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5 Recent developments in archaeometallurgical research: the Bronze Age Greek Mainland, Crete, and the Cyclades

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Metallurgy was a fundamental craft industry in the Aegean during the Bronze Age and had some form of impact on almost every aspect of life. This means that archaeometallurgy plays an important role in building our understanding of the region, and has in fact been integrated into Aegean archaeology since the inception of the discipline, well before it was recognized as a separate sub-discipline. Nevertheless, 15 years ago it was still possible for a leading scholar to describe Bronze Age Aegean archaeometallurgy as being in its 'infancy'. Acknowledged weaknesses included a lack of understanding of the Aegean-specific trajectory of metalworking development, reliance on diffusionist theories, a limited interpretative use of scientific analyses, and neglect of research questions tackling social aspects of metal use. This review assesses the progress that has been made since, whether these shortcomings have been addressed, and beneficial future directions for archaeometallurgical studies of the Bronze Age Greek mainland, Crete, and the Cyclades. It focuses on several key themes: the rapidly changing story of Early Aegean metallurgy, the employment of experimental archaeology, the development of scientific techniques and expansion of their use, experimentation with 'big data' approaches, and the varied role of indirect evidence.

Introduction

Roughly one and a half decades ago, two collections of papers on Bronze Age Aegean metallurgy were published in quick succession: *Metallurgy in the Early Bronze Age Aegean*, edited by Peter Day and Roger Doonan (2007), and *Aegean Metallurgy in the Bronze Age*, edited by Iris Tzachili (2008a). The latter noted that Bronze Age Aegean archaeometallurgy was undergoing a significant shift in focus (Muhly 2008; Tzachili 2008b); prehistoric metallurgy was changing from a generalized technological framework tied to social complexity (Mina 2018: 68) to a subject worthy of study in its own right. Metallurgy's individualized trajectory of development – its leaps forwards and setbacks, its local trends and varying pace – was recognized and prioritized for investigation (Tzachili 2008b).

Increased research into mining, smelting, and production was one result (Muhly 2008: 41), encouraged by finds from **Mochlos** (**ID1791**, **ID5459**, **ID9808**; Brogan 2008; Soles 2008), **Chrysokamino** (**ID11646**, **ID11704**, **ID11705**, **ID13318**, **ID14611**; Betancourt 2008), and **Thasos** (**ID9470**; Papadopoulos 2008). Interest in Early Aegean metallurgy was especially strong, and the significance of deliberate arsenical copper (arsenical bronze) production as a distinct stage in European bronzeworking was acknowledged (Tzachili 2008b: 11). The importance of experimental work to improve our understanding of how past technology functioned, and thus the framework of constraints and opportunities within which ancient craftspeople operated, was emphasized (Tzachili 2008b: 13–14), with examples presented in these volumes (for example, Catapotis, Pryce and Bassiakos 2008).

Nevertheless, notwithstanding over a century of research, it was still possible for James Muhly (2008: 74) to conclude that '[t]he study of Early Aegean metallurgy is still in its infancy'. Tzachili (2008b: 28–29) highlighted the many unanswered social questions. Diffusionist theories dominated and metallurgy's impact on people remained unacknowledged (Doonan, Day and Dimopoulou-Rethemiotaki 2007). However, the limited interpretative usage of scientific analyses, despite advances in techniques, was indirectly recognized and being addressed through a search for new applications (Muhly 2008: 41); Maria Mina (2018: 67) later argued they had become divorced from theoretical concerns.

What progress has been made? Since then, several important new discoveries and significant publications of older material have cast fresh light on various debates. The former includes metallurgical activities at Early Bronze Age (EBA) **Dhaskalio** (**ID6045**, **ID6541**, **ID6626**; see below) and Neopalatial **Gournia** (**ID1910**, **ID2860**, **ID4551**; Barnes *et al.* 2019). Here, metallurgical debris was associated with two locations with different characters. Building EM contained a workshop for recycling scrap and casting new objects. Two later Neopalatial rooms in the palace's southwest wing were used for storing and distributing raw material, with copper and tin ingot and debris fragments found alongside Linear A documents. Another important discovery, the 'Griffin Warrior Tomb' at **Pylos**, contained one of the largest single-mortuary context metal artefact groups excavated using modern techniques (**ID5577**; Davis and Stocker 2017). The publication of individual studies means that detailed information about several exceptional finds is already available (Davis and Stocker 2016; 2018).

Noteworthy publications of older material include an overview of the metallurgical evidence from **Poros-Katsambas** spanning from Early Minoan I/IIA to the Postpalatial Period, including a Neopalatial furnace (**ID10222**, **ID11775**, **ID13348**; Dimopoulou 2012), a summary of metalworking at **Tiryns** and its wider cross-craft context by Lorenz Rahmstorf (2015), a report by Mario Benzi (2018) on four artefacts from Dhaskalio Cave on **Kalymnos** (incorporating a survey of EBA finds from the Dodecanese), the **Stephani** hoard from Epirus (**ID15889**; Kleitsas, Mehofer and Jung 2018), and the exciting metalwork from Neolithic **Strofilas** on Andros, comprising 30 copper alloy tools and weapons, a gold bead, and metalworking by-products (**ID2690**, **ID3098**, **ID6618**, **ID11693**; Papamagkana forthcoming; Televantou 2018; 2019).

Summary handbook chapters that may interest Bronze Age Aegean archaeometallurgists include discussions of weighing, commodification, and money by Christopher Pare (2013), copper mining by William O'Brien (2013), goldworking by Barbara Armbruster (2013), tools by Nicholas Blackwell (2020), jewellery by Eleni Konstantinidi-Syvridi (2020), weapons by Matthew Lloyd (2020), and bronze vessels by Hartmus Matthäus and Christian Vonhoff (2020).

What impact have these findings, as well as advances in equipment and techniques, had on Bronze Age Aegean metallurgy? What progress has been made to overcome the interpretative problems discussed above? This review article, while not an exhaustive survey of every recent find and publication, will highlight several major trends evident in Bronze Age Aegean archaeometallurgy over the past 15 years, assess their impact, including whether they have helped address those weaknesses, and discuss future research directions. It covers the Greek mainland, Crete, and the Cyclades (**Map 5.1**); western Anatolia is not included due to significant differences in metalworking practices and socio-political context, as well as practical constraints on space. Nevertheless, western Anatolia was an important influence on the rest of the Aegean, and this review should be considered in parallel with developments in archaeometallurgy in this region (see, for example, Muhly 2011; Mehofer 2014; Pernicka 2014; Massa 2018). Examples of the interconnectedness of these two regions with southeast Europe can be found in Joseph Maran *et al.* (2020). As this review is aimed at both specialists and non-specialists alike, the author has avoided complex terminology and explanations for greater accessibility.

