Journal of Archaeological Science : Reports 2016 (accepted manuscript)
http://dx.doi.org/10.1016/j.jasrep.2016.06.013 17 June 2016

Tripod Cauldrons Produced at Olympia Give Evidence for Trade with Copper from Faynan (Jordan) to South West Greece, c. 950 - 750 BC

Moritz Kiderlen (corresponding author) [a], Michael Bode [b], Andreas Hauptmann [b], Yannis Bassiakos [c]

[a] Institut für Archäologie, Lehrbereich Klassische Archäologie, Humboldt-Universität zu Berlin, Unter den Linden 6, D - 10099 Berlin, Germany. moritz.kiderlen@hu-berlin.de

[b] Deutsches Bergbau-Museum Bochum, Abteilung Forschung, Herner Straße 45, D - 44787 Bochum, Germany. michael.bode@bergbaumuseum.de;
andreas.hauptmann@bergbaumuseum.de

[c] Institute of Nanoscience and Nanotechnology, N.C.S.R. «Demokritos», GR - 15310 Aghia Paraskevi, Attiki, Greece. y.bassiakos@inn.demokritos.gr

ABSTRACT

The large assemblages of tripod cauldrons excavated in Greek sanctuaries are well suited to trace the Early Iron Age copper trade. In this pilot study, chemical and lead isotope data of 11 tripod cauldrons from the Zeus sanctuary of Olympia are presented and discussed.

For sampling we selected tripod cauldrons that, according to recent chemical analyses of adhering remains of the casting ceramics, had been produced (cast) on the site of Olympia itself. Chronologically, these samples cover a time span between ca. 950 and 750 BC.

Lead isotope analysis (LIA) and chemical bulk analysis indicate that the copper of all tripod-cauldrons under study was produced in the Wadi Arabah, more precisely in Faynan (Jordan). Our findings point to the existence of a well-organized Levantine - Aegean copper trail, active at least between c. 950 and 750 BC. This result is the first direct evidence for the exchange of commodities between the southern Levant and Greece in this period.

KEYWORDS

Tripod cauldrons, copper, provenance studies, trade, Early Iron Age, Greece, Levant

1 INTRODUCTION

1.1 Relevance of Tripod Studies for Political and Economic History

Tripod cauldrons (henceforward: tripods) were an important object class in Early Iron Age (EIA) Greek society. They were used for the boiling of meat at communal feasts and for preparing hot water for bathing and were thus embedded in practices of conspicuous consumption. Due to their evident material value, they were prestige goods and also played a role as exchange objects. This eventually resulted in the custom to dedicate tripods to the gods, a practice which is observed in a certain range of sanctuaries in EIA Greece. The find distribution between these sanctuaries is highly significant indicating that dedications of tripods concentrated on sanctuaries which served as central meeting places for a politically active elite (Kiderlen, 2010, 91–98 with references). Consequently, archaeological inquiry can use tripods as indicators for the political activities of this elite as well as for the economic structures of the period.

Greek tripods are well suited as a study object since:

1) the number of tripod finds is high (fragments belong to about 970 catalogue numbers),

2) manufacture of tripods involved a wide scale of technologies, including both casting and hammering,

3) metal weights are high (reconstructed weight per tripod: between c. 6 and 30 kg, in some

cases even 100 kg),

4) chronological resolution is good. The typological sequence and its links to ceramic chronology are reliable meaning that most of the tripods can be assigned to one of eight chronological phases in the time span between c. 1200 and 700 BC (phases 0–7),

5) in most cases find spots are documented,

6) archaeometric investigation potentially provides further spatial data, mainly:

– the provenance of the copper (LIA; chemical bulk and microphase analysis; metallography), and

– the localisation of the casting workshops (neutron activation analysis [NAA] of residues of casting ceramics adhering to the tripod fragments; Kiderlen et al., 2015; Kiderlen et al., in print).

1.2 Previous Archaeometric Studies on Tripod Metals

Intensive archaeometric surveys on EIA tripods and other objects were conducted by a team around C. Rolley (Filippakis et al., 1983; Magou et al., 1986; Magou et al., 1991), by J. Riederer (2007), and (with an earlier chronological horizon) by Ch. Tselios (2014). Altogether, these surveys contain about 100 chemical analyses of EIA tripods and 11 metallographic analyses. Generally, these investigations were not focused on questions of metal provenance but on the history of technical knowledge in a cross-cultural and diachronic perspective. But Rolley's group also initiated a large series of LIA done by the Isotrace Laboratory in Oxford. These LIA results were presented at an archaeometrical conference (Gale et al., 1983), but were never fully published. Fortunately however, Magou printed a graphical plot with a very short but important comment stating that the copper source for these tripods is isotopically very distinct from both Cyprus and Lavrion (Magou et al., 1986, 124 and fig. 1). It was this plot that triggered our curiosity.

Other chemical and LIA data come from two tripods from a rich Late Helladic IIIC grave (ca. 1200 - 1075 BC) in the "House of the Tripods" in Mycenae (Magou & Gale, 1995). N. H. Gale interpreted his LIA measurements as an indication for copper from Lavrion, but the very high contents of lead in the alloys of the cast parts of these two tripods (up to 6 %) rather point to added lead that may have "masked" the Pb naturally contained in the copper. There is a similar interpretative problem with a tripod from a Submycenean grave of Kouvará in Aitoliaakarnania (Stavropoulou–Gatsi et al., 2012, 259; compare Gale et al., 2009).

2 MATERIAL STUDIED AND METHODS

2.1 Sample Selection

Phase	Tripod	Inv. No. of Fragment	Part	Sample	References
3 (c. 975-925 BC)	DN 772	Br 11555	leg	TPA 772.1 A	W. 14.54.164 pl. 13
	DN 1163	Br 13379	leg	TPA 1163.1 A	unpublished
5 (c. 850-800 BC)	DN 84	B 2131	leg	TPA 84.1 A	M. No. 84
	DN 93	B 6452	leg	TPA 93.1 A	M. No. 93
	DN 747	B 2512	leg	TPA 747.1 A	W. 102.165 fig. 5 pl. 27
	DN 100	Br 5400	leg	TPA 100.1 A	M. No. 100
6 (c. 800-750 BC)	DN 104	Br 3627	leg	TPA 104.1 A	M. No. 104
	DN 110	B 8850	basin	TPA 110.1 A	M. No. 110
		B 8850	handle	TPA 110.2 A	M. No. 110
		B 4350	leg	TPA 110.3 A	M. No. 110
	DN 117	B 1665	leg	TPA 117.2 A	M. No. 117
	DN 123	B 2403	leg	TPA 123.1 A	M. No. 123
	DN 1156	Br 8765	leg	TPA 1156.1	M. below No. 123

Table 1: Tripod fragments of this study according to chronological phases. M. = Maaß, 1978; W. = Willemsen, 1957.

Out of the large tripod assemblage excavated at Olympia we selected 13 metal samples from 11 tripods (Table 1). According to prior chemical analysis of adhering remains of the casting ceramics with NAA, they had been manufactured (cast) on the site of Olympia itself. Their casting ceramics belong to a chemical group defined as paste M1 that is one of the four clay pastes that currently can be assigned to Olympia (Kiderlen et al., in print).

In most cases one of the legs was sampled, but in one case (tripod DN 110) we additionally sampled the basin and one handle.

2.2 Typology and Chronology

Tripods of the types under study originally consisted of six main parts: the basin, which is hammered out of one single piece of copper alloy as well as three legs and two handles. These were separately cast in the lost wax technique and riveted to the basin (Figure 1).

Figure 1: B 1240, the only complete tripod cauldron excavated in Olympia (not sampled). Like DN 772 and 1163 it belongs to Phase 3 (ca. 975 – 925 BC). H to rim c. 50 cm. Legs and handles are cast in the lost wax technique and riveted to the hammered basin. (Photo G. Hellner, courtesy DAI Athen).

Due to the general modes of object history and deposition in the sanctuary of Olympia, the stratigraphic contexts of the tripod fragments under study are much later than the time of production. Consequently, chronology relies on internal typological grouping and links to comparanda with ceramic contexts at other sites. An overview about recent observations on typology and new stratigraphic contexts will be given in Kolonas & Kiderlen (in preparation).

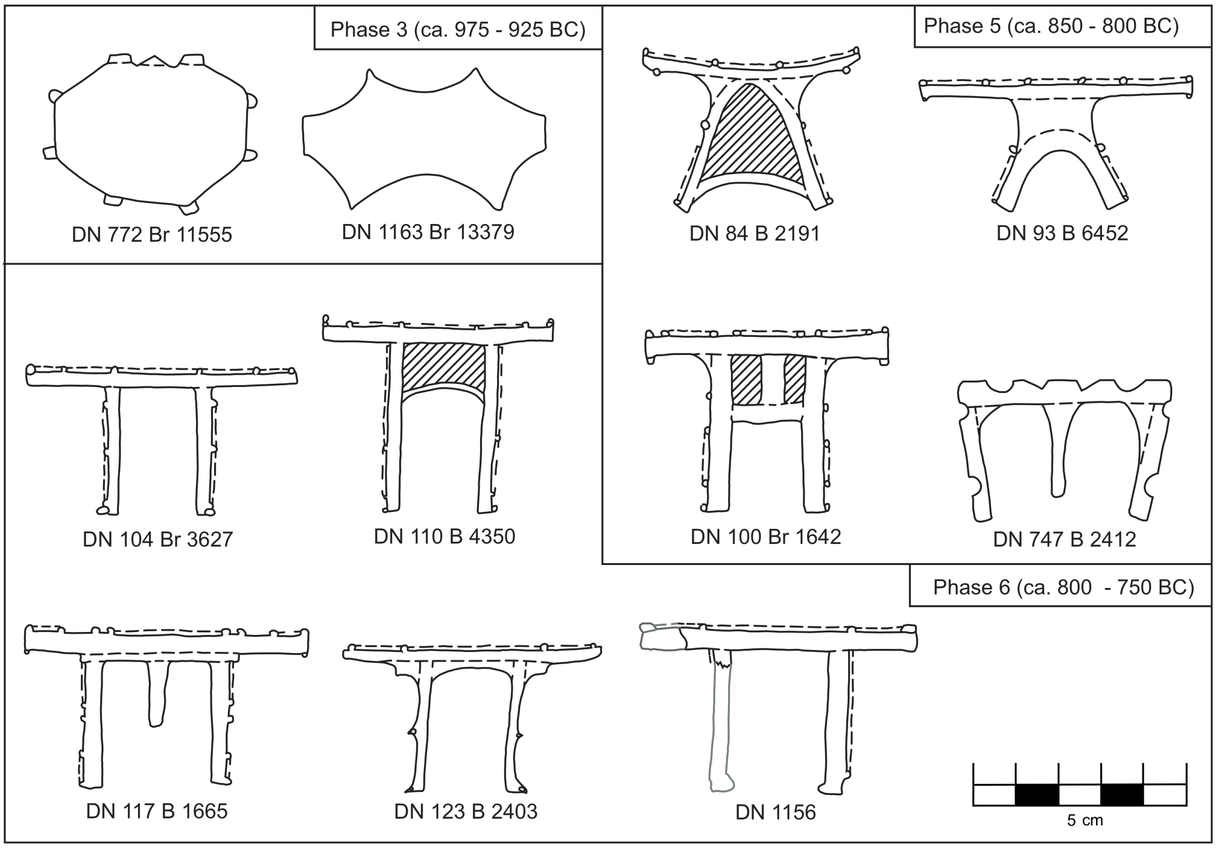

Figure 2: Sections of the sampled tripod legs. The legs were cast in the lost wax technique; DN 84, 100, and 110 with clayey casting cores. The drawings are stylized in order to demonstrate the construction of the wax models.

