etruscan Metallurgy and the Use of Leaded Bronze

The descriptions of various alloy compositions have thus far concentrated on their development in Greece. Another region that cannot be ignored in any discussion of the use of the leaded bronze alloy is that of Etruria[261]. It has already been mentioned that Greek and Etruscan metalworkers used bronze alloy compositions with similar tin percentages, but alloys used for certain classes of Etruscan objects were noticeably different.

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[256] Treister 1996, pp. 341-2. Cheap lead affected alloy recipes in a permanent manner. Metal prices for the Hellenistic period are not known, but during the Classical Period the price of tin was 70-140 times higher than for lead. In the 1st century A.D., tin cost eleven times more than lead.

[257] Tylecote 1987, pp. 36-9.

[258] Treister 1996, p. 341.

[259] Treister 1996, p. 341-2.

[260] Treister 1996, pp. 347-54

[261] An in-depth analysis of Etruscan metallurgy is outside the scope of this paper, but a number of points concerning Etruscan metal working techniques and alloying will be discussed.

The Etruscans used leaded bronze for casting statuettes and figurines in more numbers, and the lead percentages are also higher than for comparable Greek figures over time.

2.6.1 Metallurgy and Bronze Working

The Etruscan civilization had its beginnings in the 9th – 8th centuries[262]. The peak occurred in the 6th century, and the Etruscans were later absorbed by the Roman pan-Italic civilization. The rich and varied grave goods that were found in the tomb excavations in some of their principal cities, such as Veii, Cerveteri, Populonia, Vulci, Volterra and Vetulonia, provided evidence of a prosperous society that not only produced high-quality artisanal goods of all types for both local consumption and export, but also imported luxury goods of worked gold, silver and ivory for the Etruscan elite[263]. Agriculture flourished in the volcanic soil, and forest expanses supplied wood and fuel that was vital for shipbuilding and metal-working activities[264]. These resources, particularly metals such as copper, silver and iron, attracted Phoenician traders who brought Greek, Near Eastern and Egyptian wares for exchange, and many bronze, silver and ivory objects found in large Etruscan tombs show a definite oriental influence[265].

The major metal deposits of Italy are found in the region of Tuscany where Etruria is located, and Tuscan ores such as copper, iron, silver, lead and zinc (gold is not present) were known and exploited during the Bronze Age[266]. Most of the deposits of metal ores are mixed together, thus one mine could produce iron along with zinc and tin. The Etruscans worked the rich mines in the Colline Metallifere (Metal Hills) behind Piombino near ancient Populonia, which produced all of these metals[267], and evidence of Etruscan metallurgy was found in the form of huge copper slag heaps in the region surrounding

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[262] David and Francesca R. Ridgway (eds.), *Italy Before the Romans - the Iron Age, Orientalizing and Etruscan Periods*, Academic Press Inc., London, 1979, pp. 55-6. Editorial commentary: "[…] the possessors of that material culture of the Italian Iron Age which has been conventionally termed "Villanovan" […] were simply Etruscans at their Iron Age stage." See also: Boardman 1980, p. 199.

[263] Mario Torelli, "II/History: Land and People", in: Larissa Bonfante (ed.), *Etruscan Life and Afterlife: a Handbook of Etruscan Studies*, Wayne State University Press, Detroit, 1986, p. 52.

[264] Vacano 1965, pp. 3-5. The Romans relied on Etruria for their grain reserves.

[265] K. R. Maxwell-Hyslop, "Urartian Bronzes in Etruscan Tombs", *Iraq* 18 (2), 1956, p. 150.

[266] Craddock 1984, pp. 213-4.

[267] Craddock 1984, pp. 212-4.

Piombino[268]. Mines located on La Tolfa, Mount Amiata, and on the island of Elba were also exploited[269]. Tin mines are found in the Campiglian mountain region of the Colline Metallifere. There are also many lead deposits in and around the Etrurian region. Lead was used alone or mixed with copper, and from the 6th century was also used as a soft solder[270]. Sardinia was rich in copper deposits, and Sardinian ox-hide copper ingots were used in trade with other regions as early as the 2nd millennium. Elba was known in antiquity for its extensive iron deposits.

Etruria may have had direct contact with Urartian or perhaps North Syrian traders. Two bronze female double-siren cauldron fixtures, one found in a tomb at Vetulonia and another mounted on a bronze cauldron in the Bernardini tomb, have triangular patterns engraved across the base of the neck that are a feature of native Urartian siren attachments[271]. Another example from Vetulonia is a bearded male siren figure wearing a curved helmet of the type worn by Assyrian warriors, a figure which was also found on North Syrian reliefs. A large cauldron made of hammered sheet bronze, with lion and griffin protomes mounted on a conical stand that was found in the Barberini tomb (Fig. 14), may have an Urartian origin[272]. There are definite similarities between the Barberini griffins and the ones from Delphi and Samos (Figures 15-17). Another bronze cauldron with six elongated griffins facing inwards came from the Bernardini tomb (Fig. 13).

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[268] Craddock 1984, p. 215. The slags contained from 0.67 – 1.2% copper.

[269] Adrian P. Harrison, Ilenia Cattani, Jean M. Turfa, "Metallurgy, environmental pollution and the decline of Etruscan civilization", *Environmental Science and Pollution Research* 17, 2010, p. 165.

[270] Craddock 1984, p. 219.

[271] Maxwell-Hyslop 1956, pp. 151 (Plate XXVI), 165. The tombs were dated to the first half of the 7th century. The earliest Near Eastern exports that were found in Greece date to the 8th century, and if they also began appearing in Etruria at about the same time or even before, then these objects may be older than the tombs themselves. (*Ibid*, p. 162-3)

[272] Maxwell-Hyslop 1956, p. 152. At the time of publication, the author suggested that it was Urartian, but as noted in Section 2.3 concerning the origin of the griffin protome, more recent research has produced the general opinion that the griffin is probably not of Urartian origin but North Syrian, or perhaps a Greek transfer into bronze of a North Syrian motif. Adaptations to the original design that are seen on numerous Orientalizing Period cauldrons were probably produced in Greece. See: Coldstream 1979, p. 365. This piece may have been produced by two separate workshops. The bronze griffin protomes may have been made on Samos. (*Ibid*, p. 163) Metal analysis of the griffins could establish their place of origin. The alloy compositions of Near Eastern, Greek and Samian cauldron attachments are discussed in Section 3.1.1.

Fig. 13 – Bronze cauldron and stand from the Bernardini tomb, Palestrina. Total height 130 cm., stand 90 cm.
(Fig. V,1, p. 160, Ridgway 1979)

Fig. 14 – Bronze cauldron and stand from the Barberini tomb. Height of stand 90 cm.
(Fig. V,1, p. 160, Ridgway 1979)

Fig. 15 – Bronze griffin from Barberini cauldron.
Height 27 cm.
(Tafel 3, Nr. 8, Jantzen 1955)

Fig. 16 – Delphi bronze griffin.
Height 31 cm.
(Tafel 2,3, Nr. 7, Jantzen 1955)

Fig. 17 – Bronze griffin from Samos. Height 11 cm.
(Tafel 11, Nr. 33, Jantzen 1955)

Similar types of stands, between three and four feet high, were found in the Bernardini and Regolini Galassi tombs. The large conical support may be of Assyrian origin because this type of cauldron stand is usually found on reliefs from areas such as Karatepe in S. E. Turkey, and in Palestine from the 7th century. The Etruscans produced smaller terracotta imitations in one piece of this type of stand supporting a cauldron. The Bernardini tomb also produced a bronze cauldron and a tripod stand with bulls' feet comparable to what was found at Altin Tepe in Urartu[273]. The objects such as the Bernardini cauldron and tripod were undoubtedly imported into Etruria, because similar examples of earlier Etruscan manufacture have either not been found or were not produced. In the Orientalizing Period, Near Eastern bronze work and cauldrons were entering Etruria, but it is not known whether most of these objects were brought in by Phoenician traders, or whether they were imported by Euboean colonists from Greece, or perhaps obtained directly from North Syrian contacts. These imports and their artistic motifs had a direct impact on local artisanal production which reproduced the oriental styles[274].

Etruscan metallurgy and stylistics were unique in many respects, even though various motifs and techniques were adapted from the objects imported from other regions, particularly from Greece. A type of bronze cauldron assembly, or bowl, with up to six thin supporting legs, was found in numerous tombs in Etruria dated to the 7th century, and may be peculiar to the region (Fig. 18)[275]. The legs were decorated either solely with horses, or with horse and helmeted rider figures shaped in an elongated, or Wiry Geometric style[276]. The cauldron was made from hammered sheet bronze. These are small assemblies, some no more than 11 cm high. Most of these objects were found at Vetulonia, with a few other examples located at Veii and Tarquinia.

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[273] Maxwell-Hyslop 1956, p. 153. For a more complete description of the tripod stand found at Altin Tepe, see: R. D. Barnett, N. Gökce, "The Find of Urartian Bronzes at Altin Tepe, Near Erzincan", *Anatolian Studies* 3, 1953, pp. 121-9.

[274] Coldtream 1979, p. 233.

[275] Hugh Hencken, "Horse Tripods of Etruria", *American Journal of Archaeology* 61 (1), 1957, pp. 1-4. The author does not indicate if similar objects were found elsewhere, thus they may be unique to Etruria.

[276] Emeline Hill Richardson, "The Recurrent Geometric in the Sculpture of Central Italy, and its Bearing on the Problem of the Origin of the Etruscans", *Memoirs of the American Academy in Rome* 27, 1962, pp. 166-7, 181. The Wiry Geometric Style was developed in Italy from the influence of the Greek Geometric style, and it continued to be popular in Italy as a style for figurines into later periods.

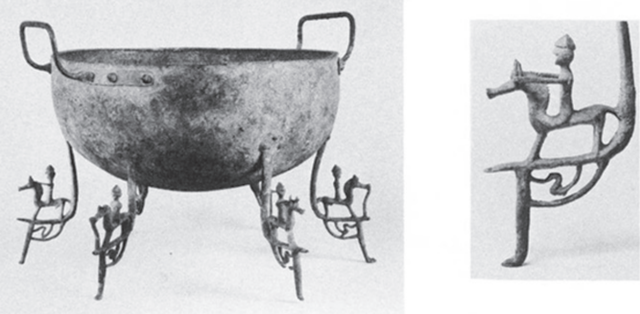

Fig. 18 – Bronze cauldron with tripod in the shape of a horse-and-rider figure. Height 23 cm. The metal is thicker on the rim. As in a similar assembly from Vetulonia, the legs are attached to the cauldron with three rivets.
(Plate 2, Fig. 7, p. 2-3. Hencken 1957)

Figs. 19 and 20 – Omphalos bowl from Orvieto, one handle, and two of six lions. Bowl diameter 37 cm, height 5.5 cm. Handle is 6.6 cm long. (Plate 110, Fig. 6, 7, and 8, p. 337. Cook 1968)

A type of bronze vessel called an omphalos bowl had a widespread distribution, and was found in Gordion, in Anatolia, Cyprus and on the Greek mainland. This is a wide shallow bowl with a round upturned hollow "navel" in the centre, with perhaps small decorations on the rim as well as two swinging or fixed handles (Figs. 19-20). An omphalos is usually found on small phialai, a shallow drinking cup resembling a saucer, where the finger tip is inserted into the hollow omphalos from below, with the thumb gripping the rim[277]. Variations on the basic design were also found in a number of Etruscan tombs dating from the 6th century[278]. Some of the Etruscan variations incorporated lion figures or rams that were attached to the in-turned rim, and with four instead of two swinging handles. The Etruscan omphalos bowls showed evidence that the handle supports were soldered to the bowl, probably with lead solder[279]. Solder present on the rims of some of

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[277] Brian F. Cook, "A Class of Etruscan Bronze Omphalos-Bowls", *American Journal of Archaeology* 72 (4), 1968, p. 343.

[278] Cook 1968, p. 340-1.

[279] Cook 1968, pp. 337-8. An omphalos bowl in the Metropolitan Museum of Art is 36.9 cm wide, 7 cm high, with an omphalos diameter of 8.7 cm. Rim is 1.2 cm wide with solder traces indicating that lion figures

these vessels indicates where the crouching lion or ram figures would have been attached. But the Etruscan bowls are too wide for the omphalos to serve a practical purpose, and the position of the figures on the rim would have made the bowls unsuitable for libation or drinking. The four handles would probably have been used to hang the assemblies. The purpose of the Etruscan bowls is not known, but it is presumed that they served as either incense burners or charcoal braziers. The lions on the rims of these bronze vessels can be explained by the Etruscan tendency to embellish vessel rims with figurines and statuettes, already quite common by the 7th century, and the same decorative style is also found on Etruscan pottery and bucchero ware[280].

2.6.2 Alloy Compositions of Etruscan Bronzes

Studies of Bronze and Early Iron Age metalwork from Italy and Sicily have provided some information on the early development of alloy compositions of various bronze objects[281]. Prior to the Early Iron Age, lead content was present in only trace amounts in the majority of bronzes, with very few containing more than 1% lead: out of 48 Bronze Age objects that were examined, two flanged axes from Umbria and Lombardy both contained more than 4% lead. Axes were usually cast in bivalve moulds, but it cannot be determined if the lead in these two axes was added to improve fluidity, since the remaining axes, including other axes from the same areas as the two just mentioned, contained very little lead. The addition of 4% lead would also not have affected the weight of the axe to any extent. Analyses of Early Iron Age objects revealed a definite increase in the number that contained more than 2% lead (seven out of 32 objects). This may be evidence that deliberate lead addition was practised to improve fluidity, but a pattern of usage is not

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were originally attached to it. A bowl at the Museo Civico in Orvieto is 37 cm wide, 5.5 cm high, with two handles each 6.6 cm wide (Fig. 19). Six detached lions were found with the bowl. No information is given as to whether the lion figures were solid or hollow cast, or on the alloy compositions of the handles and the figures.

[280] Cook 1968, p. 344.

[281] Duncan Hook, “The Composition and Technology of Selected Bronze Age and Early Iron Age Copper Alloy Artefacts from Italy”, in: Josephine Turquet, Liesl Schapker (eds.), *Prehistoric Metal Artefacts from Italy (3500 - 720 BC) in the British Museum*, British Museum Research Publication Number 159, The British Museum Press, London, 2007, pp. 308-323. Most of the objects that were examined were knives, swords, axes, and daggers. A small number of fibulae were also analyzed, as well as one figurine.

obvious since too few objects were analyzed. An interesting exception is a solid cast of two crouching figures, dated to 900 – 780 (Geometric), which contained 24.3% lead and 8.9% tin[282]. The findspot for this piece is not known (Walters 1899, no. 339), but the style is similar to animal and human figurines that were found in central and southern Italy from the Geometric-Orientalizing periods[283].

There were also variations in metallurgical techniques and alloys between various regions of Italy. In a study of bronzes from the 8th to the 6th centuries[284], it was found that Etruscan and Sardinian bronzes contained similar tin percentages, but Sardinian bronzes contained almost no lead (less than 1%). Hammered bronze work contained lead in only trace amounts for both groups. Such a low lead content is due to lead being present in the copper or tin ore. A metallographic and technical study of Italian bronzes conducted at the Hermitage Museum[285] showed that Umbrian and Sabellian cast statuettes contained less lead than Etruscan statuettes, and that it was used less often. The statuettes of the two former groups also contained higher percentages of tin, in some cases as high as 16%, whereas the Etruscan statuettes had 4 – 5% and 9 – 11%. It was also noticed that the manufacturing and finishing details on the Etruscan and Umbrian statuettes were more carefully detailed as compared with the Sabellian ones. The larger Etruscan bronzes (over 20 cm high) demonstrated superior casting quality with finer finish, polishing and more elaborate details than those from the two other groups, indicating that the techniques utilized by Etruscan bronzeworkers were more advanced[286].

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[282] Hook 2007, Table 1: Analyses of Italian Bronze Age/Iron Age metalwork.

[283] Anna Maria Bietti Sestieri, Ellen Macnamara, *Prehistoric Metal Artefacts from Italy (3500 - 720 BC) in the British Museum*, British Museum Research Publication Number 159, The British Museum Press, London, 2007, p. 26.

[284] Craddock 1984, pp. 221-2.

[285] Nadezda Gulyaeva, “The Composition of Some Bronze Statuettes in the Hermitage Museum”, *Materials and Manufacturing Processes* 24 (9), 2009, pp. 967-971. The author mentions that the analysis technique was a surface method and thus not very precise, but that it was nevertheless useful for comparison purposes. She indicates that the high tin percentages of some of the Umbrian and Sabellian bronzes “might be due to segregation or to selective corrosion of the surface with an enrichment of tin.” (*Ibid*, p. 969) It should also be mentioned that the objects from the Hermitage Museum discussed here are of undocumented origin, and thus precise dates cannot be assigned to them. The categories and probable places of manufacture of the objects were determined through stylistic comparisons with other bronzes. (*Ibid*, p. 967)

[286] Gulyaeva 2009, p. 969.

For Archaic Etruscan bronzes (7th to 6th centuries)[287], statuettes and cast sections of vessels were of leaded bronze, but vessels of sheet metalwork contained trace amounts of lead. The vessels were of tin bronze with an average tin content of 7.9%. The same alloy types were used during the 5th century. Cast metalwork was made of leaded bronze, but more lead was now present in larger castings. Statuettes contained an average tin content of 9.8%, and lead is also present in quantities, but the amounts vary from one object to another, indicating that there was no set alloy formula. This trend is also seen in the earlier statuettes. Mirrors contained on average 11% tin with almost no lead, a technical fact of the production of this type of bronze object, since the presence of lead would dull the surface reflectivity, and this is also an indicator that the Etruscans used a specific alloy consisting of high tin and no lead for mirrors[288].

Late Etruscan cast bronze work (4th – 2nd centuries) contained substantially more lead than in previous periods but the amounts are still randomly distributed, with some statuettes averaging over 20%[289]. Their tin content averaged about 7.9%, a decrease of almost 20% compared with the 5th century. A significant change in alloy compositions is noticed with mirrors that now contained more lead, some samples containing over 20%. The substantially higher lead is some mirrors may have been due to the use of a technique called "tinning"[290]. Hammered vessels contained 8.7% tin, and this tin level was found particularly in large vessels that would have been used in ceremonies or made for the elite; smaller vessels such as jugs and oinochoe contained much lower levels of tin[291].

Although not an Etruscan site, the excavations conducted at the site of Roccagloriosa, which was occupied by the Lucanians from the 5th century to the early 3rd century, provided evidence of copper smelting and bronze production as well as some

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[287] Craddock 1984, pp. 223-6.
[288] Craddock 1984, p. 227.
[289] Craddock 1984, p. 228. Greek statuettes at this time also contain more lead than in previous periods.
[290] Panseri and Leoni 1957, p. 58. This is discussed in Section 2.5. Craddock indicates that the presence of some lead in mirrors, which is seen in Greece as well at this time, may have been due to a lower alloy standard. The analyses showed that nine out of 68 Etruscan mirrors had more than 1% lead, whereas previous periods show less than 1% or only traces of lead See: Craddock 1984, pp. 230-1..
[291] Craddock 1984, p. 231.

general information on the alloy compositions[292]. Metal analyses of bronze melting residues, such as spatter droplets, artifact fragments and pieces of copper slag revealed lead concentrations from traces to greater than 10%, although half of the samples contained less than 2% lead. Twenty-one bronze samples ranged from 2 – 10% lead, and eleven contained more than 10% lead. Tin concentrations in half of the samples were also less than 2%[293]. Due to the fact that complete artifacts were not found at this site, it could not be ascertained whether the fragments came from statuettes, weapons, or pieces of sheet metal, each of which would have been made from different alloy compositions[294]. Two fragments that appeared to be nailheads showed a 11.5 – 16.0% lead content. It is thought that the metal found at this site may have been part of a stockpile or foundry hoard that was used for remelting operations[295]. The bronze may have been produced by remelting scrap bronze (a common practice in antiquity and today), by the use of imported copper and tin ingots, by using copper ingots and cassiterite (tin ore), or some combination of one or more of these three techniques; the production of bronze could have been carried out in crucibles or in small furnaces, with perhaps the same production area being used repeatedly[296]. As at Roccagloriosa, the bronze industry was active in many regions of Italy, and similar types of bronze-making operations were operating in Capua, in Calabria and Tuscany, as well as in other areas[297]. However inconclusive the results were as to the types of melting operations that were conducted at this site, the analyses proved that leaded bronze was produced at this site.

What is quite noticeable in the Etruscan cast bronzes from the 8th to the 2nd centuries, particularly the statuettes, is that lead percentages rose steadily, but tin percentages did not decrease substantially as a result of the lead addition until the Hellenistic

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[292] M. L. Wayman, M. Gualtieri, R. A. Konzuk, “Bronze Metallurgy at Roccagloriosa”, in: R. M. Farquhar, R. G. V. Hancock, L. A. Pavlish (eds.), *Proceedings of the 26th International Archaeometry Symposium*, The Archaeometry Laboratory, University of Toronto, Toronto, 1988, pp. 128-9, and Figures 186, 187. Seventy-seven samples were analyzed.

[293] M. Wayman, “Bronze-Working”, in: M. Gualtieri (ed.), *Fourth Century B.C. Magna Graecia: A Case Study*, Paul Åströms förlag, Jonsered (Sweden), 1993, p. 313. The author says that, due to the nature of the analysis, the analytical results are not completely accurate and therefore the compositions should be taken as general indications of alloy types that were used at Roccagloriosa.

[294] Wayman 1993, pp. 313-4.

[295] Wayman 1993, pp. 308-9.

[296] Wayman 1993, p. 309.

[297] Wayman 1993, p. 309.

Period, indicating that lead was not used as a substitute for tin until then. As lead percentages increased, copper amounts of course decreased in consequence[298]. The use of leaded bronze, with higher than optimal amounts of lead (greater than 2 – 3%), is considered to be characteristic of Etruscan cast objects such as vessel handles, coins and statuettes[299]. From these analyses, it can be concluded that bronzeworkers in Italy, as elsewhere in the Mediterranean, chose alloy compositions suited for specific purposes, such as mirrors and hammered bronze work, and that the techniques of bronze work were transferred between regions. Where the difference in alloy compositions is most noticeable lies in whether leaded bronze was more commonly used for cast objects in some areas than in others. Leaded bronze was definitely used in the production of Etruscan statuettes, but the alloy compositions show a random distribution in lead percentages, evidence that a definable alloy standard for leaded bronze did not exist.

The Etruscan propensity for leaded bronze in cast statuettes may be explained by close access to the tin and lead sources of Tuscany. Etruscan statuettes are composed of numerous fine details, and the use of this alloy may indicate that the bronzeworkers had knowledge of its improved casting qualities. On the other hand, the use of higher than the optimal amount of lead (2 – 3%) may simply have been part of normal metallurgical practices for cast objects in Etruria, that lead was added as part of the melting routine, and not due to any influence of foreign bronze alloy compositions, although this cannot be ruled out altogether since Near Eastern bronzes were being imported into Etruria in the 8th century. The higher amounts added to the later period statuettes and other cast objects could be related to the aesthetic appeal of the “lead sweat” that altered the surface colour of the bronze, or more likely as a partial substitute for the amounts of tin in the alloy.

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[298] Unfortunately, metal analyses of earlier Villanovan cast bronze work dating from the Protogeometric and Geometric Periods were not available for comparison. The tables of analyses in Paul Craddock’s article (Craddock 1984) do not list objects earlier than the 7th century, but if the Etruscans were already using leaded bronze by this time, then it stands to reason that the Villanovans may also have used it for casting objects. This is a tentative conclusion at best, considering that the Umbrian and Sabellian bronzes at the Hermitage Museum contained much less lead than their Etruscan counterparts.

[299] Craddock 1984, p. 237.

2.6.3 Etruria and Magna Graecia

Trade between Greece and Etruria expanded during the Greek Geometric Period, concentrating to a significant extent upon acquisition of Etrurian metal ores and possibly agricultural produce in exchange for goods. The motifs on Greek imports into Etruria had a direct influence on local Etrurian artistic designs, but it appears that a reciprocal influence between Etruria and Greece did not exist, in spite of commercial exchange between the two regions[300]. The establishment of the first Greek colonies at Cumae and Pithecusae in the 8th century introduced large quantities of Greek-style pottery, to be soon followed by Near Eastern objects. Greek colonization subsequently expanded into southern Italy and Sicily, and these regions where their cities were established would later come under the general term of Magna Graecia (Great Greece). Almost all Greek colonies were located on the coasts of Italy and Sicily, thus Greek colonists retained the advantages of maritime trade[301].

Euboean traders from Eretria and Chalcis had been conducting commercial relations with Etrurian and Campanian natives in Italy long before Greek colonies were established in these areas, and of course access to the rich metal ores was of particular interest[302]. The first western Greek colony was founded in Campania (central Italy) by the Euboeans at Pithecusae (present-day Ischia) just off the coast of Campania, and settlement at Cumae on the mainland opposite followed soon after by the Chalcidians (ca. 770 – 735)[303]. Metalworking areas for bronze and lead, tools, and quantities of iron bloom and slag excavated at Pithecusae indicate that the processing of raw metals (iron ore from Elba) and the manufacture of metal objects were the primary activities at this site[304]. The Euboeans also founded colonies in eastern Sicily (Naxos, Leontini and Catane), and Rhegium and Mylai in the Strait of Messina. Messina was founded by settlers from Cumae. Syracuse was settled by the Corinthians. The Achaeans were active in southern Italy and founded

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[300] Coldstream 1979, p. 242.
[301] Coldstream 1979, p. 223.
[302] Coldstream 1979, p. 221; Treister 1996, p. 164-5; Boardman 1980, p. 162.
[303] Coldstream 1979, p. 221; Boardman 1980, p. 163. Euboean pottery was found here, and the style is also found in early Greek vases made for export to Etruria.
[304] Jeffery Klein, "A Greek Metalworking Quarter: Eighth-Century Excavations at Ischia", *Expedition* 14 (2), 1972, p. 36; Coldstream 1979, p. 226.

Sybaris, Croton and Posidonia. Spartans and others settled in Tarentum, Siris and Locri in south Italy[305]. Many of these settlements were enabled through the displacement of native populations, thus colonizing ventures were often anything but peaceful[306]. The Etruscans retained control of metal resources in northern Etruria, although Greeks set up trading posts in southern Etruria close to towns such as Tarquinii to trade for the metal coming from the northern metal-rich regions[307].

Greek pottery, both plain and richly decorated, as well as Near Eastern artisanal production in precious metals was imported in large quantities by Greeks living in the western colonies. Greek craftsmen operated workshops reproducing pottery styles and designs, and the native inhabitants imitated and adapted many of the styles for their own reproductions. The merging of imported Corinthian pottery styles and artistic designs with local variations produced the Italo-Corinthian pottery style in the 7th century[308]. Etruscan pottery and other objects were found in Campanian cities, indicating that native production gained popularity to a certain degree[309]. Etruscan bucchero ware dated prior to 600 reached Perachora, Chios, and also the Heraion sanctuary on Samos. From 600 – 550 there was increased trade in Laconian painted wares, and Etruscan goods were imported into Sparta[310]. One Etruscan object in particular that had a widespread distribution during the 6th century in most Greek cities, both on the mainland and in Magna Graecia, was the Etruscan bucchero vase (tall, two-handled cup). The form may have been the basis for the kantharos design by Athenian and Boeotian craftsmen[311].

Bronzes produced by Etruscan metalworkers have been found in sites on mainland Greece as well as in Magna Graecia, although not in quantities comparable with bucchero ware[312]. Etruscan candelabra and bronze utensils were exported to Attica in the later

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[305] Boardman 1980, p. 163-5. Boardman gives a list of colonies founded by Greeks in Italy.
[306] Boardman 1980, p. 189.
[307] Coldstream 1979, p. 232.
[308] Coldstream 1979, p. 233.
[309] Boardman 1980, p. 192.
[310] Jean Macintosh Turfa, "III/International Contacts", in: Larissa Bonfante (ed.), *Etruscan Life and Afterlife: a Handbook of Etruscan Studies*, Wayne State University Press, Detroit, 1986, p. 70.
[311] Turfa 1986, p. 73.
[312] Boardman 1980. p. 197, 208. The author indicates that the Etruscans developed several types of fibulae that were based on Greek models, but that few were imported to mainland Greece. A bronze tripod from

6th – 5th centuries. The city of Vulci exported many tripods, quality utensils, and numerous bronze spouted pitchers that were very popular in Greece. These pitchers incorporated an appliqué decoration that perhaps was originally developed in the Peloponnesian region[313].

Greek commercial and shipping interests were apparently in direct conflict with Etruscan economic interests. Etruscan political relations with Greece and colonists in Magna Graecia started deteriorating from 535 when Phocaean colonists were expelled from Corsica by a combined Etruscan and Carthaginian fleet[314]. Etruscan interests conflicted with those of Greek colonists in Magna Graecia and led to the battle of Cumae in 474. The repercussions established Greek naval supremacy in the Tyrrhenian Sea and diminished Etruscan commerce. In turn, Greek vessels that were based in Syracuse conducted recurrent raids on Etrurian coastal habitations. In spite of these conflicts, commercial relations between Greek and Etruscan regions continued, and although there was a decline in the 5th century, Attic red-figure vases were entering Etruria in large quantities via a northern route. From the 4th century and into the Hellenistic Period, Etruscan trade and shipping with Greece and Magna Graecia had diminished to a large degree[315].

It appears that Greek pottery styles and artistic motifs were readily assimilated into the local artisanal work of Etruria. Etruscan originals such as bucchero ware attained great popularity and were exported to Greece, and although some types of Etruscan bronze work did make their way into the Greek marketplace as well as to sanctuaries, by and large the influence on Greek metalwork appears to have been very minimal. The reason for this may be that the Greeks already possessed a successful bronze work industry of their own, and thus were unlikely to have adopted alloy compositions that were different from those with which they were already familiar. It could also be assumed that the Greeks had a preference for the golden colour of tin-bronze that was used for statues in Greece, and so were unlikely to adopt a leaded bronze alloy that produced a silvery tint.

Vulci dated to about 500 was found in the Athens Acropolis. Some Etruscan objects dating to the 4th century were also found at Olympia and Dodona. See also: Turfa 1986, p. 73, 81.

[313] Turfa 1986, p. 73.

[314] Turfa 1986, p. 74.

[315] Turfa 1986, p. 83.

Chapter 3 – Analysis of Artifacts

3.1 Alloy Composition of Bronze Cauldron Protomes, Siren and Bullhead Attachments, and Vessel Handles

It has been mentioned in this paper that the addition of lead to copper and tin bronze was deliberate in many cases because it facilitated casting. The bronze casters thus had knowledge of the appropriate composition of an alloy that was to be used according to the type of object they were producing. Is proof of this knowledge demonstrated in the compositional analyses of griffin protomes, siren and bullhead attachments, as well as handles? Was the use of leaded bronze in Greece during the Orientalizing Period influenced by Near Eastern metallurgical techniques? Pictures of the figure numbers that are referred to in Chapter 3 are in the Figures annex.

3.1.1 Siren, Bullhead and Griffin Protome Attachments

There are noticeable differences in the alloy compositions that were used in the manufacture of attachments as compared with vessels and cauldrons. Cauldrons and vessels almost invariably contained little or no lead because they were usually raised out of one or more pieces of sheet metal. The repetitive hammering would have torn the thin sheet metal if it contained appreciable amounts of lead. The generally low lead content of vessels found at numerous sites in Greece, the Near East and Etruria has been noted in various studies[316]. Attachments, on the other hand, were either solid or hollow cast, or sometimes hammered from sheet metal, thus their alloy compositions often differed from those of vessels. Figure 34 illustrates how protomes and sirens were typically attached to cauldrons.