Early Aegean metallurgy

We begin at the dawn of Aegean metallurgy, in the Neolithic (**Table 5.1**). Understanding how and when metalworking reached the Aegean has always been a key goal. Although the first Neolithic metal artefacts were found by Christos Tsountas at the beginning of the 20th century, at **Sesklo** and **Dimini**, only within the last two decades has metallurgy's importance in the Aegean Neolithic been fully appreciated. The finds list is now substantial (Zachos 2010; Dimitriou 2022: 23), and contemporary metallurgical debris demonstrates beyond doubt that various forms of metallurgy were being carried out in the Aegean at this early date (Televantou 2019: 163; Maran 2021), including the employment of both pure and arsenical copper. Despite calls to modify our terminology to reflect these findings, by adopting the term 'Chalcolithic', in

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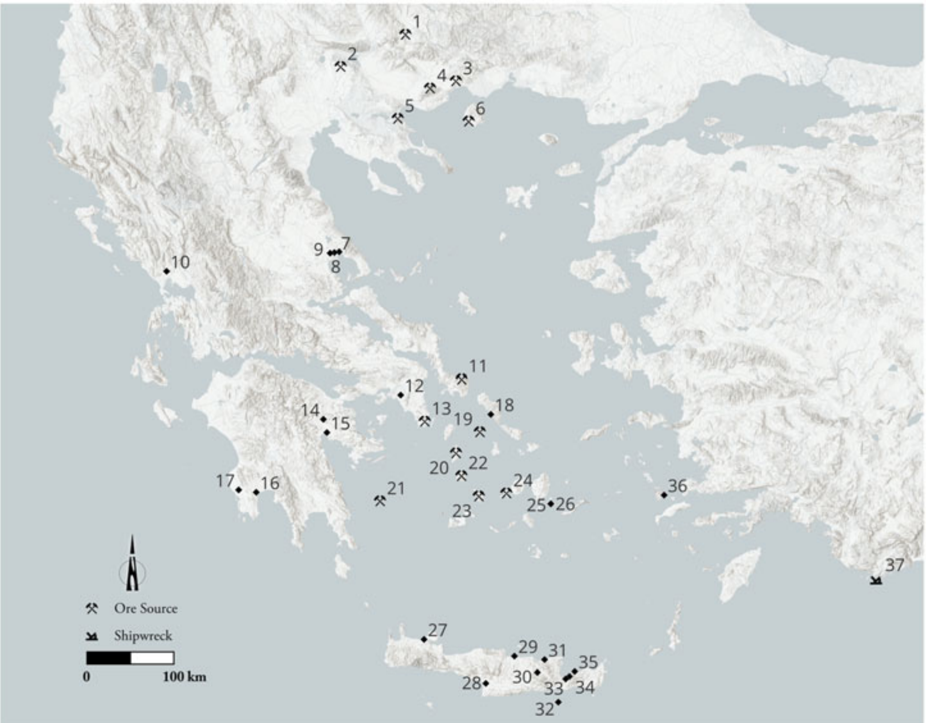
Period	Absolute Dates
Late Neolithic	*ca.* 5300–4500 BC
Final Neolithic	*ca.* 4500–3000 BC
Early Bronze Age	*ca.* 3000–2000 BC
Middle Bronze Age	*ca.* 2000–1700 BC
Late Bronze Age	*ca.* 1700–1100 BC

Table 5.1. Broad chronological table of the Neolithic and Bronze Age in the Aegean. © S. Aulsebrook.



Map 5.1. Map showing the sites mentioned in the text: 1) Angistro; 2) Vathi; 3) Palaia Kavala; 4) Pangaeon; 5) East Chalkidiki; 6) Thasos; 7) Kastro Palaia; 8) Dimini; 9) Sesklo; 10) Stephani; 11) Kallianou; 12) Athens; 13) Laurion; 14) Mycenae; 15) Tiryns; 16) Nichoria; 17) 'Griffin Warrior Tomb', Pylos; 18) Strofilas; 19) Syros; 20) Kythnos; 21) Parapola; 22) Seriphos; 23) Siphnos; 24) Antiparos; 25) Dhaskalio; 26) Keros; 27) Chania; 28) Ayia Triada; 29) Poros-Katsambas; 30) Hagios Charalambos; 31) Sissi; 32) Chyssi; 33) Gournia; 34) Chrysokamino; 35) Mochlos; 36) Dhaskalio Cave, Kalymnos; 37) Uluburun. © BSA.

widespread use in southeast Europe (Zachos 2010) 'Late' and 'Final Neolithic' remain the favoured nomenclature.

Establishing the earliest existence of Aegean metallurgy is just the first step. Characterizing the technology in use has also been an important research question. A restudy of older excavation data by Vasiliki Dimitriou (2022), especially from **Athens**, confirms the Neolithic use of perforated furnaces, previously considered an EBA advancement in extractive smelting technology; an accompanying list of defining characteristics for sherd recognition should prove useful for future investigation. Contextualized analysis of the earliest and largest selection of Aegean gold artefacts, from fifth millennium BC Macedonia (Andreou and Vavelidis 2014), demonstrates the use of basic techniques to form small, simple items through small-scale, dispersed production. Interestingly, this continued unchanged into the EBA, but gold now appeared in mortuary contexts, apparently indicating a shift in social attitudes with no coinciding technological change. A project combining experimental archaeology with microscale analysis of the