The fragments of tripods DN 772 and 1163 (Figure 2) are from legs with prismatic sections. Thanks to some hoards and grave contexts, it is clear now that the typological sequence of the tripods with prismatic legs ran through from postpalatial times (Phase 0) down to the EIA (Matthäus 1980, 118-121; Onasoglou 1995; Janietz 2001, 9-29; Stravropoulou–Gatsi 2012; Eder 2015; Lohmann 2015). The most progressive time sensitive elements of DN 772 are its five rivets, the decorative ribs along the edges of the shaft, and a trumpet-shaped knob towards the attachment plate. DN 1163 had a wide central facette running down to the foot. Both belong to Phase 3, which has new comparanda in the Protogeometric cemetery near

Stamná in Aitolia (cf. Christakopoulou–Somakou, 2009, cat. T378; Kolonas & Kiderlen [in preparation]. The new contexts at Stamná make clear that dates proposed for this typological line by Maaß [1978, 6–7; 110; 228], Rolley [1977, 105–113] and Felsch [2007, 30–37] were much too late). The absolute dates given in Table 1 are according to the conventional chronology of Protogeometric and Geometric pottery, which recently was reinforced by C14 (Toffolo et al., 2013).

Well stratified fragments of casting moulds at Lefkandi (Euboean Late Protogeometric, ca. 900 BC) testify the beginning of a new typological series of tripod legs, defined by the use of thin sheets of wax for the construction of the wax models, and by the systematic use of thin wax fillets and cut out wax ornaments for decoration of the resulting flat fronts and lateral sides of the legs (decoration in "application-technique"). The use of wax sheets for construction at first led to trapezoidal or rectangular sections with flaring edges (Kiderlen 2010, 100-102 fig. 2 [moulds from Lefkandi]; compare a leg fragment from the Argive Heraion Strøm, 1995, no. AH 2218 fig. 6-7), and then to Π-shaped or double-T-shaped sections. The leg fragments of tripods DN 82, 93, and 100 are all considerably later than the Lefkandi mould fragments and belong to Phase 5, as evident from their sections with wide protruding fronts, from the repertoire of their decoration, and from the zoning of the lateral sides. DN 747, with a trapezoidal section and decorated with grooves, also belongs to phase 5 according to the zoning of the lateral sides.

Our latest fragments (DN 104, 110, 117 [Figure 3], 123, 1156) are from so-called "Matrizendreifüsse". Here, the wax sheets for the construction of the casting models were taken out of matrices (Maaß 1978, 34–39; 48–58). The patrices of the matrices had been made of wax and decorated in application technique. The "Matrizendreifüsse" belong to Phase 6. Technically and stylistically, they form a compact group, but there are no stratigraphic contexts. Their dates are derived from their sandwich-position between the tripods with the most advanced decoration in application-technique, and the rise of two new workshop groups in the beginning of Late Geometric (ca. 750 BC): tripods with legs decorated with vertical scales ("Gratbeindreifüsse"; Maaß 1978, 49-62), and tripods with legs and handles composed of hammered bronze sheets (Maaß 1978, 63-104).

Figure 3: B 1665, leg fragment of tripod DN 117. The wax model of the shaft was constructed with sheets of wax taken from a matrix. Phase 6 (ca. 800-750 BC). (Photo Kiderlen).

2.3 Analytical Methods

Sample material was taken with hardened steel drill bits of 1.5 mm diameter. In the laboratory of the Deutsche Bergbau-Museum Bochum (DBM), about 50 mg of metal was mixed with 3 ml HCl and 2 ml HNO_3, both half-concentrated. After dissolution, the copper metal solution was diluted up to a concentration of about 1000 mg/l. The chemical composition was determined using inductively coupled plasma mass spectrometry (HR-ICP-MS, ELEMENT XR, Thermo Scientific). Quantification was done with external calibration. For elements in trace amounts, the stock solution was diluted 1:10 with 5 % HNO_3, for copper and minor elements 1:100. For quantifying gold, the sample solutions were diluted 1:10 with 2 % HCl. The analyses were carried out with a FAST SC-system, ST 5532 PFA µ-FLOW nebulizer, Peltier-cooled PFA spray chamber and 1.8 mm sapphire injector in triple detector mode for all three different mass resolutions ($m/\Delta m$). Measurements have been controlled with copper standard BAM 376 (Bundesanstalt für Materialforschung, Berlin) and tin bronze standard

BRONZE C (British Chemical Standards, Middlesbrough, UK). Relative standard deviation for trace elements varied between 0.5 and 4.5 %, for major elements between 0.6 and 1.2 % and for copper around 2 %. The data set is presented in Table 2.

	Sample	Cu	Fe	Pb	Sn	S	P	Zn	As	Co	Ni	Ag [µg/g]	Sb [µg/g]	Te [µg/g]
Phase 3	TPA 772.1	90.7	3.58	2.52	0.13	0.32	0.07	0.06	0.081	0.043	0.052	120	55	<2
	TPA 1163.1	97.5	2.56	0.49	0.01	0.23	0.13	0.08	0.039	0.079	0.048	45	30	<2
Phase 5	TPA 84.1	94.4	2.57	2.68	0.29	0.35	0.22	0.12	0.071	0.052	0.055	15	60	70
	TPA 93.1	96.8	2.43	0.73	0.25	0.32	0.22	0.11	0.064	0.058	0.056	20	40	35
	TPA 747.1	91.7	2.94	1.79	2.73	0.22	0.11	0.05	0.084	0.040	0.049	120	130	4
	TPA 100.1	94.1	2.51	1.86	0.001	0.25	0.28	0.08	0.073	0.025	0.059	55	35	25
Phase 6	TPA 104.1	97.3	2.87	0.47	0.002	0.26	0.19	0.04	0.080	0.043	0.066	85	35	15
	TPA 110.1	90.6	0.44	1.33	3.85	0.04	0.02	0.01	0.094	0.018	0.081	75	55	65
	TPA 110.2	95.1	2.19	1.04	2.52	0.06	0.07	0.02	0.079	0.040	0.080	55	30	9
	TPA 110.3	92.2	3.41	0.92	0.46	0.08	0.06	0.04	0.081	0.058	0.083	55	25	6
	TPA 117.2	93.9	2.93	2.46	0.003	0.16	0.27	0.11	0.089	0.037	0.064	70	25	5
	TPA 123.1	90.6	5.03	1.76	0.99	0.33	0.04	0.14	0.082	0.120	0.086	80	70	8
	TPA 1156.1	95.3	3.77	1.11	0.05	0.12	0.33	0.11	0.083	0.032	0.061	75	30	25

Table 2: Chemical composition of the chronologically ordered tripod fragments from Olympia. Copper and minor elements are presented in weight-% (Se < 20 µg/g, Bi < 8 µg/g, Au < 1 µg/g in all samples).

LIA were performed with a multi-collector ICP-MS (NEPTUNE, Thermo Scientific) in the laboratory of the Institut für Geowissenschaften at the Goethe-Universität Frankfurt/Main. The stock solution was diluted with 2 % HNO_3 to yield a concentration of c. 250 ppb lead, and spiked with 100 ppb thallium standard NIST SRM-997 (for details, see e.g. Klein et al., 2009). The data set with two-sigma absolute standard deviation is shown in Table 3.

	Sample	^{206}Pb/^{204}Pb	±2σ	^{207}Pb/^{204}Pb	±2σ	^{208}Pb/^{204}Pb	±2σ	^{207}Pb/^{206}Pb	±2σ	^{208}Pb/^{206}Pb	±2σ
Ph. 3	TPA 772.1	17,966	0.021	15.637	0.016	38.115	0.045	0.87041	0.00022	2.1216	0.0007
	TPA 1163.1	17.959	0.023	15.633	0.019	38.096	0.053	0.87050	0.00028	2.1212	0.0008
Phase 5	TPA 84.1	17.954	0.031	15,638	0.026	38.106	0.070	0.87097	0.00030	2.1224	0.0008
	TPA 93.1	17.953	0.023	15.637	0.018	38.101	0.047	0.87100	0.00030	2.1222	0.0008
	TPA 747.1	17.977	0.027	15.639	0.021	38.127	0.057	0.86995	0.00030	2.1208	0.0007
	TPA 100.1	17.955	0.021	15.639	0.018	38.102	0.048	0.87103	0.00030	2.1221	0.0008
Phase 6	TPA 104.1	17.955	0.021	15.637	0.019	38.099	0.050	0.87088	0.00032	2.1219	0.0008
	TPA 110.1	17.961	0.023	15.637	0.021	38.106	0.057	0.87060	0.00026	2.1214	0.0008
	TPA 110.2	17.958	0.020	15.637	0.017	38.105	0.045	0.87076	0.00024	2.1219	0.0006
	TPA 110.3	17.958	0.023	15.637	0.018	38.102	0.051	0.87077	0.00024	2.1218	0.0004
	TPA 117.2	17.952	0.021	15.635	0.019	38.094	0.048	0.87094	0.00030	2.1218	0.0009
	TPA 123.1	18.014	0.031	15.632	0.023	38.099	0.064	0.86781	0.00028	2.1150	0.0008
	TPA 1156.1	17.941	0.027	15.635	0.023	38.084	0.058	0.87148	0.00030	2.1227	0.0009

Table 3: Lead isotope ratios with 2-σ standard deviations (absolute) of the tripod fragments from Olympia in chronological order.

3 RESULTS AND DISCUSSION

3.1 Tin, Lead, and Iron Contents of the Tripods of Olympia

The chemical compositions of the 13 tripod samples are quite similar to each other (Table 2). They are significantly rich in Pb and, with the exception of TPA 110.1, also in Fe. Tin is always low concentrated compared to ideal tin bronzes and in some cases we measured only traces. Lead, Fe and Sn components are not only critical for workability both during the casting and hammering processes or for the mechanical properties of the resulting objects, but also for the color (Sn, Pb), the material value or price (Sn), potentially also for symbolic values such as prestige (Sn). In this paper we concentrate only on aspects relevant for the discussion of the provenience of the copper.