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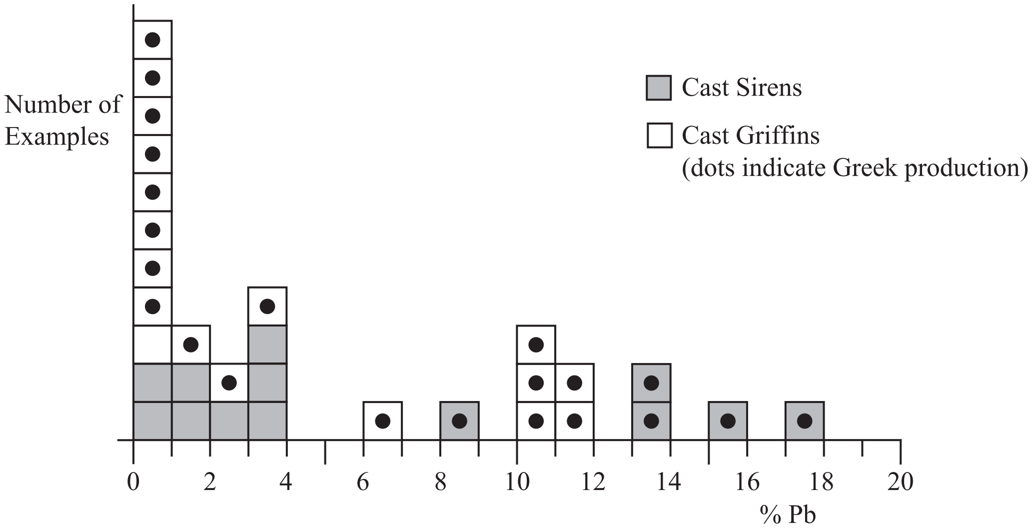
[316] Partial list: Craddock 1976 and 1977; Craddock and Gumlia-Mair 1988; Mattusch 1988; Rolley 1983.

Table 1 presents the metal analyses of a number of siren and protome attachments from Delphi, Olympia and Samos. Graph 1 below shows their lead percentages[317].



Graph 1 Lead percentages of cast sirens and griffins from Delphi, Olympia and Samos compiled in Table 1 in the Catalog

In a metallographic study[318] that was performed on a number of Oriental (Near Eastern) imports and locally manufactured Greek Orientalizing objects found at the Delphi sanctuary, such as siren and griffin protomes as well as attachments in the form of a bull, it was found that the Oriental sirens and griffins[319] contained on average more than 10% tin, but that lead quantities were low, generally from 0.25 – 1.55% (GS5 - 6). In contrast, the later Orientalizing sirens and griffins had higher lead contents ranging from 0.14 – 8.92%, with lower tin percentages averaging 7.6% (GS3, 4, and GS7, Fig. 28). One particular siren (GS8, Fig. 12) contained an unusually high value of 17.86% lead. The study also

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[317] Table 1 is a compilation of some of the metal analyses of bronze objects presented in studies by Varoufakis *et al* 1983 and Magou *et al* 1991. Although I discuss other objects that were analyzed in these studies, I have tabled only the sirens, griffins and bullheads for which dates and findspots are known. The place of origin of the Oriental imports is not mentioned in the papers. GS + number refers to Table 1 objects.

[318] Varoufakis *et al* 1983, pp. 131-2, Appendice I.

[319] Varoufakis *et al* 1983, p. 131, Appendice 1. The griffins listed under “Objets orientaux: chaudrons à protomes, supports” either have no catalogue number or are given an inventory number only, and therefore it was not possible to locate the findspots for these griffins. They are described as hammered griffins, thus the low lead amounts for these items is in keeping with the alloy composition used in hammered bronze work. The article also mentions that opinion is still divided as to the workshops that produced the Oriental sirens and griffins, namely between Urartu and North Syria. (*Ibid*, p. 122)

found that only three of the sixteen Near Eastern imports which were analyzed had much higher additions of lead. These specific cast items were the category of bullhead cauldron attachments, where the alloy compositions ranged from 1.3 / 2.86 / 22.96% lead, with tin from 7.88 / 4.61 / 7.25% respectively. The bullheads were recovered at Delphi, but their production location in the Near East is unknown. One bullhead that contained 22.96% lead may be of Phrygian origin[320]. The bull was a very common figural type found in Urartian art, so it is not surprising that bullhead protome attachments were more common in Urartu and Phrygia than in Greece, but some are also found on early Greek tripod cauldron assemblies[321]. Metal analysis of bullheads that were cast in local Greek workshops was not available, therefore alloy comparisons with the Near Eastern bullheads was not possible. In a contrasting study of Urartian bronzes[322], two cauldron attachments in the form of a bullhead both contained less than 1% lead, and between 6.8 and 8.6% tin.

Two other metallographic studies[323] of a number of Oriental and Orientalizing sirens and protomes that were found at Samos, Delphi and Olympia showed lead content in the bronze alloy of the Oriental items. Considering the Oriental cast sirens from Olympia (GS9 to 15)[324], lead content ranged from 0.79 – 3.41% (average of 2.5%), with one exception (GS10, Fig. 21) exhibiting a high 13.3% Pb value. Tin values ranged from 6.11 – 14.49% (average 9.8%), with two exceptions showing near trace amounts (GS9 and G13, Fig. 23) with high values of iron. The lead content of the Orientalizing sirens (GS16, Fig. 26, and GS17, Fig. 27) was much higher, from 13.2 – 15.8%, with tin averaging 10%. The Orientalizing cast griffins from Olympia (GS19 to 24)[325] contained markedly lower

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[320] Éléni Magou, Michel Pernot, Claude Rolley, "Bronzes orientaux et orientalisants: Analyses complémentaires", *Bulletin de correspondance hellénique* 115 (2), 1991, p. 566.

[321] Rolley 1983, p. 52-3. See also: Mitten 1965, p. 139 for Near Eastern bull protomes, and Barnett 1950 for numerous examples of the bull figure in Urartian art.

[322] M. J. Hughes, J. E. Curtis, E. T. Hall, "Analyses of Some Urartian Bronzes", *Anatolian Studies* 31, 1981, p. 142.

[323] Magou *et al* 1991, pp. 561-577. There is no category of cast Oriental griffins in this study. Magou included some of the Delphi analyses from the earlier paper by Varoufakis *et al* 1983. Also included in Table 1 are analyses of objects that were appended to Craddock's study of Etruscan bronze in *Studi etruschi* 1984, pp. 265-6. The samples were taken by Arthur Steinberg, the analytical procedures are described in Craddock 1984, p. 220.

[324] GS11, Fig. 22; GS12, Fig. 11; GS14, Fig. 24; GS15, Fig. 25.

[325] GS19, Fig. 29; GS20, Fig. 30; GS21, Fig. 31; GS22, Fig. 32; GS23, Fig. 33.

lead amounts than the sirens, ranging from trace level to 6.61% (average 1.98%), with tin levels from 6.03 – 10.97% (average 8.7%).

From the same studies (and Graph 1), many of the Orientalizing cast griffins from the Heraion sanctuary at Samos showed consistently higher lead values than for those from Delphi and Olympia (GS25 to 31)[326]. Most of the cast griffins contain more than 10% lead, with the average for the group at about 8.3% Pb. Tin levels are also comparable with Olympian griffins, which are from 5.10 – 10.4% with an average of 7.9%. It is possible that the Olympian sirens with high lead may have been produced by Samian artisans working at Olympia[327]. If Oriental imports in the main demonstrate the use of some lead in the alloy, albeit in low percentages slightly above the optimum of 2% as probable deliberate additions to the bronze, then what was the reason the Samian bronze-workers added lead in such high percentages to the casts? Firstly, it may have had to do with aesthetics, the contrasting lighter colour of the finished protomes and sirens compared with the darker bronze colour of the cauldron. However, since neither of the studies by Varoufakis or Magou in question provided information as to colour, because many of the analyses were performed on siren and protome fragments, the original colour cannot be stated with any accuracy[328]. Secondly, as Magou indicates, the Samians may have added such large amounts of lead to the alloy in the hope of dramatically improving the fluidity of the molten bronze, and not to save on tin because the tin levels were not significantly lower than what was normally used in the bronze compositions of, for example, weapons or hammered metalwork. In this case, the argument that lead was used as a cheap substitute for tin is invalid when applied to the cast griffins from Samos. Thirdly, and this is the most probable reason for its use, the final chiselling and finishing of the figures would have been much easier if the metal was softer, thus the deliberate addition of lead was not a means of using up metal scrap that had accumulated in the workshop, but a definite technique of

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[326] GS25, Fig. 35; GS26, Fig. 36.

[327] For comparison purposes, see Figures 37 and 38 which show griffins from Olympia and Samos that demonstrate almost identical workmanship. It is possible that both were made by Samian metalworkers.

[328] Most studies of bronzes will indicate the patina of the surface of the object, usually green or bluish-green, that is due to the copper reacting with the environment. See: Walter A. Franke, Magda Mircea, "Plutarch's Report on the Blue Patina of Bronze Statues at Delphi: A Scientific Explanation", *Journal of the American Institute for Conservation* 44 (2), 2005, pp. 107-8. The descriptions of the objects that are referenced by Magou and Varoufakis, and which are found in Jantzen and Herrmann, provide little information as to colour.

metalworking gained through experience with the physical characteristics and behaviour of alloys.

It could be proposed that the use of high-lead bronze for griffin attachments was a technique peculiar to Samos during the Orientalizing Period, but the two cast Greek sirens found at Olympia from the same period also contain high lead content. Because the workshop origin of the griffins is not known, it is entirely possible that they were produced at one particular Samian workshop, and therefore the alloy could be atypical of bronze work on Samos[329]. It is possible that the Olympian sirens were either imported from Samos, or that Samian artisans working at the Olympia sanctuary produced most of the high-lead sirens that were found there. Another possibility is that alloying techniques from Samos were adopted by other bronzeworkers at Olympia. Samos had a highly-developed bronze industry at this time: among the 200 griffins found at the Heraion (sanctuary of Hera) almost none show evidence of having been produced at foreign workshops[330]. And as at other Greek sanctuaries of the Archaic Period, bronze workshops were found located close to or inside the Heraion.

The two aforementioned studies contain an admittedly small sampling of bronze objects from the Near East, and it is thus impossible to categorize most cast decorative bronzes from this region as being made from leaded bronze as a rule. Nonetheless, the cast bullhead protomes certainly demonstrate that leaded bronze was used in the Near East. This may have had to do with the choice of colour for the bronze, but Near Eastern bullheads were often soldered or brazed and a high-lead content would have facilitated this method of attachment to the vessel.

What is clear from the studies is that there was no standard copper/lead/tin ratio in alloy formulae that was used by bronzeworkers in Greece or the Near East for the amounts of lead that were to be added to the bronze. Some areas used close to the optimum (Near East imports) and other areas used higher or lower ratios. The lead figures in Graph 1

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[329] Kyrieleis 1990, p. 22. Some 200 griffin protomes have been uncovered at the Heraion sanctuary on Samos, and metal analysis on only seven are presented here.

[330] Kyrieleis 1990, p. 23. It would have been interesting to compare Samian Orientalizing bronzes with other types of bronzes that were produced on Samos to determine if the use of leaded bronze for cast objects continued into the later periods.

bear this out. What is apparent is that the Samian griffins contain much more lead than their counterparts at Olympia, but no general conclusion can be made about the sirens as a whole other than that the addition of lead was deliberate in amounts above 2%, particularly for the Greek sirens and some Near Eastern ones. The lead percentages for the Near Eastern sirens probably indicate a familiarity with the use of lead to improve metal fluidity for casting since they are 4% and lower, but the Greek sirens contain much more lead than what is required, so it is not apparent if the technical reason for lead addition was in fact transmitted to the Greeks. If it was, then the high lead addition may have had to do either with aesthetics (surface colour effect of additional lead) or the substitution of lead for tin, however neither can be proven without much more extensive metal analyses of objects from the areas concerned. The small increase in weight of the bronze due to the extra lead would probably not have been considered as an important factor since they were usually attached to the cauldrons with rivets. If Greek metalworkers acquired the alloying technique of increasing the amounts of tin in bronze objects from the Near East, it is possible that the use of leaded bronze in Near Eastern imports may also have had an influence on the alloy compositions for cast objects used in Greece, even though the amounts of lead are much lower than what was used a short time later in Greece during the Orientalizing Period. However, because analyses of early Greek cauldron attachments that were manufactured prior to the arrival of Oriental imports were not available for study, the inception of this influence is not clear. Another factor to consider about the influence of Near Eastern metallurgy on Greek metalwork is that Near Eastern bronzeworkers must have encountered problems when calculating the additions of such small amounts of lead, but the following section will show that they were clearly capable of varying alloy compositions for specific purposes, such as in the manufacture of vessels and handles.

3.1.2 Cauldron, Hydria and Vessel Handles

In a study[331] of a variety of Urartian bronzes dating from the 9th to the 7th centuries, two vessel handles had tin/lead amounts of 4% / 4.8% and 6.7% / 10.6% respectively. Out

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[331] This was a metallographic study using emission and atomic absorption spectrometry of 18 bronze objects from the Urartian sites of Toprak Kale, Altin Tepe and Patnos. Wall pegs found at Toprak Kale contained less than 0.5% lead, but a similar wall peg from Nimrud contained 13.4% lead. An Assyrian example had 1.4%

of the eighteen bronze objects that were analyzed, the handles were the only items that contained appreciable amounts of lead, indicating deliberate addition (authors' comment). All the other objects contained less than 1% lead, with tin amounts varying from 2.6% to 9.4%. The bronze body of a vessel from the site of Patnos had an alloy composition of 0.22% lead and 5.9% tin, the trace lead at the level usually expected for raised vessels. The alloy is also an indication that a copper ore with very low lead was used in smelting.

A number of hydria and vessel handles dated from the Archaic to the Hellenistic Periods that were found at a Greek sites are described in Table 2 of this paper[332]. The alloy and manufacturing methods of vessels do not vary very much from the Geometric to the Hellenistic Periods. Vessels were raised almost exclusively out of sheet tin bronze that contained little lead due to the fact that leaded bronze cannot be worked satisfactorily, especially in the case of raised vessels where the walls are relatively thin, because the sheet metal would tear during hammering and shaping. This can be observed in the bowl (CH5) and hydria (CH6) that were found in Thracian tombs of the Archaic Period. The foot and handles of the bowl contain about 5% lead, whereas the composition of the rim, and thus the vessel body itself, contains almost no lead (0.11%). The hydria handle contains 3.75% lead with 0.3% lead for the rim. The base contains 3.4% lead to add some weight to the vessel. Both objects contain near optimal tin quantities, and because lead is found only in the base and handles, it is quite possible that lead was added to aid the casting of the handles, since such low lead amounts would have only a slight effect on the bronze colour.

In comparison with the thinness of vessel walls, bronze handles were usually a thick solid cast containing substantial amounts of lead, indicating again, as with the Urartian handles, a deliberate addition of lead to the tin bronze. Handles were either riveted or soldered to the vessel body, therefore it appears that lead was not added as an aid to soldering the thick handle to the thinner-walled vessels. The purpose would probably have been to cast a softer metal, whereby the fine details of ornamental figures that formed

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lead. See: M. J. Hughes, J. E. Curtis, E. T. Hall, "Analyses of Some Urartian Bronzes", *Anatolian Studies* 31, 1981, pp. 141-5.

[332] The metal compositions of these items are found in Craddock 1977, p. 118, 120, and 121. Craddock's article lists 29 handles and several sections of bowls and oinochoe. In Table 2, I have listed only the seven provenanced objects at the Ashmolean Museum.

the various parts of the handle could be finished with less difficulty after casting. The same vessel and handle alloy composition are found in the Classical Period, but for very few exceptions in the case of vessels that were cast. The rim of the Corinthian vessel (CH4) contains 8.2% lead, which indicates that it was cast separately from the vessel and attached by crimping it over the lip of the vessel. As can be seen from Table 2, almost all of the handles also have a tin component that is close to 10%, the so-called "optimum" amount for bronze, therefore the lead was obviously not introduced as a substitute to economize on the quantities of tin in the metal.

CH1 (Fig. 39) is a handle (one of two) from a bronze hydria dated to the Archaic period (610 – 590)[333]. The hydria was manufactured in Laconia during a period of bronze production when many of these and other types of Laconian vessels were exported to other areas[334]. This particular vessel was supposedly found near Mainz (Germany), but the exact findspot is not known. The details provided by the Ashmolean Museum describe it as an Etruscan hydria[335]. The semi-circular handle is attached horizontally to the vessel body, and contains a rather high amount of lead, 13.2 % with a tin component of 8.8%. No other metal analyses of large Laconian-manufactured vessels were available, so it could not be determined if the alloy composition that was used for this handle was typical of the bronze workshops in that region of Greece. The hydria may have an Etruscan origin due to the very high amount of lead that was used, since bronzeworkers in Etruria tended to use high percentages of lead in their cast bronze objects. On the other hand, the hydria may be a local copy of a Laconian bronze vessel, the latter which had a widespread distribution from the 7th to the second half of the 6th century[336]. A bronze handle from the Peloponnesian area (CH2) dated to the 6th century also contains a high percentage of lead (9.2%) and tin (9.1%). The findspot is not indicated, but it may be of Laconian manufacture due to its date and composition.

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[333] Conrad M. Stibbe, "Archaic bronze hydrai", *Babesch* 67, 1992, pp. 6-7. The metal analysis was performed only on the horizontal handle.

[334] Hodkinson 2002, pp. 102-3. The lower part of the hydria is a modern reconstruction.

[335] Stibbe identifies it as coming from Campania. Hodkinson (2002, p. 103) indicates the Mainz location.

[336] Hodkinson 2002, p. 102.

Bronze vessels were common household utensils. The more elaborate vessels were often offered as prizes at games, and dedicated at international sanctuaries[337]. The design of some of the cast vessel handles is highly detailed. Three Greek 5th century hydria handles at the Metropolitan Museum of Art are composed of scrolls, palmettes and lion's heads. A vertical handle (Fig. 40) shows evidence of riveting, whereas the horizontal handle was originally soldered onto the vessel. Richter notes that "The handles are cast and quite heavy", the vertical one measuring 22.2 cm in height and weighing about 1.4 kg[338]. These handles were not analyzed for metal composition, however from the weight it can be surmised that the bronze contains some percentage of lead.

The Vix volute-krater (CH8, Fig. 41) is probably the only large bronze vessel dating to the Archaic period whose physical characteristics, and alloy compositions of its various components, have been analyzed in minute detail. The volute-krater as a shape originated in Laconia, and it was used throughout the 6th century. Through stylistic comparisons with other similar types of volute kraters and decorative features, it was determined that the Vix krater, rather than being produced in Laconia, was probably made in a workshop located either at Siris, Rhegium or Paestum in Magna Graecia, and dated to the Archaic period ca. 540 – 520[339]. Although technically not a bronze krater of Greek manufacture according to Rolley[340], it nevertheless provides excellent insight into some aspects of metallurgy that were current during this period[341]. The krater body, the lid with its decorative statuettes, the foot and the attachment rivets all contain less than 1% lead (from 0.024% to 0.59%), the average tin percentage being around 9.6% (minimum 6.7%, maximum 12%). The cast lid handles contain less than 0.6% lead. The cast volute handles, in the form of a lion and a serpent, are the only parts of the krater that contain what appears to be deliberate additions

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[337] Gisela M. A. Richter, "Greek Bronzes Recently Acquired by the Metropolitan Museum of Art", *American Journal of Archaeology* 43 (2), 1939, p. 194.

[338] Richter 1939, p. 189. The horizontal handle is 18.6 cm wide.

[339] Stibbe 2000, p. 131. The Vix krater was found in a royal Celtic tomb in Northern Burgundy. Stibbe indicates that this is a very large and elaborately decorated bronze volute-krater produced in the Laconian (Sparta) bronze-working style that was typical from 570 – 560.

[340] Rolley excluded a Laconian origin for the krater and advanced the idea that, because of very close similarities with other kraters found in Southern Italy, its origin was not Greek. See also: Hodkinson in Fisher and Wees 2002, pp. 102-4; Rolley 2003, pp. 129, 141-3.

[341] Benoît Mille, David Bourgarit, "Composition élémentaire des bronzes", in: Claude Rolley (ed.), *La tombe princière de Vix, Volume 1*, Éditions A. et J. Picard, Paris, 2003, pp. 253-9.

of lead: tin/lead percentages 8.5% / 1.4% for the lion, and 10% / 1.2% for the serpent. The lead values for the volute handles are admittedly low, when compared with other vessel handles previously discussed, but considering the near-absence of lead in other parts of the Vix krater, its presence in these intricate handles can only indicate an addition as an aid in casting. The statuettes, handles, foot and the krater rim were all cast. The body and the lid were raised and hammered from sheet metal, demonstrating that the addition of lead was avoided where the bronze had to be extensively worked. Their different tin compositions (the body 9.9%, the lid 6.9%) are believed to have been chosen in order to produce a more reddish colour for the lid[342]. It would have been very interesting to compare the metallurgy of various sections of Laconian volute-kraters with that of the Vix krater to determine if leaded bronze was used for cast handles in Laconia, however metal analyses of Laconian vessels were not available for comparison.

An interesting example of a leaded bronze handle (CH7) comes from Hellenistic Sardis in Asia Minor. It is composed of a rather high percentage of lead (8.6%) and 9.2% tin. This handle shows the same alloy composition for bronze attachments to vessels as in other regions.

The handles and bowls in Craddock's list that do not have secure findspots are nevertheless interesting for comparison purposes as to their compositions. The Archaic handles tend to have higher lead levels than in the Classical or in the Hellenistic Periods. As examples, one Archaic Period oinochoe handle has 21% lead, and a second oinochoe handle has 16.2% lead. Tin levels are 7.1% and 5.6% respectively. For the Classical Period, one skyphos handle has 5% lead and 8.4% tin. Three unprovenanced handles had the following lead amounts: 3.9%, 15.4%, and 20.8%. In contrast, four oinochoe handles had very little lead: 0.05% , 0.31%, 0.6%, and 0.1 %. The Hellenistic handles had low lead amounts, ranging from 0.2% to 5.75%. Except for the provenanced handle from Sardis described above, the figures for the Hellenistic handles are somewhat surprising, because it is during this period that bronze coins and statuettes commonly exhibited much higher lead percentages. The discrepancy cannot be explained because the provenance of the handles is not known.

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[342] Conrad M. Stibbe, *The Sons of Hephaistos - Aspects of the Archaic Greek Bronze Industry*, Bibliotheca Archaeologica 31, « L'Erma » di Bretschneider, Roma, 2000, pp. 261-2.

A similar problem exists with the Archaic hydria handle (CH3) from Chalcidian Greece found in Sicily. It is the exception among the other objects in this table. The tin level is 10.7%, a value that is typical for statuettes and larger bronzes, but the lead content is near trace value at 0.03%. This handle would have had a lighter colour than ones that contained lead. Since almost all of the unprovenanced handles in Craddock's Archaic list have substantially higher lead levels, what would ideally be required are metal analyses of vessel handles found in Greek colonies in Sicily to compare with this handle, and thus determine what bronze alloy composition was used there during this period.

3.1.3 The Methods of Joining Decorative Attachments and Handles to Cauldrons and Vessels

Cauldron assemblies included the vessel itself, a tripod supporting structure, and cast or hammered figural attachments, some with ring handles. Decorative attachments such as griffin protomes, sirens and bullheads were usually affixed to cauldrons with rivets. The bottom of the attachment was contoured to the outside curvature of the cauldron body. Two or more holes were made through the attachment and the vessel body, rivets were inserted and the heads hammered flat against the attachment surface. Griffins and bullheads were often mounted either on the rim of the vessel, or just below it, and bullheads and sirens often incorporated ring handles for easier transport of the vessel. The majority of these attachments and handles are often found separated from their original vessels at archaeological sites, the vessels having disintegrated through corrosion. It appears that few of the attachments show evidence that they were affixed to cauldrons solely through soldering or brazing[343]. Nonetheless, there are a few examples that illustrate a combination of mechanical and metallurgical joining techniques using riveting and brazing. One such example came from an Urartian chamber tomb at Altin Tepe near Erzincan, presumed to be the gravesite of a military official[344]. Among the finds was a large hammered sheet-metal

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[343] I have not been able to locate detailed information in the available literature concerning the methods of attachment of griffins, sirens and bullheads other than the use of rivets. Nevertheless, it stands to reason that if evidence exists for the soldering of cast bullheads to cauldrons, then solid cast griffins and sirens may have also been attached by soldering in some cases.

[344] R. D. Barnett, N. Gökce, "The Find of Urartian Bronzes at Altin Tepe, Near Erzincan", *Anatolian Studies* 3, 1953, pp. 121-2.

bronze cauldron (height 0.51 m, width 0.72 m, walls are 0.003 m thick) with three cast handles in the form of bullheads (Figures 42 and 43). Each is brazed onto a triangular plate resembling a bird, the plate then affixed to the cauldron rim with four rivets[345]. A large ring tripod, with its feet in the form of bull's hooves, that may have served as the cauldron support was also found in the same tomb. The assembly was dated to the late 8th or early 7th century because of similarities with objects found at other sites in Urartu. Such a combination of casting, hammering, brazing and riveting shows that the craftsmen possessed an advanced state of metallurgical knowledge[346].

There are few Greek bronze vessels dating from the later Archaic Period and into the 4th century that have been recovered completely intact. This is because they were either melted down at some point and the metal used for other purposes, or they simply corroded away due to the thinness of the walls. Most vessel bodies were hammered out of sheet bronze, whereas the handles were cast[347]. Some complete vessels show evidence that soldering was used as a method of attaching handles to the vessel body. A good example is a Greek bronze hydria with a sculptural relief that was found in a tomb in Eretria (Figure 44), dated to ca. 350 – 320. The body was hammered out of sheet bronze, and the foot, lip and three handles were cast and attached with solder[348]. The foot was solid cast in one piece. Several decorations were inlaid with silver and niello. The type of solder that was used was not specified, but it may have been composed of a tin-lead amalgam. Alternatively, silver solder could have been employed if the vessel walls were thick enough to withstand the heat of the brazing process (wall thickness was not indicated).

Evidence of soldering was also noticed on a Greek psykter which probably served as a wine cooler (Figure 45) and on an amphora from Macedonia[349]. The vase body of

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[345] Barnett and Gökce 1953, p. 122. The sizes of the bullheads and their alloy composition is not indicated. The article mentions another set of bullheads that came from a similar cauldron found at Toprak Kale. One of the bulls is 17 cm wide and 13.5 cm high, the other is 12 cm wide and 9 cm high. Both were mounted in a similar fashion as the ones at Altin Tepe. See: Barnett 1950, p. 19.

[346] Barnett and Gökce 1953, p. 129.

[347] Gisela M. A. Richter, "A Fourth-Century Bronze Hydria in New York", *American Journal of Archaeology* 50 (3), 1946, p. 367. The author does not mention if leaded bronze was used for handles.

[348] Richter 1946, p. 361. The vessel body is 50.2 cm high, 32 cm in diameter without the handles, with the two semi-concave handle measuring about 3.7 cm wide. The main handle incorporates a sculptural relief.

[349] Dietrich von Bothmer, "Newly Acquired Bronzes – Greek, Etruscan, and Roman", *The Metropolitan Museum of Art Bulletin,* New Series, 19 (5), 1961, p. 144, Fig. 7. The psykter (capacity of one quart and 29

the psykter was made from hammered sheet bronze, the rim was cast separately and soldered onto the top circumference of the vessel. A domed centrepiece was soldered to the upturned rim of the lid. Handle attachments were made from sheet bronze, contoured to the shoulder and soldered onto it. Rings for the swinging handles were soldered to the vase. An early example of soldering was found on a Greek bronze bowl support from Olympia. The hollow-cast support develops vertically from a lion's paw foot into a human face[350]. A metal piece projecting from the back of the support contains evidence of solder.

3.2 Alloy Composition of Greek Bronze Coins

Earle Caley analysed the metallic composition of a series of early Greek bronze coins that were produced over several centuries in the areas of Macedon, Athens, Ephesus, Syria, Egypt, Megara and Eleusis[351]. Table 9 below shows the average tin and lead compositions of coins for various periods. (All dates are in BCE)

Period	Tin	Lead
Up to second half of 4th century	11.89%	1.6%
End of 4th century to beginning of 3rd century	10.96%	2.28%
First half of 3rd century	8.33%	2.98%
Second half of 3rd century	9.06%	7.21%
From first half of 2nd century	8.74%	8.53%

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ounces) was dated to the late 6th – early 5th century. On a bronze amphora of about 16 quart capacity, only the foot was soldered on; the vertical handles were riveted to the rim and the shoulder. Both objects were apparently found together in Macedonia (find-spot, alloy composition and solder type are not indicated).

[350] Joan R. Mertens, "An Early Greek Bronze Sphinx Support", *Metropolitan Museum Journal* 37, 2002, p. 25. The support was dated to the late first quarter of the 7th century. There is no information on the metallic composition of the support or of the solder.

[351] Earle Radcliffe Caley, *The Composition of Ancient Greek Bronze Coins*, Memoirs of the American Philosophical Society XI, Lancaster Press Inc., Lancaster, P. A., 1939, pp. 112-4, Table XXVI. The coins were dated and have secure provenance. The results are tabulated in the annex under Greek Bronze Coins, p. 148.

Second half of 2nd century	5.80%	25.83%
First quarter of 1st century	6.3%	19.7%

Table 9 Table of Tin and Lead Averages in Greek Bronze Coins[352]

Almost all coins with very small lead percentages were of the earlier date (4th century). Lead amounts of up to 2% were probably unintentional, perhaps from lead ore mixed in with copper ore, and only a small proportion of the coins fall between 2 – 3%. The higher percentages will in most cases be an indicator of deliberate lead addition. Some coins dated to the 4th century already exhibit deliberate lead addition (4.18%, 5.36% and 9.22% in three Athenian coins). The analyses show that lead was an intentional component of Greek coins in a number of regions by the first half of the 3rd century. Not only was lead being substituted for tin in the Hellenistic period, but another fact that is noticeable from the data is a sudden change in the proportions of tin and lead in Greek bronze coins around the mid-2nd century [353].

These changes in the tin/lead proportions over time must have some kind of explanation, as well as why the lead percentages would have increased to a very high proportion of the bronze alloy. It is known that increasing the amounts of tin well above 10% improves the fluidity of molten bronze and lowers its melting point, thus making it easier to cast objects such as large statuary bronzes, but it also increases the brittleness and hardness of the metal. The statue could be hammered and worked during the finishing and shaping stages. In the case of coins that were to be stamped with a figural design (a ruler's profile, for example) and some type of inscription, this high tin component made it difficult to shape the bronze by striking it with dies[354]. The die is used only once on each face. Early Greek bronze coins exhibit high tin levels that are similar to that contained in many

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[352] These metal averages are from Table XXVI in Caley 1939. A modified version of this table is found in the annex under Alloy Composition of Greek Bronze Coins in Various Periods.

[353] Caley 1939, pp. 129, 135. From the data presented by Caley in Table XXVI, pp. 112-4, the lead proportion in one Athenian coin in the first half of the 2nd century was 9.93%, and another dated to ca. 99 was 20.38%. The lead content of Athenian coins spanning the range from the 4th century to end of the 2nd century possess from trace amounts up to 9.93%, but it should be noted that these results were obtained from analysis of only a small number of Athenian coins with secure date and provenance. See also: Treister 1996, p. 358.

[354] Caley 1939, pp. 136-7.

cast statuary bronzes, so this was simply a transfer of prevalent working techniques from one type of object to another. Conversely, coin metal requires malleability for stamping and sufficient hardness to withstand abrasive wear, and individuals working at the mints realized that the high-tin alloy composition used for statuary bronzes was not ideal for coinage[355]. The advantages of using a high tin content would be the minting of hard coins that had a golden colour[356].

There was probably a great deal of experimentation with bronze alloy compositions in the attempt to produce a metal that was more suitable for coinage. The partial substitution of lead for tin in the production of leaded bronze came into general use earlier in some areas than others, and the knowledge of this technique probably circulated among the people who were working at mints[357]. It was found that design details were more easily impressed unto metal with a lower tin percentage where some of the tin was substituted by lead, and that the stamping dies themselves lasted longer. However, the introduction of high levels of lead from the middle of the 2nd century may have had nothing to do with technological innovation. In practical terms, additions of more than 10% lead in bronze do not improve the mechanical properties of the metal but cause it to become softer and more brittle, qualities that are obviously inappropriate for coinage[358]. The examination of highly leaded coins (20 – 30%) shows defects such as cracks as well as surface spotting caused by the segregation of lead, and their appearance is generally inferior to older high-tin coins. It is thought that the sudden and widespread increase of the use of highly-leaded bronze in the production of new coins in the mid-2nd century may have resulted from re-melting old and worn leaded bronze coins, or scrap bronze with extra lead residues thrown into the mix[359]. It is likely that the purpose was to increase metal quantities when a given weight of old coins was remelted, and surplus coins retained to cover remelting and restriking

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[355] Caley 1939, p. 137.
[356] N. Kallithrakas-Kontos, A. A. Katsanos, A. Aravantinos, M. Oeconomides, I. Touratsoglou, "Study of Ancient Greek Copper Coins from Nikopolis (Epirus) and Thessaloniki (Macedonia)", *Archaeometry* 35 (2), 1993, pp. 266-7.
[357] Caley 1939, p. 138. Caley notes that this is probably the most logical explanation for the common use of leaded bronze for coinage in so many regions.
[358] Caley 1939, pp. 143.
[359] Caley 1939, pp. 142-3.

costs[360]. Such highly-leaded bronze must have been difficult to work, and no technical or aesthetic advantages can be proposed as to why it was generally adopted.