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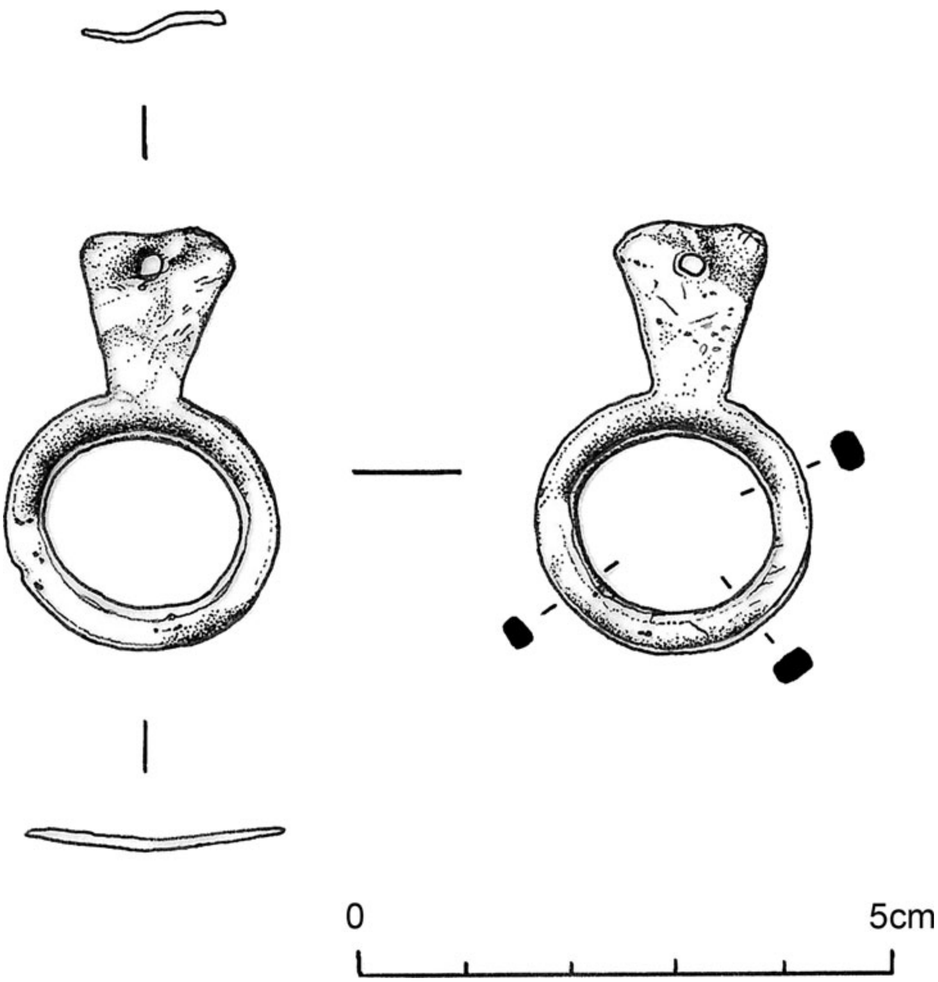

5.1. Theopetra Cave, Thessaly: gold 'ring idol', on display at the Theopetra Cave Museum. It has been dated to ca. 4500 and 3330 BC. © V. Martin.

so-called 'ring idols' (**Fig. 5.1**) by Valentine Martin (forthcoming) shows the coexistence of multiple forming techniques and *chaînes opératoires*, supporting this hypothesis of small-scale, dispersed production. Provenance analysis suggests that, although Aegean metal sources were in use already at this early stage, metals were being imported from further afield, including Anatolia and Slovakia (Stos-Gale forthcoming), and stylistic and technical considerations indicate strong links to the Balkans as well (Zachos 2010).

An important recent discovery was the, perhaps unexpected, nature of the role of Dhaskalio in EBA Cycladic metal production (Boyd *et al.* 2021; Renfrew *et al.* forthcoming). While excavation of the nearby Special Deposit South on **Keros** revealed very little metal or metallurgical debris, survey and excavation of the Kavos promontory and its vicinity recovered evidence for primary metalworking, despite the lack of local ores (**ID661**, **ID675**, **ID848**). Production included pure copper, arsenical copper enriched with lead, and possibly silver. The finds from Dhaskalio, though, dwarf these and those from every other EBA Cycladic settlement. With hundreds of metal artefacts and multiple metallurgical installations uncovered, Dhaskalio was clearly a major metal production centre throughout the EBA for the Cyclades, and perhaps beyond. Metallurgical locales were identified in the field through portable x-ray fluorescence (pXRF) soil sampling, supported by further sampling for lab-based analysis. Arsenical copper predominated. Initial results also indicate activities related to gold, silver, lead, and tin bronze. Evidence included moulds, *tuyères*, crucibles, and plaster-lined furnaces set into rock; installations were apparently differentiated by material. The islands of Dhaskalio and Keros may have simultaneously served as a cosmological, cultural, and craft production centre for the whole Cyclades, designed to be visited in-person by large groups, not just specialists or representatives, with extensive resources invested into the sites and their activities. Analysis and publication are ongoing, though it is already clear that metalworking here was deeply integrated into the social fabric and ritual practices of the entire region.

Our understanding of EBA metallurgy continues to develop by combining new analyses of recently excavated material and experimental archaeology. An experimental smelt by Nerantzis *et al.* (2017) obtained slag from an EBA-style furnace to compare against metallurgical debris from Thasos. Metallurgical debris is the best evidence for investigating primary metalworking, as finished artefacts only provide limited indirect information. Experiments like this one demonstrate the considerable effort and time smelting metals required; the furnace alone needed five days to dry before it was ready. When you add in the extra time needed to source and prepare suitable refractory materials, as well as the fact that this single-use furnace type was rebuilt from scratch for every smelting event, it becomes possible to appreciate why metal artefacts were so carefully curated. Unfortunately, of course, this means they did not metaphorically 'fall down the back of the sofa' as often as we archaeologists would like. Deliberate deposition of metalwork, particularly during the EBA, should therefore not be treated lightly; it had serious consequences for communities, to be borne in mind when using terms such as 'poor' to describe burials with few or no metal artefacts.

Another possible step forward relates to silver production. Finds of litharge, a by-product of cupellation, which separates lead from silver after smelting argentiferous lead ore (galena), have been assumed to prove EBA silver was obtained from galena found, among other locations, at **Laurion**. However, Wood, Hsu and Bell (2021) argue that galena is not a straightforward silver source; the silver is invisible until after cupellation and the yield is small, needing approximately 500kg of ore to be processed to produce 1kg of silver – a significantly worse ratio than other ores exploited at this time. They suggest the use of 'dry silver ores', such as cerargyrite, which have visible silver and higher yields but require the addition of lead to collect the silver and thus a final cupellation separation stage. This interpretation would account for the unusual hazelnut-like shape of EBA litharge, noted also by other scholars (Maran 2021: 209). Further research is required to assess this possibility, especially given its implications for provenance studies and in the light of the recent detailed study of Laurion's geology (Ross *et al.* 2021).

We cannot expect early metallurgy to fully resemble later, better-known, technical or social practices, which were themselves developed over several centuries. Myrto Georgakopoulou (2016) argues that metal source monopolies were non-existent in the EBA, with visits made to well-known or easily accessible ore sites, rather than the richest; ore prospection is another art perfected over generations. Another example is the special relationship between Kythnos and the Ezero community in Bulgaria, which, despite locally available copper ore, imported it from Kythnos for 500 years (Stos-Gale and Băjenaru 2020: 280).

Perhaps the most compelling illustration comes from a study carried out by Borja Legarra Herrero and Marcos Martinón-Torres (2021) on Prepalatial and Protopalatial Cretan gold. Artefacts from Mochlos, **Sissi**, and **Hagios Charalambos** were analysed using pXRF to study their composition and examined under an optical microscope. Combining these techniques revealed surprisingly eventful biographies for certain objects in extraordinary detail. Differing production methods were employed, and many pieces were re-used, adjusted, adapted, and re-purposed multiple times through piercing, cutting, and even ripping; damaging actions that fit uncomfortably with traditional interpretations of the high status accorded to gold. Selective sharing, generating connections of dependence to reinforce group identities, is argued as the reason behind these actions, which do not indicate a steady, constant gold supply; perhaps this particular social role for gold was only possible in its absence. This project will next investigate material from other sites, looking for inter-site links.