Tin

In some samples, Sn is only present as a trace element. In others it does not exceed 3.85 % (see Table 2). Both the use of copper without any tin and the use of copper with very low Sn contents are characteristic for tripods of the phases 3, 4, 5, and 6 (cf. published data cited above). Later in this paper we will argue that the copper for our 11 tripods derives from Faynan or Timna in Wadi Arabah. Faynan and Timna copper ores, as is well known, are not associated with Sn minerals (cf. Hauptmann et al., 1992, 8-11; Hauptmann, 2000, 46-53; 2007, 68-73; Craddock 1980, 171-172 with references). Just one analysis of copper metal from a Roman melting site at Dhubb shows a significant Sn amount of 0.84 % (Hauptmann, 2000, 232 table 17; 2007, 371 table A.17). Generally, Sn does not seem to exceed 0.01 % in Faynan copper ores (Hauptmann, 2007, 201). Therefore, if our tripods show tin values above trace level, it must have been added to the copper. Furthermore, the fact that the trace element pattern and the Fe, Pb concentration of the 11 tripods do not systematically vary with rising Sn concentrations points rather to an intentional addition of pure Sn to the copper than to a reuse of scrap metal containing tin (cf. Figure 4). Also, the lack of systematic variation of Pb isotopic ratios in relation to the Sn contents in the tripods advocates this opinion (Figure 5). Particularly the addition of scrap from Late- or Submycenean bronze objects does not seem to have been a frequent practice since these objects often contained many geologically young Lavrion Pb (Magou & Gale, 1995; Stavropoulou–Gatsi et al., 2012, 259) and this would have caused extreme "loners" in Figure 5. In any case, the lead isotope data and chemical element constellation of the tripods should directly be connected to the copper source (cf. Figures 7 and 8).

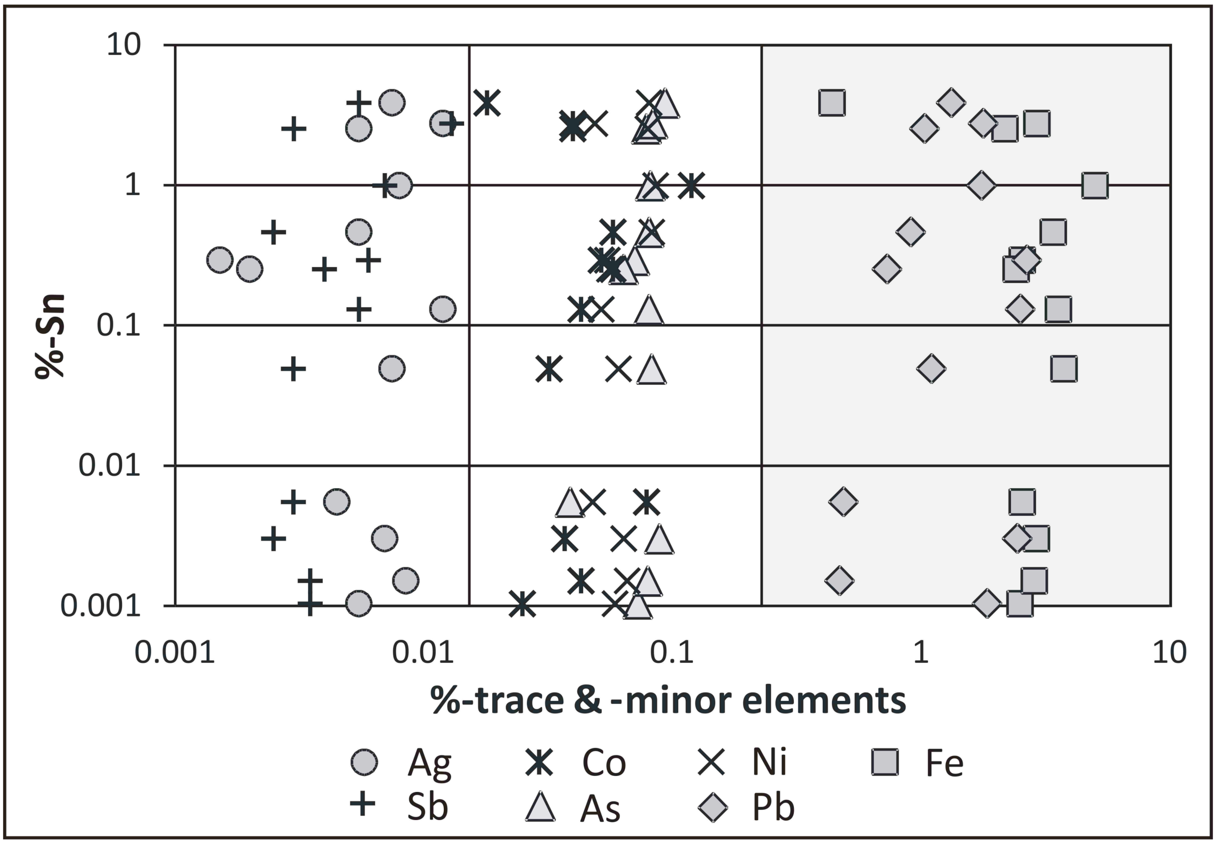

Figure 4: Double-logarithmic plot of Fe and provenance relevant minor and trace elements against the Sn values of the tripods from Olympia. There is no hint for a correlation of Sn with the other elements. Therefore, pure tin seems to have been alloyed with the copper.

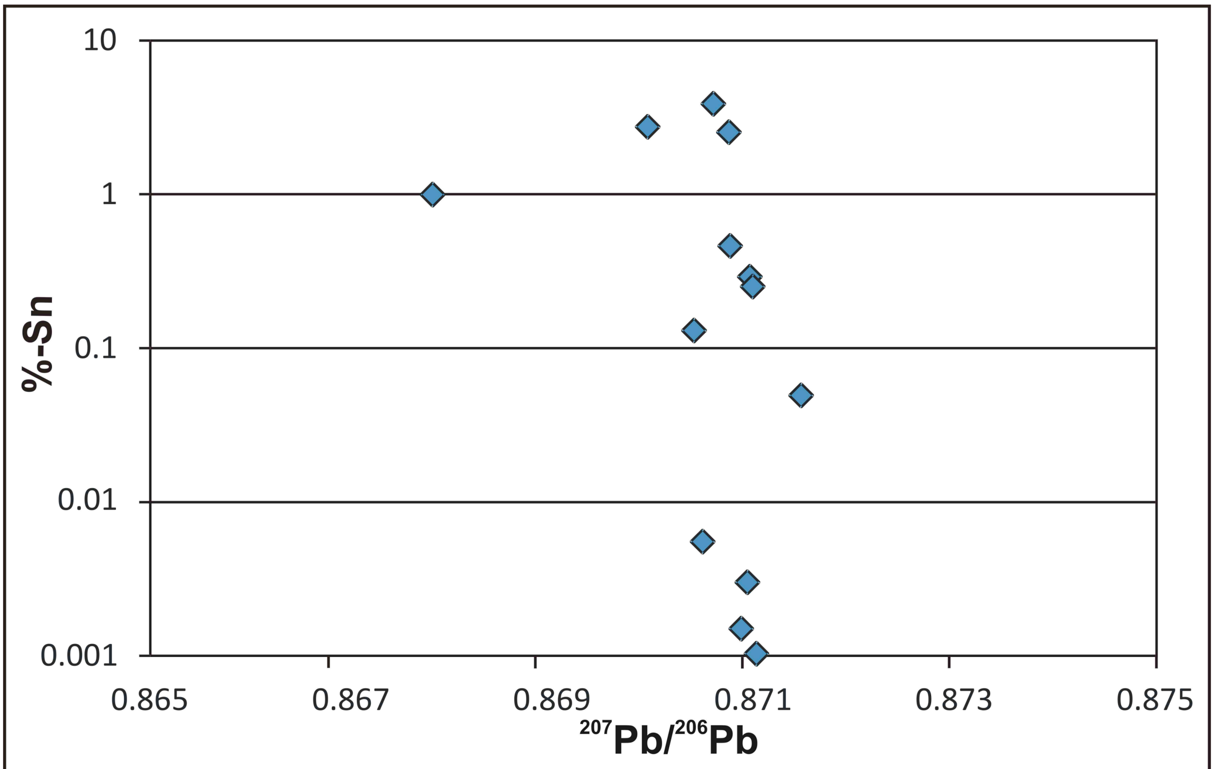

Figure 5: $^{207}Pb/^{206}Pb$-ratios of the tripods with rising Sn-contents. The enrichment in tin is not affecting the LI-ratios.

Lead

Based on their broad datasets, the group around Rolley (Filippakis et al., 1983, 121-122), as well as Riederer (2007) questioned if Pb contents in tripods between 1 and 3 % are an indication for intentional addition of Pb, or not (same discussion for Cypriote EIA objects in Charalambous et al., 2014, 213). In the case of our samples, the interpretation of lead as a natural component of the copper ore is a straightforward solution (cf. Hauptmann, 2007, 73-79; 200-202), since it is in full agreement with the proposed origin of the copper from the mines of Faynan (see below).

Iron

The relatively high Fe contents in our samples have parallels in many of the previously published tripod analyses (discussion in Filippakis et al., 1983, 120-121; Riederer, 2007, 407-408). High Fe contents is a widespread phenomenon in EIA Europe and the Near East, but is not indicative for the copper's provenance (Hauptmann, 2007, 207-211). Copper high in Fe can be explained by a combination of three factors: the use of ores and/or fluxes with a high Fe content; the practice of advanced smelting techniques with strong reducing conditions and temperatures high enough to mobilize Fe; and the lack of interest of both the smelters and the artisans to invest much energy in refining the copper. An exception is tripod DN 110, from which we analyzed samples both from cast parts (leg TPA 110.3, handle TPA 110.2) and from the hammered basin (TPA 110.1). The chemical and the LI patterns (figures 7 and 8) principally suggest that all three analyzed parts were made of the same raw copper of the type Faynan DLS. But the Fe-content in the basin is considerably lower compared to leg and handle. It should be the result of refining or remelting that obviously also has significantly lowered the Co-, Zn-, S- and P-contents in the basin copper (cf. Hauptmann et al., 1992, 20). Under the aspect of workability, the observed differences in iron content are sensible, because high iron contents make an alloy inappropriate for the procedure of hammering and annealing, but they do not cause problems during casting (cf. Papadomitriou 2001).

3.2 The Copper Source of the Tripods of Qlympia

For provenance studies it is important to combine lead isotope results with information from trace element studies of ores and metals. Such investigations should be done with a sufficient number of geochemical data of ores and of metal finds and must also be cross-checked with archaeological field evidence for mining and smelting (Compare Gale & Stos-Gale, 2000 and Pernicka, 1990 for detailed information about the use of lead isotopes and chemical elements in provenance studies).

In most cases, lead isotopes are presented in 2-dimensional plots, where the four stable isotopes are converted into ratios. Figure 7 shows four different versions. For a positive provenance result, the lead isotopy of an object should always match with that of an ore.