It is possible that deposits of tin ore that were accessible with the mining technology available at that time were being exhausted due to the high demand, but the explanation for the development of highly-leaded bronze coinage and the more common use of leaded bronze for other bronze objects such as statuettes can perhaps be found in pragmatic considerations. The first motive for this relatively sudden shift in bronze alloy composition may have had to do with the comparatively much higher cost of tin metal versus lead, thus the production costs associated in minting as well as the technical problem of using a high-tin alloy would have been solved concurrently[361]. Metal prices during the Hellenistic period are unknown, but the price of tin in the Classical period varied from 70 to 140 times that of lead[362]. The concentration on the mining of argentiferous ores during most periods in antiquity resulted in large surpluses of lead as a cheap by-product of the silver extraction process[363]. A second motivation to consider is that inter-regional conflicts during the Hellenistic period may have caused serious disruptions in deliveries of tin supplies, and thus inadvertently contributed to the increased use of leaded bronze for coins in many regions[364].

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[360] Caley 1939, pp. 149-50.

[361] Caley 1939, p. 139.

[362] Treister 1996, p. 341. Treister also discusses an inscription from 421/420 that reports on the metal expenditure for the Athena Promachos statue. The price of the tin was apparently 6.5 times that of the copper (tin was 233 drachms and copper was about 35 drachms per talent respectively). Another inscription from mid-4th century Delphi mentions the price of lead as between 2.5 to 3 drachms per talent. See: Treister 1996, pp. 248-51.

[363] Craddock and Giumlia-Mair 1988, p. 319.

[364] Caley 1939, pp. 140-2, 144-8. The tin supplies to Syracuse in Sicily, and to other areas of the eastern Mediterranean, were probably disrupted on a regular basis due to the three Punic Wars that were fought between Carthage and Rome from 264 to 146. Carthage may have had a monopoly on trade with the regions that possessed deposits of tin, and when Carthage was finally defeated in 146, it probably caused a serious decline in the shipments of tin. The Greeks had connections to tin areas by sea, and tin shipments reaching the port of Massilia from Gaul were in operation well before the destruction of Carthage, but Caley notes that the tin volume that was transported via these land routes would have been much lower than the quantities that were supplied by the Carthaginians. Caley indicates that, “It seems significant that the first noticeable use of reworked bronze coincides with the first Carthaginian Wars, and that the almost universal use of reworked bronze began at about the time of the destruction of Carthage.” See: Caley 1939, p. 190. The scarcity of tin continued into the Roman imperial period, and official issues of bronze coins by Rome were phased out sometime in the first half of the first century to be replaced by brass coinage (copper and zinc).

The composition of the sixteen Athenian coins is quite different when they are compared with coins from other areas during the 3rd to the end of the 2nd century. Only four of the Athenian coins contained amounts of lead that could be considered as deliberate additions; the entire group of coins averaged about 9.5% tin[365]. Besides a few exceptions, it appears that a leaded bronze alloy was not commonly used for coins minted in Athens, and a marked increase in lead addition is evident only in the 1st century and later[366]. What can be noticed from Caley and Kroll's studies is that there is no apparent set percentage of lead that was used. The lead values vary rather widely between regions and even within bronze coins from the same minting[367].

A metallographic study of bronze coins dating from the early to the mid-4th century at Amphipolis and Thasos suggests that disruptions in tin supplies caused by conflict led to temporary use of leaded bronze for coinage. Analysis of coins at Amphipolis dated prior to the conquest of the city by Philip II in 357 showed that they generally contained tin ranging up to 20% with very little lead; a small sample of coins were composed of about 5% tin and from 3 to 6% lead. After the conquest, coins exhibited from 2 to 8% tin but lead percentages varied from 5 to over 25%. The island of Thasos, a short distance east of Amphipolis, was alternately ruled from the 5th century by the Lacedaemonians and Athens, and later by Macedonia until 197. Coins minted before 360 contained from 12 to 15% tin with traces of lead. After 360, tin decreased to about 5% and lead content varied from 10 to 15%[368], but this composition was found only in a particular series of bronze coins that were minted during a brief period of time. Bronze coins minted later on showed a return to the previous levels of higher tin and low lead[369]. The study concludes that minting leaded bronze coinage would have provided a temporary solution for city-states in response to financial difficulties caused by wars, sieges or other reasons that resulted in

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[365] Earle Radcliffe Caley, "Chemical Investigation of Two Ancient Bronze Statuettes Found in Greece", *The Ohio Journal of Science* 51, 1951, p. 12.

[366] In a more recent study of Athenian bronze coins that was conducted in 2001, analyses produced the same conclusions as Caley. The use of higher proportions of lead was most noticeable from 166 to 32 B.C. See: John McK. Camp II, John E. Kroll, "The Agora Mint and Athenian Bronze Coinage", *Hesperia* 70 (2), 2001, pp. 152-4, Table 2.

[367] Camp II and Kroll 2001, p. 155.

[368] Guerra and Picard 1999, pp. 198-9. Eighteen coins from Amphipolis (fig. 4, p. 205) and thirty from Thasos (fig. 6, p. 206) were analyzed. Seven coins were dated post 360 from Thasos.

[369] Guerra and Picard 1999, p. 201.

problems with the procurement of tin. Leaded bronze was thus a convenient alloy for producing currency quickly out of necessity, because lead was commonly available whereas tin had to be imported[370].

In summary, during the period from the late 4th century into the first half of the 2nd century, lead in low percentages was being substituted for tin in proportional amounts to produce a bronze that was more suitable for coinage. Tin/lead ratios were constant, and the copper amounts varied very little as well except for a few exceptions. This would therefore be a definite indicator of technical innovation to improve an alloy as applied to a particular application. In contrast, from the middle of the 2nd century and onwards when high amounts of lead were being added and the percentages of both tin and copper were decreasing, this would indicate periods of lead substitution for tin due either to tin scarcity, the low relative price of lead, or the large amounts of cheap lead that were available in many areas, and not as a result of any advance on alloy innovation[371].

3.3 Alloy Composition of Statuettes and Figurines

Tables 3 though 7 exhibit metal analyses and descriptions of bronze statuettes and figurines from the Geometric to the Hellenistic Periods. Table 8 lists the Etruscan objects. It should be said at the start of this section that these tables list fewer objects than the number listed in Craddock's series of articles on bronzes. The reason is that the findspots for many items were either unknown or not indicated in museum databases, such as the Ashmolean Museum at Oxford and the British Museum. The catalogue of bronzes by H. B. Walters provided some findspots as well. The subject of this thesis is primarily concerned with the development and use of leaded bronze, therefore I have concentrated in particular on locating as many provenanced and securely dated leaded bronzes as possible.

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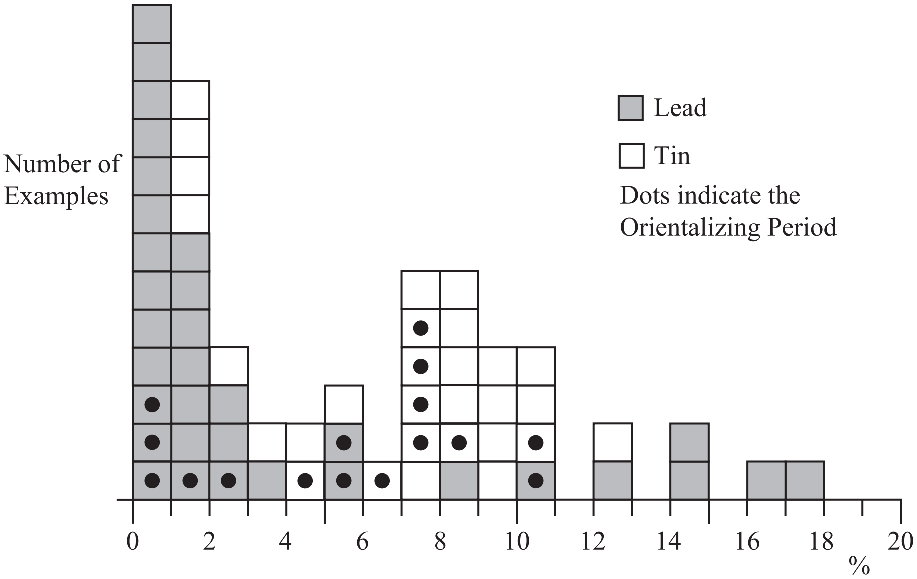
[370] Guerra and Picard 1999, pp. 201-2. The savings in the cost ratio of lead versus tin would not have factored into the decision to use leaded bronze because of the small amounts of metal that were used for minting a limited series of coins. The economy in fuel due to the lower melting point of leaded bronze would also have been minimal.

[371] Caley 1939, pp. 142.

3.3.1 Geometric and Orientalizing Periods

The objects from these periods are listed in Table 3. Graph 2 below shows the distribution of lead and tin in 31 objects[372].



Graph 2 Lead and tin percentages for thirty-one Geometric and Orientalizing bronze objects compiled in Table 3

The majority (20) of the 31 statuettes contain less than 2% lead, and although it has been previously mentionned that 2% lead improves melt fluidity, it is very likely that the percentages of these 20 statuettes reflect the presence of lead in the copper ore and are not deliberate additions. Eleven objects contain more than 2% lead. The two objects with very high lead (S1 and 2) also contain very low tin, and thus may be more accurately classified as leaded coppers. The Geometric animal figurines from Olympia (S14, 16, 23) contain almost no lead, but in two cases contain about 10% tin, which is in line with the tin compositions of Oriental cast sirens and griffins that were imported during the late Geometric Period[373]. There were few analyses available of Orientalizing Period figurines,

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[372] There are 73 Geometric statuettes listed in Craddock 1976.

[373] The few statuettes from Olympia that were analyzed for composition all contained very little lead and tin in the 8th century. By the late 8th and early 7th centuries, the tin precentages had increased substantially, usually containing from between 4 and 12%, however lead amounts remained very low. See: Andrews 1994, pp. 149-150.

so it is not known if there was an increase in the use of lead for this category of object that would follow the alloy trend for sirens and griffins. Object S15 (Fig. 47) is said to be a Geometric siren from Olympia and it contains about 8% lead and tin, which is also similar to Orientalizing sirens made at Olympia. This particular siren may be Late Geometric or early Orientalizing due to its alloy composition.

The objects from Rhodes (S2-9, 17, 28-29) present alloy compositions that show some variations, but in general the lead amounts are low. The seven Geometric Period figurines, except for three exceptions (S2, 7 and 29), contain low amounts of lead but tin percentages are in the range expected for this type of bronze at this time, the average being 7.8%. Lead amounts start to rise in the Orientalizing Period (S9, 28-29), but even then the quantities remain low. S2 could be called a leaded copper, and S7 and 29 are the only figurines that can be called leaded bronzes showing deliberate addition of lead because they also contain higher percentages tin. It is possible that the lead was added to save on tin, but a conclusion cannot be formulated from the few analyses that were available. Leaded bronze was being used during this period at Olympia and on Samos in the manufacture of sirens and griffins. The griphon (griffin) terminal from Samos (S31) exhibits the high lead that was typical of Samian cast metalwork for this type of object (10.7%). The small griffin (S30) from Kalymnos (island just to the north of Cos) is also composed of leaded bronze. It appears that Rhodian bronzeworkers used their own techniques, and were not particularly influenced by those of neighbouring Samos. Rhodes had close contacts with Crete and would have tended to follow trends there. Crete and Rhodes set up a joint colony on Gela (Sicily) in the early 7th century[374]. Being so close to the Anatolian mainland, Rhodes had commercial contacts with Phoenician and North Syrian traders, and numerous objects were imported into Rhodes, and locally produced copies were crafted as well[375]. But from these few analyses it is not known to what extent Near Eastern metalworking techniques influenced Rhodian metal work.

The figure of a deity (S26, Fig. 50) that supposedly was made in Urartu contains very low lead (0.23%) but a normal tin percentage of 8.6%. Urartian cast handles and a number of bull protomes are the only items which usually contained higher amounts of

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[374] Boardman 1980, p. 177.

[375] Coldstream 1979, p. 267. Phoenicians set up pottery workshops on Rhodes.

lead. This figurine thus follows the alloy composition trend of most other bronze objects from this region.

Many of the objects with low amounts of lead also contain near optimal percentages of tin (S13, Fig. 46; S18-22, S24-5[376], S27). The graph shows that the majority of tin distribution concentrates from about 7 to 11% in the Geometric and Orientalizing Periods. It was previously mentioned that there was a penury of tin in some areas of Greece, such as at Olympia, in the early Geometric Period, but that by the mid-8th century tin levels in bronze appeared to have increased back up to their previous Late Bronze Age levels. It is not known exactly when some of the objects listed as Geometric fall into the chronology, but from the tin levels the majority could date to the Late Geometric or Orientalizing Periods. The Geometric figure from Delphi (S19) is technically an almost pure copper figurine containing very little lead and tin, as are two figures from Crete (S10, 12). The alloy for all three was probably smelted from low-lead copper ore. The Cretan figure S11 is borderline bronze with about 3% tin and lead, but it also contains 4.6% iron.

Another observation that can be made from Table 3 is that there does not appear to be any correlation between the tin or lead content of objects and their dates of manufacture, even when comparing objects with more precise dates than the general Geometric or Orientalizing designations. More analyses of bronzes over the span of these periods from a particular region would be required for proper comparison studies.

In summary, the majority of tin levels in the statuettes dating to the Geometric and Orientalizing periods are concentrated in the optimal range, whereas the lead percentages are generally bunched at very low amounts and likely come from lead in the copper ore. The higher amounts of lead are indications of deliberate addition, especially in the objects that contain over 5%, but with the data spread out over such a wide range it must be concluded that lead was most likely added to save on tin or copper, or to produce a heavier and more stable object, rather than from a knowledge of improved casting fluidity. The probability that some bronzeworkers were familiar with this technique and employed it to make their alloy mixtures cannot be ruled out entirely. Because only 31 provenanced

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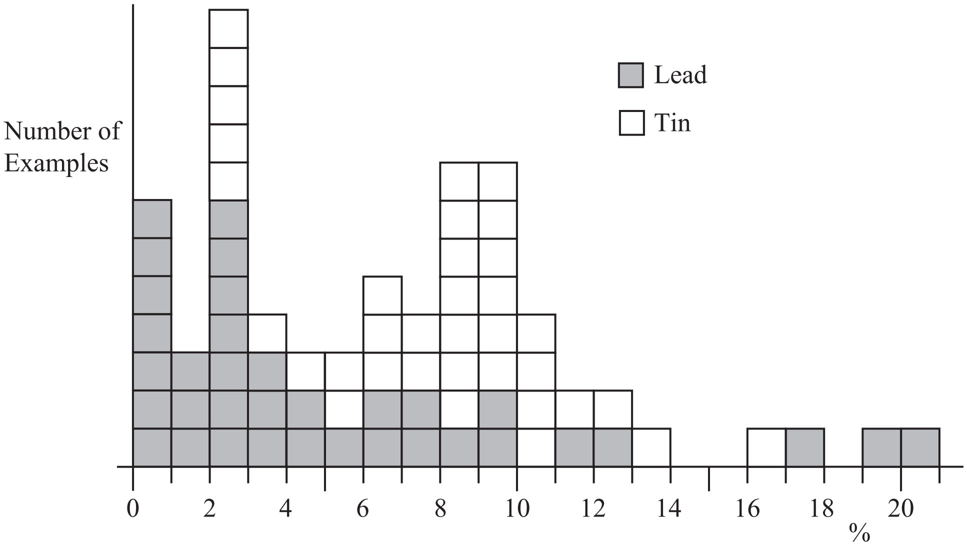
[376] S24, Fig. 48; S25, Fig. 49.

and dated bronze statuettes are presented for discussion, they obviously cannot provide a complete picture of the alloy compositions that were used during these periods.

3.3.2 Archaic Period

The objects from this period are listed in Table 4. Graph 3 below shows the distribution of lead and tin in 35 objects[377].



Graph 3 Lead and tin percentages for thirty-five Archaic bronze objects compiled in Table 4

There is a noticeable increase in the lead percentages for statuettes during this period when they are compared with the Geometric and Orientalizing objects. Only 10 of the 35 statuettes contain less than 2% lead, and 25 contain more than 2%. There is again a bunching of tin percentages in the range of 6 to 13%, with the peak from 8 to 9%. This shows that bronzeworkers were using an optimal tin percentage in many cases, and since these figures are comparable with those from the previous periods, it can be assumed that artisans in various regions had by this time developed a "standard" formula for bronze.

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[377] There are 62 Archaic statuettes listed in Craddock 1977.

Two votive figurines from Cesme in Asia Minor (S36, S37, Fig. 51) can be considered to be leaded coppers, because tin amounts are low, and with lead percentages above 19% would have had a silver colour. The other figurines from Asia Minor (S32-35, 38-39, 40) all contain low amounts of lead most likely coming from copper or tin ores; they also contain optimal percentages of tin. The exception here is a group of four figures (S38, Fig. 52) with low tin and perhaps deliberate lead addition for increased casting fluidity. The bird figures from the Temple of Artemis (S39, 44) may have been made at one workshop because of similar compositions.

The majority of the figurines from the regions of the Peloponnese, Sparta and Laconia (S41, 55-58) show deliberate lead additions. Lead votive figurines were very popular in Laconia and Sparta from the 7th to the 3rd centuries[378], so it is consistent with the local metallurgical practices to find lead in small bronzes as well. The tin and lead values vary in the five examples, and although deliberate lead addition is evident in S41, S55 (Fig. 57), S56 and S57 (Fig. 58), it is difficult to posit why it was added from these few samples. Deliberate lead addition and low tin occurs in the horseman (S56), but the Spartan warrior (S57) also has deliberate lead addition but with an optimal tin level. The lion (S58) contains optimal tin, but a lead level associated with ore deposits. There is no obvious pattern that can be garnered from the analyses, therefore these objects were most likely produced at different workshops. There was a prolific bronze-working industry in the region of Laconia at this time, particularly in Sparta, and artistic bronzework such as statuettes and bronze hydriai were exported to many areas outside Greece[379]. The production of horse figurines peaked in the later 6th century, but the casting of bronze votive statuettes for local sanctuaries decreased. The design of a new hoplite statuette style was originated in the mid-6th century in Laconia and had a widespread distribution in many areas outside Greece[380].

Only two objects are presented from Corinth (S59) and Argos (S60, Fig. 59). Both contain deliberate lead addition, but also noticeable tin percentages (6.2% and 8.3% respectively). Corinth was apparently not as prolific as Sparta when it came to manufac-

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[378] Gill and Vickers 2001.
[379] Treister 1996, pp. 55-8.
[380] Tresiter 1996, p. 58.

turing bronze statuettes. Some are known from archaeological digs that date to the second quarter of the 6th century, but the peak occured sometime in the late Archaic Period[381]. In comparison to the figurine from Corinth (S59), S43 is a statuette of a lion from the island of Corfu[382] that is a high-quality tin bronze with almost no lead and a high tin content. This is of course a comparison between only two objects, one from the founding city of Corinth and the other from its colony, which may indicate that the bronzeworkers used different methods of casting, and thus had very little influence on each other as to the techniques that each area used. However, this is an extrapolation that may be completely erroneous, and which in any case requires more analytical data to corroborate metallurgical connections between founder and colony.

Argos, like Sparta, had a thriving bronze industry, and it was in operation in the Geometric Period: bronze workshops in Argos continued to produce protomes and cauldrons, as well as statuettes and other types of bronzes, but the production of statuettes decreased and the style deteriorated over time[383]. When hollow-casting was adopted in the late 6th century at Argos, it regained its reputation as a leading centre for fine bronzework on the Peloponnesian peninsula[384]. Although no metallographic examples were available for this study, lead addition to this votive bronze wheel may have been a continuation of previous addition to protomes and cauldron handles, perhaps indicating a knowledge of the improved casting fluidity of leaded bronze.

The five bronzes from Athens (S45-49) exhibit a wide range of alloy compositions. The male figure (S47, Fig. 53) fits the definition of a leaded bronze because the tin percentage is not low, thus indicating that this alloy was probably used for some objects in Athens. The unusual composition of the Apis bull (S49) may be an indication that it was not locally manufactured, when its alloy is compared with the other statuettes. The figure of Persephone (S48, Fig. 54) may have been cast with a high amount of lead in order to produce a dark silver colour to the bronze, but when it is compared with S45 (Fig. 55) which would have acquired a more golden colour from the 13% tin, it is more likely that

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[381] Treister 1996, pp. 58-9.

[382] The objet is from the ancient site of Corcyra (site of Palaiopolis, south of the modern city of Corfu) that was founded by Corinthian colonists in 734.

[383] Treister 1996, p. 53-4.

[384] Treister 1996, pp. 54-5.

the lead was added as a substitute for tin. If both were votives as dedications in a sanctuary, why the wide spread in alloy compositions? One explanation might be that the choice of a dark silver colour for the Persephone figurine was related to her role in Greek myth as the queen of the underworld.

From the alloy data for Athens, there is little evidence that a desired improvement in casting fluidity was the reason for adding lead. For example, in comparing the appearance of the two statuettes S45 (Fig. 55) and S47 (Fig. 53), the Aphrodite S45 must have required the forming of a more complex wax mold and more chiselling during the finishing stage than the male S47, but it contains almost no lead and a high tin value. S47 is a simpler design, yet contains deliberate lead addition and less than half the tin as S45. S47 appears to be highly corroded so a colour comparison does not generate any useful information. It may be that the Aphrodite (S45) was a temple votive, and the male (S47) was produced for use as a personal object, so lead was added to save on tin costs. Unfortunately, there is no information as to the actual archaeological context of either statuette. With so few statuettes from Athens that have been analyzed, a general conclusion as to whether leaded bronze was in fact commonly used in Athens during the Archaic Period cannot be formulated with any certainty, although from the limited analytical data available, it appears that some bronzeworkers did utilize this alloy. Other statuettes from Greece (S52-54, S62 (Fig. 60), and S65) contain very low lead and generally optimal tin percentages.

Statuettes S50 through 54 (Fig. 56) show different compositions but lead amounts are generally in the low range indicating it was probably present in the copper ore. The lead in the cow from Cameiros (S51) may indicate deliberate addition. It will also be noticed that tin amounts vary quite widely for these objects. The animal figurines from the Casviri cemetery on Rhodes (S51, 50, 61) show consistently high tin values, but the stag (S61) contains a rather high percentage of lead that may have been deliberately added either for extra weight and stability because it is standing on its legs, or perhaps for easier casting.

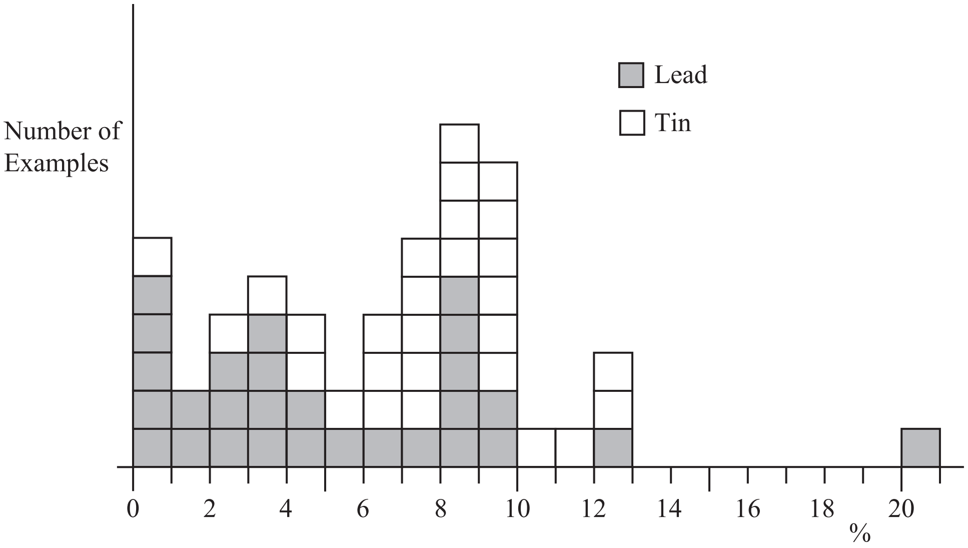
Another object, although a weapon and not a statuette, is a spearbutt from Olympia (S66) containing a high amount of lead; this object is presented here because it shows a particular use of highly-leaded bronze. The tin was added to produce a harder object than one composed solely of leaded copper, and the lead enabled the production of a weapon with extra weight and impact force.

An observation that can be made from Table 4 is that there does not appear to be any correlation between the tin or lead content of objects and their dates of manufacture. This is a similar observation to that of the Geometric and Orientalizing Period statuettes in Table 3. The availability of more analyses over the span of the Archaic period from particular regions would be required to determine if there are changes in alloy composition over time.

In summary, the majority of tin levels in the 35 analyzed statuettes dating from the Archaic period are concentrated in the optimal range, and the use of leaded bronze becomes more common for this class of object than in the previous periods. Statuettes from areas in the Peloponnesian peninsula such as Laconia, Argos, and Sparta, as well as Athens on mainland Greece and Cesme in Asia Minor show deliberate addition of lead. It is very probable that metalworkers in these areas were familiar with the improvement in casting that was afforded by leaded bronze, and the alloy formula may well have formed part of the store of techniques that they used on a regular basis. The availability of more metallographic data on statuettes from these regions would present a better idea as to the types of alloys that were used, and also aid in establishing whether leaded bronze was utilized more frequently than is presently throught to be the case.

3.3.3 Classical Period

For this section and for Table 5, it was possible to locate the findspots of only 13 Greek bronzes from Craddock's list of 28 Classical period statuettes. Graph 4 shows the distribution of lead and tin for all 28 objects, because this provides a more complete picture of the alloy percentages of some small bronzes from this period, but only the provenanced objects will be discussed in more detail.



Graph 4 Lead and tin percentages for 28 Classical statuettes in Craddock 1977, p. 119, and Figs. 3 and 3 (p. 105)

The majority (11) of the 13 provenanced statuettes contain more than 3% lead. When Craddock's statuette list is also considered in the analysis, 5 out of 28 bronzes contain 1% and lower lead amounts, the other 23 contain 2.0% and higher. One particular statuette from the group (REG 1867,0508.788) contains 20.5% lead and 7.2% tin, but the findspot is unknown. The graph shows a definite trend in the use of leaded bronze ranging from 3 to 9% with a peak at 8%. Tin values are spread from 4 to 9%, and peak at 8 to 9% as in the Archaic period.

An animal figurine from Ephesus (S69) has a high lead and tin content, very likely the lead addition is there to produce a colour effect to the outer surface.

S70 is undoubtedly a votive to be placed in a sanctuary, with little lead and an optimal tin content, but the archaeological context or the findspot in the Peloponnese is unknown. Other objects with similar compositions were not available for this period from other areas in the Peloponnese for comparison purposes. The Spartan and Laconian bronzes from the Archaic contain a definite lead percentage, so it is difficult to ascertain where this particular statuette would have come from. Small bronze votive figurines made for sanctuary dedications were exported as well as imported among the various regions of

Greece[385], and thus a stylistic comparison with other statuettes of the period would perhaps give a clue as to its place of origin. The Arcadian female (S71), probably also a votive, has a markedly different composition from the Peloponnesian bronze (S70). Its alloy mixture is closer to the alloy compositions of Spartan figurines from the Archaic, although with a higher lead content. Physical details were not available for this statuette, so its casting complexity is unknown, however the alloy composition could indicate familiarity with the characteristic fluidity of leaded bronze. The Arcadian figurine has close metallic composition to the figures from Olympia: the figure of the athlete pouring a libation (S77, Fig. 68) also contains substantial lead, as does the bull (S78) and the calf (S79).

The statuette of Apollo (S72, Fig. 64) from Thessaly contains low lead, possibly present in the copper ore deposit, but it has a relatively high tin content of 12.7%. The lustrous dark brown colour is quite interesting, and considering its high-tin content the patina should be much lighter[386]. The dark brown colour may be the result of the conservation method that was used to clean the object[387]. Its artistic form is typical of the Classical style bronzes that were manufactured during this period. The aristocracies in both Thessaly and Macedonia attracted numerous itinerant metalworkers who produced bronzes, jewelry, as well as gold and silver vessels[388]. Workshops in Thessaly were distributed throughout the region, and the male figure from northern Greece (S73) may have been made in one of these workshops.

The male figure from Thebes (S74, Fig. 65) is described as a mirror stand, and the use of leaded bronze would have aided in the production of fine details. Addition of lead

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[385] Treister 1996, pp. 265-6. Treister provides an example of a statuette of Apollo (ca. 460-450) of probable Argive workmanship that was found at Lusoi in Arcadia.

[386] Rutherford J. Gettens, "Patina: Noble and Vile", in: David G. Mitten, Suzannah F. Doeringer, Arthur Steinberg (eds.), *Art and Technology - A Symposium on Classical Bronzes*, M. I. T. Press, Cambridge, Mass. and London, England, 1970, pp. 60-1. Tin oxide corrosion is usually white or light yellow-gray when pure. The tin on the outer surface of a high-tin bronze converts over time into tin oxide (cassiterite), which is hard and compact, while the surface copper leaches out into the surrounding soil. The bronze thus retains a lustrous surface underneath the thin outer corroded layer.

[387] Alice Boccia Paterakis, "The Influence of Conservation Treatments and Environmental Storage Factors of Corrosion of Copper Alloys in the Ancient Athenian Agora", *Journal of the American Institute for Conservation* 42 (2), Objects Issue, 2003, pp. 328-9. Examination of a dark brown corrosion layer on a bronze object revealed that tin oxide and cupric oxide were the main products in this layer that resulted from various reactions to chemical cleaning. The author does not indicate the tin level of this object.

[388] Treister 1996, pp. 204-5.

would also have given extra weight to this solid-cast statuette, and thus ensured a more stable support for the entire mirror assembly. The British Museum identifies this bronze as Archaic ca. 500, but it may be early Classical, hence Craddock's attribution of it to the Classical period.

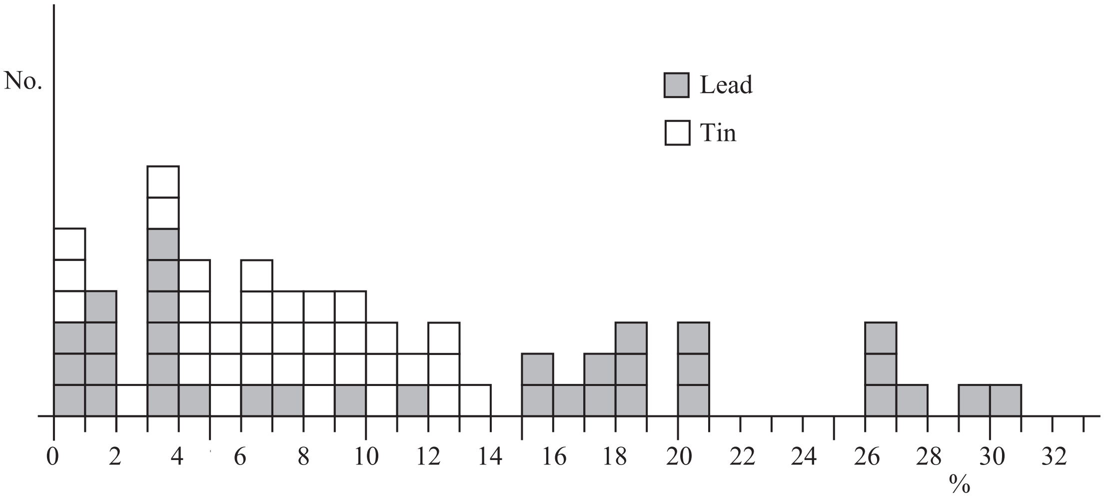
A female statuette from Athens (S75, Fig. 66) is a leaded bronze with an optimal tin level. The lead would have provided extra weight and stability and also as an aid to casting the finer details. The Pallas Athene from Pyrgos (S76, Fig. 67), which is in the same region as Olympia, is also a leaded bronze. The casting fluidity of the alloy would have enabled the reproduction of the fine details of this complex statuette. The three objects from Olympia are leaded bronzes (S77-79), although the function of the calf figure (S79) with the high lead content of 12.3% is unknown because no physical description was available as to size or whether it stood upright. Lead may have been added to give it a silver colour, but the low tin and high lead content of these figurines is most likely due to substitution of lead for tin.