Finally, it is important to note that ongoing compositional analyses of Aegean metal artefacts have proved that Crete did not generally rely on arsenical copper into the second millennium. This previous hypothesis was based mainly upon **Ayia Triada**, the only known Prepalatial site without tin bronze (Bassiakos and Tselios 2012: 156). The picture for the Middle Helladic Greek mainland is harder to

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determine, due to the paucity of metal artefacts, although work by Eleni Asderaki-Tzoumerkioti *et al.* (2018) at EBA **Kastro Palaia** demonstrates the simultaneous use of arsenical copper and tin bronze, also seen at other nearby sites.

The methods and approaches discussed above encapsulate current trends in Bronze Age Aegean archaeometallurgy. As research on metallurgy after the EBA has been much more piecemeal, and the changes in our understanding over the past 15 years less dramatic, the remainder of this article switches from a chronological progression to draw out some of these key themes and describe their impact on the discipline in more detail.

Experimental archaeology and reconstructing object biographies

The importance of both experimental and experiential archaeology rests upon their bridging between the archaeological record and theories generated through archaeometallurgical research. A well-designed and well-executed project acts as a proving ground for assumptions and hypotheses, providing a tangible link between past practicalities and surviving material traces. An assessment of experimental archaeology by Roger Doonan and David Dungworth (2013) carefully discusses the benefits and difficulties of conducting such research, and several recommendations, including incorporating time-lapse photography and video recording or integrating craft skills and experiential feedback into publications, have been acted upon (examples given in the following paragraphs).

Smelting has attracted much attention from experimental archaeologists over many decades, but the relative rarity of securely identified Bronze Age Aegean smelting locations may account for the comparatively few Aegean-specific experiments. Each smelting technology is idiosyncratic, and many questions remain concerning ore types and preparation, fuel and flux choices, furnace shape and size, operation and scheduling, etc. Aside from their useful generation of metallurgical debris for comparative purposes, this means the continuation of experiments based on Aegean-specific data is essential. Work by the Laboratory of Archaeometry in Demokritos, such as the experiment by Nerantzis *et al.* (2017: 118–20), has been especially valuable in this regard.

As production once again becomes an important archaeological research question, experimental archaeology has been employed to test ideas about artefact manufacture; in contrast, most European and East Mediterranean projects focus upon metal extraction or object usage (Dolfini 2014: 1,338). One valuable contribution has been the work of Christina Clarke (2012; 2013; 2014) on metal vessel production. Utilizing authentic-style tools, Clarke, a qualified silversmith, produced replicas of Minoan forms including, most impressively, a full-sized copper alloy hydria (**Fig. 5.2**). She overturns certain, commonly-held assumptions about metal vessel production, such as the idea that they were directly shaped from sheet, providing complete *chaînes opératoires* for artefacts that were an important Cretan export commodity. First-hand experience demonstrates the physically demanding and repetitive nature of this work, and the toll it must have taken on past smiths. While it has become almost a cliché to discuss the esoteric knowledge of prehistoric smiths, and therefore the high respect accorded to them, we must not forget metalworking was a difficult and even dangerous occupation.

Another example is an ongoing collaboration spanning more than a decade between researchers predominately based at the National Archaeological Museum at Athens and an experienced craftsman, Akis Goumas, to investigate Bronze Age goldsmithing (Konstantinidi-Syvridi *et al.* 2014; 2019; 2020; Papadimitriou, Konstantinidi-Syvridi and Goumas 2016). Their research presentations have included videos of Goumas at work (Goumas 2021), and reconstructions of the *chaînes opératoires* are vividly brought to life through Goumas' detailed drawings (https://www.akisgoumasgallery.com/research-projects.html). Each publication has high-quality colour photographs, conveying not only the relevant details under discussion, but also the researchers' extraordinary observation skills that have been crucial to the project's success. Exposing the intricacies behind Mycenaean goldworking emphasizes the high levels of expertise and the time-consuming and painstaking work for advanced techniques like 'gold embroidery', which used thousands of tiny nails to perfectly gild curved surfaces. Its use provides yet another link between the area of the Aegean and central Europe. Their research into granulation

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5.2. Upper left: Clarke raising the top section/neck of the copper hydria using a wooden stake and granite pestle. Lower left: using a fine-grained sedimentary stone to grind down sharp edges left after cutting a hole in the shoulder section with a chisel. Right: copper hydria modelled after a bronze Late Minoan IIIA1 hydria in the Archaeological Museum of Chania; 44cm high. © Upper and lower left: C. Clarke (photo by Lan Nguyen-hoan); right: C. Clarke (photo by J. Kuhnen).

demonstrates how smiths corrected issues arising from the technique's complexity. Even the production of the hundreds of gilded bone ornaments found in Circle A at **Mycenae** (**Fig. 5.3**) required precision, patience, and the careful application of geometrical principles. The mainland preference for gold has contributed to unfavourable judgements of Mycenaean achievements in the arts. The level of refinement revealed by this project should prove the final nail in the coffin for such arguments.

A similar project by Romain Prévalet (2013) studies Cretan and Levantine goldworking techniques, integrating experimental and ethnographic data to consider how physical workspaces were organized and the tools required. Reconstruction of the *chaînes opératoires* meant production differences between the two areas were traced, and Aegean influence on goldworking identified at Ugarit and Alalakh. Workshop attribution for metalwork has been attempted by many scholars, with varying results. Although this type of research is difficult and requires careful consideration of hybridity and imitation, recent advancements in both optical and scanning electron microscopy (SEM) should provide more robust evidence. This is because they enable examination of more subtle details, which may indicate a single crafting unit (workshop or individual). The impact of these advances in microscopy on eastern Mediterranean research was the subject of a session at the Annual Meeting of the European Association of Archaeologists in 2022, organized by the author, Betty Ramé and Valentine Martin.

