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James D. Muhly

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8. The role of the Apliki mine region in the post *c*. 1400 BC copper production and trade networks in Cyprus and in the wider Mediterranean

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The distinguished contributions of James Muhly to ancient history, archaeology, and archaeometallurgy have embraced both traditional and very new approaches to research. Muhly long ago perspicaciously advocated that the study of the Late Bronze Age Mediterranean metals trade had to begin with learning all that we could about the copper oxhide ingots, especially 'how they were made, why they were made and where they were made' (Muhly 1977, 81). Muhly thereby inspired, and made major contributions to, over 30 years of research in this field. He was also quick to appreciate, and engage with (Muhly 1983), the new field of applying lead isotope analysis (LIA) to the study of the provenance of copper (Gale and Stos-Gale 1982). Indeed, Muhly (2005, 508) was kind enough to describe LIA applied to provenancing the copper in oxhide ingots as the second major development in the field of copper oxhide ingot studies during the past 20 years, the first being a major increase in the corpus of known exemplars (especially from the Uluburun and Gelidonya Bronze Age shipwrecks and from Sardinia (Lo Schiavo 2005)). Nevertheless the conclusion from lead isotope analyses that oxhide ingots dating after *c.* 1400 BC[1] from sites throughout the Mediterranean were made from copper from the Apliki mining region in Cyprus (Stos-Gale *et al.* 1997; Gale 1999; Gale and Stos-Gale 2005) proved unexpectedly controversial (*e.g.* Knapp 2000), so a closer look at the evidence seems appropriate.

Another major advance was the recent intensive study of the metallography and chemical composition of copper oxhide ingots from the Uluburun Bronze Age shipwreck (Hauptmann *et al.* 2002). From these studies they argued against the hypothesis of the casting of oxhide ingots directly from a single charge of molten smelted copper metal from the furnace. They found that there was but weak evidence that oxhide ingots were made by melting down bun ingots. Moreover, Hauptmann *et al.* (2002) observed microscopic features (internal cooling rims) in some Uluburun ingots, which they write 'could be caused by pouring several batches of the metal into a mould to complete an ingot'. This supports earlier macroscopic observations by Pulak (1998, 196; 2000, 142) of layered textures in the edge of oxhide ingots, which suggested that at least some of the oxhide ingots were finished by multiple pouring.

Implications for lead isotope provenancing

Problems might ensue for lead isotope provenancing if oxhide ingots were made by several pourings of molten copper into the same mould, in particular if the different pourings came from different batches of copper metal smelted from different ore sources. However, the evidence of the tight coherence of lead isotope analyses of many different copper oxhide ingots argues against the existence of such a problem (Gale and Stos-Gale 2005; Gale 2011). Moreover detailed lead isotope analyses were made by multi collector inductively coupled plasma mass spectrometry (MC-ICPMS) in Oxford for a number of cores drilled through the thickness of three different oxhide ingots and one bun ingot from the Uluburun wreck. Analytical procedures and the numerical data were reported by Gale (2005). In summary, the MC-ICPMS lead isotope data for cores taken through three Uluburun copper oxhide and one bun ingots support that at least some oxhide and bun ingots were made by the successive pouring of different batches of molten copper into the mould. However all the MC-ICPMS data prove further that the different batches of copper in a given Uluburun ingot come from the same ore deposit, which has an isotopic composition identical with the earlier thermal ionization mass spectrometric (TIMS) measurements of the lead isotopic composition of surface samples from some 300 Uluburun copper oxhide and bun ingots. Consequently, the evidence derived from these MC-ICPMS determinations of the lead isotope compositions of samples from cores through Uluburun ingots validates the lead isotope provenancing method for determining the ore sources of copper used in making these ingots.

Lead isotope analyses of Cypriot ores

Prior to 1995 relatively few lead isotope analyses had been made of ores from Cyprus. Those that existed had mostly been made for geological purposes (*e.g*. Spooner and Gale 1982; Hamelin *et al.* 1988), with a few made for archaeological provenancing (*e.g.* Stos-Gale *et al.* 1986). Prior to 1995 there existed only 33 lead isotope analyses for Cypriot ores; these included only one ore from Apliki (donated by Tylecote), but this one ore from Apliki had an isotopic composition which overlapped with a number of copper oxhide ingots. In order to increase the number of LIA for reliable samples of Cypriot ores we organized, with the Cypriot Geological Survey Department, a field trip to Cyprus in 1995. During this field trip we had the immense good fortune to meet, in the Skouriotissa mine, the chief geologist of the Hellenic Mining Co. Ltd., Dr. G. Maliotis, who took us to many mines to which we would otherwise not have had access, including the mine of Apliki. In 1997 we published lead isotope data for these ores (Stos-Gale *et al*. 1997; Gale *et al.* 1997), which increased the data set by a further 194 isotopic analyses. Figure 8.1 shows graphical plots of these data[2] together with data for ores from Lavrion in Attica, Greece, which are clearly separated from the Cypriot data. Note that the data for the Cypriot mine of Apliki are well separated from data for other Cypriot copper mines. Further, the data for ores from the Sha and Kalavasos mines are well separated from each other and from other Cypriot mines.

The facts and the problems

1) At Oxford we made lead isotope analyses of several hundred copper oxhide ingots in comparison with ores from Cyprus, Sardinia, etc. (*e.g.* Stos-Gale *et al.* 1997; Gale 1999; Gale and Stos-Gale 2005).