The male athlete S67 (Fig. 62) is very similar in composition to S43 (Archaic Corfu) with very low lead and high tin. The composition of S68 (Fig. 63) may be evidence of technical familiarity with the improved fluidity of leaded bronze in casting, because the tin value is optimal at 9% and the percentage lead content is deliberate. In spite of its small size, this would have been a complex figure to produce, as seen from the description and photo of this statuette. The variations in alloy compositions may indicate that they were produced by different workshops on the island.

In summary, following upon the trend in the Archaic Period, the use of leaded bronze appears to have become more common in the Classical Period. The tin values are, for the most part, in the optimal range, indicating that in many cases lead was not used as a substitute for tin, but perhaps rather for aesthetic reasons, for stability in the object, or in some cases as an aid in casting finer details on small bronzes. The availability of further compositional analyses, dated and provenanced from the regions in the study, would aid in establishing whether the technique of casting with leaded bronze was more common in the workshop production of one particular region than in others.

3.3.4 Hellenistic Period

The findspots of only nine mainland Greece and eastern Greek bronzes, which are listed in Table 6, could be located from Craddock's list of 35 Hellenistic statuettes[389]. In consequence, it was considered necessary to include all 35 objects in order to provide a more complete picture of the alloy percentages of small bronzes in this period. Graph 5 shows their distribution of lead and tin. As in the case for the Classical period statuettes, only the provenanced objects will be discussed in detail.



Graph 5 Lead and tin percentages for 35 Hellenistic statuettes in Craddock 1977, p. 120, and Figs. 6 and 7 (pp. 107-8)

When the metallographic analyses of all 35 statuettes are examined, it becomes evident that the majority are leaded bronzes, some with a lead content over 20% such as the Aphrodite from Olympia (S86, Fig. 72). There is a higher number of statuettes composed of leaded bronze than in any of the preceeding periods[390]. Only three figurines contain less than 1% lead, and the maximum is 30.5% (S84, Fig. 71); the tin content ranges between 2% and 13.8%, with the average at 7.6 %[391].

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[389] Craddock 1977, p. 120.

[390] Craddock 1977, p. 107.

[391] Craddock 1977, p. 107. Three objects are omitted from this summary of lead and tin percentages: two are brass figures, the other is a copper fragment of drapery.

Most of the provenanced bronzes come from the site of Paramythia in Epirus, which is also close to the site of Dodona. The five statuettes are from a group of bronzes that were manufactured at the end of the 4th century, probably by different workshops because their alloy compositions are different[392]. The eyes on the figures were inlaid with silver and the pupils were incised. Except for an Aphrodite (S84), which could be termed a leaded copper because of the low tin content, the other four (S80-83) all have a high tin content, but only one figure (S82, Fig. 70) shows a high lead percentage. S80 (Fig. 69) has the lowest lead content of the group. According to one researcher, these statuettes were finely modelled from wax and then cast to high standards, which had the effect of producing a very smooth patina over time[393]. These bronzes have a smooth, almost glossy outer finish when compared with S86 and 87. Two of the bronzes were restored after their discovery in 1792 and 1796 at Smyrna, but they are not listed in the Table 6[394]. It is of course entirely possible that all of the Paramythian statuettes were restored and polished after their recovery[395].

The Aphrodite from Patras, or perhaps Olympia (S86, Fig. 72) is a highly-leaded bronze. Various sections of the figure were analyzed; it may have been cast in one pouring because it is only 21.5 inches tall. The description does not indicate if it was solid or hollow cast. From the analysis, the different lead figures may be evidence of lead segregation, or lead "pooling" inside the metal, that would concentrate in some areas more than in others in such a highly leaded bronze. The tin levels are also close to optimal value, which indicates that lead was not substituted for tin. A curious feature is that the back contains a markedly lower amount of lead in comparison with the other parts of the statu-

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[392] Arthur H. Smith, *A Guide to the Department of Greek and Roman Antiquities in the British Museum*, Third edition, Published for the Trustees, William Clowes & Sons, Ltd., London, 1908, p. 156. The author mentions that the workmanship is inconsistent among the statuettes in the group.

[393] Dorothy Kent Hill, "Bracatae Nationes", *The Journal of the Walters Art Gallery* 7/8, 1944/45, pp. 79-80. Hill compares the workmanship of the Paramythian bronzes with another bronze of uncertain date that also has silver eyes and a smooth patina. See also the commentary on the Classical period statuette from Thessaly (S72, Fig. 64) which has a smooth finish. The lustrous effect may be due to the tin content as well, but the Paramythian statuettes have a much lower incidence of surface pitting when compared with other statuettes with a similar composition, for example Figure 73 (S87), which contains 12.5% tin but the pitting is quite noticeable.

[394] Smith 1908, p. 156.

[395] The brown tint of the Apollo (Fig. 69, S80) and the Castor (Fig. 70, S82) figures may be due to cleaning (previously noted for S72, Fig. 64).

ette[396]. The other Aphrodite from the Peloponnese (S87, Fig. 73) has a markedly different composition, with low lead and optimal tin. Walters indicates that this may be a copy of a Praxitelean original. Small reproductions of larger statues that had been produced by well-known artisans was current in the mid-2nd century, and although this figure may have been a votive, it is more likely that it had been commissioned by a wealthy client as a decoration for his residence[397].

Another Hellenistic bronze is a head (S88, Fig. 74), which the description from the British Museum database notes as being from a statue, but it is more likely that it is a portrait bust typical of the period[398]. It is thought to be a representation of Sophocles. The eyes were originally inlaid. Several alloy compositions were used to produce some interesting colour effects to the piece. The lips are cast of almost pure copper, which would have imparted a reddish colour. One of the curls would have had a slightly more golden appearance than the other by virtue of its higher tin content. The lead content is very low, perhaps unusual in a small bronze from this period, but perhaps the addition of lead in this case was not considered as necessary for casting. Bronze coins are heavily leaded by this time (mid-2nd century). The various casting and forming techniques used in the manufacture of this bronze bust evidence that metallurgical knowledge had advanced to a considerable degree by the Hellenistic period.

The analyses of Greek coins show that lead was an intentional component of coinage that was being minted in a number of regions by the first half of the 3rd century, and that lead was substituted for tin in the Hellenistic period. The data for Greek coins also show a sudden change in the proportions of tin and lead that were used around the mid-2nd century [399]. These changes in alloy compositions of coinage may also be reflected in the metallic proportions used for statuettes, therefore information on their dates is extremely relevant. But it became apparent while searching for provenance of the bronzes that more

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[396] Walters 1899, p. 38. Walters notes that “Both arms are lost, and a large piece is broken out of the back; the surface is in poor condition.”

[397] Treister 1996, pp. 327-8.

[398] Walters 1899, p. lvi. Walters places this bust in the Graeco-Roman period of the mid-2nd century, when the influence of Rome, and the interest of Romans in reproductions of Greek originals, was on the ascendancy. See also: Smith 1908, pp. 156-7. The bust was apparently brought from Constantinople in early 17th century AD and became part of the Arundel collection.

[399] Caley 1939, pp. 129, 135. See also: Treister 1996, p. 358.

exact dates of manufacture, such as whether the statuettes were early or late Hellenistic, was not available in most cases. Therefore, it cannot be determined if the abrupt change in alloy composition of bronze coinage during the mid-2nd century was also reflected in large increases in the lead percentages of statuettes made from leaded bronze. In summary, the use of leaded bronze became much more common during the Hellenistic period, and its use parallels the general trend of higher amounts of lead in coinage, although the average tin percentage does not change appreciably from the Classical period.

3.3.5 Summary of the Alloy Compositions of Greek Statuettes from the Geometric to the Hellenistic Periods

This section discusses a series of the more numerous statuettes from a number of findspots, and discusses the changes in alloy composition over time.

Athens

There are few statuettes presented in the tables that are from Athens, and most are from the Archaic period (S45-49). Two of them have very little lead, and the other three are definitely leaded bronzes with various amounts of tin, so it is difficult to determine why the compositions are so different one from another. The high lead and low tin in S48 may be an indication of lead substitution for tin, but then S47 also has a substantial lead level and a medium level of tin (5.9%). It is possible that both objects present evidence of substitution for the sake of economy. They may have been produced by the same workshop, considering that not only the alloy compositions, but the dates are also fairly close together. The Apis bull (S49) may in fact be an import, considering that its alloy composition is unlike that of the rest of the statuettes. The one other statuette dates from the Classical period (S75) and it is a leaded bronze with this alloy composition for purposes of stability, since the figure is a mirror support.

Olympia

The cast sirens and griffins that were produced at the sanctuary of Olympia during the Geometric and Orientalizing periods are leaded bronzes, often containing substantial quantities of lead. Many of these objects may have been produced by Samian artisans who had set up workshops at Olympia, and who also used high leaded bronze in the manufacture of cauldron attachments at the Heraion on Samos itself. Nevertheless, analyses of some of the cast statuettes that were produced at Olympia prior to, as well as at the beginning of the Geometric period, showed that they contained very low amounts of lead with usually optimal amounts of tin (about 10%), and this is reflected in the listed objets (S14 and 16). The next set of statuettes from Olympia comes much later in the sequence, from the Classical period (S77-79). The lead content has risen dramatically, and tin content has decreased substantially. This is likely due to the substitution of cheaper lead for tin, rather than from technical knowledge to improve the casting of objects. Since no statuettes are listed from the Archaic period, it is not possible to posit precisely when such a dramatic shift occurred towards the use of leaded bronze at Olympia. What can be said is that the noticeable change in alloy compositions for votive statuettes shows that metalworking practices can change quite significantly over time.

The Peloponnesian Peninsula: Laconia, Arcadia and Sparta

There are few listed objects in these areas from the Geometric and Orientalizing periods (S13, 22, 24, 25). They all contain very little lead and between 7.6 and 10.4% tin. In the Archaic period, lead quantities increase (S41, 55-58) and tin percentages range from 2.3 to 10.2%. The alloy compositions for the Classical period vary to some degree between the regions (S70, 71, 76): low lead and high tin from a site in the Peloponnese S70, high lead and some tin at Arcadia (S71), and high lead and near optimal tin at Pyrgos (S76). A Hellenistic object that comes from a site in the Peloponnese (S87) has low lead and high tin. The only observable change is from the Geometric to the Archaic, which may indicate a knowledge of the improvement in fluidity with leaded bronze casting.

Eastern Greek Areas

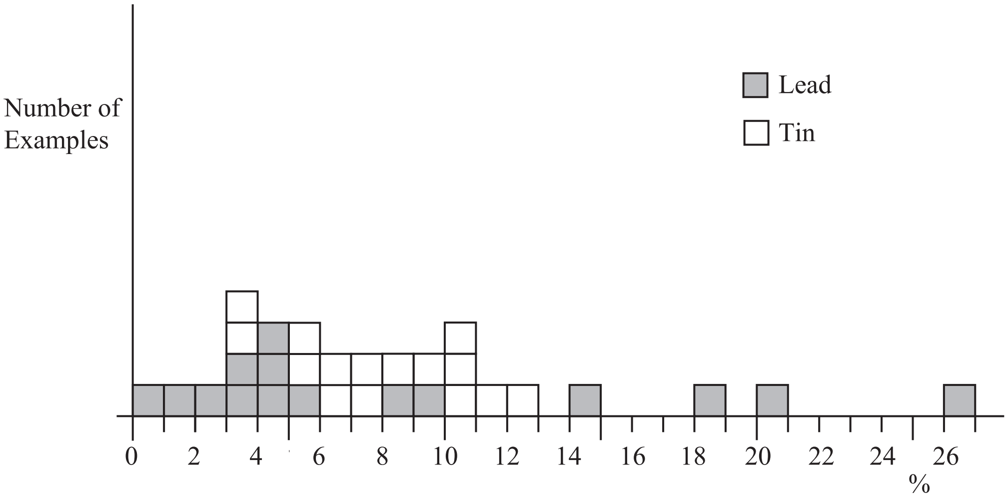
Most of the statuettes from eastern areas of Greece (the Dodecanese, the coast of western Anatolia and Aegean islands) come from Rhodes, from Cameiros and the Casiviri cemetery, with some findspots indicated as Rhodes in general. Two objects (S2 and 7) can be termed leaded coppers, which could indicate either a continuation of metallurgical practices from the ProtoGeometric period when there may have been a penury of tin, or the output of a particular workshop. S29 is composed of leaded bronze. Besides these three exceptions, the Rhodian bronzes from the Geometric period (S2-9, 17) are composed of low lead and from mid- to optimal tin amounts. They generally parallel the statuette compositions from Geometric Olympia. The three Archaic statuettes from Rhodes (S50, 51, 61) have a variety of different compositions, more so than in the previous periods, ranging from low lead and optimal tin, to both high lead and tin in the same object (S61). Additional bronzes from following periods were not available, but the change in alloy compositions on Rhodes appears to occur in the Archaic period, similar to the Peloponnesian bronzes.

Archaic statuettes from eastern Greek areas such as Kos, Sardis, Smyrna, and Ephesus (S33-35, 39, 40) generally have low lead, whereas tin is in the optimal range. The exception is Cesme (ancient Kysos), which is situated on a mainland promontory of Turkey opposite Chios. The two objects (S36-7) are highly leaded coppers. Another object (S38) does not have a particular findspot (Asia Minor), but it has a different composition from the other bronzes. It is a leaded bronze, which may indicate familiarity with the more fluid quality of the alloy. The two other eastern Greek bronzes date much later to the Hellenistic period. The horse from Sardis (S85) is a highly leaded bronze, probably for the colour effect impart by a high amount of lead. The supposed bust of Sophocles from Smyrna (S88) is a high quality piece using various alloy compositions to produce different colour effects on the surfaces of the various sections that were separately cast.

There is only one statuette from Samos. Samian artisans were very prolific in the production of leaded bronze sirens and griffins during the Geometric and Orientalizing periods. Figure S26 may in fact have been imported into Samos, perhaps from Urartu considering its Near Eastern style.

3.3.6 Western Greek (Magna Graecia)

The provenanced statuettes from the Archaic to the Hellenistic periods are listed in Table 7, and Graph 6 shows the distribution of lead and tin. The findspots of 15 Western Greek bronzes could be located in Craddock's list of 24 South Italian Greek Bronzes[400].



Graph 6 Lead and tin percentages for 15 Western Greek statuettes in Craddock 1977

The majority of the statuettes are leaded bronzes, and only two contain less than 2% lead. In the other 13 bronzes, the lead amounts range between 2.98 to 26%. The average level of tin is 7.9%, ranging from 3.2 to 12.8%, bunching from 6 to 11%.

The female mirror support (S89, Fig. 75) is from Croton in southern Italy, and remains of bronze workshops were found in the area. The alloy composition is a leaded bronze, probably added for stability. Laconian artisans from Sparta had a definite influence on the styles and types of local metalwork that was produced in southern Italy. The local production of mirrors with figural handles reached a peak during the Classical period at Locri (S93, Fig. 77), and it is thought that many mirrors were produced in this style at local workshops in Medma, Tarentum and at Croton[401].

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[400] Craddock 1977, p. 122. As well as a few unprovenanced bronzes, a number of the objects in Craddock's list are currently termed Etruscan in the British Museum database and were not included in this graph, but were inserted into Section 3.3.7 (Etruscan Bronze Statuettes) and distributed in Graphs 7 and 8.

[401] Treister 1996, p. 72.

Locri (Locri Epizephyrii) is located on the southern tip of Italy and was colonized by inhabitants from the region of Locris in central Greece in 673[402]. The colonists established another settlement at Hipponium in the late 7th century. Numerous finds of bronze articles from the necropolis were dated to the second half of the 6th century, proving that local bronze-casting was in operation at that time[403]. From a total of six figurines that were analyzed from this area, three of the listed objects (S92, 93 and 95) are leaded bronzes, and five are dated to the Archaic period. Some of these Archaic period figures are heavily leaded, probably from the influence of Etruscan metallurgical practices, although not all statuettes from Etruria are heavily leaded during this period. The "Ugento god" is also dated to this period[404]. S94 also contains low amounts of lead, but optimum tin levels. The two analyses on this statuette showed a consistency in the alloy that was used, without great variations between the sections that were analyzed.

The female figures (S90, Fig. 76, and S91) are variably leaded bronzes with relatively low amounts of tin, which may evidence lead substitution for tin. However, from observation of the overly thick arm stretching upward on Figure 76, the figure's posture, and that it carried a musical instrument (*κανουν*), it is more likely that the extra lead was added primarily for weight and stability rather than to save on the cost of tin. The female figure S91 is even more heavily leaded, and it could have had a similar function. Both figures are only 3.5 inches high, so only an inconsequential quantity of tin would have been saved. These two statuettes may have been part of a decorative group.

The female mirror support (S93, Fig. 77) was probably a product of the Laconian influence on local bronze working. It does not contain as much lead as is usually found in mirror supports (see S89). The Hellenistic figure of a satyr (S95, Fig. 78) is a hollow-cast, heavily leaded bronze (18.8% lead) that may date to the period when very high amounts

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[402] Coldstream 1979, p. 238; Boardman 1980, pp. 184-5.

[403] Treister 1996, pp. 72, 207. Locri and Tarentum were the major metal-working centres of southern Italy in the Classical period.

[404] Mattusch 1988, pp. 14-5, 68-71. This statue is considered to be the product of a workshop in Tarentum. The body contains 3.58% lead, the base 19.58%. The Tarentine school of artistic metalworking was probably responsible for most of the Archaic bronze horse statuettes, group figures and statuettes that have been recovered at archaeological sites in southern Italy. See also: Treister 1996, pp. 71-2..

of lead were being added to bronze coinage, but its 8.5% tin level is in the optimum range. Why so much lead was added is unknown.

Three bronzes from Sicily (S96-98) were probably produced in local bronze workshops. Selinus was founded in the 7th century. Several large Doric temples, a walled acropolis, as well as a great deal of Corinthian pottery were found at this site. Early bronze work also showed a definite Corinthian influence[405]. Pottery from later periods is Athenian, Rhodian, and Spartan, among others. S96 is from the Classical period and shows the typical figure composition of relatively low lead and optimum tin, and may either be a Greek import or was made at Selinus. S97 from Centorbi shows an alloy composition with less tin and slightly more lead, but the head S98 is completely different with high tin and only trace lead. Again, workshops undoubtedly had their own techniques and it is difficult to differentiate local production from possible imported statuettes from so little data.

The male figure from Campania (S99, Fig. 79) is a bronze of optimum tin and little lead. It may have been a mirror support. Similar types were also found in Ionian-Attic work dated from 480 – 470. Euboeans founded their colonies in the Campanian region soon after the establishment of their first colony at Pithecusae. Campanian metal workshops continued their activities during the Classical period.

The votive axe (S100), a heavily leaded bronze, was made for ritual sacrifice and has ceremonial reliefs and an inscribed blade. The lead may have been added for aesthetic purposes, or perhaps to give the axe extra weight to perform clean cuts.

The group of horse and rider (S101, Fig. 80) that was found at Armento[406] in southern Italy shows sparse amounts of lead as well as tin, probably the result of a local workshop using its own casting techniques, since lead percentages in other Archaic figures increased during this period. Both figures are solid cast separately. Numerous imported bronzes were found in the 6th century tombs at Armento. The elongated form of the horse has been described as similar to other types found in Laconia and at Tarentum, but the

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[405] Treister 1996, p. 71.

[406] This figure has been alternately called the Armento Rider and the Grumentum Rider (BM database).

rider is typical of a style found in Magna Graecia and was probably made by indigenous bronzeworkers[407].

A Classical period warrior figure (S102) is ascribed to either southern Italy or to Corfu. Its alloy composition is quite different from the Corfu statuettes dating to the same period, except for sharing the same lead quantity with S68 (5.8%). There may be artistic similarities between this statuette and other warrior figures that were found at Corfu[408].

The greaved leg of a warrior statue (S103, Fig. 81)[409] is a fragment of a Classical period colossal statue from Tarentum. This hollow-cast leg is composed of fourteen pieces and shows a limited range of alloy compositions. Most of the lead values range between 5.14 and 5.68%, with one exception at 12.7%. The tin average is about 9%. The fragments of another very large bronze statue dating from this period have been found at Tarentum[410].

In summary, bronze statuettes from Magna Graecia evidence that leaded bronze was a common alloy composition. Bronzes dating from the end of the Archaic and during the Classical period usually contain amounts of lead addition, probably an influence of Etruscan metallurgical practices which tended to use leaded bronze as a norm[411]. Greek bronzeworkers were also among the colonists who emigrated to Magna Graecia, and the finds at numerous archaeological sites show that objects of all types were regularly imported from Greece. The fact that the use of leaded bronze became more common in Greece during the Archaic and Classical periods attests to communication and the sharing of techniques among metalworkers in various regions. It is known that schools of metal working in Greece had an influence on local bronze working (Laconia's influence on Locri and Croton). It is possible that the use of this alloy by bronzeworkers at Greek colonies in southern Italy was transferred and thus adopted by metalworkers on the Greek mainland, but it is difficult to evidence a direct link.

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[407] Rolley 1983, p. 124. Rolley says that the statuette is of local native production. The style has a direct Greek influence, but it has very close similarities with Etruscan bronzes ("[...] *la transition est insensible avec les bronzes étrusques*.")

[408] A photo of this statuette was not available on the British Museum database or in the Walters 1899 catalogue.

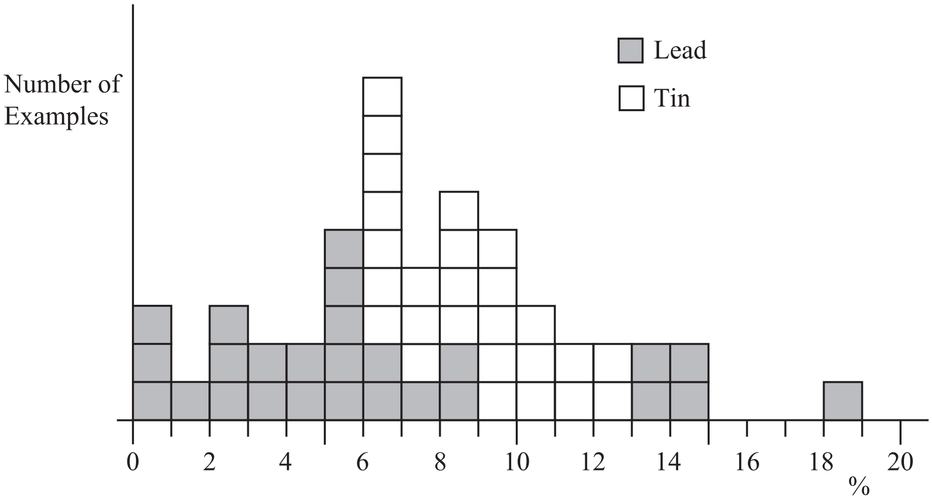
[409] Another photo of the same leg in the British Museum has a light green patina.

[410] Fragments of a colossal bronze statue of a mounted warrior. One fragment is the folds of a cloak about 13 inches in height, dated to ca. 470-450. (BM No.: 1886,0324.7.e)

[411] Treister 1996, pp. 208-9.

3.3.7 Etruscan Bronze Statuettes

Bronze statuettes for the Archaic Etruscan to later periods[412] are listed in Table 8. Graph 7 shows the distribution of lead and tin in 26 objects from the Archaic period, while Graph 8 presents 21 statuettes dating after the Late Archaic Etruscan period and into the Etrusco-Latin period. The Etrusco-Latin designation for certain objects is from the British Museum database. Some of the analyses presented in the graphs are found in Craddock's list (1977), but the large majority are from the compilations of analytical data for various types of Etruscan bronze objects found in *Studi etruschi*[413].



Graph 7 Lead and tin percentages of 26 Archaic Etruscan statuettes[414]

The majority of the statuettes dating from the Early to the Late Archaic periods (600 – 450) are leaded bronzes, and it is evident that there was deliberate addition of lead. Four of the 26 bronzes contain less than 2% lead, the other 22 bronzes containing from 2 to 15%, with one object at over 18%. Compared with Greek bronzes from the Archaic

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[412] Richardson 1983, p. xiv. Etruscan dating is on the Chronology page. The Archaic date divisions are based on the development of the *kouros*, but are valid for all archaic types of figures. The dates after 450 are based on similarities with Greek artistic styles because Etruscan bronzes are rarely purely Greek. See: http://www.noteaccess.com/Texts/Etruscan/9Introduction.htm. Consulted October 10, 2011.

[413] Craddock 1977, p. 122; Craddock 1984, pp. 247-256. Table 8 contains a random sampling of all the Etruscan statuettes presented in Craddock 1984 for the periods under study. There were 28 objects listed for the 7th to 6th centuries, 38 from the 5th century, and 46 in the 4th to 2nd centuries. The British Museum database indicated general findspots for a number of the bronzes. Most of the figurines in Table 8 were provenanced.

[414] Craddock 1977 and 1984.

period (35 examples), the number of Etruscan leaded bronzes is higher. There are many more examples of lower-lead statuettes (1% and less) in the Greek group (29%) than in the Etruscan one (18%), but there is a 13% increase in the number of Etruscan bronzes above the 2% threshold compared with Greek examples (22/26 versus 25/35), even when the limited sampling used to construct this graph in taken into account. Etruscan statuettes thus demonstrate a tendency to contain higher amounts of lead with more frequency, an indication that the use of leaded bronze was commonplace[415].

When the tin values are compared with those for statuettes from the Greek Archaic period, some Greek bronzes contain low tin amounts in the 2 to 4% range, whereas the lowest tin value for an Etruscan figurine from Craddock's list is 3.9%[416]. The Etruscan tin values shows a peak at 6%, as well as from 8 to 9%, with a spread of 6 to 12 %. These values are generally similar to the tin content of the Greek bronzes. For this reason, it appears that this particular aspect alloying mixtures used in metallurgical practices at the time was fairly common in at least these two regions, and perhaps in others as well.

The male figures (S105, Fig. 82 and S107, Fig. 83) are very similar typologically. Their lead contents are different, which is quite noticeable from their patinas, S105 having a dark silver colour due to its much higher lead content (18.6%), whereas S107 has a more golden appearance. Earlier schematic-types of this figurine became popular in the Geometric period in Greece, and soon after were also seen in Etruria. These two figures are of a later date and much more elaborate, but it is evident that the style remained popular[417]. S106 is a typical Archaic-style votive bronze with left foot slightly forward, long braided hair and stiff posture, similar to stone and marble kouroi in early Archaic Greece[418]. Deliberate addition of lead is also present in this bronze.

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[415] The noticeable gap in Graph 7 for lead values in the 9 to 12% range is curious. Craddock's analytical results for 66 bronzes show only two objects containing lead in this range: one is a cista lid statuette with 9.5%, and the other is a pole cap finial with 9.6%. See: Craddock 1984, pp. 242-3, 247-8.

[416] The base of the boxer figure (S125) has 3% tin, but the figure itself contains 10.6% tin.

[417] Richardson 1962, pp. 168-9. This type of pose, with right arm raised possibly to hold a weapon, and the left hand extended forward to carry a shield, is called a Striding Warrior and the style dates back to the Predynastic period of Egypt. The very early types from Etruria are in the Wiry Geometric style. See also: Emeline Hill, "Etruscan Votive Bronze Warriors in the Walters Art Gallery", *The Journal of the Walters Art Gallery* 7/8, 1944/45, pp. 110, 114.

[418] Pedley 2002, pp. 174-5, figure 6.34 dated 600, and the Sunion Kouros (Fig. 6.35), dating to ca. 580.

The korai (S109, Fig. 84) dates to the Late Archaic period and its style is typical of the period, with both hands stretched forward, and one foot in advance[419]. From the description, this figure is hollow-cast, a casting method that was used in many regions at this time. Iron was used in the core although it is not known if an iron armature was used since the bronze is only 24 inches in height. For large bronze statues, constructing a clay core over an iron framework for stability would probably have been a normal procedure. It also contains very little lead, which is unusual considering that bronzes at this time contain lead addition.

Two figures of Scythian riders (S111, Fig. 85 and S112, Fig. 86), both decorative attachments to the lid of a cinerary urn show the elongated Geometric style, but with long pointed caps, a style that is usually seen on female statuettes. Urns were usually decorated with numerous figures. From the size and shape of the figures, they must have been cast in the same workshop, but their alloy compositions are different, probably for aesthetic reasons having to do with the colour of the bronze. One has 13.2% lead (S111), the other 7.1% (S112), and the effect is quite noticeable in their respective patinas, the figure with higher lead is a darker silver and the original colour on the low lead figure was more golden, although over time it has developed a verdigris finish.

The next two figures have the same catalogue number (S113a, Fig. 87 and S113b, Fig. 88). There were a total of nine figures decorating the urn. Walters indicates that figurine S113a was one of four horse-and-rider figures decorating the urn, along with the four sirens and the female statuette mounted on top of the lid. The difference in the alloys could again be for colour effects, the figural groups having been cast separately. The embellishing of vessel rims with many figurines was an Etruscan custom. The vessel was made from hammered bronze and would have contained very little lead. Vessel bodies produced in Etruria were composed of similar alloys that were used in Greece and elsewhere[420], in other words with very little lead because they were manufactured from hammered bronze,

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[419] Richardson 1983, p. 249.

[420] Craddock 1977, p. 106. Greek vessel handles were heavily leaded, the vessels were made of unleaded tin bronze.

and with a range of tin percentages from about 5 to 11%. The vessel handles were cast and usually contained relatively high amounts of lead[421].

S115 (Fig. 89) is a votive statuette of a warrior produced in an elongated, almost Wiry Geometric aspect, but highly detailed with a large head in comparison with the body, wearing a huge Attic helmet. The style is called Mannerist Geometric and was developed in Umbria in the 5th century[422]. Mannerist elongation was common in Etruria and in Greece during the Geometric period. Lead content is a low 1.9% probably from the copper ore, but the tin level is optimal at 11.3%.

The female deity (S116, Fig. 90) is representative of another popular korai style during the period. She wears a long pointed cap, and lifts and pulls the skirt to the side with the left hand, bending slightly forward[423]. This statuette was locally produced in Perugia (Umbria), where the manufacture of bronze figurines began supplanting Etruscan imports only towards the end of the 6th century. It is a leaded bronze but with an optimal amount of tin which gives the figure a slightly golden tint.

The two male figurines (S119, Fig. 91 and S120, Fig. 92) have similar poses, both hands free of the body, elbows bent, hand extended in an offering position, in this case a ball and a stirgil. This type of pose is a modification of Greek types in this period[424]. Both are small statuettes and have similar tin contents. S120 was probably a free-standing figure on its small round base. But S119 has substantially higher lead which would added extra weight and stability to the figure if it was used as the support for a candelabrum. These figures demonstrate that Etruscan bronzeworkers utilized different types of alloy compositions according to their intended purposes. Figures that were used as support stands for candelabra and mirrors quite often contained substantial amounts of lead[425].

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[421] Craddock 1984, pp. 224, 249. The hammered portions of Etruscan vessels contain little lead, but the cast handles generally contain substantial amounts of lead, sometimes as much as 18%.

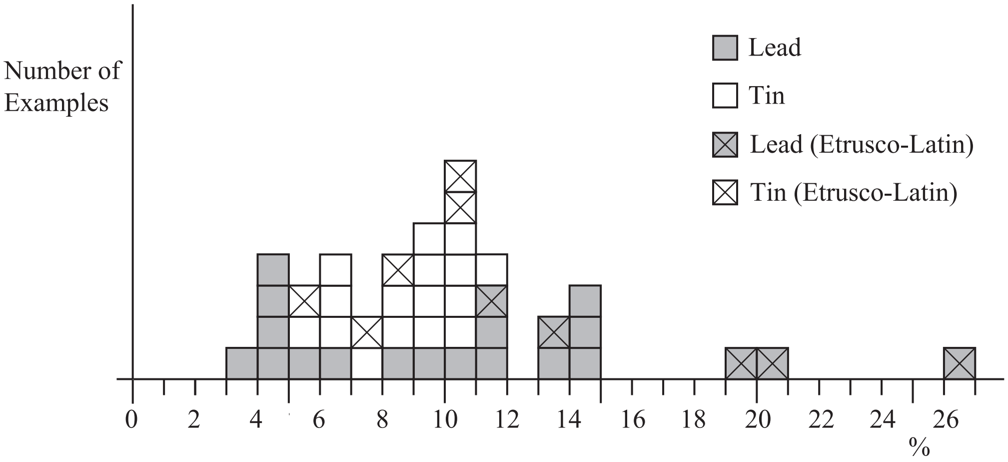
[422] Richardson 1962, pp. 195-7. Almost no statuettes of local manufacture have been found in Umbria for the Geometric period, and what was found were Etrurian imports. The Mannerist Geometric style is the first example of locally-produced bronze statuettes in Umbria.