Combining optical microscopy and SEM with other techniques, such as x-ray imaging or compositional analyses, means objects can now be investigated to an unprecedented degree. This approach has settled the argument about the Mycenaean use of 'niello'; the black substance in question is not niello (metal sulphide) but a specially patinated copper alloy (Giumlia-Mair 2012). It has also significantly raised the bar in terms of the detail attainable for prehistoric object biographies. The restudy of the possibly Bronze Age Aegean cup from Dohnsen (Suchowska-Ducke *et al.* 2021) and an exhaustive survey of metal headbands by Ramé (2019; forthcoming) aim to reconstruct artefacts' full lifecycles. New techniques have been developed to achieve this, such as using vector line tracing to demonstrate that two components of the composite gold necklace from the tomb of the 'Griffin Warrior' at Pylos were made from the same mould (Davis and Stocker 2018: 616). Barry Molloy *et al.* (2016) combined 3D modelling with experimental

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5.3. Mycenae: example of a gilded bone ornament from Grave Circle A, on display at the National Archaeological Museum at Athens. The bone core is clearly visible where the gilding has been damaged. © S. Aulsebrook.

archaeology to improve wear trace analysis and address some of the legitimate concerns raised over this technique (Dolfini and Crellin 2016). However, Bronze Age Aegean experimental archaeometallurgy has clearly focused on production over the past few years. Although scholars working on metalwork have made important contributions to wider archaeological debates about object biographies post-production, including Kate Harrell's (2015) research on fragmentation, experimental archaeology projects such as that by Maria Lowe Fri (2014) studying the impact of use on bronze chisels (**Fig. 5.4**) are relatively rare, despite their valuable insights. Further research in this area should be welcomed.

Scientific analyses: provenancing and beyond

Meanwhile, efforts to scientifically trace the sources of metals used in the Bronze Age Aegean continue. Although copper, gold, lead, and silver are available in the Aegean (copper: Kythnos, Laurion, **Parapola**, **Seriphos**, **Siphnos**, Thasos; gold: **Angistro**, **east Chalkidiki**, **Kallianou**, **Palaia Kavala**, **Pangaeon**, Siphnos, Thasos; lead/silver: Angistro, **Antiparos**, east Chalkidiki, Kallianou, **Kythnos**, Laurion, Palaia Kavala, Pangaeon, **Syros**, Siphnos, Thasos, **Vathi**; Bassiakos and Tselios 2012: 151; Ross *et al.* 2020, fig. 2; 2021) many of these deposits are quite small, and tin is particularly notable by its absence. Not all these sites have evidence for prehistoric mining, but such traces are often destroyed by later mining activities. Determining provenance reveals the various forms of trade required for Bronze Age Aegean societies to function. It can pinpoint favourable locations in terms of access to exploitable resources and/or as trading network nodes, which would have affected settlement patterns, hierarchies, and socio-political trajectories. Provenancing metals has been a core goal for archaeometallurgical science for several decades, but integrating these analyses into the wider archaeological picture has not always been straightforward (Tzachili 2008b; Killick, Stephens and Fenn 2020).

Nevertheless, the central role of lead isotope analysis (LIA) in identifying the provenance of copper, lead, and silver is now widely accepted, as is the dominant role of Cyprus in supplying copper to the western and central Aegean after the EBA (Bassiakos and Tselios 2012). The 'age of constant dialogue' (Tzachili 2008b: 29) has reaped dividends. Our understanding and interpretation of LIA has been refined and improved, and a broad consensus reached regarding terminology, particularly the use of 'consistent' to signal compatibility between an artefact and ore source, while acknowledging possible future modifications in the light of new data. The importance of studying more ore bodies to produce higher-quality data (Vaxevanopoulos *et al.* 2022), and thus more robust results, is now widely recognized; the effectiveness of all isotopic analysis depends upon the availability of isotopic ore data. While OXALID remains the largest

5.4. Athens: two examples of typical bronze chisels from the Acropolis hoard, on display at the Acropolis Museum. In use on stone, these tools develop burrs and scratches, as well as deformation of the working edge. Further changes to the profile of the working edge are introduced when the chisel is periodically resharpened. © S. Aulsebrook.

open access database for Aegean isotopic ore data, thorough systematic geological, geochemical, and isotopic surveys, such as mapping the galena deposits in the Cyclades Mineral District by Sandra Wind *et al.* (2020), are extremely important to the discipline's future. Assessments of the overall isotopic situation enable areas with currently overlapping LIA fields, such as Thasos and the Anatolian Taurus mountains (Stos-Gale forthcoming), to be targeted for refinement. It is argued that modelling lead crustal age via LIA provides better distinction than only considering traditional-style bi-plots normalized to the lead isotope ^{204}Pb, by reducing statistical noise (Vaxevanopoulos *et al.* 2022), thus increasing precision and reliability. Examples of the benefits of modern LIA for EBA metallurgy have been discussed above.

In its infancy just over a decade ago (Tzachili 2008b: 19; Haustein, Gillis and Pernicka 2010), tin isotopy is now being combined with LIA and trace element composition to characterize tin ore sources across Eurasia, and therefore reconstruct long-distance trade routes; Eurasian tin ore is rare and unevenly distributed, and not all sources have evidence for BA mining (Nessel *et al.* 2018: 71–73). Employing tin isotopy in isolation is problematic (Martinón-Torres 2019: 163–64), hence the multi-pronged approach. Analysis by Daniel Berger *et al.* (2019) shows that the tin ingot from Mochlos is consistent with a central Asian source and other tin ingots from Israel are consistent with British sources, although results from the **Uluburun** ingots were inconclusive. A more recent study of the Uluburun tin ingots, by Wayne Powell *et al.* (2021), argues for the exploitation of two different sources, one consistent with central Asia (Tajikistan, Uzbekistan, and Kyrgyzstan) and the other with the Taurus mountains.

The central Asian results are also consistent with British sources, a hypothesis rejected by Powell *et al.* (2021) on the grounds that there is more evidence for contact between the Aegean and central Asia than the British Isles. While reasonable, such an approach calls into question the role of scientific analyses within provenancing: do they just confirm pre-existing interpretations already apparent in the archaeological record, or should they provide an independent means of reconstructing long-distance trading networks?

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5.5. Dendra: tinned ceramics from chamber tomb 10, on display at the Archaeological Museum of Nauplio. The coating is damaged on most examples, but modern techniques could make possible the extraction of a useable sample for investigating tin provenance. © S. Aulsebrook.

To achieve the latter, a replicable distinction must be found between central Asian and British ores, thus characterization of the latter is currently underway as part of *Project Ancient Tin*, led by Ben Roberts (https://projectancienttin.wordpress.com/). Initial characterization across Eurasia was carried out by the project *BRONZEAGETIN: Tin Isotopes and the Sources of Bronze Age Tin in the Old World*, led by Ernst Pernicka (Berger *et al.* 2018; 2019; Berger, Brügmann and Pernicka 2019).