2) We found that this evidence showed that all post *c.* 1400 BC oxhide ingots were smelted from copper ores from the Apliki ore deposit in Cyprus – this includes ingots and fragments from Cyprus itself, Sardinia, Kyme, Mycenae, Bulgaria, Bogazköy, Sarköy, Antalya, Chios, Kommos, Mochlos, Egypt, the Cape Gelidonya shipwreck, etc.

3) However we also found that many other 'bronze' artefacts excavated from Cypriot Late Bronze Age sites were made from other copper ore deposits around the Troodos (Stos-Gale and Gale 1994.) This is consistent with the limited direct evidence of LBA exploitation of Cypriot ore deposits, such as the proven Bronze Age mine at Ambelikou (Merrillees 1984) and with the excavation of the LBA primary smelting workshop at the site of Politiko-*Phorades* (Kassianidou 1999). It also agrees with Bernard Knapp's reasonable hypothesis that multiple copper ore deposits around the Troodos were exploited in the Bronze Age – however the lead isotope evidence is that only Apliki was exploited to make copper oxhide ingots. Why?

4) Some scholars have found it difficult to accept the primacy of Apliki as a source of bulk copper for export in the form of oxhide ingots, though they have found it difficult to produce logical arguments or proven evidence against it. One apparent problem is the suggestion (Muhly 2009) that it seems improbable that, although oxhide ingots were broken into fragments for use even in Cyprus, no 'bronze' artefacts seem to have been made from copper with LIA matching Apliki ores. Muhly's suggestion is in fact incorrect. If we consider the published lead isotope data for the five sites of Kalavasos-*Ayios Dhimitrios,* Maroni-*Vournes,* Hala Sultan Tekke, Maa and Pyla, then Table 8.1 shows that not

Site	No. of Ingots	No. of Artefacts
Kalavasos- *Ayios Dhimitrios*	4	8 out of 28
Maroni-*Vournes*	6	1 out of 13
Maa-*Palaeokastro*	2	1 out of 12
Pyla-*Kokkinokremos*	3	1 out of 7
Hala Sultan Tekke	0	3 out of 22
All listed oxhide ingots and artefacts have lead isotope compositions which match the copper ores from Apliki		

Table 8.1. lists five Cypriot Late Bronze Age sites for which lead isotope analyses have been made on excavated bronze artefacts and copper oxhide ingot fragments. The table records that all the oxhide ingots were made of copper smelted from Apliki ores, and records the number of artefacts from each site which contain copper smelted from Apliki ores.