[423] Richardson 1983, pp. 247-9. The pointed cap was the most popular head cover among women in Etruria during the Middle Archaic, and it is sometimes seen on Greek statuettes as well.

[424] Richardson 1983.

[425] Craddock 1977, p. 107. Greek mirror handles were made of leaded bronze.

The male figurine throwing a discus (S122, Fig. 93) was probably the central figure on the lid of a lebes. It has a high lead content (14.5%), probably for colour. In contrast, the figure of the youth with a trumpet (S123, Fig. 94), also from a lebes, has a much lower lead percentage. These two statuettes pose an interesting question as to why such different alloys were used for the same type and size of figure that was to be mounted on a cinerary urn. Both have similar dates, and both were found in Campania, so presumably if they were made at the same workshop it indicates that there was no particular alloy standard in use. If made at different workshops, or if one predates the other in the time sequence, then individual flexibility in metal working practices was the norm and also explains why the alloy compositions have no particular formula.



Graph 8 Lead and tin percentages of 21 Etruscan statuettes after the Archaic period[426]

The majority of the figures are leaded bronzes, and higher percentages of lead are used in a greater number of statuettes in the post-Archaic periods; some figurines did contain less than 2% lead, although this is not noted in the graph[427]. The tin amounts are spread from 5 to 11%, with a peak from 8 to 10%, the optimum tin level, as in the Greek Classical period[428]. Statuettes in Greece also show an upward tendency in the use of leaded

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[426] Craddock 1977 and 1984.

[427] Due to the random sampling used to produce this graph, lead percentages lower than 2% do not appear, however in Craddock's list of 38 bronzes from the 5th century, eight contained less than this figure, thus some bronzes contained very little lead. Through the course of locating more information about these bronzes in the British Museum database, it was found that a number of the bronzes that were placed by Craddock in the category of "5th century" have been updated to a later date.

[428] The time frame from 450 – 300 in Etruria corresponds approximately with the Greek Classical period.

bronze, but the lead percentages in the Etruscan figurines are usually higher, and it is more common to find them with this alloy composition.

The hollow-cast body parts (S129, 134) appear to be from the same large votive statuette. They have very similar alloy compositions, but their proportions are quite different when compared to the same leg position with a human body, the arm being too long with respect to the leg. Greek statuary in the Classical period shows an adherence to symmetrical body proportions[429], and since the Etruscans followed Greek trends very closely, it is highly unlikely that the artisan who made the wax model would have erred in the proportions to such a degree. Therefore it is quite likely that they are from different statuettes found in the same archaeological context.

The next series of statuettes (S130-135) come from the Tuscany region. They contain similar lead content, with a slightly lower tin content for S132 and S135. The alloy compositions used for the warrior figure (S133, Fig. 95) show the use of lead to colour the bronze, the helmet would have had a dark silver appearance. The shield and the helmet were separately cast. The figures (S136-140) show increasing lead content. The statuette of the youth (S137, Fig. 96) carries an inscription on the thigh that says the votive bronze is dedicated by Larthi Lethanei to the god Silvanus. The figurine itself is very realistic, and the model may have been the client who commissioned the work from the artisan. It would have had a dark silver colour, perhaps a preference of the client. The figure shows more symmetrical body proportions, which was current in Classical Greece, The bronze handle from a situla (S138, Fig. 97) in the form of a young Hercules would have had a definite colour contrast with its vessel, which would contained very low lead and optimum tin. This is a very complex figure and shows hands that are grasping objects, one holding a club and the other three apples. The figure would have been cast separately from the handle itself, the club, apples and the figure details then chiselled and finished. When completed, figure and handle were then assembled. There is no indication whether the handle was soldered or riveted to the figure, but soldering was a common attachment technique used in Greece during the Classical period, so it was undoubtedly used by Etruscan bronze smiths as well.

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[429] Pedley 2002, pp. 275-6.

In later periods, starting at about 300, Etruscan statuettes show a sharp increase in lead percentages (S141-145) and lead is a common addition in all bronze figurines. Either it was the fashion at this time to use leaded bronze, since the colour is a rich dark silver which may have had a particular aesthetic appeal for many people, or the addition of lead to all metal mixtures used for casting smaller bronze figures became routine. The bust of Juno (S141, Fig. 98) may have been a decoration on a piece of furniture and is highly leaded. The eyes were probably inlaid with either ivory or silver. The figure of a seilenos (S142, Fig. 99) is reminiscent of the "rococo" period of the Greek Hellenistic period, and may be an example of the transference of this particular artistic style into Etruscan art[430]. The male and female figures (S144, Fig. 100 and S145, Fig. 101) are very similar in their stance, head inclination, position of arms, and dress. Both are holding out small containers in their left hands. The only difference between them is that they were made in different areas, which demonstrates the popularity of a particular figural style at the time. The male figure contains more tin, but this is probably not very significant, since both were produced at different workshops and in any case the precise control of alloy mixtures was not possible in antiquity, and variations in composition are noticed even in objects produced at the same workshop.

By the first century, Etruscan culture had been absorbed by the Romans[431]. Etrusco-Latin bronzes from 200 – 100 in particular are very highly leaded (S146 - 149, Figs. 102 - 3). The three statuettes from the Sanctuary of Diana at Nemi are strikingly similar in their pose, stance and hand gestures. The votive of a goddess (S149, Fig. 104) is a large statuette in comparison with the other two figures. It was cast in nine separate pieces, and considering the alloy composition, there would not have been a great difference in colour between the individual pieces. There is little information about this figure and no description of the various parts, but the reason for casting separate drapery sections was that the folds of the garment are very complex, the bottom drapery extending under the top section. All large bronzes were cast in sections, and it would have been impossible to reproduce such an effect for this particular figure with a complete wax model reproduced in one pouring.

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[430] Pollitt, J. J., *Art in the Hellenistic Age*, Cambridge University Press, Cambridge, 1986, p. 138, fig. 149.

[431] Nancy H. Ramage, Andrew Ramage, *Roman Art, Romulus to Constantine*, Third edition, Prentice Hall Inc., New Jersey, 2001, pp. 11-12.

The time frame of the Etrusco-Latin bronzes corresponds with that of the highly leaded bronze coins and statuettes of Hellenistic Greece. The lead content of bronze coins had increased dramatically by the mid-2nd century. This was also the period when the Roman Republic was attaining significant political, military and economic power. Lead was an important component in Roman industrial activities, and it was used in a wide variety of applications[432]. Roman mining activities in Britain, Gaul, Iberia and elsewhere produced copious quantities of the metal. It has been mentioned that there may have been temporary problems with the availability of sufficient quantities of tin for bronze-working, and that this may have been the main reason why lead became a common substitute for tin during this period. It is also possible, although it may be entirely coincidental, that the use of lead for diverse purposes by the Romans may have contributed to the increase in the use of leaded bronze.

In summary, metallographic analyses show that many statuettes from the Archaic Etruscan period were made of leaded bronze, and although this alloy was not used for all small figural bronzes, the data indicates that its use was fairly common among Etruscan metalworkers. Analytical data for the earlier Geometric period was not available so it was not possible to notice a sequence of use into the Archaic period, but it may be logical to assume that the use of the alloy was a continuation of previous metallurgical practices. The use of the alloy is seen in increasing numbers of statuettes during the 5th century, and the lead content of many statuettes is augmented. By the 4th century and into the later period, leaded bronze becomes the standard alloy for most figurines. A corresponding increase in the use of leaded bronze in Greek statuettes is also noticed from the Archaic to the Classical periods, although not in the same numbers. The two regions coincide during the late Hellenistic period in their extensive use of the alloy, when lead percentages increased dramatically.

The Etruscans absorbed many Greek artistic styles from the Archaic to the Hellenistic periods and reproduced them for local production[433]. From an archaeological

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[432] Jean David C. Boulakia, "Lead in the Roman World", *American Journal of Archaeology* 76 (2), 1972, pp. 139, 143-4.

[433] Emeline Hill, "Etruscan Votive Bronze Warriors in the Walters Art Gallery", *The Journal of the Walters Art Gallery* 7/8, 1944/45, pp. 123-4.

context, the number of imported Greek artisanal objects into Italy greatly surpassed what the Etruscans exported to Greece. Bronzeworkers in these two regions clearly exchanged their knowledge of metallurgical techniques. The processes of hollow casting, the tin proportions in bronze destined for casting and for sheet metalwork, and the use of leaded bronze for vessel handles and mirror stands were metal-working techniques they held in common. Bronze smiths were undoubtedly aware of the working properties of various alloys for a variety of purposes. Another common factor was that both regions also had access to lead deposits. However, Etruscan bronze-casters tended to use leaded bronze more frequently for cast statuettes than their Greek counterparts. There is no technical explanation for this phenomenon that can be proposed from the analytical data, except that each region's metalworkers were comfortable working with the particular alloy formulas that they had developed over time. Greek bronze casters were using leaded bronze for very specific purposes during the late Geometric period, and it became another useful technique in their metallurgical practices. Thus the fact that the Etruscans used leaded bronze to a greater degree than the Greeks in casting their statuettes probably had minimal influence on Greek alloy formulas.

Conclusion

From the first uses of basic metals such as copper and lead to the development of various types of metal alloys, the progression, diffusion and technological innovation of new metallurgical techniques in metal-working and casting practices of metals demonstrate increasing complexity over time. Metallurgical skills were adapted for the manufacture of a widening variety of new products from iron and bronze. Metalworkers preferred using tin bronze, or "true" bronze, over the copper-arsenic alloy because of its superior qualities in casting and metal working, as much as for its lower toxicity. Through experimentation in varying the amount of tin mixed with the copper, it was discovered that various types of bronze could be produced for specific purposes. By adding from 8 to 11% tin to copper, the "optimum" mixture, the bronze acquired characteristics of both hardness and durability which made it ideal for almost all types of products: weapons, armour, statues, cauldrons, vessels, etc. This alloy composition is the one used most often in bronzes. The metal was easily workable, and annealing and hammering actually improved the final result. Higher amounts of tin over 10% made it brittle to hammer, but the cast alloy had a brighter, almost golden appearance which was aesthetically suited for both large and small votive statues that were dedicated at sanctuaries and temples.

Lead had been used to make various types of objects, and at some point it began to be added not only to copper, but to bronze as well. Metalworkers undoubtedly realized that adding lead to copper improved the fluidity of the molten metal and reduced the formation of air bubbles in the cooled metal. Mixing tin with copper improves the fluidity of copper, but the combination of lead, tin and copper actually enhances the effect. Finer details carved in the wax model are more easily reproduced, necessitating less finishing work. Leaded bronze is also chiselled and finished more easily than tin bronze because it is softer. Lead is naturally present in varying amounts in copper ore deposits, and the fact that only a small amount, about 2% addition, is enough to produce an improvement in fluidity means that in some areas the metalworker using the smelted product was unaware that the effect was produced by lead. Leaded bronze, as it is defined by many archaeometallurgists, is formed through the deliberate addition of lead in amounts greater than 4 to 5%, because most copper deposits do not contain such high levels of lead. The fluidity is improved, and the melting temperature of the alloy varies inversely with the quantity of lead. Large amounts cause a "sweat" the colour of dark silver to form on the bronze surface, which may have been popular in some regions such as Etruria, perhaps the reason why high amounts were added to bronze.

Bronzeworkers were cognizant of the characteristics of tin bronze, and they must also have been familiar with the effects of lead addition to bronze. The fact that lead was often used as a cheap substitute for tin cannot be ignored. But determining whether this applied to a given bronze object is often difficult to determine with absolute certainty from metallographic data. Unlike for tin bronze, a standard formula to produce leaded bronze did not exist. The data shows wide variations in lead percentages, even for objects that were produced in the same region. A cast object that initially appears to show evidence that the artisan used leaded bronze because of his technical knowledge of its properties, could on the contrary also be explained by the random addition of scrap bronze or lead into the mixture. However, for objects where lead levels are high and tin amounts are low, lead substitution can be assumed. Where lead levels are from between 4 and 10%, with little or no reduction of the tin from its optimum level (8 to 11%), then technical knowledge could in general be presumed to be the reason for its use. This is borne out by the fact that due to its brittle quality, leaded bronze was almost never used in the manufacture of hammered objects such as vessels and cauldrons that were raised from sheet metal. Handles and supports on the other hand often contained lead. Lead was often added to bronze arrowheads for extra impact force, but rarely for spearheads and swords due to the extra weight and brittleness it imparted, qualities which were obviously undesirable in these types of hand-held weapons. Most of the statuettes that were discussed are composed of the leaded bronze alloy, and from their compositions a good number of them show evidence that the metalworker distinguished between the properties of bronze and leaded bronze.

In considering the first query, the penury of tin that occurred at the end of the Bronze Age caused significant problems for bronze working in many areas. In some regions of Greece, such as at Olympia, metalworkers began using lead as a partial substitute for tin to produce the bronze they required in the manufacture of tripods. However, the scarcity of tin appears to have been a short-lived phenomenon. Examination of bronzes from other sites show that some tin was available, although not in the quantities that were imported during the Late Bronze Age. As evidence, the analyses of statuettes at Olympia show that tin quantities in bronze did not decrease to very low levels. It is likely that the leaded bronze, or more accurately leaded copper, used in tripods was a reaction to a brief lack of sufficient tin, but even after tin imports had resumed, the metallurgical practice of using leaded bronze for some objects continued for a short period. This is an indication that alloy formulas did not experience rapid change, and that metal working and casting practices which served their purposes were not abandoned outright. The influx of Near Eastern bronze work to Greece signalled the resumption of commercial relations in the Eastern Mediterranean, and bronzes that were produced after the mid-8th century show that tin contents had increased back to their previous Late Bronze Age levels. The Near Eastern bronzes, such as cast sirens and hammered cauldrons contain tin levels at about 10%, which is more or less the same level noted in locally produced Orientalizing bronzes a short time later. The lead levels in the Near Eastern bronzes are low, except in the cast bullhead attachments, where leaded bronze was used in many instances, probably because it facilitated soldering the figures with a tin/lead mixture to mounting plates that were then riveted to the cauldrons. In contrast, almost all of the Orientalizing cast sirens and griffins also contained lead, but they were attached with rivets, even in sirens containing appreciable amounts of lead. This contrast in metal working is undoubtedly due to the fact that it was technically easier to use rivets rather than solder, and may be proof that the Near Eastern artisans were technically in advance. The lead quantities in the cast Greek protomes, particularly from Samos, were much higher than in their Near Eastern originals, and although it is possible that the use of lead in the cast objects was a result of influence by North Syrian or Urartian metallurgical techniques, the higher lead levels cannot be explained satisfactorily, because tin levels are near or at optimum levels in the same bronzes. The highly-leaded bronze protomes were probably a preference of individual workshops, perhaps for aesthetic reasons. Data from other sites on Samos was not available, so this aspect could not be verified.

The artistic motifs of Near Eastern bronzes were adopted and modified for local Greek production, as well as their bronze compositions. It is of course entirely possible that Greek bronzes contained more tin in the Orientalizing period simply because it became widely available, but Claude Rolley indicates that Greek bronzes show a general increase in tin levels after the influx of the Near Eastern imports, and thus concludes a

Near Eastern, perhaps North Syrian, influence on Greek metallurgy. Concerning metallurgical influence from the Near East where leaded bronze is concerned, Greek statuettes from the Geometric period in general contained low amounts of lead, and it is only from the Late Geometric and into the following Orientalizing period that lead levels show a tendency to increase. From the low number of analyses that were available, particularly for bronzes from the Near East, a direct positive link that the deliberate addition of lead to bronze was in fact transferred from the East to Greece cannot be suggested at this time, but it remains a possibility nevertheless. An aspect of possible influence that should be researched is whether the bullhead protomes that were made in North Syria and Urartu are also found at Greek sites. These were often cast from leaded bronze with quite appreciable lead content. If they were also imported into Greece, then the use of leaded bronze may be linked to these objects, particularly if some variations were also produced locally with deliberate lead addition. However, until more analyses become available this issue remains unanswered.

The second query concerns the interpretation of metal analyses in order to ascertain which objects exhibit deliberate lead additions, as well as the practicality of using a mechanical rather than a metallurgical join that may have been dependant upon the level of technical expertise of individual bronzeworkers. Due to their complex forms, vessel handles and cauldron attachments would have been easier to cast using molten leaded bronze because of its higher fluidity. Where bronzes exhibit lead levels in the range of 2 to 3% , or even slightly higher, such as in some of the Near Eastern sirens and Greek adaptations, it is difficult to determine whether it was a deliberate addition, or a natural component of the particular copper ore deposit that was smelted, or if scrap metal was added to bulk up the volume. It should be kept in mind that exact measurements of copper, tin and lead were not possible at the time. Since higher amounts of lead provide only slight improvements in fluidity, it is likely that it was added to provide stability and weight for vessel bases, and to differentiate between the colour of the handle and the vessel.

There is also the question of using soldering or brazing rather than rivets as a means of attaching decorative affixes such as sirens, griffin protomes, and handles to cauldrons and vessels. For the early periods, there are very few examples besides the bullhead protomes that demonstrate the use of a metallurgical joining technique. The solid cast attachments were thicker than the vessel walls, and the vessels themselves have corroded and disintegrated over time, so usually only these thick objects are found at archaeological sites, and in most cases there are no traces left of a solder, if it was used. Ancient metalworkers did not have any means of concentrating intense heat on a metallic join, other than tipping the vessel on its side into a charcoal fire, heating the handle, and when both were of sufficiently high temperature, pouring molten tin-lead solder onto the join and then sanding off the surplus. Metallurgical joins may have been possible with smaller vessels such as small hydriae and bowls, but using the same procedure with a heavy vessel or a massive cauldron may have been impossible. The use of rivets, although less reliable than a metallurgical join, was undoubtedly the more practical joining method and all the cauldron attachments were affixed in this manner. There is evidence in a few examples from later periods that handles composed of leaded bronze were soldered to vessel walls, but it is not known if metallurgical joining was a common practice everywhere in Greece.

For Query three, in examining the metal analyses of Graphs 1 though 7, one particular aspect that stands out in the alloy compositions is that they exhibit variations which in many respects are difficult to interpret conclusively. Except for the Samian cast griffins that contain a leaded bronze alloy with consistent high lead and tin, and two cast Olympia sirens that may have been produced by Samian metalworkers at the sanctuary itself, there are not enough analyses of statuettes from other individual Greek sites that would show the same trend occured elsewhere. Nevertheless, the bronzes that contain more than 4 or 5% lead can be considered to be leaded bronzes with deliberate addition of lead, because at levels less than 2% it is probable that lead was naturally associated with the copper ore. This low figure is itself suspect because the sole means of verifying whether lead was deliberately added would be to trace the original copper deposit that was smelted through lead isotope analysis and analyze its lead content. Archaeometallurgists such as Earle Caley proposed benchmarks of 4 to 5% which leave little question as to lead addition. The Samian griffins contain much more lead than is necessary to improve bronze fluidity, as well as an optimum tin level of about 10 to 11%. This indicates that cheaper lead was not present as a substitute for tin, because in direct substitution the tin levels should decrease in consequence. The copper levels diminish somewhat, but copper was not a costly metal and was widely available, so its reduction in an object cannot be interpreted as the parsimonious use of the metal.

In enlarging the scope to include the archaeological significance of metallographic analyses, the interpretation of the data can provide more information about an object and thus a better understanding of its purpose: whether lead was added for extra weight and stability such as in figures that functioned as mirror supports, for perhaps an aesthetic reason to alter the bronze colour as noted in some Etruscan statuettes that may have been a popular artistic style, or as simply a cheap tin substitute, as for example in later Hellenistic coins and statuettes. Its presence in a bronze does not necessarily indicate that this alloy formula was adopted in any one region as a means of improving fluidity in casting. It can be presumed that, in a number of statuettes where lead is about 4 to 7% and tin is optimal at about 10%, the casts were made by metalworkers who were aware of this particular characteristic, but proving it is unfeasible. Lead percentages have such wide variations because there was no particular standardization in leaded bronze alloy formulas, even in objects that were uncovered in the same general area, as in Archaic Athens or on Rhodes. In special cases, such as with early Hellenistic Greek bronze coins that contain between 3 to 8% lead during the 3rd century, the addition of lead was seen to improve the quality of stamping details on the surfaces, as well as facilitating the manufacturing process, and here the knowledge of fluidity and the softening effect of lead was fairly obvious. This alloy was used specifically for casting small bronze objects, which follows on the assumption that bronzeworkers chose alloy formulas according to the types of objects that were to be produced, which is also borne out by the data. If they were familiar with the characteristics of bronze, this implies that the properties of leaded bronze were also known to them.

For Query 4, it is evident that the changes apparent in Greek bronze casting and manufacturing techniques during the Late Geometric period resulted from the influence of Near Eastern bronze working techniques. When the analyses for Etruscan and Greek statuettes are compared from the Archaic to the early Hellenistic periods, leaded bronzes occur more frequently and lead is usually present in higher percentages in the Etruscan than in the Greek bronzes. Its use appears to be more common in Etruria than in Greece. An interesting characteristic of the data for Greek statuettes during this period is that the use of leaded bronze was not very much lower for this particular class of objects. If the benchmark of 4% lead is used for Graph 3 (Archaic), fifteen of the thirty-five statuettes contain more than this quantity. This outcome may be due in part to inherent errors caused by concentrating solely on metal analyses for provenanced objects for Etruria as well as Archaic Greece, which may have skewed the end results. However, the graphs for Classical and Hellenistic Greek statuettes were compiled from all of the objects in Paul Craddock's series of metal analyses for these periods, and the majority of the figurines are leaded bronzes. Greek bronzeworkers in Magna Graecia also produced objects from leaded bronze, and using the 4% benchmark again, the data shows that the majority of the figurines were made from this alloy. If the metalworkers in Magna Graecia were influenced by Etruscan metallurgy, did they pass on the use of this alloy to their compatriot artisans in Greece? The data suggests otherwise. The use of leaded bronze in all three regions was contemporaneous, as well as being an alloy with which many artisans were familiar. Etruscan artwork and styles were in many cases adaptations of Greek original motifs and trends in the decorative arts, but a direct reciprocal transfer of alloy techniques between these regions is not evident from the metallographic analyses.

The alloy that was used in Greek bronze coins shows an interesting dynamic. The alloy used in the early coins was modified for technical reasons to facilitate the die stamping process and improve coin quality. In the mid-2nd century, lead addition increased abruptly to very high levels that had little to do with improving the minting of coins, a factor that caused deterioration in coin quality and durability. Greek statuettes at this time were also produced from highly leaded bronze and tin levels in bronze for both groups decreased. The increase in lead for statuettes was not a direct result of its use in coins at this time, but rather by external circumstances. In Greece, it is very likely that the modification of bronze alloy mixtures was a direct consequence of the penury of tin, which must have affected the alloy composition used for objects other than coins and statuettes as well, although metallographic analyses were not available to verify this. The problems with tin procurement in sufficient quantities to satisfy a burgeoning bronze production market has been suggested by a number of authors as the reason why leaded bronze became a regularly used alloy for many cast objects. That the Etruscans were also casting statuettes from this high-lead alloy during the Etrusco-Latin period was not unusual. The propensity for leaded bronze was already noted in earlier periods, and the extensive use of lead among the Romans no doubt influenced its use by artisans in Italy.

The metallographic data presented in this study of small bronzes suggests that leaded bronze was used in Greece prior to the Hellenistic period: at Athens, Olympia, Corcyra, sites in Northern Greece, in the Peloponnese (region of Laconia, and at Sparta) and in some Greek colonies of Eastern Greece. The data also indicates that the frequency of its use appears to be low, and there are a number of factors that could have produced such a result. Some regions appeared to have used leaded bronze more than others, such as in the figurines from Laconia. Only six votive bronzes were located from Athens, most of them dating from the Archaic period, with one probably an import (Apis bull). Three statuettes contained deliberate lead addition. Six figurines is a very low number, and it would be illogical to assume that their bronze compositions can be construed to be representative of the majority of statuettes that were produced as votives for the major temples in Athens from the Late Geometric to the Hellenistic periods. The compositions of many more statuettes would have to be analyzed before any definite conclusion can be formulated concerning the frequency of the use of leaded bronze.

One of the particular interests of this study was to track the chronology and usage patterns of leaded bronze at various sites in Greece, but problems arose while attempting to link objects with specific sites, resulting in the exclusion of such an analysis. The small number of bronze objects from mainland Greece that are listed in the tables is due to problems with establishing provenance for a significant number of the analyzed bronzes in the original published articles. This necessitated elimination of many objects with unknown findspots, and the number of bronzes that were actually used compared with the totals is noted in the graphs for each period. If the relatively small sampling used in this study reveals that leaded bronze was in fact being used in Greece, then it is very likely that more examples of its use would have become available if the findspots for all of the analyses in the source articles could have been located, particularly those for the Archaic and Classical periods. The development of alloys and manufacturing processes advanced rapidly during these periods, particularly in the indirect casting of colossal statues using the lost-wax method, with iron armatures as supports; mass production of statuettes and small bronzes that re-used the same moulds; improvements to furnaces and casting procedures. The finds of more analyzed objects from Athens, Delphi, Corinth, and the regions of Boeotia and Thessaly would have been of particular interest, since these were all important metal working centres. But for the moment, I think that the query concerning whether leaded bronze was commonly used in mainland Greece cannot be answered satisfactorily. Perhaps when further metallographic analyses of Greek small bronzes become available, then this question will be resolved.

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Chronology

Greek Chronology

Period	Date
Early Bronze Age	ca. 3100 – 2000
Middle Bronze Age	ca. 2000 – 1550
Late Bronze Age	ca. 1550 – 1100
Subminoan	ca. 1100 – 1000
Protogeometric	ca. 1000 – 810
Geometric	ca. 810 – 700
Orientalizing	ca. 700 – 600
Archaic	ca. 600 – 480
Classical	ca. 480 – 323
Hellenistic	ca. 323 – 31

Based on chronological tables in Muhly and Sikla 2000, and Pedley 2002, pp. 5-7. Dates are in BCE.

Etruscan Chronology

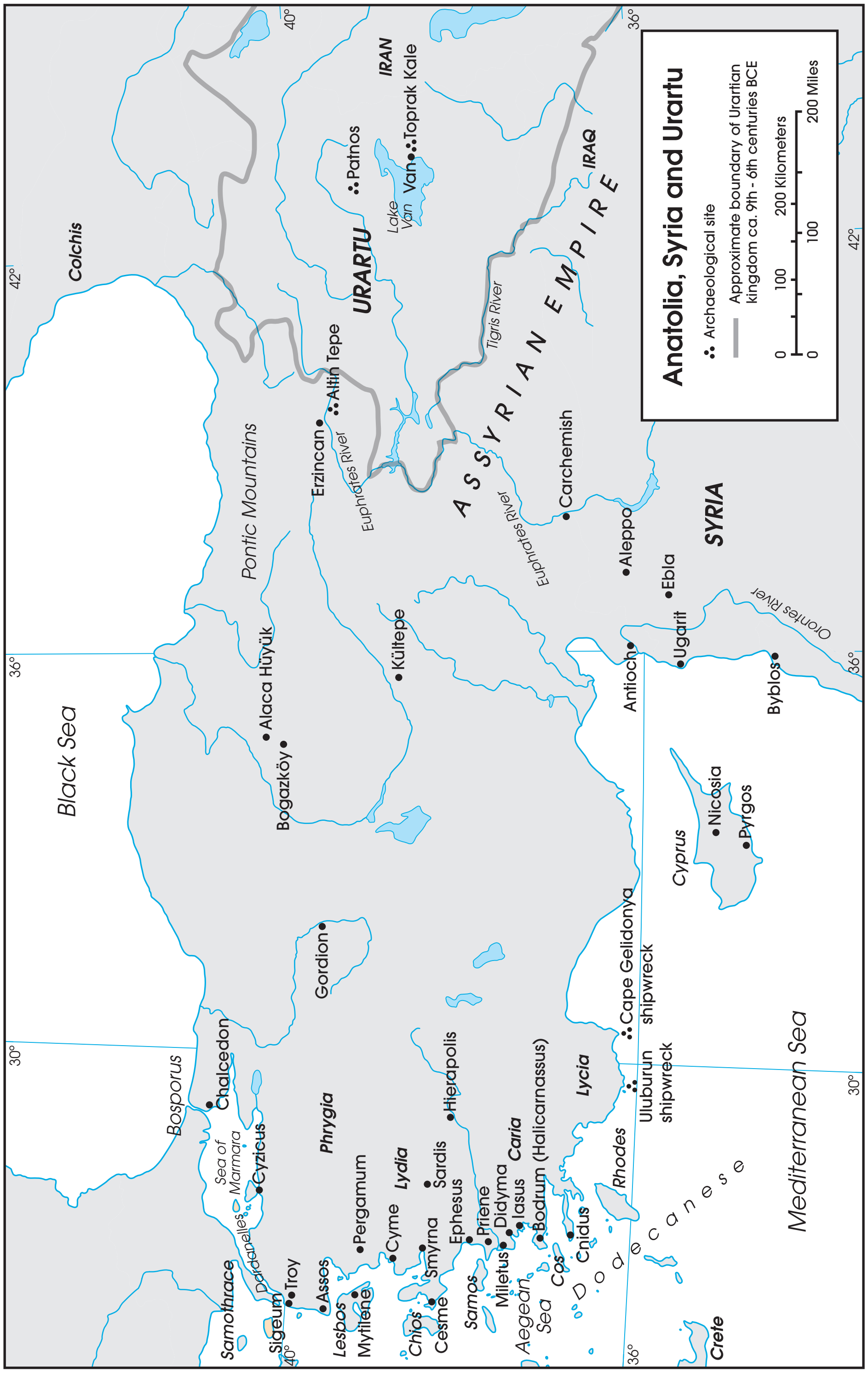
Period	Date
Geometric	ca. 700 – 650
Orientalizing (Early Etruscan)	ca. 650 – 600
Early Archaic	ca. 600 – 550
Middle Archaic	ca. 550 – 515
Late Archaic	ca. 520 – 450

Based on chronological information in Richardson 1983, p. xiv. Dates are in BCE.

Maps

Map 1 – Greece and Aegean Area

Outlines and legends for the three maps were re-drawn in Illustrator CS3 from a copyright-free atlas source. A number of maps were used in locating the place names.