The lead isotope dataset of our 11 tripods forms a compact cluster (Figure 7, green diamonds). Not only the LIA, but also the chemical element pattern of the tripod copper is similarly compact (Figure 8). This strongly suggests a single copper source. Because all sampled tripods consist of this copper and cover a long time span from c. 950 to 750 BC, the copper source must have been an important deposit, which was mined in a well-organized fashion and embedded in a well-developed trade network.

Exclusion of Cyprus and the "Aegean Field"

The lead isotope ratios of the tripod cluster generally point to late Precambrian to early Cambrian ores (cf. Hauptmann, 2007, 57). Many important copper deposits of the ancient eastern Mediterranean are geologically younger and therefore can be ruled out as potential sources. This is true for the massive sulfidic copper ore deposits of Cyprus whose isotopic signatures are significantly more radiogenic than our samples. Generally, there is a great gap between the tripod cluster and Cyprus data (LI from Stos-Gale et al., 1997), which are outside the plots of Figure 7. For the same reason Lavrion and the mining areas of south eastern Turkey can be excluded, as well as all the other ores of the so-called "Aegean Field" (cf. Pernicka et al., 1984, fig. 28; Gale & Stos-Gale, 1992, 72 fig. 4).

Exclusion of Sardinia

All the copper sources that at least partly overlap isotopically with the tripod samples are geographically quite distant from southwestern Greece. To begin with Sardinia, its importance for the copper metal trade in prehistory is not clear. Lead isotope comparison shows that ingots in Nuragic times were not exclusively imported from Cyprus, the perhaps most important copper source in the Late Bronze Age (LBA), but could also have been produced on the island itself (Begemann et al., 2001, 57). Some local copper production on Sardinia is said to have taken place in the LBA / EIA, but because of the absence of large slag heaps rather to a lesser extent and just for a short period (Lo Schiavo et al., 2005, 137). However, a very few LIA of copper ores and slags from southwest and central Sardinia are within or close to the field of the Olympia tripod group in Figure 7. With a lack of chemical data of these ores and slags, a trace element check is done with Nuragic copper finds and two copper ingots, which LI composition is comparable with those of the tripods (cf. Begemann et al., 2001, 52-55, 60-61, 70-71, 75). Figure 6 shows that with a view to the As, Sb, Ag and Ni (and Co [not shown]) contents almost all copper-based objects can clearly be distinguished from the tripod samples.

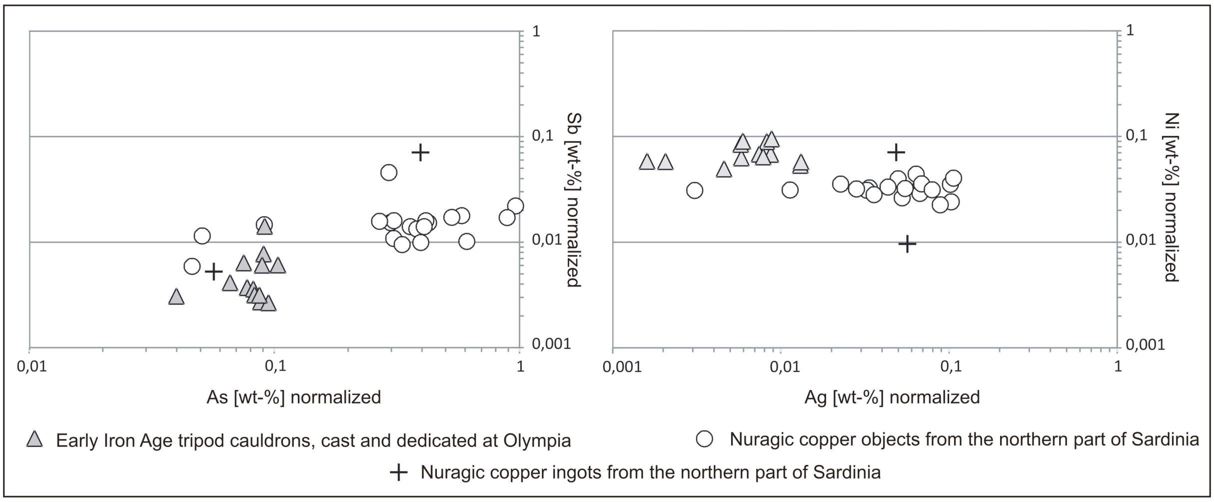

Figure 6: As/Sb- and Ag/Ni-diagrams of Nuragic copper-based objects and two copper ingots from northern Sardinia in comparison with the tripod cauldrons from Olympia. With just a few exceptions the Nuragic finds can easily be distinguished geochemically from the tripod analyses (reference data from Sardinia: Begemann et al., 2001, 52-53, 60-61).

Exclusion of the Alpine (and Apennine) region

In the eastern Alpine region, particularly in the Inn Valley in Austria (Tirol), there is strong archaeological as well as LI evidence for an important copper production, especially in the LBA (Höppner et al., 2005, 298; Artioli et al., 2013, 55). Late Bronze Age mining is also expected for parts of the Mitterberg mining district (Steiermark, Austria) (cf. Stöllner et al., 2004, 97 with references). However, data graphs convincingly demonstrate that either the chemical or the LI pattern of the local sulfidic copper ores and fahlores from Schwaz/Brixlegg (Tirol), the Mitterberg and also Kitzbühel-Kelchalm (Tirol) do not fit to the composition of the tripod assemblage of this study (cf. Lutz & Pernicka, 2013; Stöllner et al., 2016, both with no numerical data). The central-eastern Southern Alps also certainly played an important role for the prehistoric copper trade. About 200 smelting sites alone in the Trentino region are mainly dated to the Late/Final Bronze Age (14./13.-12. century BC), and perhaps later (Perini, 1992; Cierny, 2008, Marzatico & Tecchiati, 2001). In the Western Alps copper was produced e. g. in Oberhalbstein, Canton Graubünden (Swiss) or in the French part at St. Véran (Hautes Alpes) (in summary in Fasnacht, 2004; Maass, 2004 with references). Unfortunately, for the ancient copper ores of the Trentino region, there is so far not enough analytical data available for a sufficient provenance study. Artioli et al. (2009), Nimis et al. (2012) and Giunti (2011) published LIA for copper ores from the central-eastern Southern and Western Alps (with St. Véran) as well as the Lingurian and northern Apennines with Giunti (2011) also presenting chemical analyses (pp. 139-146). Both LI and chemical results scatter a lot and clearly show the complexity of Alpine and Apennine copper ores. In Figure 7, this data set is reduced to LIA of copper ores from the central-eastern Southern and Western Alps as well as from the Ligurian Apennines to illustrate the large isotopic variety. It does not match the tight cluster of the Olympia tripods, which is also the case for 18 EIA bronze objects from Chiusa di Pesio (Cuneo) in the Piedmont region (Figure 7, cf. Artioli et al., 2009, 171 table 3). They scatter in the same way like the Alpine ores do.

Jung et al. (2011) performed a chemical and LI investigation of 35 Middle to Final Bronze Age copper-based objects from the Italian mainland and concluded that most of them consist of copper from Trentino and adjacent areas. Interestingly, these objects do not conform to the cluster of the 11 Olympia tripods. Just a single LI result could fit to the tripods and especially the Ag, Bi and Sb contents in the tripod samples are all significantly lower (cf. Jung et al., 2011, fig. 23.2-23.7 with no numerical data). To finally conclude, on the basis of accessible analytical data from the Alps and the Apennines as well as the Italian mainland, the copper of the 11 Olympia tripods should not come from there.

Exclusion of the Sinai peninsula and Egyptian eastern desert

In the Near East, the Sinai peninsula and the Egyptian eastern desert were the setting for mining and metallurgy of copper up to the LBA and EIA. But the size of the deposits and their copper mineral content is generally rather small in comparison to other copper districts such as Cyprus or Faynan (e. g. Hauptmann, 2000, 46; 2007, 11; 14). At least around Bir Nasib, a smelting site in Sinai with impressive slag heaps, large amounts of copper ore must have been mined. The site dates to the LBA / EIA and later, but unfortunately is not properly investigated. However, two published LIAs of smelting slag from Bir Nasib do not match with the tripod data as well as other data from Sinai or the Egyptian eastern desert (not shown in Figure 7) (information about Bir Nasib in Rothenberg, 1987; Hauptmann, 2000, 46; 2007, 62; 83; Abdel-Motelib et al., 2012, 14-17; 50-52).