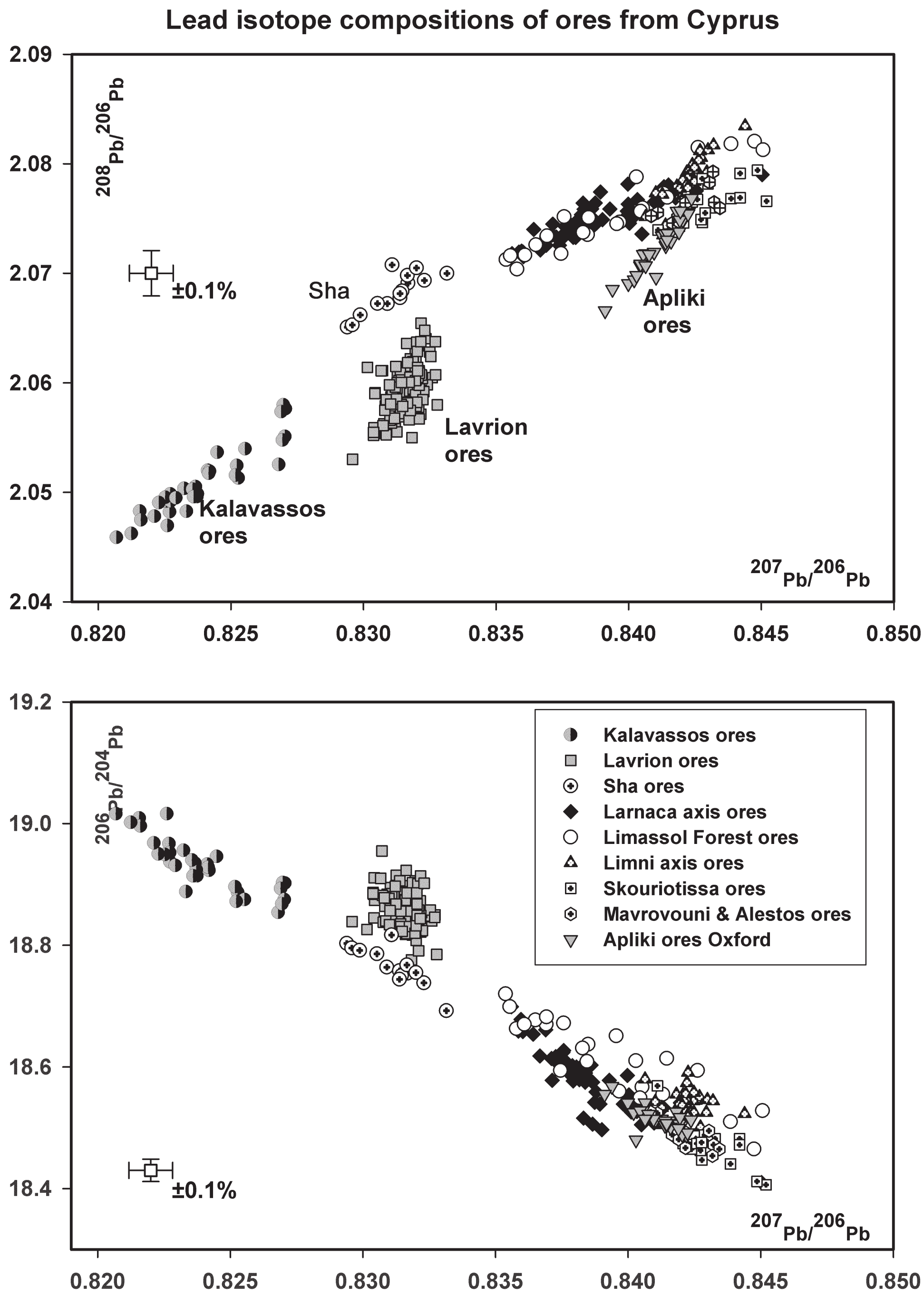

Fig. 8.1. Lead isotope compositions of ores from Cyprus and Lavrion (Attica). The samples of Cypriot ores were collected chiefly in 1995, with the active collaboration and participation in the field of Dr G. Maliotis, Hellenic Mining Company, Cyprus.

only do all oxhide ingot fragments from these sites have lead isotope compositions matching Apliki ores, but so do some of the bronze artefacts from these sites, though it is true that many of the artefacts match other copper ore deposits around the Troodos.

Logical Problems

Muhly concludes an article on copper in the LBA Aegean by writing (Muhly 2005, 509):[3] 'I cannot endorse the Apliki hypothesis, but I do believe that the oxhide ingots dating to post-1400 BC were made of Cypriot copper', and that

(Muhly 2005, 510): 'My conclusion is that the oxhide ingots, wherever found, were made of a very pure, unalloyed copper. This copper, I would argue, is what the Gales have designated 'Apliki copper'. The metal was most likely smelted from Cypriot ores, but I believe that the lead isotope data tells us more about the quality of the copper being used to cast oxhide ingots than about the provenience of the ores being smelted to produce that copper'.

We find this an astonishing assertion, since we know of nothing in the quite large volume of published work about LIA which supports that such analyses can in any way tell us anything about the quality of the copper containing the lead metal. Neither do we know of any published suggestion that this is so, or any theoretical or scientific basis for such an idea (Brill 1970; Farquhar and Vitali 1989; Gale and Stos-Gale 2000). The application of lead isotopes to archaeology was from its inception firmly to establish provenance (Grögler *et al.* 1966; Brill and Wampler 1967). Moreover if we were to accept Muhly's baffling idea that the lead isotope compositions of copper oxhide ingots measured the quality of the copper used to make them, rather than its provenance, we should be faced with the logical difficulty that there would then be no evidence left that the copper came from any Cypriot ore deposit.

Though they have not endorsed the particular argument from Muhly mentioned above, some scholars have nevertheless unwittingly fallen into similar logical contradictions. For example Knapp (1999, 2000), Kassianidou (2001, 2006, 2009) and Muhly (2005, 2009) incline to reject the Apliki hypothesis but all affirm their belief that the great majority of copper oxhide ingots were made of copper smelted from Cypriot ores, largely on the basis of lead isotope analyses. In fact throughout the long history of the serious study of oxhide ingots (beginning with Buchholz 1959) there was no firm evidence for this belief prior to the application of comparative analyses of lead isotope compositions of oxhide ingots and ores from Cyprus (Gale and Stos-Gale 1986; Gale 1991b**;** Stos-Gale *et al.* 1997; Gale 1999).

We know of no objective archaeological evidence proving absolutely that the oxhide ingots found in Sardinia, in Crete, in Mycenae etc., were made on Cyprus, or were made of Cypriot copper. After all, many more oxhide ingots and fragments have been excavated on Sardinia, and from the Uluburun shipwreck, than on Cyprus. Moreover, though a number of scholars, including Knapp (1996), have argued persuasively for the identification of *Alashiya* with Cyprus, the evidence from the texts (Knapp 1996) is almost wholly about the LBA supply of Cypriot copper to the east, to places such as Egypt, Ugarit, Hattusa, etc. Muhly (1991, 180–181) goes so far as to write that the Linear B texts, though they do apparently record an insignificant trade in alum from Cyprus to Minoan Crete, 'certainly provide no evidence in support of a LBA copper industry on Cyprus or of a LBA trade in Cypriot copper'. As for the many hundreds of fragments of copper oxhide ingots found on Sardinia, the archaeological evidence was for a long time interpreted in terms of these ingots having been produced on Sardinia from Sardinian ore deposits (*e.g.* Zwicker *et al.* 1980; Lo Schiavo 1985; Vagnetti and Lo Schiavo 1989; Muhly 1991). That the oxhide ingots found in Sardinia were made of copper smelted from Cypriot ores was eventually proved from lead isotope analyses made by two independent laboratories (Gale and Stos-Gale 1987; Gale 1999; Begemann *et al.* 2001)

However the lead isotope compositions for the post *c.* 1400 BC copper oxhide ingots do not in fact match the lead isotope compositions of most Cypriot ores (Stos-Gale *et al.* 1997; Gale 1999; Gale and Stos-Gale 2005). Most Cypriot ores are excluded as the source of copper for oxhide ingots; the match is solely with the ores from the Cypriot ore deposit of Apliki. This is shown more clearly in the expanded diagram of Fig. 8.2 for oxhide ingots found on Cyprus and in the Cape Gelidonya shipwreck. It follows that acceptance that comparative lead isotope analyses show that the great majority of copper oxhide ingots were made of copper smelted from Cypriot ores necessarily carries with it the corollary that they were made of copper smelted from ores from the Apliki ore deposit. The lead isotope analyses do not allow acceptance of a Cypriot origin for the copper used to make oxhide ingots without accepting that the source in Cyprus is the Apliki ore deposit.