We are probably a step closer to answering the long-standing question of how tin moved across Eurasia, with potential implications not only for our knowledge of BA trade and contact, but also the study of the Late Bronze Age (LBA) collapse, as trade network ruptures have been considered a possible contributing factor. The geology of the Mediterranean and its surroundings plus the archaeological record, especially the paucity of tin artefacts, place constraints on what can be achieved (Killick, Stephens and Fenn 2020). The former may be mitigated within the Aegean by assessing the analytical suitability of tinned ceramics (**Fig. 5.5**), potentially opening up a much larger and widely distributed corpus for tin isotopy. Analysis of emerging new finds, such as the tin ingots from Gournia and **Chyssi** Island, may also have an unexpected impact on this debate.

Provenance, though, is no longer enough. New uses are being sought for scientific analyses, which are considered underutilized in the Aegean (Dolfini, Angelini and Artioli 2020). Recognition of the need to integrate scientific analyses with archaeological theory is exemplified by a recent publication dedicated to that endeavour (Armada, Murillo-Barroso and Charlton 2019a). Broader questions concerning the organization of mining are currently being asked (Powell *et al.* 2021), which, as demonstrated by the study of the Welsh Great Orme mine, can only be answered through combining ore geology, mineralogy, archaeometallurgy, and analytical geochemistry (Williams and Le Carlier de Veslud 2019: 1179).

The recycling and perhaps associated mixing of metals from different ore sources, previously characterized as an impediment to LIA (Dolfini, Angelini and Artioli 2020), is now described as a promising research area (Radivojević *et al.* 2018). Mixing varied according to technological and social practices specific to each culture (for example, Nørgaard, Pernicka and Vandkilde 2019; Dolfini, Angelini and Artioli 2020), thus providing a new subject for study. Charilaos Tselios (2020) highlights significant differences between alloying practices in the Prepalatial and Palatial southwest Peloponnese, with the former mixing recycled arsenical copper and tin bronze, and the latter using fixed copper:tin ratio 'recipes'

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based on artefact type. Previously mostly used to examine alloying technology, the possibilities for compositional analysis have been revised by the introduction of the 'Oxford system'. Derived from the older Studien zu den Anfängen der Metallurgie (SAM) classification system that classified metals by composition, the Oxford system works by tracing the biography of a unit of copper by analysing the loss of volatile elements and other related changes (Perucchetti *et al.* 2015). Its proponents are employing it to study recycling and mixing practices, among others. Possible recycling episodes for silver artefacts in Levantine hoards have been hypothesized by comparing the modelled crustal age of their ore against their gold content (Wood 2022). Although the results of this pilot study are not clear-cut and require further consideration of various methodological and confounding factors, it is heartening to see important socially embedded processes, like recycling, becoming the focus of investigation. Provenance will stay a dominant theme for scientific analyses, but their use to explore other topics is a welcome development, and further testing of their potential should be supported.

Metallographic analyses remain rare in Bronze Age Aegean archaeometallurgy. This destructive analysis is currently the only way to achieve a detailed understanding of chemical and physical changes to metal artefacts and metallurgical debris, revealing otherwise inaccessible evidence for production techniques. A recent metallographic study and hardness testing of objects from Epirus (Kleitsas, Mehofer and Jung 2018), including from the Stephani hoard, demonstrates that the hoard's double axes were readied for use, and their smiths understood that selectively cold-hammering their edges without a subsequent reheating cycle (annealing) increased their hardness. Nerantzis *et al.* (2017) use metallography to compare experimental and archaeological slag samples. Results from research by Tselios on Mycenaean-era copper alloy artefacts from the Peloponnese are due to be published soon. The recent resurgence of archaeological interest in production and the widespread and successful use of metallography elsewhere in the world may encourage other institutions holding Bronze Age Aegean artefacts to take the plunge.

Big data and contextual analysis

The continued integration of computers and other digital devices into archaeological practices has encouraged an expansion in datasets, both in size and detail. The benefits for fieldwork and research have been ably described by Boyd *et al.* (2021). Larger datasets enable the employment of more complex statistical analyses, thus potentially revealing macro-scale spatial and chronological trends that, in theory, ought to enable assessment of metal production and usage at a much broader societal level.

Two researchers in particular have pursued this 'big data' quantitative approach for Bronze Age Aegean metallurgy: Lena Hakulin (2013; 2016) and Maria Kayafa (2008), studying Cretan and Peloponnesian data respectively. Both utilize datasets incorporating thousands of artefacts to assess trends in metal use over several centuries, and claim to observe long-term changes in metal flow, such as Hakulin's argument that Minoan and Mycenaean societies used copper alloy for different reasons. Hakulin's innovative methodology, replacing frequency with weight for quantification, is a welcome step forward for investigating metal distribution, given the significant size variability of metal artefacts; although corrosion and breakage may affect their modern weight to some degree, only weighing enables different object categories to be properly compared. The routine publication of weight for metal objects is described as 'crucial' for other research questions too, including the emergence of standardization and weighing systems (**Fig. 5.6**; Radivojević *et al.* 2018).

These approaches have been successfully employed in northern and central Europe, where enormous caches of metal artefacts provide an excellent resource for statistical studies. However, the Bronze Age Aegean archaeological record is not as well-suited. With hoarding relatively rare (**Fig. 5.7**), the diversity of contexts from which metal artefacts are recovered is much wider, with shifts between periods (Clarke 2016), making statistical analyses much more susceptible to biases introduced not only by taphonomic factors, but also fieldwork practices (Aulsebrook 2022), including the uneven state of research. Martinón-Torres (2019) cautions against assuming that large datasets and broad trends provide all the information we need. Although these approaches show great future promise, once our understanding

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5.6. Thebes: two lead balance weights found in the palace and on display at the Archaeological Museum of Thebes. Such artefacts are routinely weighed, in order to test to which weighing system they belong. Unfortunately, the weights of other metal artefacts are rarely published. © S. Aulsebrook.

5.7. Mycenae: the contents of the 'Mylonas Hoard', displayed at the Archaeological Museum of Mycenae. There are fewer than 20 LBA hoards found in Greece; their relative rarity in comparison to the majority of the rest of contemporary Europe is quite striking. © S. Aulsebrook.

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of these issues has improved, fundamentally the number of assumptions currently required to enable analysis to take place seriously undermines its validity (Clarke 2016).

A related bottom-up approach, integrating contextual analysis, may have more success in the short term. Jamie Aprile (2013) studies the intra-site distribution of objects, including metalwork, at **Nichoria**, to reconstruct the settlement's political economy. Gold and silver are limited in both quantity and distribution, whereas copper alloy is found over a much wider area and was apparently accorded a lower curation priority, as demonstrated by the frequency of accidental loss. Lead, absent from the Pylian Linear B archive, is not quite as common as the latter, and is concentrated in certain locations, especially the megaron. These findings help show how metals were used within Nichoria, and their role within the settlement and its political economy. A similar, larger, project focusing on day-to-day use of metals is currently in progress at Mycenae (Aulsebrook 2020). Generating detailed site-specific datasets, within which biases can be more readily identified and mitigated without recourse to assumptions, should make it possible to compare evidence across regions and time to more thoroughly investigate the trends highlighted by Hakulin and Kayafa.