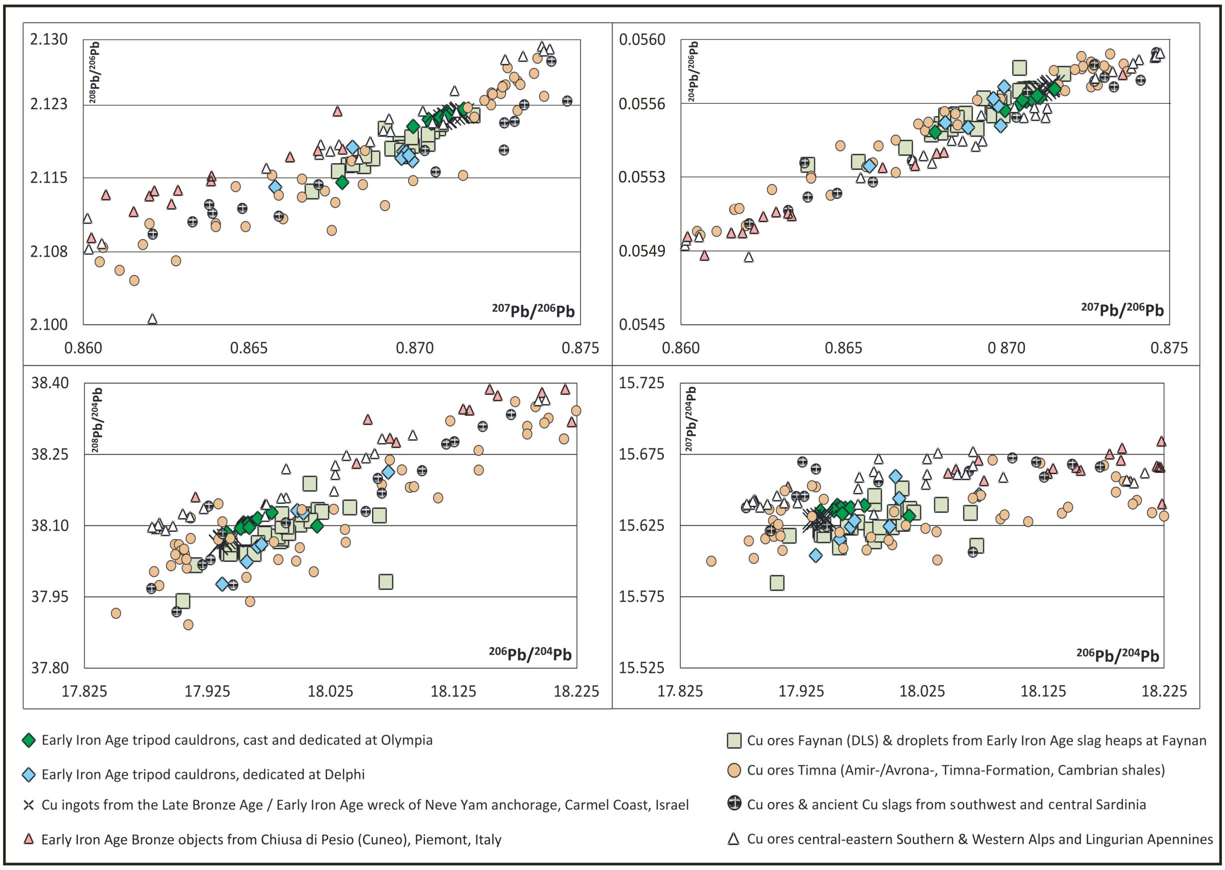

Figure 7: Lead isotope ratio diagrams with data of the tripods from Olympia in comparison with data of contemporaneous tripods from Delphi and ore deposits from Sardinia, Faynan DLS, Timna and the southeastern Alps (reference data from Faynan: Hauptmann, 2000, 216; 236; Jansen, 2011, 100. Timna: Hauptmann, 2000, 217; Segal et al., 2015, 224. Sardinia: Stos-Gale et al., 1995, 412; Begemann et al., 2001, 75. Central-eastern Southern Alps, Western Alps, Lingurian Apennines: Artioli et al., 2009, 170; Giunti, 2011, 130-131; Nimis et al., 2012, 28-29. Data of the tripods from Delphi: OXALID data base. Data of Cu ingots from Carmel Coast, Israel: Yahalom-Mack et al., 2014, 172 table 3. Data of Bronze objects from Chiusa di Pesio (Cuneo), Piemont, Italy: Artioli et al., 2009, 171 table 3).

Faynan and Timna in the Wadi Arabah

A critical look to the 4 different plots of Figure 7 shows that the ores of the Dolomite-Limestone-Shale unit (DLS) of Faynan and EIA copper production sites where these ores were processed fully correspond with the tripod data. Also the chemical “fingerprint” of copper metal waste and metallic slag inclusions from Iron Age sites in the Faynan area where DLS ores and the corresponding manganese rich fluxes were processed, match (Figure 8). Copper production with DLS ores boomed at these sites in the EIA (Hauptmann, 2000, 97 table 9; 2007, 147 table 5.3). Not plotted in Figure 8 is phosphorus. Its high contents in some of the tripod samples fit very well to the DLS and to the geology of Wadi Arabah in general (Table 2; cf. Hauptmann, 2007, 210-211).

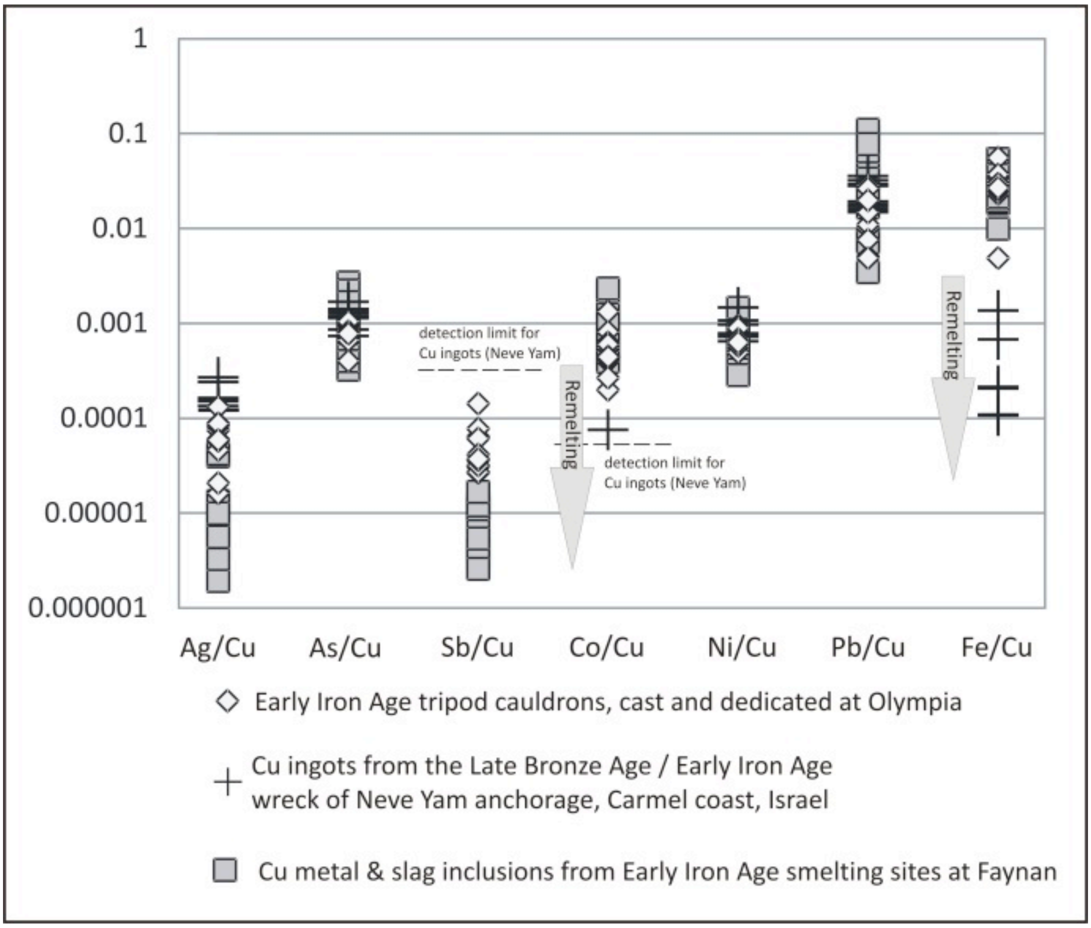

Figure 8: Copper-standardized trace and minor element contents of the tripods from Olympia compared with data of metallurgical remains from Iron Age smelting sites at Faynan and copper ingots from the LBA / EIA wreck of Neve Yam anchorage off Carmel Coast, Israel (data from Hauptmann et al., 1992, 22; 2000, 232; 234; 2007, 369; Yahalom-Mack et al., 2014, 170).

Recently, a provenance from Faynan was convincingly argued for copper ingots from a LBA or EIA wreck at the anchorage of Neve Yam off the Carmel Coast of Israel (Yahalom-Mack et al., 2014, 169-171). These ingots perfectly coincide isotopically with the 11 tripods from Olympia and also form a very compact cluster (Figure 7, diagonal crosses). In addition, they follow the chemical element pattern of the Olympia tripods as well as the metallurgical remains from Iron Age sites at Faynan do (Figure 8). The relatively low iron (as well as cobalt) content in the ingots is said to be the result of copper refining prior to casting (Yahalom-Mack et al., 2014, 164), but perhaps this could also be explained as a result of a less developed (earlier) smelting technology with lower temperatures and less reducing conditions (see generally Hauptmann, 2007, 207-211. The excavators of the wreck initially proposed a LBA date and reported "a set of hematite weights in a wheat grain shape, a bronze adze, a socketed spear head with wooden remains and bronze tongs" [Galili et al., 2011, 68-69]).

The mining sites of Timna ca. 105 km south of Faynan belong to the same geological context. Results of a new research program indicate that also at Timna copper production reached a peak in EIA (Ben-Yosef et al., 2012; Ben-Yosef & Levy, 2014). Nevertheless, according to estimations based on the ore resources and the size of the slag heaps, the overall output during EIA must have been much smaller at Timna than at Faynan (see Bachmann & Rothenberg, 1980, 232-233. A compact comparison between the Faynan and Timna ore deposits and their exploitation is given by Yahalom-Mack et al., 2014, 163; detailed comparisons by Hauptmann, 2000, 46-61; 2007, 63-83 and Ben-Yosef, 2010, 93-104 with references). The LI- and chemical trace element pattern of the copper produced at Timna during EIA is not properly defined yet, because there is no published analytical data of industrial remains from the smelting sites like copper chunks, droplets, or metallic slag inclusions. We only rely on Cu-ore data. LI-pattern of Cu-ores of the Amir/Avrona Formations, which at Timna were the main target of mining during antiquity including EIA, scatters much wider than the dense cluster of the DLS-ores of Faynan and related industrial remains (Figure 7). Also, Cu-ores from the Amir/Avrona Formations in the median are richer in Sb and poorer in Pb than the Cu-ores of Faynan DLS (e. g. Hauptmann et al., 1992, 15; Hauptmann, 2000, 57 table 6;

2007, 201).

For the last technological phase of EIA copper smelting in the Wadi Arabah, which is characterized by a new type of tuyères and larger tap slags and started according to C14 around 900 BC (Ben-Yosef & Levy, 2014), there is a special problem. In this period, the smelters at Timna used manganese rich ores of the so-called Timna Formation as flux instead of the formerly used iron rich fluxes of the Amir/Avrona Formations. This is well documented at Timna site 30 Layer I (Ben-Yosef et al., 2012, 48 with references). Since the Timna Formation is the direct geological equivalent of Faynan DLS, lead and other metallic components of these manganese rich fluxes hypothetically might have formed a copper very similar to contemporary copper from Faynan DLS. On the other hand, the production output of Timna in this last technological phase probably was limited in comparison to contemporary Faynan, because according to preliminary statements (Ben-Yosef & Levy, 2014, 924, 940; Sapir-Hen & Ben-Yosef, 2014, 776) the sites and archaeological contexts with respective tuyères ("large type") and slag ("Type A") are few and relatively small.

To conclude, a discriminant analysis of EIA Faynan versus EIA Timna is a desideratum and should be based on well stratified copper remains from the smelting sites of both areas. Up to then, we label the copper of the 11 Olympia tripods as "copper of the type of Faynan DLS", acknowledging that copper with this LI- and chemical pattern perhaps was not only produced at Faynan, but in a limited scale also at Timna.

3.3 LIA by the Isotrace Laboratory in Oxford 1981-1983 of EIA Tripods Excavated at Delphi

Significantly, all of the lead isotopic measurements conducted at Oxford 1981-1983 from Delphi tripods fall quite close to the measurements of our new samples from Olympia (Figure 7, blue diamonds; cf. also Magou et al., 1986, 124 fig. 1. In Figure 7, we only plot samples 2,

http://dx.doi.org/10.1016/j.jasrep.2016.06.013 17 June 2016

4, 10, 39, 41, 49, 55, 58. We excluded four analyses because OXALID qualified the run quality less than "good"). Evidently, like the sampled Olympia tripods also these Delphi tripods were made of copper stemming from outside of the "Aegean Field". The Delphi tripods cover a significantly larger area than the Olympia tripods, but all of them are within the DLS data cloud. The contents of chemical trace and minor elements are again similar to our Olympia samples (Figure 9), although some provenance-relevant elements were not measured (especially As, Bi, P, Sb, Se, Te). Both LIA and chemical measurements of the Delphi tripods give good reason to suggest that there is a link to the Wadi Arabah, and especially to the copper of type Faynan DLS, as well.