Lead isotope analyses applied to copper oxhide ingots

The introduction of comparative lead isotope analyses as a method for provenancing copper (Gale and Stos-Gale 1982) was followed by a sterile and largely useless debate (*e.g.* *Archaeometry* 34(2), 1992, 311–336; *Journal of Mediterranean Archaeology* 8(1), 1995, 1–75, Special Section) which was full of errors. It is disturbing still to find extracts from that debate being quoted as *ex cathedra* statements as though they add anything to current scholarship; they do not. An example is where Muhly (2009, 29) quotes Pernicka (1995, 60) as stating 'It is time to realize that there is no unique isotopic fingerprint for Cypriot ore deposits, and thus for Cypriot copper'. This was incorrect when it was written, and the lead isotope field for Cypriot ores and Cypriot copper has subsequently been unequivocally established by new lead isotope data published in a number of papers (*e.g.* Stos-Gale *et al.* 1997; Gale *et al.* 1997; Gale 1999, 2006). *Ex cathedra* pronouncements repeating superseded statements have no place in modern archaeology, which must be an evidence-based subject, an approach followed rigorously in the admirable paper by Hauptmann (2009).

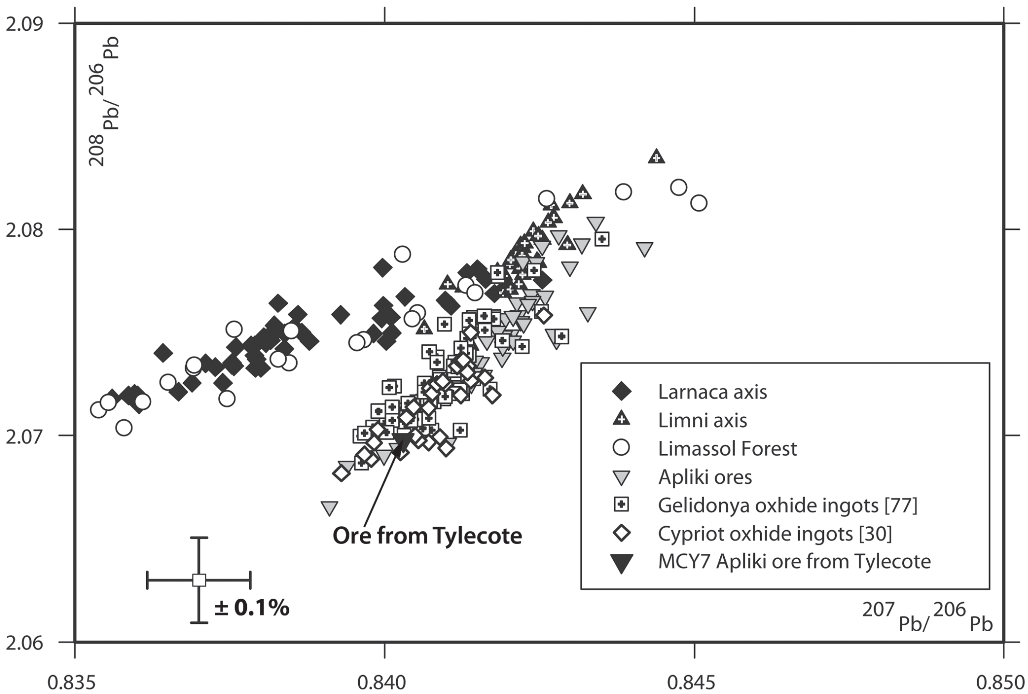

Fig. 8.2. Expanded lead isotope diagram of Cypriot ores, including the many ores collected from Apliki with Dr G. Maliotis in 1995 and the one ore from Apliki available in Oxford in 1994. Shown also are the lead isotope ratios for 30 copper oxhide ingots and fragments from Cyprus (Kalavasos-Ayios Dhimitrios*, Enkomi, Maa, Maroni, Mathiati, Pyla, Skouriotissa), 34 whole ingots and 43 fragments from the Cape Gelidonya shipwreck. The lead isotope ratios for 90% of these ingots do not match any Cypriot ores except for the ores from Apliki in Cyprus.*

It is therefore disappointing to find elements of this old, discredited, debate still muddying the waters in recent papers (*e.g.* Muhly 2009, 27–30; Kassianidou 2009, 61–63). It seems worthwhile to summarize just how discredited that past debate now is, in the hope that at last it may be left behind.[4] Apart from the problems associated with the misguided attempts, initiated by Pollard (see Gale 1989, 489, fig. 13), to interpret lead isotope analyses using multivariate statistics (Baxter and Gale 1998), the other criticisms of lead isotope provenancing by the Bradford group have all fallen by the wayside, and were long ago recognized by Tite (1996) as insubstantial 'straw men'. The most fundamental criticism was the suggestion (Budd *et al.* 1995b) that lead isotopes might be fractionated by ancient metallurgical processes such as smelting, refining, etc., since if true this would completely invalidate lead isotope provenancing. Budd *et al.* (1995b) based their idea that lead isotopes would be fractionated by smelting etc. on a theoretical study (Mulliken and Harkins 1922) of non-equilibrium evaporation applied to evaporation of mercury in a vacuum where the evaporate was efficiently collected and removed on a cold surface; it is very difficult to understand how they thought this might be applied to the very different conditions in a smelting or cupellation furnace, and of course it could not. Direct experimental evidence showed that in practice roasting, smelting, cupellation and refining processes do not change the isotopic composition of lead, within the ±0.1% accuracy of measurement by TIMS of lead isotope ratios (Barnes *et al.* 1978; Gale and Stos-Gale 1996a).