Indirect evidence: old and new approaches

Indirect evidence can usefully fill lacunae caused by various issues that make studying metals somewhat challenging (Aulsebrook 2020: 240–41). Some activities will always remain archaeologically invisible, such as the physical process of retrieving placer gold (Andreou and Vavelidis 2014). Iconography and texts are the main evidence used to supplement the archaeological record.

Unlike contemporary societies, such as Ancient Egypt, Bronze Age Aegean iconography sheds little light on metal artefact production, and their identification is not always straightforward (**Fig. 5.8**; for example, Papageorgiou 2000: 959). Images from other east Mediterranean locations may help, such as depictions of silver ingots carried by Cretans in Theban tomb images (Kelder 2016: 315), but their primary purpose was as propaganda, not authentic renderings of actual events and people. Generally speaking,

5.8. Tiryns: fragment of a pictorial painted krater showing a seated figure with a drinking cup (kylix), displayed at the Archaeological Museum of Nauplio. The artistic conventions of this period and limitations of the medium make it impossible to determine whether a metal or a ceramic cup was intended to be shown here. © S. Aulsebrook.

Aegean iconography can add a more nuanced understanding of typical usage (for example, as weapons), but cannot contribute as strongly as texts.

Linear B, the only deciphered Bronze Age Aegean script, explicitly mentions metals, and continues to be employed to investigate metal use within Mycenaean societies. Recent engagement with this topic includes Barbara Montecchi (2012), Julie Hruby (2013), Dimitris Nakassis (2015), Tom Palaima (2015), Nicholas Blackwell (2018a), and Anna Michailidou (2019). The Jn series, the Pylian tablet series relating to bronzeworkers, remains a central focus for debate, especially for craft organization and palatial control over metalworking. The strength of the evidence provided by the current Linear B corpus is disputable (Aulsebrook 2020: 243–47). Nevertheless, the appearance of paraphernalia related to scribal activities in conjunction with metallurgical facilities at Tiryns may indicate palatial involvement (Rahmstorf 2015: 147). The association between Linear A documents and small-scale metal fragments at Gournia is likewise used to suggest palatial control, in this case over resource distribution (Barnes *et al.* 2019). Whether this extended outside the palace is unclear.

Another form of indirect evidence proving fruitful is tool marks. By examining surviving stonework from Mycenae's monuments, Blackwell (2018b) demonstrates the use of an otherwise unattested metal tool: the pendulum saw. Understanding its operation required extensive modern experimentation with different blade types: another example of experimental archaeology bridging gaps in our knowledge. Work by Blackwell (2014) on the Lion Gate at Mycenae shows how different metal tools were used in combination. The potential of tool marks to unlock information about the use of metal tools in different types of activities (see, for example, Greenfield 2013) is currently underexploited in the Bronze Age Aegean, and could be a promising path for future investigation.

Particularly noteworthy and promising are results from the analysis of dental calculus (Buckley *et al.* 2021). While studying microtraces preserved in archaeological dental calculus, lignite was discovered in three LBA individuals from **Chania**, and six LBA and two Early Iron Age individuals from Tiryns. Lignite, or brown coal, is still available throughout Greece as a surface deposit, and would have been readily accessible; nevertheless, lignite use was not previously believed to predate the Classical period. At Tiryns, it seems the lignite was transported over a significant distance. Further bioarchaeological analysis indicated that three individuals had experienced hard physical labour, and the study presumes the lignite was utilized for pyrotechnical industries, rather than ordinary domestic hearths, although not necessarily metalworking. This new technique embodies the surprising nature of archaeological research and the capacity of archaeologists to find innovative ways to interrogate the past.

Some concluding thoughts

Before discussing the many positive recent developments in Bronze Age Aegean archaeometallurgy, it is necessary to address the elephant in the room in terms of interpretation: preservation. We know the archaeological record is not a faithful reflection of the past, especially for metals. What continues to be up for debate is the proportion of original material our current evidence represents. Taking the Uluburun shipwreck as a quick example, we attain two very different understandings of the role of metallurgy in Mycenaean communities, and ultimately of the whole picture of Mycenaean society, depending on whether we interpret such cargoes as rare supplements to the Aegean metal supply or a regular occurrence. Are we currently studying, for example, *ca*. 0.1% of the total metal supply, or *ca*. 10%? The impact of this lacuna cannot be overstated. It is a basic problem of contextualization. Without being able to fully contextualize our evidence against the background of the total metal supply, we cannot know if our results are meaningful. Returning to the example of the Uluburun shipwreck, we still have little idea as to whether the ship carried a typical cargo. If the voyage was a special rare event, then would the tin onboard necessarily be representative of the ordinary metal supply and does its provenance tell us anything about the wider picture? And if similar ships sailed once a month to the Aegean, can we be certain that the Uluburun cargo provides an accurate summary of the main tin sources, given possible seasonal fluctuations in supply routes? This contextualization is key to understanding meaning and applying interpretation, but it is rare for Bronze Age Aegean archaeometallurgists to explicitly state our own position or discuss its impact on our work. The void this problem creates raises the danger that the equation of metal technology with social complexity, which archaeometallurgists have been working hard to overcome, will be replaced by a presumed link between metal quantity and social complexity, simply shifting the type of assumptions made.

Of course, we can only work with the material in front of us. However, we need to develop methods to account for this 'known unknown' and integrate these uncertainties into our interpretations. One way of doing so is to investigate the potential visibility of various metallurgical activities in the archaeological record. For example, Vana Orfanou *et al.* (2022) demonstrate that, despite the intense heat generated during smelting, air-dried *tuyères* and the upper part of furnaces are not necessarily fired to ceramic, affecting their survival in certain depositional contexts. Thus, experimental work can provide insights into artefact survival rates, as can research into recycling practices. However, big data approaches, which would perhaps be one of the best ways to tackle this issue, do not yet have the evidence base necessary to produce a clear understanding of the overall situation and instead currently rely upon assumptions about the total metal supply, making them unsuitable for such research due to the likelihood of circular arguments. At the moment, increased openness about the interpretative problems caused by preservation and our assumptions about the total metal supply is essential, while we work to engage with and actively address this problem.