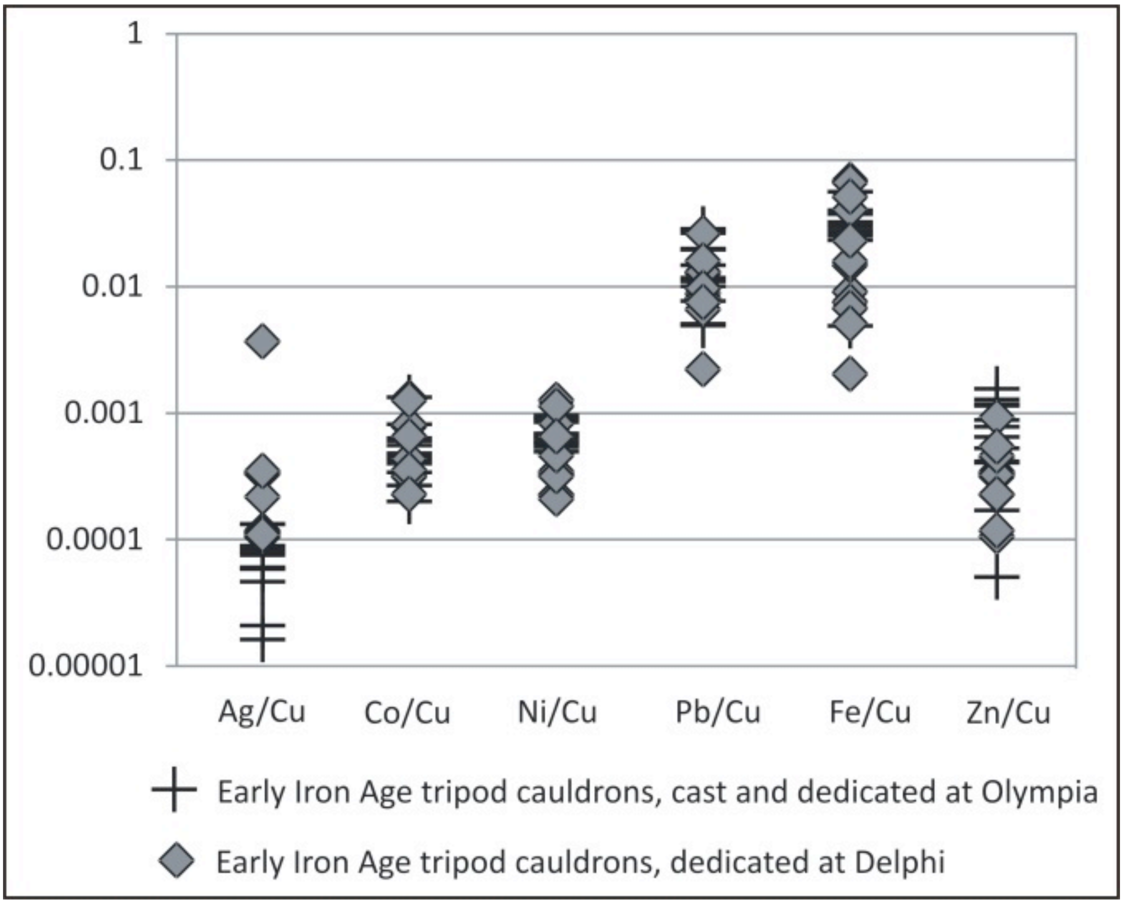

Figure 9: Copper-standardized trace and minor element contents of the tripods from Olympia and Delphi. Chemical data of Delphi tripods from Filippakis et al., 1983.

4 CONCLUSIONS AND PERSPECTIVES

Our suite of data from 11 tripods manufactured at Olympia in the phases 3, 5, and 6 both isotopically and chemically forms a compact group. We connect this group with the mining districts of Faynan in the Wadi Arabah but concede that also Timna might be involved. Further enlightening data are expected from microscopic, micro-phase analyses and metallography planned at the National Center for Scientific Research (NCSR) «Demokritos» at Athens, which could give evidence for inclusions e.g. of Fe phosphides that are typical for Wadi Arabah (cf. Hauptmann, 2007, 208-211). However, the data from the 11 Olympia tripods as well as the data of the tripods from Delphi indicate a very strong, constant and long-standing influx of copper from Faynan to the markets where the contractors of these tripods purchased the copper they needed.

As it seems, not only new copper was available to the contractors, but also new tin. This advocates the existence of some kind of tin trade in the Mediterranean during this time and is in accordance with findings of M. Kayafa (2006, 226-229) derived from diverse objects excavated at Nichoria, Lefkandi, and Thasos in Greece as well as with findings of Charalambous et al. (2014, 210-213) derived from objects from the necropolis of Palaepaphos Skales on Cyprus.

One of the markets for copper may well have been established at Olympia itself, because NAA-Analysis has proven this sanctuary to have been a major centre for the manufacturing of tripods (and consequently perhaps of other prestige goods). Also, the presence of many economically very potent visitors at the sanctuary attested by dedications of tripods must have predestinated the site as a hub for expensive commodities. However, since Olympia was a supraregional sanctuary already in phase 3 and mobility of the elite active at Olympia was generally high, some of the contractors of the tripods may have come from quite distant regions and may have acquired the copper near to their home regions. Contractors could also have bought the copper during voyages to other areas far away. Obviously, much more analytical work covering more production places and find spots of tripods is needed in order to understand the retailing systems of the different mining areas, including Faynan, and their geographical and organizational overlaps.

The exchange system that connected the Wadi Arabah with the Aegean may be referred to as "Levantine-Aegean copper trail". The new data gives evidence for the second half of phase 3 (c. from 950 BC) to the end of phase 6 (c. 750 BC). Since Olympia tripods of phases 1 and 2 were not analyzed yet, the beginning of the influx of Faynan copper to markets significant to Olympia still has to be defined. The same is true for the end of this influx, since tripods of phase 7 were not analyzed yet.

Concerning the tripods from Delphi, we do not know the production places of these eight tripods but only the find spot and their chronological sequence (phases 3, 4, 5 and 6). Although the LI data of the Delphi tripods shows a significantly wider distribution than the Olympia tripods (Figure 7), they also match the Faynan DLS data. Also the available chemical data of the copper indicate that it most likely stems from the same sources as those of the Olympia tripods, Faynan and perhaps Timna (Figure 9).

In addition to the EIA tripods, the OXALID-data originally published in Magou et al., 1986, figure 1 contain many data of orientalizing Greek and of Oriental objects of the early 7th century BC. According to these data, copper of type Faynan DLS therefore seems to have vanished from markets significant to Delphi no later than the early 7th century BC.

Functional Elements of the Levantine-Aegean Copper Trail

Future research requires intense interdisciplinary work in order to understand the Levantine-Aegean Copper Trail as a social system.

According to recently published results of the team around T. Levy, M. Najjar, and E. Ben-Yosef (Levy et al., 2014), the EIA mines and smelting sites of Faynan and Timna were run by seminomadic tribal societies. Levy et al. (2014) hypothesize that these people formed a confederation and centered in the uplands to the east of Faynan later becoming the core of the political entity of Edom that is known from written sources. Martin & Finkelstein (2013) argue that there was a close relation with the seminomads in the Negev.

The economic ups and downs of mining and smelting are quite well dated with numerous C14 data from both stratigraphically excavated slag heaps and dwellings including imported (mostly Egyptian and Cypro-Phoenician) artefacts and the sequence of local pottery (Levy et al. 2014). It seems that a first boom started in the late 11th / early 10th century BC. Interrupted by a short phase of social reorganization and technical innovation after a military expedition of Pharao Shoshenq I around 925 BC, mining and smelting continued with high intensity until the end of the 9th century. After that time it seems to have ceased rapidly. There are no indications for copper smelting on an industrial scale during the 8th and 7th century BC, except perhaps at the important smelting installations at Khirbet Faynan site 5 (Hauptmann 2007, 97-103). There, a charcoal sample from locus 2 was dated with C14 to 825-795 BC (1σ) (Hauptmann 2007, 101 and table 5.1). If the "old wood effect" is taken into account, one can't exclude that industrial activity might have continued here well into the 8th century BC.

It is debated what triggered the boom of mining activity at Faynan. Levy et al. (2014) do not exclude inspiration by external agents, but interpret this boom as a self-organizing process that responded to market opportunities generated by foreign demand. It is not yet clear, however, in which parts of the Old World this demand was situated, how its chronological sequence was, how important these demands actually were and in which directions transport routes should be expected to run (Hauptmann & Löffler, 2013, 80).

If we look on the trail between Faynan and South West Greece only, trafficking of copper from the mines of Faynan to the shores of the Levantine coast and then westwards will have needed complex economical and political negotiations and logistic arrangements like route stations and reliably administrated harbors involving various political entities, some of them at this time being in statu nascendi or at least undergoing formative phases (for the general situation cf. The Mediterranean Mirror, 2015 with references).

The shortest trail would have been to cross the Negev following the Beersheba valley and to ship the goods from the port of Gaza (cf. Ben-Yosef 2010, 76-79 with maps fig. 2.4-5 of the route system and Yahalom-Mack et al., 2014, 174 with references). Alternative land routes would go southwards to the Nile delta and its ports, or northwards to the coastal town of Dor at the Carmel coast or further on to Tyrus. Political and economic entities that are candidates to have been involved - depending on time and changing political constellations - are therefore the Philistine Pentapolis with Gaza, Egyptian polities of the Third Intermediary Phase, the kingdoms of Judah and Israel, and the southern Phoenician towns. Agents based on Cyprus could have played a distinct role in connecting western demand with the resources of the Wadi Arabah, even if it is a puzzling question how this may have coincided with the marketing of copper produced on the island itself (cf. Kassianidou 2014 for EIA copper production on Cyprus). The find distribution of Cypriote metal vessels indicates a link to the elites of Greece and the central Mediterranean (Matthäus, 2001), while at the same time Cyprus was closely interacting both with the emerging Philistine and southern Phoenician centres (Gilboa & Goren, 2015). We also may not neglect an initiative of Greek centres, as depicted in a famous scenario of the Odyssey (1.180-185) with western Greek "Taphians" trading a shipload of iron for copper (cf. Papadopoulos 2014, 182-4).

To detect the routes, hubs and agents of the Levantine-Aegean copper trail, the most straightforward method will be to work with archaeometrical data from contextualized copper ingots excavated along suspected routes, supplemented by archaeometrical data from workshop-debris along these routes and by typologically or otherwise well-provenanced bronze objects such as the Greek tripods.