We have referred above to the incorrect idea that no distinctive lead isotope composition exists for Cypriot ores, or that overlaps exist between the LIA for Cypriot ores and Sardinian or other ores; these suggestions have been disproved in a number of papers (*e.g.* Stos-Gale *et al.* 1997; Gale 1999; Gale and Stos-Gale 2005). Hauptmann (2009, 505–6) suggests that there is an isotopic similarity between the copper oxhide ingots found on Sardinia and the geologically young copper ores which occur in Sardinia at Calabona, Capo Marargiu and Castello di Bonvei[5] He argues on the basis of comparative lead concentrations that the ingots were not made from these ores. Gale (1999, 113–115, figs 4, 8) had already shown that LIA of copper oxhide ingots found on Sardinia do not in fact match the LIA of these three copper ore deposits. However, although the LIA data for the ore deposits of Castello di Bonvei and Capo Marargiu had already been published by Stos-Gale *et al.* (1995), the data for copper ores from Calabona had not. This data is therefore published here in Table 8.2.

The bizarre hypothesis that the oxhide ingots represent

Sample No.	Ore	Region	208/206	207/206	206/204	Date
CDC8a	malachite	Due Contatti	2.0900	0.8452	18.533	28/07/1997
CDC9a	malachite	Due Contatti	2.0895	0.8449	18.533	28/07/1997
CFS10c	dispersed malachite	Ferrari shaft	2.0888	0.8451	18.530	28/07/1997
CFS13a	chalcopyrite	Ferrari shaft	2.0876	0.8443	18.549	28/07/1997
CFS16 a	chalcopyrite	Ferrari shaft	2.0885	0.8445	18.551	28/07/1997
COB17 a	malachite/haematite	Dump near Office	2.0871	0.8447	18.538	20/12/1996
COB18b	malachite	Dump near Office	2.0864	0.8445	18.530	19/12/1996
CSG2B/1	pyrite	San Giovanni 2	2.0855	0.8439	18.538	30/07/1997
CSG2B/2	pyrite	San Giovanni 2	2.0901	0.8448	18.550	30/07/1997
CSG3	malachite	San Giovanni 2	2.0867	0.8444	18.536	18/12/1996
CSG7	malachite	San Giovanni	2.0880	0.8449	18.517	30/07/1997
CV1	malachite/haematite	Calabona Vessus	2.0858	0.8436	18.540	24/02/1986

Table 8.2. Lead isotope compositions for ores from the Jurassic-Palaeozoic Calabona mine in north west Sardinia.

the mixture of both recycled metal and copper that originated from various mines around the Mediterranean that belonged to a *koine* (Budd *et al.* 1995a, 25–27) is now completely discredited (Gale and Stos-Gale 1995, 35–36; Gale 2001, 122–123; Knapp 2000, 43; Kassianidou 2001, 102–103; Hauptmann 2009, 504). Scholars can perhaps now agree to disregard this old controversy in its entirety, and accept the assessment of it by Tite (1996) and Hauptmann (2009).

The size and position of the Apliki mine

It has been objected that the Apliki deposit is the smallest if compared with Mavrovouni and Skouriotissa, is not nearer to the surface, is the deposit that is highest up on the foothills of the Troodos, is the farthest from the sea and the Mesaoria plain and is farthest from the Cypriot sites having oxhide ingots and where the final stages of metal extraction seem to have been carried out (Kassianidou 2009, 62). To characterize Apliki as 'a fairly small mine' (Muhly 2005, 508) could be done only by one who has not seen the large open cast pit formerly operated by the Cyprus Mines Corporation (CMC), and who has not read contemporary accounts of its exploitation. McMahon (1965, 269) records the reserves of the Mavrovouni mine as 2.06 million short tons and the reserves of the Apliki mine as 1.85 million short tons of ore. The CMC exploitation was recorded by the USGS in 1969: 'the company's planned output of ore in 1969 was about 300,000 tons from the Skouriotissa mine, which is expected to remain active through 1971; and about 300,000 tons from the Apliki mine, a new open-pit mine still considered in the development stage in early 1969' (Slatick 1969). It is in fact not particularly relevant which is the largest mine in terms of modern exploitation of the relatively copper-poor pyritic ores since, as we shall see, it is likely that it was copper-rich supergene ores that were exploited in the Bronze Age. In that connection it is noteworthy that it was gold that was first exploited in modern times by CMC at Apliki; it was extracted from the leached capping at the Apliki gossan, which gossan was underlain by supergene ores. While extracting gold from the gossan CMC discovered a cupriferous pyritic ore body 60 feet below ground (Bear 1963; Lavender 1962).

On the question of the distance of Apliki from the sites where oxhide ingots are found, such as Enkomi, Kalavasos-*Ayios Dhimitrios*, Maa-*Palaeokastro* etc., the observations of Dikaios (1969–71, 11) are interesting: 'Catling suggests that Enkomi drew its supplies of copper ore from the industrial site of Troulli, ten miles north of Larnaca, rather than from the distant Troodos hills. This may be so, but the second alternative may be equally possible. In support of this I may quote the following instance: Until about fifty years ago, before the introduction to Cyprus of mechanical production of ice, villagers from the village of Prodromos which lies below the Troodos summit, used to carry to Nicosia, during the summer season, ice (ice, at that time, was indispensable for the treatment of typhoid fever, which was almost endemic during summer) on donkey back, from pits on the highest summit of Troodos, in which snow accumulated during the winter and where it was carefully preserved until the summer. According to information given me by old inhabitants of Prodromos, they loaded the donkeys at sunset and travelled all the way down to the plain along short cuts across hill country, reaching Nicosia on the following morning. If then ice could be carried from the summit of Troodos to Nicosia in one night, surely copper ore could be transported from the Skouriotissa and other mines which lie on the northern foothills of Troodos (the chief source of copper: Catling 1964, 20 ff.) during the same length of time or somewhat longer. There were, probably, organized convoys of donkeys or mules carrying regularly ore to industrial towns such as Enkomi and others (ibid. p. 17)'.