Map 2 – Near East – Anatolia, Syria and Urartu

Map 3 – Etruria and Magna Graecia

Greek Bronze Coins

Alloy Composition of Greek Bronze Coins in Various Periods

Period	Medial date	Place	Cu %	Sn %	Pb %
Second Half of 4th Century	348	Macedon	83.80	14.74	1.42
	348	“	85.35	13.10	1.42
	330	“	85.04	14.34	0.30
	330	“	86.52	13.14	0.02
	330	“	86.87	13.02	nil
	330	“	86.67	13.02	0.06
	330	“	87.81	11.81	0.04
	330	“	87.72	11.70	tr
	330	“	88.25	9.71	1.00
	330	“	88.52	8.15	2.97
	325	Eleusis	88.94	10.78	0.05
	325	“	87.38	10.57	1.55
	320	Macedon	84.25	14.55	0.98
	320	“	85.12	12.17	tr
	320	“	90.42	9.48	nil
	319	Athens	82.23	12.76	4.18
	319	“	81.73	12.49	5.36
	319	“	82.33	8.41	9.22
	304	Myrina	86.20	11.91	1.89
		Averages	**86.06**	**11.89**	**1.60**
End of 4th and Beginning of 3rd Century	297	Syracuse	81.35	14.08	0.42
	297	“	85.71	12.73	1.13
	297	“	85.14	7.43	7.13
	297	Ephesus	85.93	13.05	nil
	297	“	86.41	12.83	0.17
	295	Macedon	89.05	10.48	0.41
	295	Athens	87.49	10.67	1.29
	295	“	87.28	10.57	1.73

These three tables were re-formatted and abbreviated from Table XXVI in Caley 1939, pp. 112-4, and do not include alloy data from the second and third centuries A.D. Four samples of about a gram each were taken from each coin; wet chemical analysis was used to determine the presence and amounts of tin, lead, copper and other metals. The majority of the analyses were performed at the Department of Chemistry at Princeton University. As for accuracy of the results, “only analytical methods representative of the best modern practice were used, and check determinations were made when summation of an analysis fell short of or exceeded 100% by more than two or three tenths of one percent.” (Caley 1939, pp. 1-2)

Alloy Composition of Greek Bronze Coins in Various Periods (*cont.*)

Period	Medial date	Place	Cu %	Sn %	Pb %
	295	"	87.51	10.49	1.68
	295	"	83.57	10.24	5.70
	295	"	88.81	9.80	1.36
	295	"	83.88	9.20	6.38
		Averages	**86.01**	**10.96**	**2.28**
First Half of 3rd Century	282	Epidaurus	86.96	8.33	3.89
	275	Megara	84.73	9.25	4.85
	275	"	83.53	8.56	7.14
	275	Sicyon	86.77	7.65	4.86
	275	"	87.10	6.66	6.16
	266	Egypt	85.61	12.37	0.53
	<261	Athens	89.64	10.40	0.01
	<261	"	89.54	9.40	0.54
	256	Macedon	84.53	13.77	1.34
	256	"	87.80	11.66	0.46
	256	"	86.80	8.24	4.66
	256	"	90.78	8.12	1.17
	256	"	89.02	7.01	3.18
	256	"	90.78	6.88	1.82
	256	"	88.68	6.48	4.45
	254	Syria	88.72	8.54	2.56
		Averages	**87.56**	**8.33**	**2.98**
Second Half of 3rd Century	242	Sciathos	78.25	7.30	13.83
	213	Egypt	77.37	10.30	10.36
	205	Syria	90.80	6.52	2.25
	200	Macedon	85.77	12.67	0.99
	200	Macedon	85.31	11.15	2.86
	ca. 200	Sicyon	79.92	6.40	12.98
		Averages	**82.90**	**9.06**	**7.21**

Alloy Composition of Greek Bronze Coins in Various Periods (*cont.*)

Period	Medial date	Place	Cu %	Sn %	Pb %
First Half of 2nd Century	ca. 192	Athens	86.38	10.56	2.73
	ca. 188	Argos	89.03	9.61	1.29
	181	Syria	80.12	6.18	13.12
	ca. 172	Athens	88.74	11.10	0.22
	171	Euboea	77.69	5.23	13.97
	<166	Delos	86.97	11.86	1.10
	<166	Delos	83.00	10.49	5.59
	<164	Athens	81.25	8.54	9.93
	158	Egypt	65.11	5.12	28.78
		Averages	**82.03**	**8.74**	**8.53**
Second Half of 2nd Century	142	Syria	80.84	5.94	11.84
	137	Egypt (Cyprus)	68.10	7.20	23.97
	137	Egypt (Cyprus)	56.99	4.17	36.76
	121	Syria	64.32	4.07	31.70
	114	Syria	67.13	7.62	24.90
		Averages	**67.48**	**5.80**	**25.83**
1st Century B.C. and 1st Century A.D.	99	Egypt	69.58	4.49	25.49
	?	Athens	71.23	6.84	20.38
	ca. 88	Athens	78.21	7.56	13.26
	?	Syria	82.56	7.62	9.62
	6	Athens	81.44	7.72	10.35
	26 A.D.	Sardis	73.21	9.84	16.61
	? A.D.	Athens	70.55	5.93	23.03
		Averages	**75.25**	**7.14**	**16.96**

Catalogue

Table 1 – Metallurgical Analysis of Griffin Protomes and Sirens

Obj. #	Catalogue Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
GS1	P384 Inv: 1225	Hammered griffin	Delphi (opisthodome)	Oriental import	86.58	0.08	11.15	Half-circle incisions. Height 0.19 m.	FDelph Tome V, 1
GS2	P249 Inv: 1717	Tripod foot	Delphi	Oriental import	77.57	5.50	10.48	Tripod foot in form of a lion. Tripod legs are made of iron.	FDelph Tome V, 1
GS3	P382 Inv: 2640	Cast griffin	Delphi	Orientalizing Period (Greek)	67.93	0.53	7.41	Whitish colour, very hard, with incised braids. Height 0.19 m.	FDelph Tome V, 1
GS4	P386 Inv: 2885	Cast griffin	Delphi	Orientalizing Period (Greek)	87.43	0.14	9.15	Incised braids. Height 0.18 m.	FDelph Tome V, 1

Unless otherwise indicated (see **Comment** below), the catalogue numbers, metal analyses data and the dates in Table 1 are taken from Magou *et al* 1991, pp. 562-6, who base their chronology on Herrmann.
– GGT + number refer to Plates and Number in Jantzen (1955), with corresponding catalogue number at the Samos Archaeological Museum.
– G + number refers to Herrmann in *Olympische Forschungen Band XI*.
– P + number refers to Perdrizet in *Fouilles de Delphes*, Tome V, 1, with the inventory number at the Delphi Archaeological Museum.
– A + number refers to Herrmann in *Olympische Forschungen Band VI*.
– AM + B + number refers to object in article by Jantzen in *Athenische Mitteilungen* 73 (1958).

The metal analyses of samples from the objects were performed using the analytical procedures described in Hughes *et al* 1976 (see the note for Table 3, p. 160). Sample sizes were 5 x 5 mm. A minimum of three measurements were taken of ten elements in each sample, and the results averaged. The precision of the results was referenced with the alloy standards available at the Laboratoire du Musée National as controls. See: Magou *et al* 1986, pp. 121, 124-5, and Varoufakis *et al* 1983, pp. 115-117.

Comment: Object numbers GS9 through GS12 are from Craddock 1984, *Studi etruschi*, p. 265. The metal analyses are of samples taken by A. Steinberg (see note in Table 1, p. 154). For all of the objects in Table 1 that are noted as being sampled by A. Steinberg, Craddock indicates that between 5 and 10 mg samples were taken from the objects, but there is no mention of how many samples were taken from each object, whether the results were averaged, or the degree of accuracy and the control precision that was used. The analysis was done at the Research Laboratory for Archaeology and the History of Art, Oxford. See: Craddock 1984, p. 220.

Table 1 – Metallurgical Analysis of Griffin Protomes and Sirens (*cont.*)

Obj. #	Catalogue Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
GS5	P367 Inv: 1347	Cast siren	Delphi	Oriental import	80.30	1.55	10.90	Two-headed siren, missing arms, wings and tail. Incisions on neck; large incised serrations on torso and arms. Height 0.10 m, width 0.12 m.	FDelph Tome V, 1
GS6	P361 Inv: 3810	Cast siren	Delphi	Oriental import	88.77	0.25	11.41	Small figure, found with piece of a bronze vessel attached to it. Height 6 cm, width 6 cm.	FDelph Tome V, 1
GS7 Fig. 28	P369 Inv: 1248	Cast siren	Delphi	Late Geometric (4th quarter of 8th century) (Greek)	81.13	8.92	6.34	Tail broken, long hairpiece; ears are incised. Torso is ornamented on the edge with triangles. Height 0.18 m.	FDelph Tome V, 1
GS8 Fig. 12	P370 Inv: 1666	Cast siren	Delphi	Orientalizing Period (Greek) ca. 700	68.60	17.86	7.61	Similar to P369. Serration ornament on front of torso. Two incised palmettes on shoulders. Width 0.175 m.	FDelph Tome V, 1
GS9	*B27	Cast siren	Olympia	Oriental import	87.20	3.70	0.10	Tafel 16 in Herrmann VI. Winged siren with tail. Rivet on tail, hole in wing. Height 7.5 cm, width 20.7 cm.	Herrmann VI p. 31

* B27: a metal sample from this siren was taken by A. Steinberg, and the metal analyses were included in Craddock 1984, *Studi etruschi*, p. 265. This siren also contains 5.00% iron. (see note in Table 1, p. 154)

Table 1 – Metallurgical Analysis of Griffin Protomes and Sirens (*cont.*)

Obj. #	Catalogue Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
GS10	B1570	Cast siren	Olympia	Oriental import	78.20	13.30	6.30	Tafel 14 in Herrmann VI. Siren with wings and tail. Rivet holes in wings and tail. Height of bust is 8 cm, wingspan is 25.4 cm.	Herrmann VI p. 31
GS11 Fig. 22	B4312	Cast siren (bearded)	Olympia	Oriental import	85.90	2.10	10.30	Tafel 11 in Herrmann VI. Bearded winged siren with high headgear, the tip falling forwards. Wing rivets, hole in tail. Height of bust 11.5 cm, wingspan 21.5 cm.	Herrmann VI p. 31
GS12 Fig. 11	‡B4313	Cast siren	Olympia	Oriental import	85.90	1.50	11.80	Tafel 8 in Herrmann VI. Siren with wings and tail. Rivets in wings and tail. Height of bust 6.2 cm, wingspan 19.5 cm.	Herrmann VI p. 30
GS13 Fig. 23	A11 *B4298	Cast Siren	Olympia	Oriental import	85.64 (88.80)	3.34 (3.50)	not given (0.11)	Tafel 17 in Herrmann VI. Head and fragment of torso, hair in ringlets around neck, serration pattern on torso. Width 11 cm, torso height 7.5 cm.	Herrmann VI p. 31

* B4298: a sample from this same siren was taken by A. Steinberg, and the metal analyses were included in Craddock 1984, *Studi etruschi*, p. 265. Craddock gives a slightly different analysis figures (in brackets) than in the analysis listed in Magou *et al* 1991, p. 562. Craddock includes the % Sn data; this siren also contains 4.1 % iron (Craddock 1984, p. 265). The sample was analysed at the Oxford Laboratory using optical emission spectrography (see note in Table 1, p. 154). Magou used atomic absorption spectrometry for the analysis. (see note in Table 1, p. 151) The figures from Magou were used for Graph 1 and the discussion, the Craddock figures are for comparison purposes only.

‡B4313: Herrmann notes that this is one of two separate pieces, the other being B4681, that were joined together.

Table 1 – Metallurgical Analysis of Griffin Protomes and Sirens (*cont.*)

Obj. #	Catalogue Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
GS14 Fig. 24	A16 *B751	Cast Siren	Olympia	Oriental import	81.63 (89.20)	0.79 (0.52)	14.49 (9.40)	Tafel 21.1 in Herrmann VI. Right wing of siren. Lower arm, hand and fingers visible, uncommonly large. Rivet hole in wing. Width 17.5 cm.	Herrmann VI p. 32
GS15 Fig. 25	A17 Br. 9525	Cast Siren	Olympia	Oriental import	82.44	3.41	6.11	Tafel 21.2 in Herrmann VI. Part of right wing with rivet hole, hand and fingers visible, width 5 cm.	Herrmann VI p. 32
GS16 Fig. 26	A20 **B1690	Cast Siren	Olympia	Late Geometric Period (Greek) (4th quarter of 8th century)	71.80 (83.60)	13.20 (6.60)	9.49 (8.10)	Tafel 30 in Herrmann VI. One of two sirens on a cauldron. Wing rivet hole. Width 15.3 cm, height 14 cm.	Herrmann VI p. 91-2, 102
GS17 Fig. 27	A22 B28	Cast Siren	Olympia	Orientalizing Period (Greek) (first quarter of 7th century)	66.88	15.80	10.54	Tafel 32 in Herrmann VI. Long hair pendants from ears. Rivets in wings and tail. Width 20.3 cm, torso height 6 cm.	Herrmann VI p. 92, 102
GS18	G26 Br. 8526	Hammered Griffin	Olympia	Orientalizing Period (Greek) 690 - 680	83.13	0.11	8.92	Tafel 12,1 in Herrmann XI. Poor condition, few details visible. Height 16 cm.	Herrmann XI p. 22

*B751 and **B1690: samples from these sirens were taken by A. Steinberg, and the results of the metal analyses were included in Craddock 1984, *Studi etruschi*, p. 265. Craddock gives different results (in brackets) from those indicated by Magou *et al* 1991. The differences in the lead amounts, particularly wide for B1690, may be explained that the Steinberg samples were analysed using solely optical emission spectrography (Craddock 1984, p. 220), which is not as accurate and precise as atomic absorption spectrometry (see note in Table 3, p. 160). The wide discrepancy is more likely due to samples obtained from areas in the object where the lead or tin had "pooled". Nevertheless, this does not satisfactorily explain the wide variations in Cu, Pb and Sn compositions in the analytical results. For purposes of discussion of these objects, the results from Magou were used (p. 78).

Table 1 – Metallurgical Analysis of Griffin Protomes and Sirens (*cont.*)

Obj. #	Catalogue Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
GS19 Fig. 29	G69 B 5650	Cast Griffin (hollow cast)	Olympia	Orientalizing Period (Greek) ca. 680 - 630	84.99	0.87	8.98	Tafel 42,2.3 in Herrmann XI. Protome head. Knob projecting from top of head. Height 14.8 cm.	Herrmann XI p. 37
GS20 Fig. 30	G91 B 1771	Cast Griffin (hollow cast)	Olympia	Orientalizing Period (Greek) (first quarter of 7th century)	80.45	6.61	8.34	Tafel 51,3.6 in Herrmann XI. Protome fragment with inserted eyes, without ears, small head knob, and pressure-fitted rivets. Height 12.8 cm.	Herrmann XI p. 42
GS21 Fig. 31	G95 B 1900	Cast Griffin head (hollow cast)	Olympia	Orientalizing Period (Greek) (mid-7th century)	88.49	0.18	6.03	Tafel 57 in Herrmann XI. Head of large protome, with ears, head knob, hollow eyes, incised eyebrows, and tongue. Height 22.5 cm.	Herrmann XI p. 45
GS22 Fig. 32	G104 B 145 + B 4315	Cast Griffin head (hollow cast)	Olympia	Orientalizing Period (Greek) (mid-7th century)	80.66	2.88	6.92	Tafel 66.67 in Herrmann XI. Head of large protome, with ears, head knob, hollow eyes, incised eyebrows, and tongue. Height 27.8 cm.	Herrmann XI p. 49-50
GS23 Fig. 33	G76 Br. 4159	Cast Griffin (hollow cast)	Olympia	Orientalizing Period (Greek) ca. 620	82.36	trace	10.86	Tafel 46,1.2 in Herrmann XI. Griffin head, ears and tongue tip missing. Knob projecting from top of head. Height 12.2 cm.	Herrmann XI p. 40

Table 1 – Metallurgical Analysis of Griffin Protomes and Sirens (*cont.*)

Obj. #	Catalogue Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
GS24	G79 B 6103	Cast Griffin (hollow cast)	Olympia	Orientalizing Period (Greek) ca. 620	86.92	1.32	10.97	Tafel 48,3 in Herrmann XI. Griffin neck with decorative incised patterns. Three rivet on neck base. Height 11.4 cm.	Herrmann XI p. 40
GS25 Fig. 35	GGT22.2 Jantzen: Nr. 64, Samos B.713	Cast griffin	Heraion Sanctuary, Samos	Orientalizing Period (Greek)	85.85	0.36	8.11	Tafel 22.2. Very corroded. Knob on top of head, tongue tip missing. Original height unknown.	p. 18 (Jantzen, 1955)
GS26 Fig. 36	GGT52.2 Jantzen: Nr. 151, Samos B.55	Cast griffin	Heraion Sanctuary, Samos	Orientalizing Period (Greek)	69.63	11.60	7.73	Tafel 52.2. Eartips broken, incised decorations, rivets in neck. Height: 0.1 m.	p. 25 (Jantzen, 1955)
GS27	AM B32.2	Cast griffin	Heraion Sanctuary, Samos	Orientalizing Period (Greek) 690 - 680	67.13	10.8	10.4	Samos Museum number: B. 846 Almost complete protome. Tips of tongue, ears; attaching knob missing; eyes filled. Height 0.115 m	AM p. 30
GS28	AM B46.5	Cast griffin	Heraion Sanctuary, Samos	First quarter of 7th century	77.70	10.13	6.92	Samos Museum number: B. 831 Partial piece; part of ring attachment visible. Height 0.16 m.	AM p. 44
GS29	AM B49.3	Cast griffin	Heraion Sanctuary, Samos	Mid-7th century	69.08	10.45	8.9	Samos Museum number: B. 139. Attachment knob and ears missing; part of ring attachment visible. Height 0.125 m.	AM p. 45

Table 1 – Metallurgical Analysis of Griffin Protomes and Sirens (*cont.*)

Obj. #	Catalogue Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
GS30	*B. 8 (Samos Museum number)	Cast griffin	Heraion Sanctuary, Samos	Last quarter of 7th century	83.20	11.10	5.10	One complete ear, half of another ear, eyes missing. Height 0.26 m.	AM p. 41, 43
GS31	*B. 11 (Samos Museum number)	Cast griffin	Heraion Sanctuary, Samos	Last Quarter of 7th century	86.80	3.50	8.30	Partial ears, eyes missing. Knob on top of head. Height 0.31 m.	AM p. 41, 43
GS32	AM B35.1	Cast griffin head, large size	Heraion Sanctuary, Samos	Mid-7th century	73.9	0.19	8.97	Very small sample taken. Samos Museum number: B. 822. Small part of right ear; fragment of wall of the head. Height 0.127 m.	AM p. 33
GS33	AM B37.4	Cast griffin head, large size	Heraion Sanctuary, Samos	Mid-7th century	96.39	–	1.78	Samos Museum number: B. 945. Left eye of large figure; partial inscription. Height 2.1 cm, depth 2.9 cm, length 6.2 cm.	AM p. 34
GS34	AM B36.1	Hammered griffin, large size	Heraion Sanctuary, Samos	Either Oriental import, or Orientalizing (Greece)	77.68	–	12.33	Samos Museum number: B. 943. Right eye with bubbles in the glass, blue rim, greenish eyeball with a green iris. Height 3.1 cm, width 4.9 cm.	AM p. 33

* B. 8 and B. 11: samples from these protomes were taken by A. Steinberg, and the metal analyses were included in Craddock 1984, *Studi etruschi*, p. 266. Dates and descriptions are from Jantzen 1958.

Table 2 – Metallurgical Analysis of Cauldrons, Handles, and Bronze Bowls

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
CH1 Fig. 39	A.1890.590 AN1890.00590	Hydria handle	Mainz?	Archaic	78.0	13.2	8.8	Part of an Etruscan bronze hydria.*	ASH
CH2	A.1965.288 AN1965.00288	Hydria handle	Peloponnesian	6th century (Archaic)	82.0 (?)	9.40	9.1	Bronze hydria handle. Height 17.5 cm, width 19 cm.	ASH
CH3	A.1890.222 AN1890.00222.a AN1890.00222.b	Hydria handle	Chalkidian Greek (Centorbi, Sicily)	Archaic	87.0	0.03	10.7	Two similar handles listed in the museum catalogue. Same find-spot for both.	ASH
CH4	A.1889.1008 AN1889.01008	Handle and rim of oinochoe	Corinth (tomb)	ca. 480	Handle: 90.0 Rim: 82.0	H: 5.50 R: 8.20	H: 3.7 R: 9.7	No description available.	ASH
CH5	A.1948.100 AN1948.00100	Bowl	Dalboki, Bulgaria (Thracian tomb: Eski-Saqhra)	5th century	Foot: 86.5 Handle: 87.0 Rim: 88.0	F: 4.50 H: 4.90 R: 0.11	F: 8.0 H: 7.8 R: 10.5	Bronze bowl, height 10 cm, diameter 25.5 cm.	ASH

The catalog numbers and metal analysis figures used in Table 2, except for the Vix krater (CH8), are located in Craddock 1976 and 1977. **A** refers to Craddock's old catalog number at the Department of Antiquities at the Ashmolean Museum at Oxford; **AN** is the current Accession number at the Ashmolean Museum. Finds-pots, physical details on the objects, and most of the dates were provided by Dr. Yannis Galanakis and Helen Hovey at the Ashmolean Museum at Oxford (**ASH**). For comments on the analytical procedures used on samples from the objects, see note with Table 3, p. 160.

* Hodkinson describes this hydria, dated to 610-590 B.C., as being one of a number of large Lakonian-manufactured vessels that were exported. See: Stephen Hodkinson, "Lakonian artistic production and the problem of Spartan austerity", in: Nick Fisher and Hans van Wees (eds.), *Archaic Greece: New Approaches and New Evidence*, Gerald Duckworth & Co. Ltd, The Classical Press of Wales, London, U. K., 2002, p. 102.

Table 2 – Metallurgical Analysis of Cauldrons, Handles, and Bronze Bowls (*cont.*)

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
CH6	A.1948.101 AN1948.00101	Hydria	Dalboki, Bulgaria (Thracian grave group?)	5th century	Base: 86.5 Main handle: 86.5 Rim: 87.0	B: 3.40 MH: 3.75 R: 0.3	B: 8.5 MH: 8.13 R: 9.8	Height is 40.5 cm, width is 31.1 cm.	ASH
CH7	A.1937.232 AN1937.00232	Jug handle	Sardis, Asia Minor	Hellenistic	82.5	8.60	9.2	Length 13.9 cm, width 1.1 cm.	ASH
CH8 Fig. 41	Vix Krater	Volute krater	Châtillon-sur-Seine, Northern Burgundy	Archaic ca. 520 - 540	not indicated	Body: 0.024 Foot: 0.03 Rim: 0.20 Lion: 1.4 Snake: 1.2 Cover: 0.028 Handle 1: 0.49 Handle 2: 0.59 Statue: 0.16	B: 9.6 F: 11 R: 10 L: 10 Sn: 10 C: 6.9 H1: 9.6 H2: 7.9 St: 10	Height, 1.63 m, without handles 1.495 m. Diameter of cover 1.05 m. Left handle length 33.7 cm. Total weight 208.6 kg. Statuette 1.23 kg. Handles: 45.6 and 46.15 kg	*p. 90, 254

*Physical descriptions for pages 90 and 254, and alloy compositions for the Vix krater are found in: Claude Rolley (ed.), *La tombe princière de Vix*, Volume 1, Éditions A. et J. Picard, Paris, 2003.

Table 3 – Metallurgical Analysis of Bronze Statuettes and Figurines in the Geometric and Orientalizing Periods

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S1	CAT 397	Bull	Etruscan (no findspot)	Geometric	81.5	17.2	1.3	Mounted on base, crude, length 2 in., height 1.38 in	p. 58
S2	CAT 138	Female	Cameiros, Rhodes	Geometric	80.5	16.5	2.4	Jointed doll, upper half, height 2.75 in.	p. 11
S3	CAT 159	Duck on wheel	Cameiros	Geometric	93.5	1.2	4.1	One of two ducks on a four-spoke wheel, height 1.6 in.	p. 12
S4	CAT 142	Stag	Cameiros	Geometric	91	2.5	7.6	Stiff proportions, large antlers, legs together, height 3.2 in.	p. 11

The catalogue numbers **CAT**, **REG** and **A** as well as the metal composition of the statuettes and objects in Tables 3 through Table 7 are from a series of articles written by Paul T. Craddock on Greek, Etruscan and Roman metallurgy in the *Journal of Archaeological Science* 1976, Vol. 3 and 1977, Vol. 4. Samples from the objects were analyzed at the British Museum Research Laboratory (BMRL) using emission spectrography (qualitative) and then atomic absorption spectrometry, or AAS (quantitative). The procedures are described in Hughes *et al*, 1976. The sample sizes ranged from 10 to 30 mgs, but Craddock does not note how many samples were taken from each object, except for CAT 265 (S103) where two samples produced slightly different lead amounts (Craddock 1976, p. 97). Emission spectrography is a preliminary analysis of the sample to determine which elements are present, and their amounts in major, minor or trace amounts (*Ibid*, p. 22). AAS depends upon the absorption by atoms present in the sample of light emitted from a hollow-cathode lamp of the element being analysed (*Ibid*, p. 19). Hollow-cathode lamps for over 65 elements were available at the publishing date of the article. The detection limits of the particular instrument that was used for analysis of the object (using an acetylene flame procedure) for Cu, Pb and Sn were 0.00025%, 0.0025%, and 0.0025% respectively; the flameless heated graphite atomiser (HGA) method had detection limits of 0.125, 0.125 and 2.5 ppm respectively (*Ibid*, Table 1, p. 20). The sample size for this type of analysis is usually about 10 mg. Each element is determined separately and major elements are accurate to ±1%. For elements present at concentrations from 0.5%-0.05 wt%, the approximate accuracy is about ±5%, and about ±15% for trace elements under 0.05wt%. Using HGA, the latter figure can be improved to ±5%. As a test of accuracy, samples of other objects obtained from the Bureau of Analysed Samples (*Ibid*, p. 26) were analysed at the BMRL using the above described procedures. The results showed a BMRL standard deviation for Cu/Sn/Pb of 0.66/0.20/0.04, and percentage variations of 0.76/1.9/3.6% respectively (*Ibid*, Table 3, p. 26).

CAT refers to objects that are described in two volumes of bronzes compiled by H. B. Walters (1899 and 1928); **REG** refers to the Department of Greek and Roman Antiquities at the British Museum, and **BM** is the current corresponding British Museum registration number, if applicable; **A** refers to Craddock's old catalogue number at the Department of Antiquities at the Ashmolean Museum at Oxford; **AN** is the current Accession number at the Ashmolean Museum.

Unless otherwise indicated, the page numbers in the **Source** column refer to Walters 1899. **Walt 1** refers to Walters 1899 for respective Plate numbers;
Walt 2 refers to Walters 1928 for respective Plate numbers.

Information and details about the statuettes and objects were collected from the volumes of bronzes by H. B. Walters 1899 and 1928, the British Museum collection database (**BM**), and through personal correspondence with Dr. Yannis Galanakis and Helen Hovey at the Ashmolean Museum at Oxford (**ASH**).

Table 3 – Metallurgical Analysis of Bronze Statuettes and Figurines in the Geometric and Orientalizing Periods (*cont.*)

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S5	CAT 172	Two rams	Rhodes	Geometric	91	1.05	7.8	Front half of two rams, joined back-to-back, shoulders perforated, length 1.75 in.	p. 13
S6	CAT 176	Horse	Phana Valley, Rhodes	Geometric	88.5	1.9	8.4	Rivetted fore-legs joined by a crossbar, vertical hole through body, length 3 in.	p. 13
S7	CAT 134	Man	Rhodes	Geometric	78.5	14.5	8.4	Crude. Feet together, hands on breast, with short girt chiton. Hole through head and under feet, height 1.6 in.	p. 10
S8	CAT 140	Heifer	Cameiros	Geometric	88	1.4	9.5	Cow lying down, height 1 in.	p. 11
S9	* CAT 133 BM reg. no: 1844,0511.38	Man	Rhodes	ca. 700	88 85.5	2.0 0.9	10.7 11.8	Two male figurines. Protruding lips, wide cheeks, crude. Height 3.5 in.	p. 10
S10	REG 1930 6.17.1 BM reg. no: 1930,0617.1	Man	Crete	Geometric	97.5	0.3	1.4	Bronze figure of man with a club, feet together. Height 8 cm.	BM database
S11	REG 1924 7.15.1 BM reg. no: 1924,0715.1	Man	Crete	Geometric 800 - 700	88.5	3.60	3.0	Torso and head, arms and lower legs missing. Height 8 cm.	BM database
S12	REG 1930 6.17.2 BM reg. no: 1930,0617.2	Figure of Sphinx	Crete	10th century	97.0	1.20	1.0	Figure of a bearded wingless sphinx. Craddock lists this as a centaur.	BM database

* Craddock indicates the same catalogue number for two male figurines, each with a different Lab. number. (Jour. of Archaeo. Sci., 1976, No. 3, p. 109).

Table 3 – Metallurgical Analysis of Bronze Statuettes and Figurines in the Geometric and Orientalizing Periods (*cont.*)

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S13 Fig. 46	REG 1905 10.24.5 BM reg. no: 1905,1024.5	Horse	Find at Bassae, probably made in Sparta	ca. 700	91.5	0.36	7.6	Horse on a base, decorated underside with two warriors (Siamese twins - representation of Aktorione) Height 4 in.	BM database
S14	REG 1925 4.22.1 BM reg. no: 1925,0422.1	Horse	Olympia	Geometric	91.5	0.025	9.5	Bronze figure of horse, height 9 cm.	BM database
S15 Fig. 47	REG 1914 4.11.1 BM reg. no: 1914,0411.1	Siren	Olympia?	Geometric 800 - 700	82.5	8.00	8.4	Winged siren from rim of bronze tripod cauldron. Length 6.3 in.	BM database
S16	REG 1925 4.22.4 BM reg. no: 1925,0422.4	Bird	Olympia?	ca. 800	89.5	0.80	10.0	Bronze figure of a bird. Height 4 cm.	BM database
S17	REG 1845 5.19.161 BM reg. no: 1854,0519.161	Animal	Phanaes, Rhodes	ca. 750	88.5	2.20	9.0	Bronze figure of an animal, may be a horse. Height 3 in.	BM database
S18	REG 1939 6.8.1 BM reg. no: 1939,0608.1	Bird	Ithaca	Geometric 800 - 700	87.0	0.4	12.5	Bronze seal with geometric design and handle in form of a bird. Height 3 cm.	BM database
S19	REG 1939 6.10.1 BM reg. no: 1939,0610.1	Male	Delphi?	Geometric 800 - 700	97.5	0.7	1.0	Warrior figure, height 8 cm. Craddock lists it as Archaic.	BM database
S20	REG 1951 6.6.1 BM reg. no: 1951,0606.1	Horse	Asklepieion	Geometric	85.5	0.95	13.0	Bronze figure of horse, height 2 in.	BM database

Table 3 – Metallurgical Analysis of Bronze Statuettes and Figurines in the Geometric and Orientalizing Periods (*cont.*)

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S21	A.1949.330 AN1949.00330	Bird	Megalopolis	Geometric	87.0	1.80	9.5	Bird stamp (material is noted as copper, silver, gold and alloys)	ASH
S22	A.G. 397 AN1896-1908 G.397	Horse	Tegea	Geometric (9th - 7th century)	88.0	0.25	10.4	Cua (long tail?) horse.	ASH
*S23	A.1922.220 AN1922.00220.a	Horse	Olympia?	Geometric (9th - 7th century)	Front: 93.5 Rear: 81.5	0.15 14.0	4.3 12.9	The Ashmolean cat. number describes only the rear legs of a horse.	ASH
S24 Fig. 48	REG 1923 2.12.506 BM reg. no: 1926,0212.506	Animal	Sanctuary of Artemis Orthia (Sparta)	Orientalizing ca. 700 - 600	90.5	0.7	7.6	Figuring of a horse with feet embedded in platform. Height 6.4 cm.	BM database
S25 Fig. 49	REG 1929 10.16.4 BM reg. no: 1929, 1016.4	Male	Peloponnese (?)	Geometric ca. 800 - 700	92.0	0.52	5.7	Figure of warrior carrying dagger. Height 9.6 cm. (Craddock lists it as Archaic)	BM database
S26 Fig. 50	REG 1951 6.6.2 BM reg. no: 1951,0606.2	Human figure	Urartu (?) Found in Samos at Kastania	Geometric 8th century - 7th century	90.0	0.23	8.6	Figure of a deity, low horned tiara, long belted garment (Craddock lists it as Archaic). Height 4 in.	BM database

*S23 Craddock gives analysis numbers that add up to over 100% for the rear legs of the horse (Jour. of Archaeo. Sci., 1976, p. 110). The figures are included here, but they are ignored in the descriptions in Section 3.3.1

Table 3 – Metallurgical Analysis of Bronze Statuettes and Figurines in the Geometric and Orientalizing Periods (*cont.*)

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S27	CAT 204 BM reg. no: 1866,1005.1	Female	Cerigo (Kythera)	7th century	89.5	0.5	8.6	Phoenician in character. Long tight chiton, lower body part is columnar, like a *xoanon*. Height 3.5 in.	p. 19, and BM database
S28	CAT 168 BM reg. no: 1863,0330.25	Two-headed bull	Cameiros, Casviri cemetery	7th century	83.5	1.7	7.5	Bull heads on wheel base, with suspension hook between heads. Height 2.5 in.	p. 13, and BM database
S29	CAT 1811 BM reg. no: 1864,1007.397	Cow or heifer	Cameiros, Casviri cemetery	7th century	86.0	5.5	7.3	Bronze figure of cow, height 3.5 in.	BM database
S30	REG 1856 8.26.503 BM reg. no: 1856,0826.503	Griphon terminal (cauldron fitting)	Kalymnos	7th century	86.5	5.6	4.9	Bronze griffin head, was attached to cauldron shoulder. Height 9.5 cm.	BM database
S31	REG 1824 4.40.2 BM reg. no: 1824,0440.2	Griphon terminal (cauldron fitting)	Samos	7th century	81.0	10.7	6.8	Bronze griffin's head, once attached to cauldron shoulder. Height 11 in.	BM database