ACKNOWLEDGMENTS

For her interest in this research and her support we are obliged to G. Chatzí, the former Ephoros of Antiquities of Elia, and to her staff. The Greek Ministry of Culture approved our application for sampling (No. ΥΠΠΟΑ/ΓΔΑΠΚ/ΔΣΑΝΜ/ΤΕΕ/Φ44/220878/4680). We also thank the German Archaeological Institute (DAI) at Athens for its support, especially the team of the excavations at Olympia with its head R. Senff. The samples were taken by Th. Mavridis, conservator.

Z. A. Stos-Gale generously supplied us with the numerical data of the LIA of the tripods and other objects from Delphi, published in a graph in Magou et al., 1986, fig. 1.

Will Kennedy revised the English text.

The archaeological part of this research resulted from M. Kiderlen's project "Die Fundverteilung von Dreifuß–Dedikationen als Indikator für die Entwicklung von regionalen und überregionalen Öffentlichkeiten im frühen Griechenland (11. bis 8. Jh. v. Chr.)", which was funded (as was the presented research) both by the German Research Foundation (DFG; Projekt Nr. 53401101) and by the Humboldt–Universität (Exzellenzinitiative von Bund und Ländern, Förderlinie Freiräume 1, Projekt Nr. 01900028), and which profited from the debate within the network "Olympia in context" initiated by the former President of the DAI, H.–J. Gehrke, and G. Chatzí.

Finally, we want to thank the anonymous reviewers.

REFERENCES

Abdel-Motelib, A., Bode, M., Hartmann, R., Hartung, U., Hauptmann, A., Pfeiffer, K., 2012. Archaeometallurgical expeditions to the Sinai Peninsula and the Eastern Desert of Egypt (2006, 2008). Metalla 19, 3-59.

Artioli, G., Angelini, I., Giunti, I., Omenetto, P., Villa, I., 2009. La provenienza del metallo degli oggetti di Monte Cavanero: considerazioni basate sugli isotopi del Pb e sulla geochimica delle mineralizzazioni cuprifere limitrofe, in: Venturino Gambari, M., (Ed.), Il ripostiglio del Monte Cavanero di Chiusa di Pesio (Cuneo). Alessandria, pp. 167-178.

Artioli, G., Angelini, I., Nimis, P., Addis, A., Villa, J.M., 2013. Prehistoric copper metallurgy in the Italian Eastern Alps: recent results. Historical Metallurgy 47 (1), 51-59.

Bachmann, H.-G., Rothenberg, B., 1980. Die Verhüttungsverfahren von Site 30, in: Bachmann, H.-G., Rothenberg, B., Antikes Kupfer im Timna-Tal. 4000 Jahre Bergbau und Verhüttung in der Arabah (Israel). Der Anschnitt, Beiheft 1. Bochum, pp. 215-236.

Begemann, F., Schmitt-Strecker, S., Pernicka, E., Lo Schiavo, F., 2001. Chemical composition and lead isotopy of copper and bronze from Nuragic Sardinia. European Journal of Archaeology 4, 43-85.

Ben-Yosef, E., 2010. Technology and social process: oscillations in Iron Age copper production and power in southern Jordan. PhD dissertation, University of California, San Diego. b6973658. Retrieved from: http://escholarship.org/uc/item/5t72d1xp (accessed

20.05.16).

Ben-Yosef, E., Shaar, R., Tauxe, L., Hagai, R., 2012. A New Chronological Framework for Iron Age Copper Production at Timna (Israel). Bulletin of the American Schools of Oriental Research 367, 31-71.

Ben-Yosef, E., Levy, T.E., 2014: The material culture of Iron Age copper production in Faynan, in: Levy, T.E. (Ed.), New Insights into the Iron Age Archaeology of Edom, Southern Jordan. The Cotsen Institute of Archaeology Press, Los Angeles, pp. 887-959.

Charalambous, A., Kassianidou, V., Papasavvas, G., 2014. A compositional study of Cypriot bronzes dating to the Early Iron Age using portable X-ray fluorescence spectrometry (pXRF). Journal of Archaeological Science 46, 205-216.

Christakopoulou–Somakou, Y., 2009. Το νεκροταφείο της Σταμνάς και η πρωτογεωμετρική περίοδος στην Αιτωλοακαρνανία. PhD–thesis, Univ. Athens. DOI 10.12681/eadd/18271, http://hdl.handle.net/10442/hedi/18271 (accessed 20.05.16).

Cierny, J., 2008. Prähistorische Kupferproduktion in den südlichen Alpen, Region Trentino Orientale. Der Anschnitt, Beiheft 22. Bochum.

Craddock, P.T., 1980. The Composition of Copper Produced at the Ancient Smelting Camps in the Wadi Timna, Israel, in: Craddock, P.T. (Ed.), Scientific Studies in Early Mining and Extractive Metallurgy. British Museum Occasional Papers 20. London, pp. 165-172.

Eder, B., 2015. Die Kontinuität bronzener Ringhenkeldreifüße im sozialen Kontext der

Transformation der mykenischen Welt zwischen 1200 und 700, in: Nawracala, S., Nawracala, R. (Eds.), ΠΟΛΥΜΑΘΕΙΑ. Festschrift für Hartmut Matthäus. Shaker, Aachen, pp. 115-133.

Fasnacht, W., 2004. Prähistorischer Kupferbergbau in den Schweizer Alpen I, in: Weisgerber, G. (Ed.), Alpenkupfer – Rame delle Alpi. Der Anschnitt, Beiheft 17. Bochum, pp. 107-111.

Felsch, R.C.S. (Ed.), 2007. Kalapodi. Ergebnisse der Ausgrabungen im Heiligtum der Artemis und des Apollon von Hyampolis in der antiken Phokis, Vol. 2. Mainz, Zabern.

Filippakis, S., Photou, E., Rolley, C., Varoufakis, G., 1983. Bronzes grecs et orientaux, influences et apprentissage. Bulletin de Correspondance Hellénique 107, 111-132.

Gale, N.H., Kayafa, M., Stos-Gale, Z.A., 2009. Further evidence for Bronze Age Production of copper from ores in the Lavrion ore district, Attica, Greece, in: Giumlia Mair, A., Craddock, P., Hauptmann, A., Bayley, J., Cavallini, M., Garagnani, G., Gimour, B., La Niece, S., Nicodemi, W., Rehren, T., (Eds.), Proceedings of the 2nd International Conference: Archaeometallurgy in Europe, 2007. Milan, pp. 158-176.

Gale, N.H., Stos-Gale, Z., Photos, E., Philippakis, S., 1983. Differentiation of provenance of stylistically similar Greek objects by lead isotope studies. Congress on Archaeometry, Naples 1983.

Gale, N.H., Stos-Gale, Z., 1992. Lead Isotope Sudies in the Aegean (The British Academy Project). Proceedings of the British Academy 77, 63-108.

Gale, N.H., Stos-Gale, Z., 2000. Lead isotope analysis applied to provenance studies, in:

Ciliberto, E., Spoto, G. (Eds.), Modern Analytical Methods in Art and Archaeology. New York, pp. 503– 584.

Galili, E., Gale, N., Rosen, B., 2011. Bronze Age Metal Cargoes off the Israeli Coast. Skyllis 11, 64-73.

Gilboa, A., Goren, Y., 2015. Early Iron Age Phoenician Networks: An Optical Mineralogy Study of Phoenician Bichrome and Related Wares in Cyprus. Ancient West & East 14, 73-110.

Giunti, I., 2011. Geochemical and isotopic tracers in copper deposits and ancient artifacts: a database for provenance. Dissertation University of Padua. http://paduaresearch.cab.unipd.it/3982/ (accessed 09.09.15).

Hauptmann, A., Begemann, F., Heitkemper, E., Pernicka, E., Schmitt-Strecker, S., 1992. Early Copper Produced at Feinan, Wadi Araba, Jordan: The Composition of Ores and Copper. Archaeomaterials 6 (1), 1-33.

Hauptmann, A., 2000. Zur frühen Metallurgie des Kupfers in Fenan/Jordanien. Der Anschnitt, Beiheft 11. Bochum.

Hauptmann, A., 2007. The Archaeometallurgy of Copper. Evidence from Faynan, Jordan. Springer, Berlin Heidelberg New York.

Hauptmann, A., Löffler, I., 2013. Technological Innovations and Organisational Structures of Prehistoric Mining and Metal Production – Examples from Faynan, Jordan, in: Burmeister, S., Hansen, S., Kunst, M., Müller-Scheeßel, N. (Eds.), Metal Matters. Innovative Technologies and Social Change in Prehistory and Antiquity. Leidorf, Rahden/Westfalen, pp. 65-89.

Höppner, B., Bartelheim, M. Huijsmans, M. Krauss, R., Martinek, K.-P., Pernicka, E., Schwab, R., 2005. Prehistoric Copper Production in the Inn Valley, Austria, and the Earliest Copper in central Europe. Archaeometry 47, 293-315.

Janietz, B., 2001. Untersuchungen an geometrischen Bronzen. PhD–thesis Universität Freiburg, urn:nbn:de:bsz:25-opus-1998, http://www.freidok.uni-freiburg.de/volltexte/199/ (accessed 20.05.16).

Jansen, M., 2011. Möglichkeiten und Grenzen der Cu-Isotopie in der Archäometallurgie des Kupfers (unpublished Masterthesis, Ruhr-Universität Bochum).

Jung, R., Mehofer, M., Pernicka, E., 2011. Metal Exchange in Italy from the Middle to the Final Bronze Age (14th-11th Century B.C.E.), in: Betancourt, P.P., Ferrence, S.C. (Eds.), Metallurgy: Understanding How, Learning Why. Studies in Honor of James D. Muhly. Prehistory Monographs 29, Pennsylvania, pp. 231-248.

Kassianidou, V., 2014. Cypriot copper for the Iron Age world of the Eastern Mediterranean, in: Webb, L.M. (Ed.), Structure, Measurement and Meaning. Studies on Prehistoric Cyprus in Honour of David Frankel. Åströms Förlag, Uppsala, pp. 261-271.

Kayafa, M. (2006). From Late Bronze Age to Early Iron Age: Copper Metallurgy in Mainland Greece and Offshore Aegean Islands, in: Deger-Jalkotzky, S., Lemos, I. (Eds.), Ancient Greece: From the Mycenaean Palaces to the Age of Homer. Edinburgh Leventis Studies 3.

Edinburgh University Press, Edinburgh, pp. 213-232.

Kiderlen, M., 2010. Zur Chronologie griechischer Bronzedreifüße des geometrischen Typs und den Möglichkeiten einer politisch–historischen Interpretation der Fundverteilung. Archäologischer Anzeiger, 91–105.

Kiderlen, M., Mommsen, H., Hein, A., Müller, N. S., 2015. Use Of Neutron Activation Analysis (NAA) for provenancing artefacts cast in the lost wax technique. A pilot-study with EIA tripod-cauldrons found at Olympia and Kalapodi/Abai. Archaeometallurgy in Europe IV. Madrid, June 1 - 3 2015.