This could clearly apply equally to Apliki and, since at present we have no idea where in Cyprus copper oxhide ingots were cast, it might be ingots rather than ore which

Sample	Site location	208/206	207/206	206/204
AK 1	Room 7 (33a)	2.0712	0.8407	18.510
AK 2	Room 3 (2a)	2.0830	0.8483	18.356
AK 13	Room 2 – VII(9)	2.0708	0.8405	18.509
AK 19	Room 2 – VII(9)	2.0716	0.8410	18.501
AK 20	Room 2 – VII (9)	2.0794	0.8471	18.375
AK 22	Room 3/ 1b – 19	2.0760	0.8422	18.513
AK 24	AK1938	2.0735	0.8420	18.496
AK 25	Room 2 – VII(8) – 31a	2.0787	0.8430	18.464
AK 27	Room 2 – VII(9)	2.0711	0.8416	18.505

*Table 8.3. Lead isotope analyses of slag samples from Apliki-*Karamallos *excavated by J. Du Plat Taylor. The samples are from the collections of material from the excavations held by the Institute of Archaeology, UCL, London, and were brought to Oxford by S. van Lokeren, with the permission of J. D. Muhly.*

were transported by donkeys from the Apliki region to Enkomi or other coastal sites where they might be loaded onto ships for export. Evidence for the use of pack animals for the bulk transport of copper to the coast of Cyprus has for example been discussed by Knapp and Cherry (1994, 419). Jones (2007, 86–87) has conveniently summarized the evidence for the transport by pack animals of tin and copper in the Bronze Age and the evidence that the shape of the oxhide ingot may have been designed specifically for land transport: the handles would have made them more convenient to lash to a packsaddle on a donkey.

Chronology of copper mining in the Apliki region

What direct evidence is there for ancient mining of the ores in the Apliki/Skouriotissa region? Most people are familiar with the extremely large copper smelting slag heaps at Skouriotissa (see figs 1 and 3 in Stos-Gale *et al.* 1998); these are so large that no one would associate the majority of them with the Bronze Age, and the three C-14 dates reported for samples from these slags by Zwicker (1986b) are 310, 260, and 200 AD. However Zwicker also reports that wood from timbered galleries in the Skouriotissa mine is C-14 dated to 620, 580 and 485 BC. Around the nearby large mine of Mavrovouni there are also large amounts of 'ancient', though not Bronze Age, slag (Bruce 1948, 216). Taylor (1952, 150) reported the existence of a large slag heap at Apliki at the foot of the hill near the river which she described as 'in general appearance of Roman date'.[6]

Shaft timberwork was found in the Apliki mine itself, and is now held in the German Mining Museum at Bochum (Weisgerber 1982, pls 1–3); this timber has been C-14 dated to 420 BC. Thus we have direct evidence for fairly early underground mining both in Apliki and Skouriotissa. On the general principle, followed by miners throughout history, of re-exploiting what their predecessors have begun, this may be a weak argument for at least not discounting possible LBA exploitation of copper ores at Apliki, and perhaps also at Skouriotissa. This is a possibility made even more acceptable by the direct evidence for Early Cypriot III mining in the much smaller Ambelikou mine in the same region (Merrillees 1984). There is of course definite evidence at the Middle Cypriot I site of Ambelikou-*Aletri* for crucible copper smelting (Merrillees 1984). Most persuasive of all is the evidence from the LC IIC–LC IIIA Bronze Age miners' settlement of Apliki-*Karamallos* (Taylor 1952; Muhly 1989), which had apparently lasted from *c.* 1300 BC to *c.* 1200 BC (Manning and Kuniholm 2007). Much evidence of copper smelting (slag, tuyères, etc.) was found in Apliki-*Karamallos* (Taylor 1952, 150–153; Muhly 1989). In its neighbourhood, du Plat Taylor (1952) found several remnants of ancient mining galleries, including one connected with a dump containing pottery contemporaneous with the Bronze Age settlement. We were kindly provided by S. van Lokeren with samples of stratified slags from Taylor's excavations[7] for which we made lead isotope analyses by TIMS; the data is given in Table 8.3 and plotted in Fig. 8.3. It is clear that the lead isotope analyses of the copper slags from the LC IIC–LC IIIA mining/metallurgical site of Apliki-*Karamallos* match those for copper ores from the Apliki mine, confirming that these were the ores being exploited at this site. This provides clear evidence that the copper ores from the Apliki mine region were indeed being exploited in the Bronze Age.

The nature of the Cypriot copper ores

Too little emphasis has been placed on the nature of the copper ores in Cyprus by archaeologists attempting to discuss the nature and organization of copper extraction and metallurgy in Cyprus in the Chalcolithic and Bronze Age periods.