Table 4 – Metallurgical Analysis of Bronze Statuettes and Figurines in the Archaic Period

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S32	A.1967.518 AN1967.518	Female	Ionian or Cnidian?	Archaic 550 - 530	90.0	0.02	9.1	stylistically East Greek	ASH
S33	A. 1937.237 AN1937.237	Satyr	Sardis tombs, Asia Minor	Archaic	89.5	0.07	9.5	no description	ASH
S34	A.G. 407 G.407	Gryphon	Mt. Pagus, Smyrna	Archaic	88.0	2.2	8.8	no description	ASH
S35	A.1911.51 AN1911.51	Lion mask	Ephesus?	Archaic	87.5	2.6	9.0	no description	ASH
S36	REG 1951 3.29.4 BM reg. no: 1951,0329.4	Mouse	Cesme (ancient Kysos, Asia Minor)	6th century (Eastern Greek)	76.5	19.6	3.3	Bronze mouse, perhaps votive dedicated to the Cybele fertility cult. Length 3 in.	BM database
S37 Fig. 51	CAT 228 BM reg. no: 1875,0313.13	Sphinx	Cesme (ancient Kysos, Asia Minor)	6th century (Eastern Greek)	76.0	20.0	2.5	Running sphinx. Perhaps votive dedicated to the Cybele fertility cult. Height 2 in., length 2.5 in.	p. 22 and BM database
S38 Fig. 52	CAT 180 BM reg. no: 1852.0901.13	Ploughman with team of oxen	Probably made in Asia Minor	Archaic	90.5-92.5	5.5-6.8	2.3-2.4	Group of four figures: ploughman, two oxen and plough. Length 5 in., height 2 in.	p. 13 and BM database
S39	REG 1907 12.1.258 BM reg. no: 1907,1201.258	Bird	Temple of Artemis (East Greek)	6th century	88.5	1.2	8.8	Bronze figure of a duck. Height 1.3 in.	BM database

Table 4 – Metallurgical Analysis of Bronze Statuettes and Figurines in the Archaic Period (*cont.*)

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S40	CAT 227	Sphinx	Kos	Archaic	90.5	2.5	5.9	Head looking up, recurved wings and inlaid eyes. Height 3.2 in.	p. 22
S41	A. G. 416 G.416	Athena	Aigion, north Peloponnese	550-500	89.5	7.2	2.3	no description	ASH
S42	A. G. 415 G.415	Warrior	Dodona, Epirus	600-400	83.0	9.6	7.3	Dedicated by Nikias	ASH
S43	CAT 232	Lioness	Corfu	End of 6th century	87.5	0.09	12	Ionic Greek art, height 3.75 in., length 6.75 in. (Plate IV in Walters 1915)	p. 23
S44	REG 1907 12.1.257 BM reg. no: 1907,1201.257	Hawk	Temple of Artemis	Archaic	91.0	0.12	8.0	Bronze figure of hawk, length 3.1 in.	BM database
S45 Fig. 55	CAT 195 BM reg. no: 1853,0609.2	Aphrodite	Athens	Archaic	87.5	0.4	13.0	Kore with a long chiton and himation over right shoulder falling in *pteryges*, height 4.2 in.	p. 17 and BM database
S46	REG 1951 6.6.8 BM reg. no: 1951,0606.8	Horse	Athens	6th century	95.0	0.4	6.3	Bronze figure of horse, length 2.5 in.	BM database
S47 Fig. 53	CAT 218 BM reg. no: 1875,0420.3	Male	Athens	ca. 540	85.5	8.6	5.9	Male with pointed beard and long hair falling in two plaits down back. Height 3 in.	p. 21 and BM database

Table 4 – Metallurgical Analysis of Bronze Statuettes and Figurines in the Archaic Period (*cont.*)

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S48 Fig. 54	REG 1900 7.27.2 BM reg. no: 1900,0727.2	Female	Athens	ca. 560	86.5	9.8	2.7	Woman with torch and pomegranate, perhaps Persephone. Height 4.5 in.	BM database
S49	REG 1900 7.21.3 BM re. no: 1900,0727.3	Bull	Athens	ca. 500	77.5	11.6	11.2	Statuette of Egyptian bull Apis, with dedication inscription.	BM database
S50	CAT 139 BM reg. no: 1864,1007.167	Lion	Casviri cemetery, Cameiros	6th century	86	1.03	10.8	Crouching bronze lion placed on a bronze slab, with Egyptian style reclining body and an Assyrian lion aspect to the face. Height 1.5 in., length 4 in.	p. 11, and BM database
S51	CAT 141	Cow	Cameiros	Archaic	86.5	4.2	7.3	Reclining cow, face facing front. Height 1 in.	p. 11
S52	REG 1913 11.13.6 BM reg. no: 1913,1113.6	Lion	Macedonia	ca. 510	85.5	2.1	10.0	Bronze figure of lion, length 3.6 in.	BM database
S53	REG 1868 1.10.177 BM reg. no: 1868,0110.177	Bull	Greece	550 - 500	87.5	3.1	8.9	Bronze figure of bull, height 2 in., length 2.5 in.	BM database
S54 Fig. 56	REG 1946 11.29.1 BM reg. no: 1946,1129.1	Male	Greece	ca. 550	92.0	3.2	4.5	Bronze figure of youth, height 4 in.	BM database

Table 4 – Metallurgical Analysis of Bronze Statuettes and Figurines in the Archaic Period (*cont.*)

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S55 Fig. 57	REG 1909 5.22.1 BM reg. no: 1909,0522.1	Cow	Laconia, Sparta	ca. 530	90.5	3.6	6.1	Bronze cow, with inscription on back: "Lakos dedicated (me) to Hera". Length 3.5 in.	BM database
S56	CAT 1616 BM reg. no: 1859,0301.18	Horseman	Laconia	ca. 550	91.0	5.4	2.6	Horseman astride, horse missing. Height 3.5 in.	BM database
S57 Fig. 58	REG 1929 10.16.6 BM reg. no: 1929,1016.6	Warrior	Sparta	6th century	83.5	6.2	9.3	Figure holding shield in left hand, right arm once held a spear. Height 10 cm.	BM database
S58	A.1923.187 AN1923.187	Lion	Sparta?	Archaic	87.5	2.6	10.2	no description	ASH
S59	REG 1928 1.17.7 BM reg. no: 1928,0117.7	Goat	Corinth	550 - 500	88.5	4.5	6.2	Bronze figure of goat, length 7.2 cm., height 5.2 cm.	BM database
S60 Fig. 59	CAT 253 BM reg. no: 1880,1211.1	Votive wheel	near Argos	6th century	85.0	7.2	8.3	Bronze model of chariot wheel, dedicated to Zeus by Eudamos, with inscription. Diameter 4 in.	p. 28 and BM database
S61	CAT 143 BM reg. no: 1864,1007.400	Stag or ram	Kareimos, Casviri cemetery	ca. 600	77.5	12.0	10.9	Walters lists it as figure of a ram, BM lists it as a stag. Broad horns with tips touching. Height 3 in.	p. 11 and BM database
S62 Fig. 60	REG 1909 6.19.1 BM reg. no: 1909,0619.1	Female	Probably Greece	ca. 500	87.0	1.1	9.6	Bronze head from a kore statuette or a goddess. Height 2.6 in.	BM database

Table 4 – Metallurgical Analysis of Bronze Statuettes and Figurines in the Archaic Period (*cont.*)

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S63 Fig. 61	REG 1922 7.12.1 BM reg. no: 1922,0712.1	Male	Probably Greece	ca. 500	88.0	2.0	8.5	Kouros-style figure of Apollo or youth carrying pan-pipes in left hand. Height 10.5 cm.	BM data-base
S64	REG 1951 6.6.5 BM reg. no: 1951,0606.5	Animal	Thebes (Boeotia)	Archaic ca. 600 - 550	81.0	0.06	16.5	Figure of a goat. Length 2 in.	BM data-base
S65	REG 1951 10.12.1 BM reg. no: 1951,1012.1	Male	Delphi (?)	Archaic ca. 520 - 500	87.5	2.2	9.6	Figure of kouros (youth). Long hair, falling in locks on chest. Left arm across body, perhaps holding object. Height 2.5 in.	BM data-base
S66	REG 1915 7.14.1 BM reg. no: 1915,0714.1 Inscription 948.a	Weapon	Olympia (?)	Archaic ca. 500	74.0	17.0	8.1	Spear-butt with inscription (Theodorus dedicated (me) to (Zeus) the king)	BM data-base

Table 5 – Metallurgical Analysis of Bronze Statuettes and Figurines in the Classical Period

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S67 Fig. 62	CAT 213 BM reg. no: 1868,0110.158	Male athlete	Corfu	Classical ca. 440 - 430	90.0	0.05	9.3	Nude athlete standing in Pheidian manner, height 4.5 in. (Plate II in Walt. 1)	p. 20 and BM database
S68 Fig. 63	CAT 206 BM reg. no: 1868,0110.163	Female	Corfu	Walters lists it as Archaic; Craddock and BM as Classical ca. 460	85	5.8	9.0	Female figure, right foot advanced, right hand extended, long sleeved chiton with apoptygma. Height 3.25 in.	p. 19 and BM database
S69	A. 1884.670 AN1884.670	Cockerel	Probably from Smyrna or Ephesus	500 - 400	81	9.2	9.2	no description	ASH
S70	A. G. 417 G.417	Female	Peloponnese	500 - 450	87.0	1.1	9.6	no description	ASH
S71	A. 1971.875 AN1971.875	Female	Arcadian	ca. 450	85	8.8	6.0	no description	ASH
S72 Fig. 64	CAT 271 BM reg. no: 1879,0610.1	Apollo	Thessaly	Classical BM dates it as Hellenistic, 3rd – 2nd century	84.0	3.1	12.7	Standing Apollo with left leg crossed over the right. Height 8.75 in. (Plate V in Walt. 1)	p. 35 and BM database
S73	A.1971.874 AN1971.874	Male	Northern Greece (?)	500 - 400	89.5	4.3	6.2	no description	ASH

Table 5 – Metallurgical Analysis of Bronze Statuettes and Figurines in the Classical Period (*cont.*)

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S74 Fig. 65	CAT 224 BM reg. no: 1896,1019.1	Male	Thebes (Boeotia)	Walters lists it as Archaic, Craddock as Classical	89.5	6.1	4.2	Male figure, served as mirror stand, long hair falling down back. Solid cast. Height 6.5 in. (Plate III in Walt. 1)	p. 22 and BM database
S75 Fig. 66	CAT 239	Aphrodite	Obtained at Athens in 1813	Walters lists it as Archaic, Craddock as Classical	84.0	7.8	8.6	Mirror stand in form of Aphrodite, long chiton, right hand holding a dove. Height 5.4 in.	p. 24
S76 Fig. 67	REG 1909 7.17.1 BM reg. no: 1934,0717.1	Pallas Athene	Said to be from Pyrgos	ca. 480	83	8.2	8.1	Figure of Pallas Athene on a base, right arm raised and may have held a spear. Height 12 cm.	BM database
S77 Fig. 68	REG 1934 11.16.1 BM reg. no: 1934,1116.1	Athlete	Olympia	ca. 470	84	8.3	7.2	Bronze athlete pouring a libation. Height 8.2 cm.	BM database
S78	A. 1933.472 AN1933.472	Bull	Olympia, Elis, Peloponnese	Classical	86	8.9	5.3	no description	ASH
S79	A 1933.473 AN1933.473	Calf	Olympia, Elis, Peloponnese	500 - 400	83.5	12.3	4.8	no description	ASH

Table 6 – Metallurgical Analysis of Bronze Statuettes and Figurines in the Hellenistic Period

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S80 Fig. 69	CAT 272 BM reg. no: 1824,0405.2	Apollo	Paramythia, Epirus	Hellenistic mid-2nd century	86.5	0.5	11.7	Bronze Apollo bending forward to left, positioned as if stringing a bow. Height 10 in. (Plate V in Walt. 1)	p. 36 and BM database
S81	CAT 273 BM reg. no: 1824,0405.3	Mask of Apollo	Paramythia, Epirus	Hellenistic	83.0	3.2	12.7	Full face mask, hair curled around face, incised pupils. Diameter 3.25 in.	p. 36 and BM database
S82 Fig. 70	CAT 277 BM reg. no: 1824,0429.1	Male	Paramythia, Epirus	Hellenistic	81.5	9.1	9.3	One of the Dioscuri, probably Castor. Hands may have held something. Eyes were inlaid with silver. Height 13 in. (Plate VI in Walt. 1)	p. 37 and BM database
S83	CAT 280 BM reg. no: 1824,0490.4	Aphrodite (Venus in Craddock)	Paramythia, Epirus	Hellenistic	86.0	3.7	10.6	Figure stoops forward, leg raised and bent, wearing a sphendonè. Height 6.9 in. (Plate VII in Walt. 1)	p. 37-8 and BM database
S84 Fig. 71	CAT 279 BM reg. no: 1824,0428.1	Aphrodite	Paramythia, Epirus	Hellenistic	63.0	30.5	3.0	Could also be Dione. May have held spear in right hand. Silver-inlaid eyes. Height 12 in. (Plate VI in Walt. 1)	p. 37 and BM database
S85	A. 1937.234 AN1937.234	Horse	Asia Minor, Sardis tombs	Hellenistic	73.0	17.4	9.3	no description	ASH

Table 6 – Metallurgical Analysis of Bronze Statuettes and Figurines in the Hellenistic Period (*cont.*)

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S86 Fig. 72	CAT 282 BM reg. no: 1865,0711.1	Aphrodite	Patras (Achaea), or perhaps Olympia?	Hellenistic ca. 200 - 100	Back: 87 Head: 69 R. Heel: 68 L. Heel: 63 L. Arm: 59.5	4.4 22.3 24 29.5 33	8.0 6.8 7.2 6.2 8.3	Figure type is the Euploia. Stands on right foot, lifting left foot as if attaching sandal. Nude. Left arm rests on a column or rudder. Height 21.5 in., weight (including base) is 9 kg. (Plate XXVIII in Walt. 2)	p. 38 and BM database
S87 Fig. 73	CAT 1084 BM reg. no: 1865,0103.37	Aphrodite	Peloponnese	Hellenistic ca. 200 - 100	86.5	1.75	12.5	Figure type is the Pselioumene (Walters indicates it as a Anadyoneme). Nude. both hands raised. Height 10 in. (Plate V in Walt. 2)	p. 193 and BM database
S88 Fig. 74	CAT 847 BM reg. no: 1760,0919.1	Head of Sophocles	Smyrna	Hellenistic 2nd century	Curl 91.5 Curl 89.0 Lips 97.0 Head 91.5	0.68 0.03 0.15 0.27	7.2 10.0 2.4 6.75	Head from statue, probably Sophocles. Hair bound by rolled band, like a diadem usually associated with Hellenistic rulers. Height 11.5 in.	p. 153 and BM database

Table 7 – Metallurgical Analysis of Western Greek Bronze Statuettes and Figurines

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S89 Fig. 75	CAT 549 BM reg. no: 1824,0472.4	Female	Crotone ? (Western Greek)	ca. 500	82.5	8.0	10.5	Female (Aphrodite) holding a pomegranate, bronze mirror support. Height 8.5 in.	p. 77 and BM database
S90 Fig. 76	CAT 201 BM reg. no: 1873,0820.20	Female	Locri, Calabria (Western Greek)	End of Archaic period	81.0	9.0	3.2	Canephoros. Female figure with long chiton and patterned himation. May have carried a musical instrument. Height 3.5 in.	p. 18
S91	CAT 202	Female	Locri (Western Greek)	End of Archaic period	74.0	21	3.6	Canephoros. Female figure with long chiton and plain himation. Height 3.5 in.	p. 19
S92	CAT 200 BM reg. no: 1873,0820.61	Female	Locri (Western Greek)	550 - 490	78.0	14.9	7.1	Female wearing long chiton, long hair down back. Possibly Archaistic rather than Archaic. Height 13.3 cm.	p. 18 and BM database
S93 Fig. 77	CAT 550 BM reg. no: 1824,0472.3	Female	Locri Epizephyrii (?) (Western Greek)	ca. 470	84.0	4.3	10.9	Bronze mirror support of a woman holding a quince. Height 8 in. Walters says this is an Archaic Etruscan Aphrodite.	p. 77 and BM database
S94	CAT 189 BM reg. no: 1873,0820.59	Athene	Locri Epizephyrii (?) (Western Greek)	ca. 450 Walters lists it as Archaic.	86.5 base: 90	3.1 base: 1.5	9.2 base: 8.1	Bronze Athene on a base, right arm stretched out, left may have held a spear. Height 5 in with base.	p. 16 and BM database

Table 7 – Metallurgical Analysis of Western Greek Bronze Statuettes and Figurines (*cont.*)

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S95 Fig. 78	REG 1824 4.97.13 BM reg. no: 1824,0497.13	Male	Locri (western Greek)	Hellenistic ca. 200	69.5	18.8	8.5	Male nude. Craddock describes it as a satyr. Height 43 cm.	BM database
S96	CAT 677 BM reg. no: 1867,0508.797	Male	Selinus, southern Sicily	ca. 450 (Western Greek)	83	3.6	11	Bronze statuette of youth or an athlete. Height 5 in. Walters dates it as Late Etruscan.	p. 112 and BM database
S97	A.1890.221 AN1890.221	Kouros	Centorbi, Sicily (Chalcidian style?)	600 - 400	87.5	4.8	7.4	no description	ASH
S98	REG 1873 8.12.179 BM reg. no: 1873,0820.179	Head	Sicily?	ca. 500	85.0	0.05	12.8	Bronze head of bearded man from a statuette. Height 3 in.	BM database
S99 Fig. 79	CAT 515 BM reg. no: 1824,0402.2	Male	Found in Rome, probably made in Campania	460 - 450	87.0	1.1	10.2	Bronze male nude, perhaps part of mirror stand. Similar to Ionic-Attic work in 480-470. Height 18.4 cm.	p. 71 and BM database
S100	CAT 252	Votive Axe	Near S. Agata in Calabria	Archaic	67.5	26.0	6.3	May be a ritual sacrifice axe. On heft are two palmettes in relief with volutes on either side. Blade inscribed in Achaian characters. Height 6.5 in, diameter 3.5 in.	p. 27-8

Table 7 – Metallurgical Analysis of Western Greek Bronze Statuettes and Figurines (*cont.*)

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S101 Fig. 80	REG 1904 7.3.1 BM reg. no: 1904,0703.1	Figure on horse	Armento (in Basilicata, Southern Italy)	Archaic ca. 560 - 550	horse: 91.5 Rider: 93.0	H: 2.98 R: 1.55	H: 5.2 R: 4.5	Warrior on horseback with Corinthian-style helmet. Once held spear and reins. Height 10 in., length 10.5 in.	BM database
S102	REG 1868 1.10.160 BM reg. no: 1868,0110.160	Male	Southern Italy, perhaps Corfu?	ca. 350	88.0	5.80	5.4	Warrior (Ares?) with helmet and spear. Left arm once held a shield. Height 5.25 in.	p. 191 and BM database
S103 Fig. 81	CAT 265 BM reg. no: 1886,0324.1	Greaved leg of a warrior (Ares?)	Magna Graecia, probably from Tarentum	ca. 450	82-85	4.57-12.7	6.6-9.60	Large greaved leg of a colossal statue from the foot to just above the knee, composed of fourteen pieces. Gorgon figure over the kneecap. Height 2 ft. 8 in. (Plate XII in Walt. 2)	p. 33 and BM database

Table 8 – Metallurgical Analysis of Etruscan and Latin Bronze Statuettes and Figurines

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S104	CAT 496 BM reg. no: 1836,0701.4	Female	Italy	575 - 550	89.0	0.90	8.80	Archaic type (*xoanon*) votive of a woman wearing long belted tunic, holds right hand in offering gesture. Height 5 in.	p. 68 and BM database
S105 Fig. 82	CAT 513 BM reg. no: 1772, 0302.9	Male	Italy	ca. 550 - 515	69.0	18.6	9.0	Naked male figure, may be priest. Right hand raised, may have held an object in each hand. Height 8.5 in., weight 1.55 kg.	p. 71 and BM database
S106	CAT 510 BM reg. no: 1873,0820.16	Male	Chiusi (Tuscany)	550 - 530	Fig. 88.0 Base 87.0	Fig. 6.40 Base 6.90	Fig. 6.60 Base 6.50	Archaic-style votive of naked youth with hands at sides and long hair. Stylistic influence from Greek cities in Asia minor and Samos. Holes in base for attachment. Height 8.5 in.	p. 70 and BM database
S107 Fig. 83	CAT 512 BM reg. no: 1873,0820.17	Male	Chiusi (Tuscany)	530 - 480	83.0	5.90	10.7	Votive of naked youth. Raised right hand may have held spear, fragment of object in left hand. Slightly Archaic in style. Height 10.5 in.	p. 70 and BM database

For Table 8, the catalogue numbers as well as the metal composition of the statuettes and objects are found in articles on metallurgy written by Paul T. Craddock: the *Journal of Archaeological Science* 1977, Vol. 4, and in *Studi etruschi* 52, 1984. The analysed objects from *Studi etruschi* were subjected to the same analytical procedures that are described in the note for Table 3 on page 160. Craddock indicates a precision of ±1% for major elements and ±20% for trace elements. Detection accuracy was at least 0.005% in the metal (Craddock 1984, p. 220). The catalogue numbers from both articles by Paul Craddock have been combined for inclusion in this table. Both series of objects were analyzed using the same procedures.

Information and details about the statuettes and objects were collected from two volumes of bronzes compiled by H. B. Walters, and the British Museum collection database. Unless otherwise indicated, the page numbers in the Source column refer to Walters 1899. **Walt 1** refers to Walters 1899 for respective Plate numbers; **Walt 2** refers to Walters 1928 for respective Plate and page numbers.

Table 8 – Metallurgical Analysis of Etruscan and Latin Bronze Statuettes and Figurines (*cont.*)

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S108	CAT 1752 BM reg. no: 1852,0522.1	Animal	Italy	Etruscan 520 - 500	81.5	2.90	12.8	Figure of seated lion, perhaps from a bronze brazier. Height 3 in., length 4 in.	p. 277 and BM database
S109 Fig. 84	CAT 447 BM reg. no: 1864,0316.1	Female	Capua (?) (Walters indicates find was at Sessa)	Archaic Etrusco-Campanian 515 - 480	92.5	0.11	7.30	Girl with hands in gesture of offering. Iron used in the core during casting process. Height 24 in.	p. 61 and BM database
S110	CAT 599 BM reg. no: 1847,1101.23	Female	Vulci	510 - 490	Base: 85.0	Base: 5.20	Base: 9.40	Bronze incense burner with Archaic-style girl dancing on a table, supporting the shaft with bowl. Bowl lost. Walters describes it as a candelabrum. Height 8.5 in.	p. 88 and BM database
S111 Fig. 85	REG 1856.12-26.796 BM reg. no: 1856,1226.796	Male	Capua	Archaic Etrusco-Campanian ca. 510 - 490	76.5	13.2	10.0	Mounted Scythian (Amazon) archer, bow aimed backwards. Decorative attachment from rim of Campanian cinerary urn. Height 4.5 in, length 6 in.	BM database
S112 Fig. 86	REG 1856.12-26.800 BM reg. no: 1856,1226.800	Male	Capua	Archaic Etrusco-Campanian ca. 510 - 490	82.5	7.10	9.20	Mounted Scythian (Amazon) archer, bow aimed forwards. Decorative attachment from the rim of Campanian cinerary urn. Height 4.5 in, length 6 in.	BM database

Table 8 – Metallurgical Analysis of Etruscan and Latin Bronze Statuettes and Figurines (*cont.*)

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S113a Fig. 87	CAT 558 BM reg. no: 1873,0820.262	Male	Campania	Etrusco-Campanian 500 - 480	91.0	2.55	6.70	One of four figures from the rim of a Campanian lebes. Boy dismounting from horse. Walters indicates that these figures are from the lebes with the same catalogue number.	p. 79 and BM database
S113b Fig. 88	CAT 558 BM reg. no: 1873,0820.262	Urn figures	Campania	Etrusco-Campanian 510 - 490	Siren: 85.5 Lid fig: 84.5	Siren: 8.50 Lid fig: 5.80	Siren: 6.20 Lid fig: 9.80	Bronze cinerary urn (*lebes*). Rim decorated with siren figures, wings spread, with a goddess standing in centre of lid wearing long-sleeved chiton and himation. Height 17 in.	p. 79 and BM database
S114	CAT 556 BM reg. no: 1831,1201.1	Male	Etruria	Etruscan 500 - 480	90.0	2.85	6.00	Figure of reclining banqueter, probably from a cista. Wears a tunic, holds a libation bowl. Height 6 in., length 13 in.	p. 79 and BM database
S115 Fig. 89	CAT 444 BM reg. no: 1814,0704.962	Male	Umbria	Archaic Umbrian 500 - 475	86.5	1.90	11.3	Votive figure of a warrior with Attic helmet, cuirass, greaves. Once held a spear and shield. Elongated. Height 28.2 cm.	p. 61 and BM database
S116 Fig. 90	CAT 497 BM reg. no: 1838,0317.2	Female	Perugia (Umbria)	ca. 500	83.0	4.60	11.4	Figure of a female deity wearing a pointed cap and a long girt chiton. Height 6.5 in.	p. 68 and BM database

Table 8 – Metallurgical Analysis of Etruscan and Latin Bronze Statuettes and Figurines (*cont.*)

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S117	CAT 555 BM reg. no: 1893,0524.9	Male	Civita Castellana (Etruria)	Archaic (Faliscan)	87.5	5.00	7.50	Figure of shepherd (Hermes Kriophoros?) carrying a ram on shoulders, standing on a round base. Perhaps from a candelabrum or a cista. Height 10.5 cm.	p. 79 and BM database
S118	CAT 468 BM reg. no: 1824,0466.1	Male	Pistoia (Etruria)	500 - 475	88.0	5.30	6.10	Reclining satyr (Marsyas) wearing a himation, holding flutes. Probably from a vessel rim. Length 5.75 in., height 2.75 in.	p. 65 and BM database
S119 Fig. 91	CAT 500 BM reg. no: 1867,0508.794	Male	Italy	Archaic Etruscan 500 - 475	78.0	13.4	9.2	Boy holding a ball, perhaps from candelabrum. Beardless, thick hair mass in back. Height 3 in.	p. 69 and BM database
S120 Fig. 92	REG 1907.10-20.3 BM reg. no: 1907,1020.2	Male	Arezzo	Archaic Etruscan ca. 500 - 475	81.0	8.10	9.70	Athlete scraping thigh with strigil. Height 4.2 in.	BM database
S121	CAT 448 BM reg. no: 1868,0520.51	Female	Chiusi	Etruscan 490 - 470	88.0	3.90	7.30	Bronze incense burner with girl (Aphrodite?) on three-legged table, once supporting a bowl. Walters indicates that it may be from a candelabrum. Height 7.5 in.	p. 62 and BM database
S122 Fig. 93	CAT 675 BM reg. no: 1772,0302.10	Male	Campania	Archaic Etrusco-Campanian ca. 480 - 460	78.0	14.5	6.50	Figure of youth on a small base throwing a discus. Perhaps from a cinerary urn. Height 6.5 in.	p. 112 and BM database

Table 8 – Metallurgical Analysis of Etruscan and Latin Bronze Statuettes and Figurines (*cont.*)

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S123 Fig. 94	CAT 223 BM reg. no: 1856,1226.779	Male	Torre Annunziata (Campania)	Archaic Etrusco-Campanian ca. 480 - 460	85.0	5.80	8.00	Youth blowing a trumpet, possibly from cinerary urn. Eyes are bronze pellets separately attached. Height 6 in.	p. 22 and BM database
S124	CAT 602 BM reg. no: 1865,0712.11	Female	Sarteano (Italy) Walters indicates Amelia in Etruria as the findsite.	Archaic Etruscan 475 - 450	cart: 87.0 fig: 87.0	3.10 3.30	8.30 8.90	Votive of seated woman (Demeter?) in a cart wearing belted chiton and mantle. There may have originally been animals drawing the cart. Height 4 in., length 8.5 in. (Plate XII in Walt.2)	p. 89 and BM database
S125	CAT 526 BM reg. no: 1873,0820.37	Male	Italy	Archaic Etruscan ca. 475 - 450	base: 80.5 body: 82.4	1.10 6.70	3.00 10.6	Boxer with belt tied in front. Height 3.63 in.	p. 72 and BM database
S126	CAT 454 BM reg. no: 1772,0302.231	Male	Italy	480 - 460	77.0	14.3	8.20	Warrior (Mars?) with helmet and bird's head crest-holder, greaves and cuirass. May have held a spear and shield. Height 21.5 cm.	p. 63 and BM database
S127	CAT 481 BM reg. no: 1847,0806.130	Female	Etruria	5th century	88.0	0.25	12.00	Figure of Eos carrying Kephalos. Fine markings on the wings. Height 4.25 in.	p. 66 and BM database
S128	A.1888. 1432 AN1888.1432	Seated sphinx	Etruria, perhaps made in Corinth	Archaic	88.5	4.4	6.6	no description	ASH

Table 8 – Metallurgical Analysis of Etruscan and Latin Bronze Statuettes and Figurines (*cont.*)

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S129	CAT 616 BM reg. no: 1847,1101.9	Fragment of figure	Falterona (Italy)	Etruscan 425 - 375	84.5	4.10	9.90	Arm from a large votive statuette, hand holding part of a rod. Length 9.5 in.	BM database
S130	CAT 613 BM reg. no: 1884,0614.57	Female	Italy	Etruscan 425 - 400	84.5	4.15	10.65	Votive of praying woman in a sleeved tunic. Ribbon on shoulder. Good execution. Height 5.5 in. (Plate XIV in Walt 1)	p. 91 and BM database
S131	CAT 611 BM reg. no: 1865,0712.12	Male	Sarteano (Tuscany)	Etruscan 400 - 350	84.5	4.40	11.20	Athlete standing on right leg looking to right. Inscription to the god Silvanus on base. Height 6 in.	p. 91 and BM database
S132	CAT 473 BM reg. no: 1862,0515.1	Figure	Chiusi (Tuscany)	Etruscan	86.0	5.60	8.90	Figure of satyr looking back. Horse's hoofs, long tail, long hair down the back. Stands on a pierced plate, probably an attachment to top of a cista. Height 4.6 in.	p. 66 and BM database
S133 Fig. 95	CAT 459 BM reg. no: 1847,1101.5	Male	Falterona (Tuscany)	Etruscan	Left arm: 81.5 Helmet: 78.0	Left arm: 7.30 Helmet: 13.60	Left arm: 10.30 Helmet: 9.60	Figure of warrior wearing an Athenian-type helmet. Left arm carries a shield, the right held a spear. Shield and helmet crest were cast separately. Height 12.6 in.	p. 64 and BM database
S134	CAT 615 BM reg. no: 1847,1101.8	Body part	Falterona (Italy)	Etruscan 425 - 375	84.5	3.70	10.4	Hollow-cast leg from a large votive statuette. Height 12 in.	p. 91 and BM database

Table 8 – Metallurgical Analysis of Etruscan and Latin Bronze Statuettes and Figurines (*cont.*)

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S135	CAT 688 BM reg. no: 1873,0820.44	Male with animal	Vulci (Italy)	Etruscan 410 - 390	87.0	4.80	8.70	Boy with goose, exaggerated sizes of left hand and goose. Height 4 in.	p. 114 and BM database
S136	REG 1966.3-28.17 BM reg. no: 1966,0328.17	Male	Norcia (SE Umbria)	Etruscan 400 - 380	76.5	11.80	10.80	Reclining youth holding lyre and a plectrum. Probably from a vessel rim. Length 8 cm.	BM database
S137 Fig. 96	CAT 678 BM reg. no: 1824,0497.3	Male	Etruria	400 - 350	79.5	11.4	7.60	Votive of beardless youth wearing a short mantle, with inscription to the god Silvanus on the thigh. Height 6 in.	p. 112 and BM database
S138 Fig. 97	CAT 1249 BM reg. no: 1824,0446.12	Male	Italy	350 - 300	84.0	9.60	6.20	Bronze handle from a situla cast as a young Hercules; three apples from Hesperides in left hand, right hand holds club. Handle height 25.2 cm; figure height 14.7 cm.	p. 213 and BM database
S139	CAT 605 BM reg. no: 1867,0508.769	Male	Italy	Etruscan 325 - 250	80.0	8.65	10.2	Figure of beardless Hercules, lion skin over head, tied under chin. Probably held an object in each hand. Height 6.25 in.	p. 90 and BM database
S140	REG 1925.7-15.1 BM reg. no: 1925,0715.1	Male	Etruria	Etruscan 300 - 275	87.0	6.15	5.60	Warrior wearing tunic and cuirass, modelled to torso. May have had a helmet, carried a shield and spear. Height not specified.	BM database