Kiderlen, M., Hein, A., Mommsen, H., Müller, N. S. (in print). Production sites of EIA Greek tripod cauldrons – First evidence from Neutron Activation Analysis of casting ceramics. Geoarchaeology.

Klein, S., Domergue, C., Lahaye, Y., Brey, G. P., von Kaenel, H.-M., 2009. The lead and copper isotopic composition of copper ores from the Sierra Morena (Spain). Journal of Iberian Geology 35, 59-68.

Kolonas, L., Kiderlen, M., (in preparation). Χάλκινοι ταφικοί λέβητες από τον Πρωτογεωμετρικό τύμβο της Σταμνάς Αιτωλοακαρνανίας", to be published in the Minutes of the 2nd International archaeological and historical Conference "Archaeological work in Aitoloakarnania and Leukas", Mesolonghi Dec. 6 - 8 2013 (2ο Διεθνές αρχαιολογικό και ιστορικό συνέδριο «Το αρχαιολογικό έργο στην Αιτωλοακαρνανία και στη Λευκάδα από τους προϊστορικούς έως τους ρωμαϊκούς χρόνους» Μεσολόγγι, 6 – 8 Δεκεμβρίου 2013).

Levy, T. E., Najjar, M., Ben-Yosef, E., 2014. Conclusions, in: Levy, T.E. (Ed.), New Insights into the Iron Age Archaeology of Edom, Southern Jordan. The Cotsen Institute of Archaeology Press, Los Angeles, pp. 977 - 1001.

Lohmann, H., 2015. Ein verkannter mykenischer Dreifußkessel in den Staatlichen Museen zu Berlin. Archäologischer Anzeiger, 1-18.

Lo Schiavo, F., Giumlia-Mair, A., Sanna, U., Valera, R., (Eds.) 2005. Archaeometallurgy in Sardinia from the origin to the Early Iron Age. Monographies Instrumentum 30. Montagnac.

Lutz, J., Pernicka, E., 2013. Prehistoric copper from the Eastern Alps, in: Tykot, T.H. (Ed.), Proceedings of the 38th International Symposium on Archaeometry, May 10th -14th 2010, Tampa, Florida. Open Journal of Archaeometry; 1:e25, doi:10.4081/arc.2013.e25 (accessed 20.05.16).

Maaß, M., 1978. Die geometrischen Dreifüße von Olympia. Olympische Forschungen X. De Gruyter, Berlin.

Maass, A., 2004. Zur chalkolithisch-frühbronzezeitlichen Kupferproduktion von St. Véran/Hautes Alpes, in: Weisgerber, G. (Ed.), Alpenkupfer – Rame delle Alpi. Der Anschnitt, Beiheft 17. Bochum, pp. 117-119.

Magou, E., Philippakis, S., Rolley, C., 1986. Trépieds géométriques de bronze, Analyses complémentaires. Bulletin de Correspondance Hellénique 110, 121-136.

Magou, E., Pernot, M., Rolley, C., 1991. Bronzes orientaux et orientalisants: Analyses complémentaires. Bulletin de Correspondance Hellénique 115, 561-577.

Magou, E., Gale, N., 1995. Χημική εξέταση χάλκινων Αντικειμένων, in: Onasoglou, 1995, pp. 50 - 52.

Martin, M.A.S., Finkelstein, I., 2013. Iron IIA Pottery from the Negev Highlands: Petrographic Investigation and Historical Implications. Tel Aviv 40, 6-45.

Marzatico, F., Tecchiati, U., 2001. The Bronze Age in Trentino and Alto Adige/Südtirol. Preistoria Alpina 34, 27-60.

Matthäus, H., 1980. Die Bronzegefässe der kretisch-mykenischen Kultur. C.H. Beck, München.

Matthäus, H., 2001. Studies on the Interrelations of Cyprus and Italy during the 11th to 9th Centuries B.C.: A Pan-Mediterranean Perspective, in: Bonfante, L., Karageorghis, V. (Eds.), Italy and Cyprus in Antiquity: 1500-450 BC. Proceedings of an International Symposion Held at the Italian Academy for Advanced Studies in America at Columbia University, November 16-18, 2000. Nicosia, pp. 153-214.

Nimis, P., Omenetto, P., Giunti, I., Artioli, G, Angelini, I., 2012. Lead isotope systematics in hydrothermal sulphide deposits from the central-eastern Southalpine (northern Italy). European Journal of Mineralogy 24, 23-37.

Onasoglou, A.A., 1995. Η οικία του τάφου των τριπόδων στις Μυκήνες. Βιβλιοθήκη της εν Αθήναις Αρχαιολογικής Εταιρείας, Athens.

Papadimitriou, G., 2001. Simulation Study of Ancient Bronzes: Their Mechanical and Metalworking Properties, in: Bassiakos, Y., Aloupi, E., Facorellis, Y. (Eds.), Archaeometric Issues in Greek Prehistory and Antiquity. Hellenic Society for Archaeometry, Athens, pp. 713-733.

Papadopoulos, J.K., 2014. Greece in Early Iron Age: Mobility, Commodities, Polities, and Literacy, in: Knapp, B., Van Dommelen, P. (Eds.), The Cambridge Prehistory of the Bronze and Iron Age Mediterranean. Cambridge University Press, New York, pp. 178-195.

Perini, R., 1992. Evidence of metallurgical activity in Trentino from Chalcolithic times to the end of the Bronze Age, in: Sanpaolo, E.A. (Ed.), Archeometallurgia. Ricerche e prospettive, Atti del colloquio Internazionale di Archeometallurgia, Bologna – Dozza Imolese, 18-21 Otobre 1988, pp. 54-80.

Pernicka, E., Seeliger, T.C., Wagner, G.A., Begemann, F., Schmitt-Strecker, S., Eibner, C., Öztunali, Ö., Baranyi, I., 1984. Archäometallurgische Untersuchungen in Nordwestanatolien. Jahrbuch des Römisch-Germanischen Zentralmuseums 31, 533-599.

Pernicka, E., 1990. Gewinnung und Verbreitung der Metalle in prähistorischer Zeit. Jahrbuch des Römisch-Germanischen Zentralmuseums Mainz 37, 21-129.

Riederer, J., 2007. Die metallurgische Zusammensetzung der Kupfer- und Bronzefunde aus

Kalapodi, in: Felsch, 2007, pp. 389-422.

Rolley, C., 1977. Les trépieds à cuve clouée. Fouilles de Delphes V, 3.

Rothenberg, B., 1987. Pharaonic Copper Mines in Southern Sinai. Institute for Archaeo-Metallurgical Studies, Newsletter 10/11, 1-7.

Sapir-Hen, L., Ben-Yosef, E., 2014. The socioeconomic status of Iron Age metalworkers: animal economy in the 'Slaves' Hill', Timna, Israel. Antiquity 88, 775-790.

Segal, I., Bar-Matthews, M., Matthews, A., Harlavan, Y., Asael, D., 2015. Provenance of ancient metallurgical artifacts: implications of new lead isotope data from Timna ores, in: Hauptmann, A., Modaressi-Tehrani, D. (Eds.), Archaeometallurgy in Europe III. Proceedings of the 3rd International Conference. Deutsches Bergbau-Museum Bochum. June 29 –July 1, 2011. Bochum, pp. 221-228.

Stavropoulou–Gatsi, M., Jung, R., Mehofer, M., 2012. Τάφος «Μυκηναίου» Πολεμιστή στον Κουβαρά Αιτωλοακαρνανίας. Πρώτη Παρουσίαση, in: Stampolidis, N.C., Kanta, A., Giannikouri, A. (Eds), Athanasia. The Earthly, the Celestial and the Underworld in the Mediterranean from the Late Bronze and Early Iron Age. International Archaeological Conference Rhodos 2009. University Press, Heraklion, pp. 249–266.

Stöllner, Th., Eibner, C., Cierny, J., 2004. Prähistorischer Kupferbergbau Arthurstollen. Ein neues Projekt im Südrevier des Mitterberg-Gebietes (Salzburg), in: Weisgerber, G. (Ed.), Alpenkupfer – Rame delle Alpi. Der Anschnitt, Beiheft 17, pp. 95-106.

Stöllner, Th., Rüden von, C., Hanning, E., Lutz, J., Kluwe, S., 2016. The Enmeshment of Eastern Alpine Mining Communities in the Bronze Age. From Economic Networks to Communities Practice. Der Anschnitt, Beiheft 29, Bochum, pp. 75-108.

Stos-Gale, Z.A., Gale, N.H., Houghton, J., Speakman, R., 1995. Lead isotope data from the Isotrace Laboratory, Oxford: Archaeometry data base 1, ores from the Western Mediterranean. Archaeometry 37, 407–415.

Stos-Gale, Z.A., Maliotis, G., Gale, N.H., Annetts, N., 1997. Lead isotope characteristics of the Cyprus copper ore deposits applied to provenance studies of copper oxhide ingots. Archaeometry 39, 83-123.

Strøm, I., 1995. The Early Sanctuary of the Argive Heraion and its External Relations (8th.-Early 6th. Cent. BC). Proceedings of the Danish Institute at Athens, 1, 36-127.

The Mediterranean Mirror, 2015. Babbi, A., Bubenheimer-Erhart, F., Marín-Aguilera, B., Mühl, S. (Eds.), The Mediterranean Mirror: cultural contacts in the Mediterranean Sea between 1200 and 750 B.C. International Post-doc and Young Researcher Conference Heidelberg, 6th-8th October 2012. Verlag des Römisch-Germanischen Zentralmuseums, Mainz.

Toffolo, M.B., Fantalkin, A., Lemos I.S., Felsch, R.C.S., Niemeier, W.-D., Sanders, G.D.R., Finkelstein, I., Boaretto, E., 2013. Towards an Absolute Chronology for the Aegean Iron Age: New Radiocarbon Dates from Lefkandi, Kalapodi and Corinth. Plos One 8, 1-11; doi:10.1371/journal.pone.0083117 (accessed 20.05.16).

Tselios, Ch., 2014. Όψεις του κοινωνικού μετασχηματισμού στη Νοτιοδυτική Πελοπόννησο κατά την Μυκηναϊκή εποχή, όπως αυτές αποκαλύπτονται από τη συνδυασμένη αρχαιολογική και τεχνολογική μελέτη των χαλκών τεχνέργων. Congress «Μεταλλουργία και μεταλλουργικές εγκαταστάσεις στην Πελοπόννησο», Tripolis 25.10.2014.

Willemsen, F., 1957. Dreifußkessel von Olympia. Olympische Forschungen III. De Gruyter, Berlin.

Yahalom-Mack, N., Galili, E., Segal, I., Eliyahu-Behar, A., Boaretto, E., Shilstein, S., Finkelstein, I., 2014. New insights into Levantine copper trade: analysis of ingots from the Bronze and Iron Ages in Israel. Journal of Archaeological Science 45, 159-177.