Useful reviews of copper ores in Cyprus have however

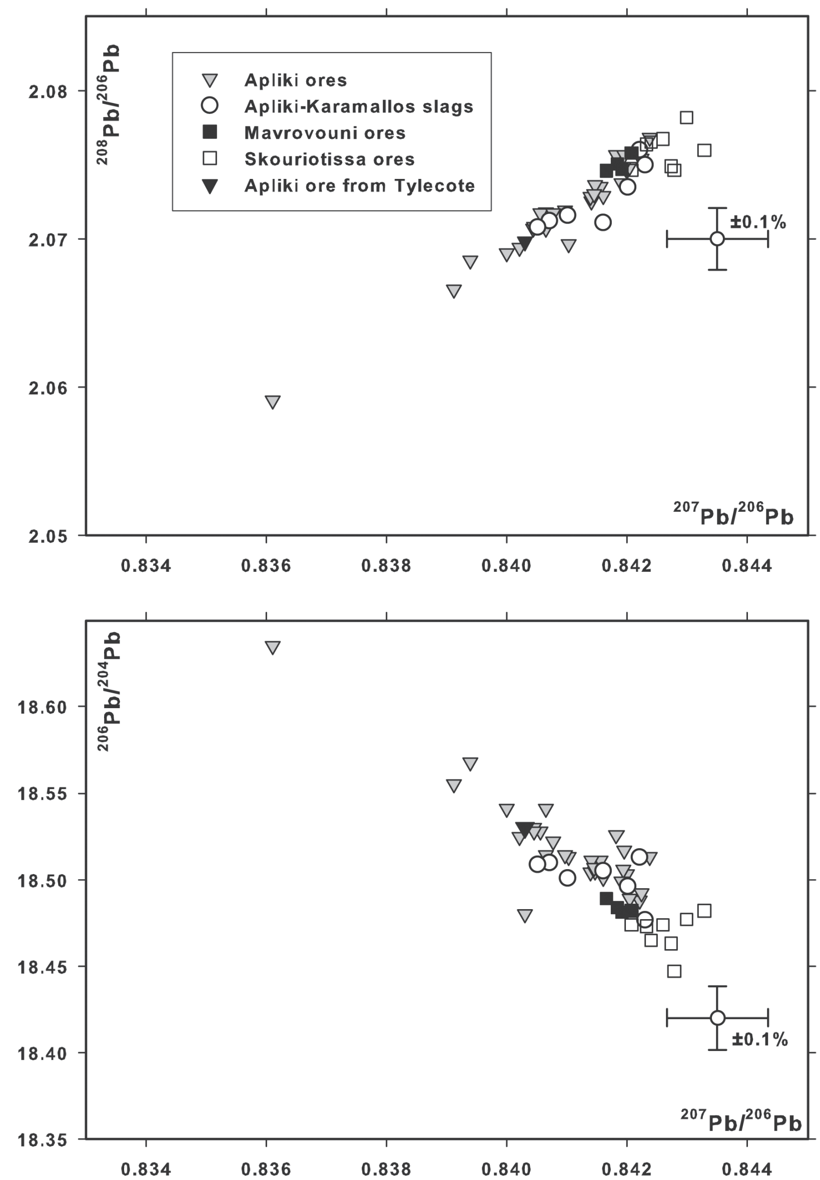

*Fig. 8.3. Lead isotope analyses of slags from the site of Apliki-*Karamallos *compared with the isotopic analyses of ores from the Apliki, Mavrovouni and Skouriotissa mines.*

been given over the years by Bruce (1937, 1948), Bear (1963), Constantinou (1982, 1992, 1999), Constantinou and Govett (1973), Stos-Gale *et al.* (1997) and Gale (1999). It has sometimes been suggested (*e.g.* Constantinou 1982, 1992, 1999) that native copper, which does occur sparsely in Cypriot copper deposits, was most probably the first copper to be used in prehistoric Cyprus, but this hypothesis is not supported by scientific work on Cypriot native copper and Chalcolithic copper artefacts (Gale 1991a). Though copper sulphate ores (brochantite, chalcanthite, etc.) occur in reasonable amounts in various localities in Cyprus (*e.g.* Troulli, Skouriotissa), and have been successfully smelted to copper metal in a replica of the large Enkomi crucible by Zwicker (1986a, 82–83), these ores do not exist in sufficient quantities in Cyprus to underpin the production of copper oxhide ingots, whilst comparative lead isotope analyses exclude sulphate ores as a source of copper for such ingots (Stos-Gale *et al.* 1997, Gale 1999).

The dominant ores in Cyprus are of course the primary sulphidic ores of pyrite and chalcopyrite which occur in the Pillow Lava Series of the Troodos Ophiolite and are distributed around the Troodos mountains (Constantinou and Govett 1973). However, with an average copper concentration of 0.5% to 4.5%, these primary ores are not rich enough in copper to have been a likely source in the Bronze Age of copper for the copper oxhide ingots. The uplift of the Troodos Ophiolite and the consequent exposure of the primary ores to subaerial weathering and oxidation processes involving oxygenated rainwater led in part to the production of acid solutions of copper and iron which interacted with limestone formations to produce oxidized copper ores of malachite (green) and azurite (blue) (*e.g.* Constantinou 1992; 1999). These colourful copper ores are very easily reduction smelted to copper metal (Donnan 1973; Gale *et al.* 2009, 166), and Constantinou (1992, 1999) has suggested that malachite and azurite were the first minerals to be used for the pyrometallurgical production of copper in Cyprus. Evidence has been published that such Cypriot oxidized ores were indeed smelted to produce copper at the MBA site of Alambra in Cyprus (Gale and Stos-Gale 1996b).