Table 8 – Metallurgical Analysis of Etruscan and Latin Bronze Statuettes and Figurines (*cont.*)

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S141 Fig. 98	REG 1824.4-52.1 BM reg. no: 1824,0452.1	Female	Italy	Etruscan 300 - 100	77.0	15.0	6.9	Bust of goddess Juno, probably from a furniture piece. Height 20 cm, width 11.4 cm	BM database
S142 Fig. 99	CAT 608 BM reg. no: 1873,0820.40	Male	Italy	Etruscan 300 - 200	79.0	10.2	9.60	Figure of a seilenos (god of drinking). Faliscan inscription on the legs: POTICNU. Height 5.25 in.	p. 90 and BM database
S143	CAT 665 BM reg. no: 1873,0820.2	Female	Palestrina	Etrusco-Latin ca. 300	78.5	11.8	8.2	Stirgil handle is a figure of Aphrodite who stands on a small base, holding a stirgil in left hand; raised right hand. Total height: 16 in.	p. 110 and BM database
S144 Fig. 100	CAT 683 BM reg. no: 1873,0820.13	Male	Faliscan Territory (ancient Latium)	Etruscan or Faliscan? 300 - 250	76.0	14.5	9.2	Youth (Alexander the Great?) holding a cup and incense box in offering gesture. Top of head is hollowed out. Height 12.12 in.	p. 113 and BM database
S145 Fig. 101	CAT 1696 BM reg. no: 1873,0820.64	Female	Castellani (Tuscany)	Etruscan 200 - 150	79.5	14.40	6.60	Woman with wreath holding out a pyxis. Long chiton, and himation over arm. Height 6.5 in.	p. 271 and BM database
S146 Fig. 102	REG 1921.5-12.1 BM reg. no: 1921,0512.1	Male	Nemi, Sanctuary of Diana	Etrusco-Latin 200 - 100	87.0	26.1	5.5	Votive of youth or priest, holding incense box. Height 25 cm.	BM database
S147 Fig. 103	REG 1913.5-29.1 BM reg. no: 1913,0529.1	Female	Sanctuary of Diana	Etrusco-Latin 200 - 100	69.0	19.5	10.9	Votive of woman or priestess, pouring libation from a phiale. Height 10 in.	BM database

Table 8 – Metallurgical Analysis of Etruscan and Latin Bronze Statuettes and Figurines (*cont.*)

Obj. #	Catalog Number	Figurine Type	Find Location	Date	Cu %	Pb %	Sn %	Details	Source
S148	CAT 1251 BM reg. no: 1873,0820.25	Male	Italy	200 - 100	75.0	13.1	10.5	Figure of young, beardless Heracles holding club and lion skin. Height 4 in.	p. 214 and BM database
S149 Fig. 104	REG 1920.6-12.1 BM reg. no: 1920,0612.1	Female	Sanctuary of Diana	Etrusco-Latin 2nd century	Eight sections: 71.0 - 74.0	17.6 - 20.8	6.6 - 7.7	Votive of young woman, priestess or goddess. Hellenistic chiton. Half-lifesize, cast in nine separate pieces. Height 95 cm.	BM database

Figures

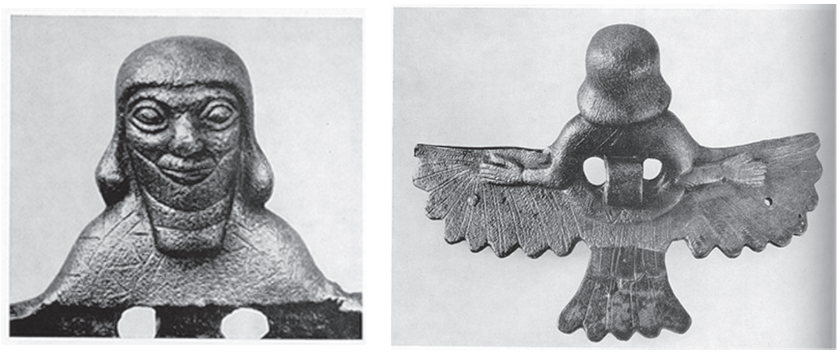


Fig. 11 – Oriental siren from Olympia.
(Tafel 8 in Herrmann 1966, *Olymp. Forsch* VI)
Obj. #: GS12

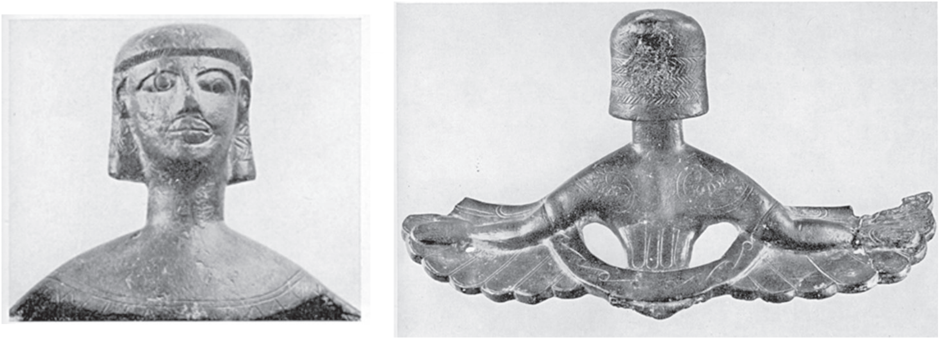


Fig. 12 – Greek siren from Delphi.
(Tafel 35 in Herrmann 1966, *Olymp. Forsch* VI)
Obj. #: GS8

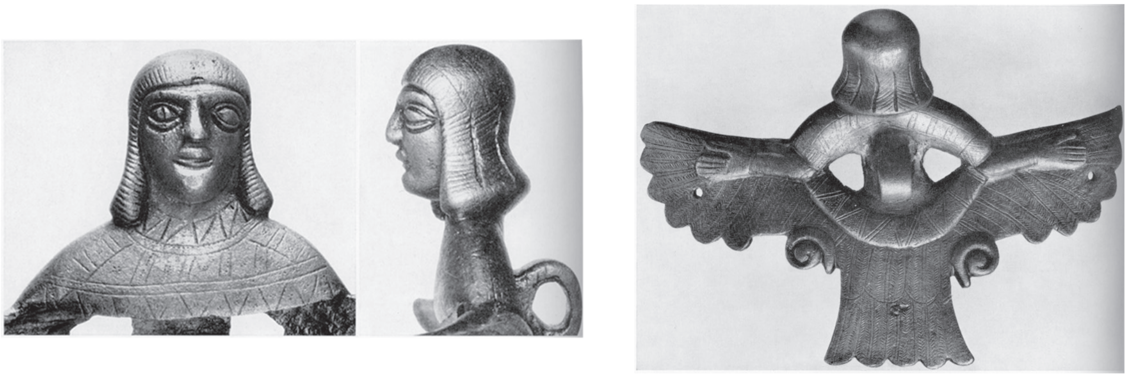


Fig. 21 – Oriental siren from Olympia.
(Tafel 14 in Herrmann 1966, *Olymp. Forsch* VI)
Obj. #: GS10

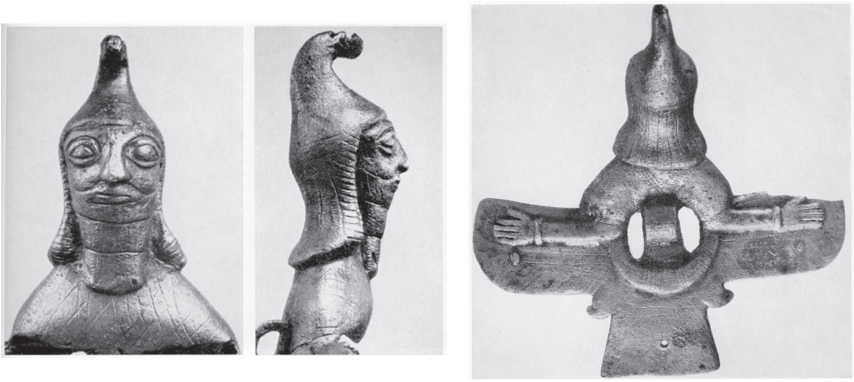


Fig. 22 – Oriental siren from Olympia.
(Tafel 11 in Herrmann 1966, *Olymp. Forsch* VI)
Obj. #: GS11

Fig. 23 – Oriental siren from Olympia.
(Tafel 17 in Herrmann 1966, *Olymp. Forsch* VI)
Obj. #: GS13

Fig. 24 – Oriental siren from Olympia.
(Tafel 21.1 in Herrmann 1966, *Olymp. Forsch* VI)
Obj. #: GS14

Fig. 25 – Oriental siren from Olympia.
(Tafel 21.2 in Herrmann 1966, *Olymp. Forsch* VI) Obj. #: GS15

Fig. 26 – Greek siren from Olympia.
(Tafel 30 in Herrmann 1966, *Olymp. Forsch* VI)
Obj. #: GS16

Fig. 27 – Greek siren from Olympia.
(Tafel 32 in Herrmann 1966, *Olymp. Forsch* VI)
Obj. #: GS17

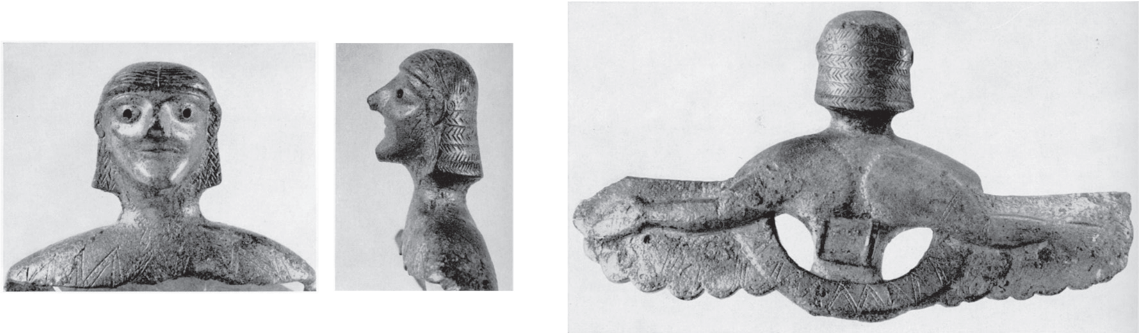


Fig. 28 – Greek siren from Delphi.
(Tafel 34 in Herrmann 1966, *Olymp. Forsch* VI)
Obj. #: GS7

Fig. 29 – Greek griffin from Olympia.
(Tafel 42(2, 3) in Herrmann 1979, *Olymp. Forsch* XI)
Obj. #: GS19

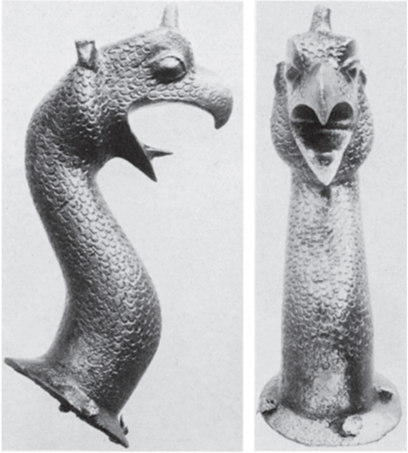


Fig. 30 – Greek griffin from Olympia.
(Tafel 51(3, 6) in Herrmann 1979, *Olymp. Forsch* XI) Obj. #: GS20

Fig. 31 – Greek griffin head from Olympia.
(Tafel 57 in Herrmann 1979, *Olymp. Forsch* XI)
Obj. #: GS21

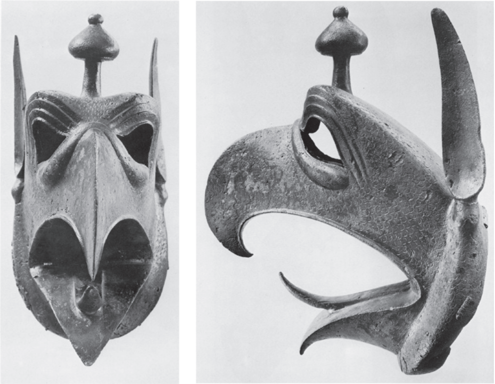


Fig. 32 – Greek griffin head from Olympia.
(Tafel 66 and 67 in Herrmann 1979, *Olymp. Forsch* XI) Obj. #: GS22

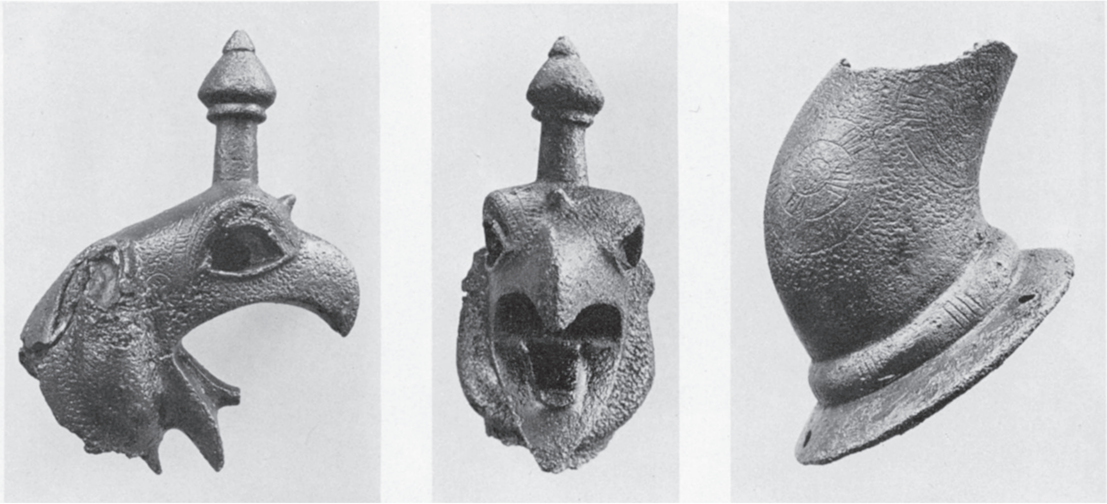


Fig. 33 – Greek griffin head from Olympia.
(Tafel 46(1, 2, 3) in Herrmann 1979, *Olymp. Forsch* XI)
Obj. #: GS23

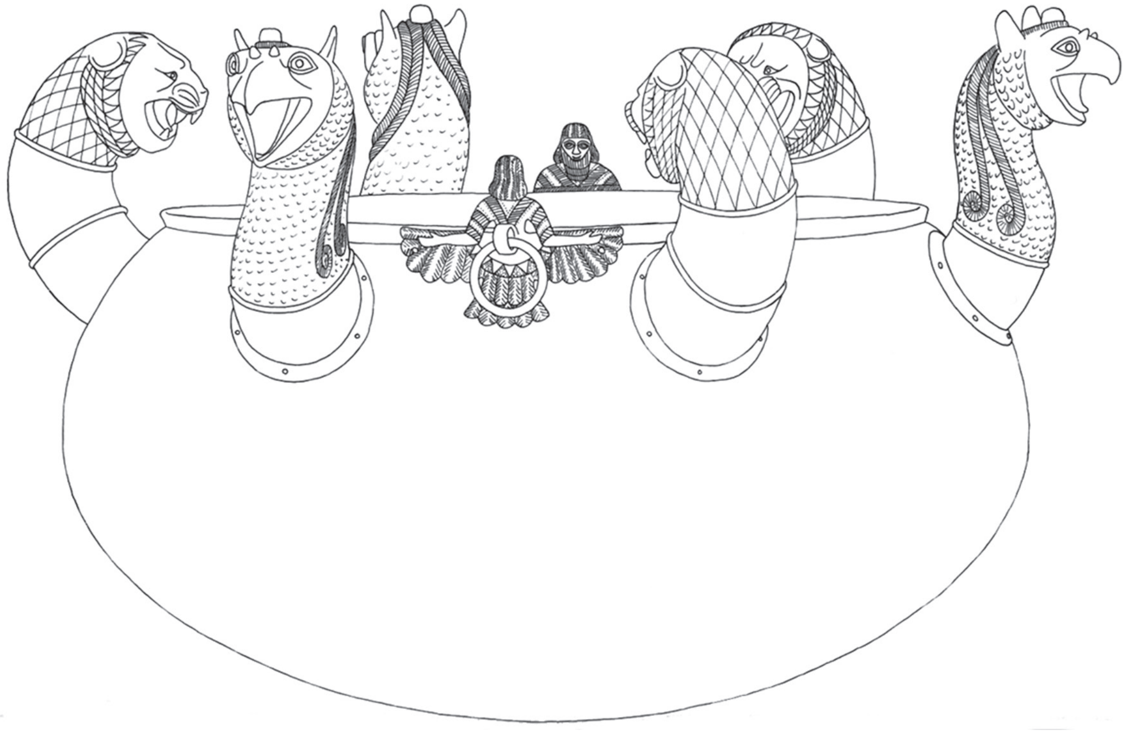


Fig. 34 – Reconstruction of Olympia cauldron B4224.
(Tafel 4 in Herrmann 1966, *Olymp. Forsch* VI)

Fig. 35 – Samian griffin from the Heraion.
(Tafel 32.2 in Jantzen 1955)
Obj. #: GS25

Fig. 36 – Samian griffin from the Heraion.
(Tafel 52.2 in Jantzen 1955)
Obj. #: GS26

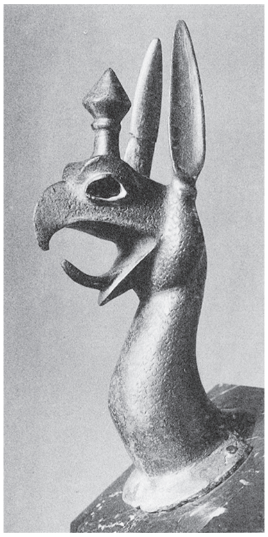


Fig. 37 – Samian griffin from the Heraion.
(Tafel 36.1, No. 103a in Jantzen 1955)
Samos #: BB795

Fig. 38 – Olympia griffin.
(Tafel 36.2, No. 94 in Jantzen 1955)
Olympia #: B.288

Fig. 39 – Laconian hydria.
(8. B1, p. 7, Stibbe 1992)
Ashmolean #: 1890.590

Fig. 40 – Hydria handle.
(Fig. 1b, p. 190, Richter 1939)
Metropolitain Museum Acc. No:
38.11.11A–C.

Fig. 41 – Vix krater, ca. 530
(261, p. 220, Boardman 1980)

Fig. 42 – Altin Tepe cauldron and tripod with bullhead attachments
(Plate XIII, Barnett and Gökce 1953)

Fig. 43 – Bullhead attachment detail from Altin Tepe cauldron
(Plate XIX (1), Barnett and Gökce 1953)

Fig. 44 – Bronze hydria from Eretria
(Plate XXII, Richter 1946, Metropolitain Museum of Art)

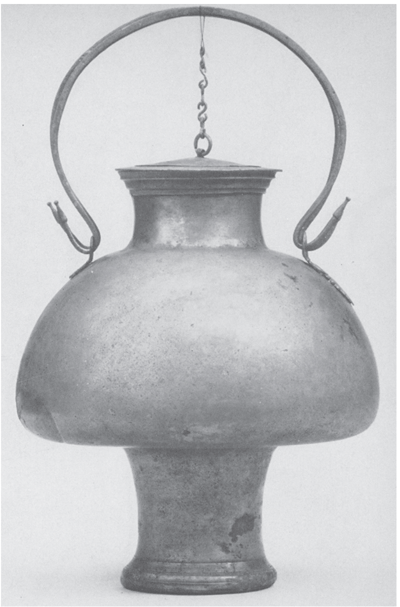


Fig. 45 – Greek Psykter from Macedonia
(Fig. 7, Bothmer 1961, Metropolitain Museum of Art)

Fig. 47 – Siren attachment (Olympia)
REG 1914,0411.1
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Fig. 46 – Geometric bronze horse (Bassae)
REG 1905,1024.5
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Fig. 48 – Bronze animal (Artemis Orthia)
REG 1923,0212.506
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Fig. 49 – Bronze male (Peloponnese)
REG 1929,1016.4
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Fig. 50 – Bronze deity (Urartu?)
REG 1951,0606.2
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Fig. 51 – Sphinx (Cesme)
REG 1875,0313.13
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Fig. 52 – Plough group (Asia Minor)
REG 1852,0901.13
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Fig. 53 – Male (Athens)
REG 1875,0420.3
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Fig. 54 – Female (Athens)
REG 1900,0727.2
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Fig. 55 – Aphrodite (Athens)
REG 1853,0609.2
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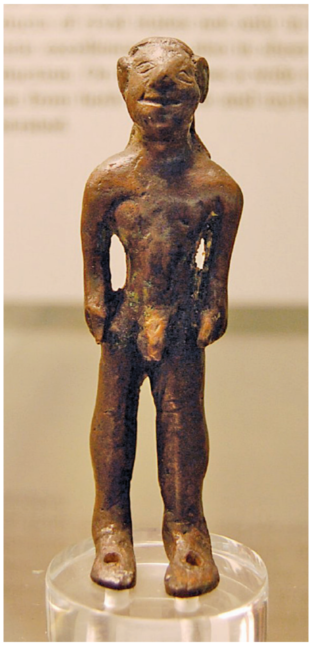

Fig. 56 – Male (Greece)
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Fig. 57 – Cow (Laconia)
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Fig. 58 – Warrior (Sparta)
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Fig. 59 – Votive wheel (Argos)
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Fig. 60 – Kore (Greece)
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Fig. 61 – Kouros (Greece)
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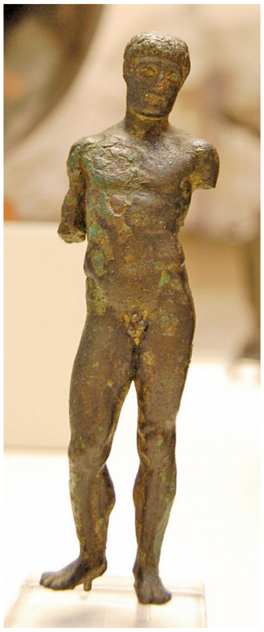

Fig. 62 – Male athlete (Corfu)
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Fig. 63 – Female (Corfu)
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Fig. 64 – Apollo (Thessaly)
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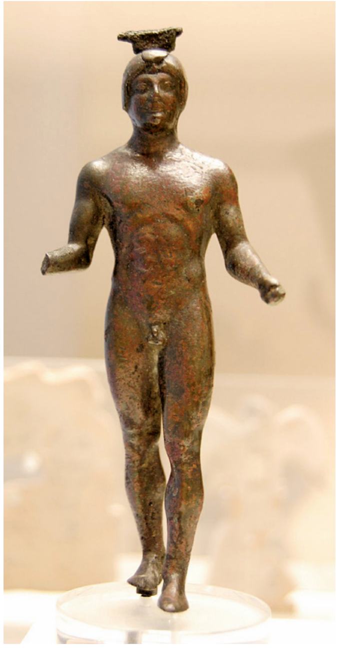

Fig. 65 – Male – mirror stand (Thebes)
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Fig. 66 – Aphrodite (Athens)
REG 1842,0728.640
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Fig. 67 – Pallas Athene (Pyrgos)
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Fig. 68 – Athlete (Athens)
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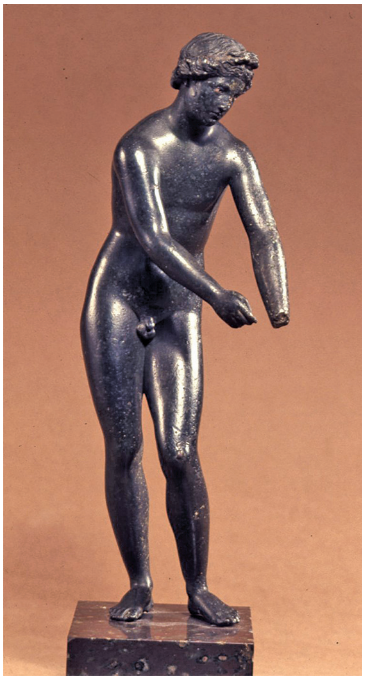

Fig. 69 – Apollo (Paramythia)
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Fig. 70 – Castor (Paramythia)
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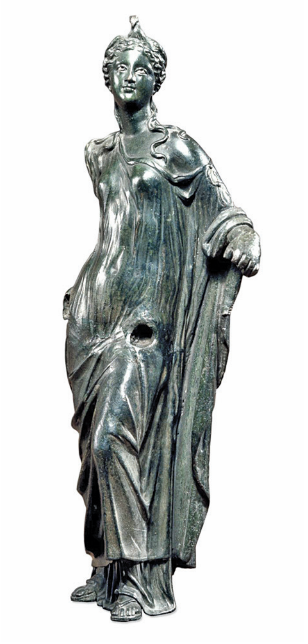

Fig. 71 – Aphrodite (Paramythia)
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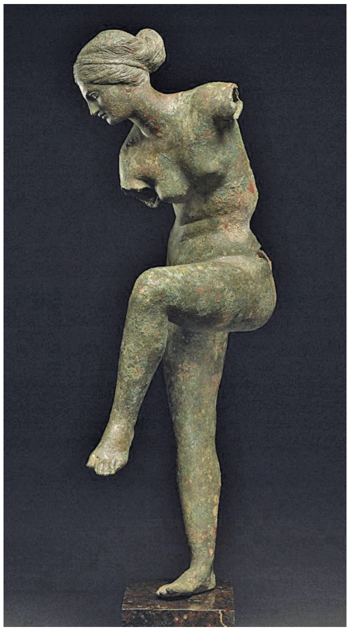

Fig. 72 – Aphrodite (Patras or Olympia)
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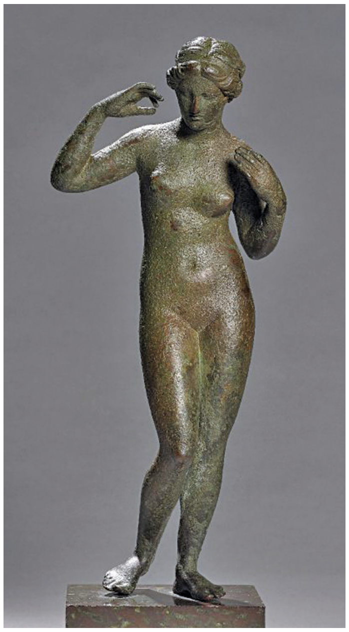

Fig. 73 – Aphrodite (Peloponnese)
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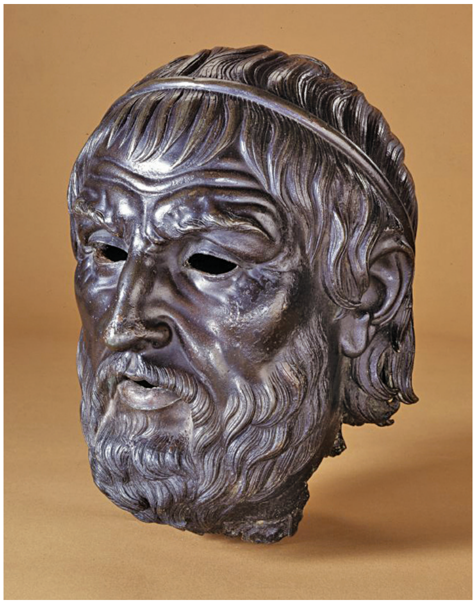

Fig. 74 – Bust of Sophocles (Smyrna)
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Fig. 75 – Aphrodite (Croton)
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Fig. 76 – Female (Locri)
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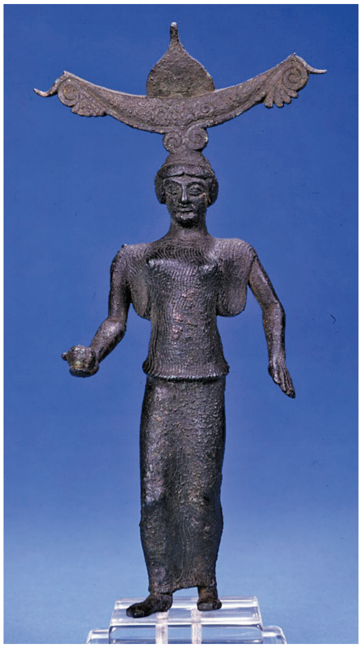

Fig. 77 – Female (Locri)
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Fig. 78 – Satyr (Locri)
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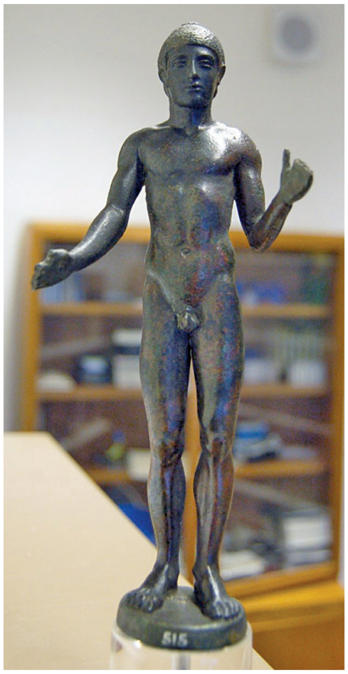

Fig. 79 – Male (Campania)
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Fig. 80 – Armento Rider (Armento)
REG 1904,0703.1
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Fig. 81 – Greaved leg (Tarentum)
REG 1824,0497.13
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Fig. 82 – Male (Italy)
REG 1772,0302.9
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Fig. 83 – Male (Chiusi)
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Fig. 84 – Female (Capua)
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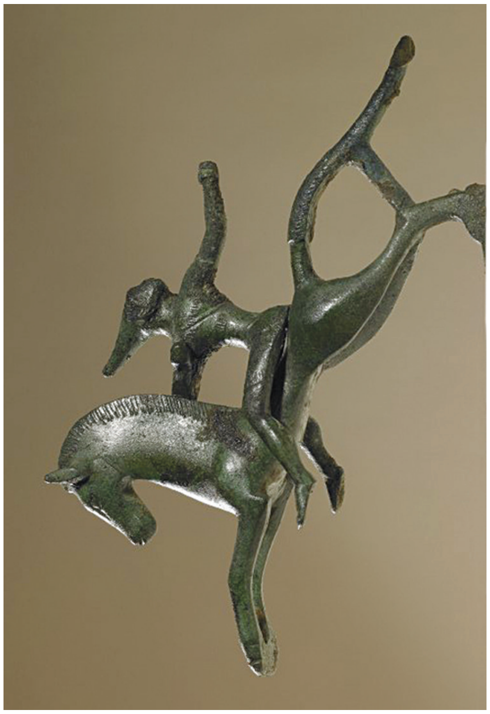

Fig. 85 – Scythian Rider (Capua)
REG 1856,1226,796
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Fig. 86 – Scythian Rider (Capua)
REG 1856,1226,800
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Fig. 87 – Male Rider (Campania)
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Fig. 88 – Cinerary Urn (Campania)
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Fig. 89 – Warrior (Umbria)
REG 1814,0704.962
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Fig. 90 – Female Deity (Umbria)
REG 1838,0317.2
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Fig. 91 – Male (Italy)
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Fig. 92 – Athlete with stirgil (Arezzo)
REG 1907,1020.2
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Fig. 93 – Youth with Discus (Campania)
REG 1772,0302.10
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Fig. 94 – Youth with Trumpet (Campania)
REG 1856,1226.779
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Fig. 95 – Warrior (Falterona)
REG 1847,1101.5
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Fig. 96 – Youth (Etruria)
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Fig. 97 – Hercules (Italy)
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Fig. 98 – Juno (Italy)
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Fig. 99 – Seilenos (Italy)
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Fig. 100 – Youth (Faliscan Territory)
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Fig. 101 – Female (Tuscany)
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Fig. 102 – Male (Nemi)
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Fig. 103 – Female (Nemi)
REG 1913,0529.1
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Fig. 104 – Female (Nemi)
REG 1920,0612.1
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