Let us now consider what progress has been made on the main issues raised 15 years ago: the neglect of social research questions, relying instead on diffusionist explanations, and the limited interpretative use of scientific analyses. Beginning with the former, clear headway has been made on using archaeometallurgy to study social practices. The importance of contextualizing evidence within Aegean-specific trajectories has been recognized: 'it is more productive to explore metallurgy as a technological process that binds together people, artefacts, materials and products, and forms part of an integral part of historically-situated social and economic contexts' (Mina 2018: 67). Production has been the main beneficiary, with considerable advancement in our understanding of Aegean-specific early metallurgical practices and the initial stages of objects' lifecycles, enhanced by experimental archaeology. Metallurgy itself is less commonly treated as monolithic, allowing, for example, specialization of metallurgical activity locales to be explored as meaningful choices (Muhly 2020). More complex narratives about the social role of metals have emerged that move away from assumptions, particularly 'one-size-fits-all' interpretations (for example, Aulsebrook 2018; Legarra Herrero 2019).

However, generally, efforts to understand the actual use of artefacts and related social practices remain underdeveloped in comparison to production, which is a problem across all archaeometallurgy. Use-wear is not straightforward to study, and many metallurgists have participated in experimental or experiential archaeological experiences related to production, but opportunities to try out authentic prehistoric metalwork are much rarer. These two factors have contributed to a lack of research into sensorial dimensions influencing engagement with metalwork, upon which there have already been wider calls for more detailed studies (Martinón-Torres 2019), such as Susan Sherratt (2019) linking silver and wine drinking, rather than broad aesthetic overviews. Simple improvements, such as the wider availability of colour illustrations, can help us move from thinking about ancient objects as study subjects, to appreciating them as the interactive components of the material world that they undoubtedly were.

This growing appreciation of the unique metallurgical trajectory for the Aegean and its impact on society and social practices is also helping to remove dependence upon simplistic diffusionist explanations. Instead, scholars are increasingly concentrating on specific points of contact between societies and the details of how these facilitated the exchange of ideas, technologies, and material culture. As well as progressively building upon this success, it is imperative that Bronze Age Aegean archaeometallurgists continue to proactively reach out to colleagues working in other areas, especially the rest of Europe and the east Mediterranean, to communicate these findings. It is still relatively common for the Aegean to be sidelined during discussions of Europe-wide trends or for any included information to be derived from out-of-date sources, both of which make it easy for this region to be used for diffusionist explanations. Only

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consistent engagement can prevent the Aegean from being stereotyped as a generally peripheral irrelevance, a communication route between places of greater interest (*ex oriente lux*) or even a socio-political aberration metaphorically labelled 'here be dragons' (*terra incognita* – to be either avoided or populated with whatever best fits a certain theory) whenever these grander narratives are being woven. With our increased understanding of Aegean metallurgy, we must have the confidence to challenge poor interpretations based on these assumptions and stereotypes.

Bronze Age Aegean archaeometallurgists could also play a larger role in the development of interpretative uses for scientific analysis. With a few notable exceptions, the studies discussed above have either included the Aegean within a wider regional project, or focused on another area entirely; more Aegean-specific use of recent technical and interpretative advances in scientific analyses are required. These advances are founded in improved communication between specialists and non-specialists, leading to the boundaries between archaeologists and archaeometallurgists becoming increasingly blurred (Martinón-Torres and Killick 2015). Aegean archaeometallurgy suffered a particularly strong rupture between these two groups, but the trajectory of better understanding observed by Tzachili (2008b) has continued; this should pave the way for increased Aegean-specific use of scientific analyses to address questions concerning social practices.

It is important that while pursuing ever greater detail, demanding increasingly expensive and time-consuming techniques, we do not lose sight of the overall picture. In general, better awareness of why we choose to engage with particular research questions is necessary for the discipline to continue to mature and contribute to Aegean archaeology. Certain research questions that are of importance to archaeologists, such as provenancing, may not always have been especially meaningful in the past (Georgakopoulou 2016). However, these choices are not made in a vacuum. Aegean archaeometallurgy has to contend with a great deal of legacy data and comparatively fewer metal artefacts than scholars working on many contemporary societies, making it harder to persuade institutions to agree to destructive testing. The current popularity of pXRF can be traced, in part, to the fact that it is considered more acceptable rather than because it urgently answers long-standing questions. Unfortunately, this means it is sometimes used in less than ideal conditions, for objects with badly corroded or otherwise unrepresentative surfaces, risking the generation of results that are essentially meaningless. Only respectful dialogue and the adoption of modern minimally destructive techniques, such as obtaining samples with 1mm drill holes or via laser ablation (LA-MC-ICP-MS) (Armada, Murillo-Barroso and Charlton 2019b: 5), can prevent certain research avenues being closed down. The potential of the latter is already being exploited elsewhere in the Aegean (Numrich *et al.* forthcoming), with portable laser ablation being used on gold artefacts from Troy and Poliochni to analyse the metal's composition and provenance. Such techniques could, for example, be gainfully employed to better understand the accumulation of gold that accompanied early state formation processes on the Greek mainland, as manifested in the Mycenae shaft graves.

Therefore, is it possible to state that Bronze Age Aegean archaeometallurgy is no longer in its infancy? Certainly we know much more since Muhly's assessment was published. Some of this knowledge gain has been driven by new finds from well-documented excavations, but several projects discussed above demonstrate that Aegean archaeometallurgy is not reliant on these, and much more remains to be discovered by re-investigating material from older excavations. The discipline has also matured in terms of its use of data. A collaborative spirit is highly visible in modern research, with previously 'rival' approaches (for example, scientific and experiential research, compositional analysis and LIA) being integrated into a single project. Many funding bodies now stipulate, or plan to otherwise encourage, the provision of open access data, which should be helpful in further improving the understanding and usage of archaeometallurgical data (Radivojević *et al.* 2018). Of course, disagreements and debates will continue, but that is a marker of a healthy academic environment.

We have also become better at questioning assumptions. We should expect that aspects of metallurgy that we take for granted today – the techniques used, the problem-solving employed, its social importance – differed in the past, especially during its early phases. This is, in the author's own opinion, one of the things that makes archaeometallurgy so interesting, but is only achievable through due consideration of

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details, for it is in those that past people have the ability to surprise and intrigue us. We need to concentrate on overturning two sets of remaining assumptions: the volume of the metal supply, and the belief that metal use is self-evident because it is always inherently 'better', particularly in the context of display purposes. Fortunately, in this regard, Bronze Age Aegean archaeometallurgists have access to one of the most diverse datasets in Europe. We ought, therefore, to work on unlocking its potential in terms of these lingering research questions, continuing to push the potential of scientific analyses and place the Aegean at the forefront of metallurgical studies.

What we have mainly discovered over the past few years is 'complexity'. Paradoxically, making more detailed examinations, rather than stepping back to assess the general picture as a whole, has enabled us to better appreciate the enormity of the research task ahead. In the future we must assume that every society, every community, even every individual had a different relationship to metal, and, while now developing the tools we need to investigate these details, contextualization should always remain our wider goal.

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