Subaerial weathering of primary ores also produced the spectacular yellow and red coloured 'ironhats' or gossans containing iron hydroxides,[8] which probably attracted Bronze Age people to associated copper deposits (Constantinou 1992, 59–60). When the acid, metal containing solutions from weathering percolated down to the water table they encountered reducing conditions which precipitated out copper as a variety of secondary copper sulphide and oxide minerals including chalcocite, bornite, covellite and cuprite, sometimes intimately associated with primary chalcopyrite (Bear 1963, 39, 43, 45, 47, 48). These minerals occur in the zone of secondary copper sulphide enrichment (the supergene or cementation zone) (see Robb 2005, esp. 239 fig 4.13). Such secondary enrichment zones in Cyprus contain from 10% to in excess of 15% of copper;[9] Constantinou (1992, 57) records his observation that these zones '…were extensively exploited, producing most of the copper in ancient Cyprus', an opinion which he also emphasizes elsewhere (Constantinou 1999, 41).

The Secondary Enrichment Zone Hypothesis

An important point was made long ago by Bruce (1937) and Constantinou (1982, 18–19), that no traces of water pumps have been found in any 'ancient' Cypriot mine, and that 'the limitations imposed by the water table level compelled the ancient miners to leave behind sulphide ore for the modern mining industry of the island.' By sulphide ore Constantinou meant the pyritic ore mined in modern times as a source of copper and sulphur (Spooner 1975) by CMC, Hellenic Mining, etc. It is possible that in the Bronze Age the pyritic ore was also a difficult proposition for the extraction of copper because the copper concentration was relatively low. It seems more probable that Bronze Age people discovered and mined the supergene copper ores mentioned above. The level of the water table in each mine was of course controlled by its stratigraphy, geology and tectonic structure.

In an important and imaginative paper Hauptmann (2009) has recently drawn attention to factors in the structure of ore deposits and recent developments in economic history which may help to explain the dominance of Apliki as a source of copper for oxhide ingots. He wrote that everywhere mining and metal production focus at first on rich ores near the surface, often in or just below the gossan (iron hat), in so called secondary enrichment, supergene or cementation zones. Such zones in copper deposits contain rich ores such as covellite, bornite, chalcocite, cuprite, even native copper, from all of which it is much easier to smelt copper metal than it is from the relatively poor levels of copper in the underlying primary pyritic ores.

Such supergene zones have been mentioned in Cyprus by Kortan (1970) and Constantinou (1982, 1992, 1999) as having more than 15% Cu and at depths reached by ancient miners. Constantinou (1992, 57; 1999) wrote that from these zones came the main part of copper production in ancient Cyprus. Stech *et al.* (1985, 398) wrote that the ores available in the Bronze Age were probably covellite, chalcopyrite, cuprite, bornite, chalcocite – possibly they were thinking of the cementation zone, where just these ores occur?

A very important recent innovation (Hauptmann 2009, 507) in the study of archaeometallurgy and provenance studies in Cyprus is to consider the structure of ore deposits and developments in economic history. Hauptmann (2009) has pointed out that mining and metallurgical activities are largely dependent on the geology and mineralogy of ore deposits. Hauptmann (2009) writes 'These factors determine their extent and their economic success and they also determine technological developments in exploitation, beneficiation and smelting processes.' Moreover the exploitation of a rich ore deposit may lead to social, economic and political changes (Bartels 1997; Stöllner 2003). Hauptmann drew attention to such changes caused by the intensive exploitation in Medieval Germany of rich ores in enrichment zones. For example, rich silver ores caused an explosive development of the city of Joachimsthal in the 16th century AD, followed by a painful crisis when the rich ores were exhausted.

By analogy, it is possible that similar, relatively short term, mass production of copper, used to make oxhide ingots, took place in Bronze Age Cyprus when, following earlier use of oxidized ores such as malachite and azurite (such as at Alambra), enriched supergene ores were discovered, causing structural changes similar to those in Medieval Germany. Brightly coloured gossans, which themselves contain no copper, may well have led people to rich supergene copper ores lying at the base of the gossan. In earlier papers we have suggested that it is a matter of chance when and where in the Bronze Age, governed by the location and accessibility of rich supergene ores, really rich copper ores will have been discovered in Cyprus, but once discovered they are likely to have become a focus of exploitation to supply the need for copper exports, as ingots in a convenient form. Once discovered a rich copper source will have been intensively exploited, whilst further prospecting will temporarily cease, except perhaps for small local ore sources to supply local needs within Cyprus. Hauptmann (2009) has considerably refined and strengthened that suggestion by emphasising the probable nature (supergene) of the rich copper ores found, and by setting the situation in Bronze Age Cyprus in terms of the analogous developments in Medieval Europe, for which written records exist (Bartels 1997; Stöllner 2003).

Conclusions

1) Lead isotope analyses show that post *c.*1400 BC oxhide ingots were made of copper from the Apliki deposit in Cyprus. If this is rejected, there remains no evidence that oxhide ingots were made of copper from Cyprus.
2) The fact that LIA for Bronze Age slags from Apliki-*Karamallos* match the LIA for ores from the Apliki deposit confirms that LIA are reliable for provenancing, and that copper ores from the Apliki deposit were smelted in LC IIC–LC IIIA times at Apliki-*Karamallos*.
3) LIA through cores taken from Uluburun ingots confirm that oxhide ingots were made by successive pourings of molten copper into a mould, but show that the separate pourings were of copper derived from the same ore source, so that lead isotope provenancing of the copper used to make ingots remains valid (Gale 2005).
4) Present evidence shows that, on Cypriot sites where there are both oxhide ingot fragments and 'bronze' artefacts, that some artefacts were made from 'Apliki copper' and some from copper smelted from other Cypriot ore deposits around the Troodos.
5) LIA show that slags at Enkomi reflect the use of various ore deposits around the Troodos, with a very limited use of Apliki ore
6) LIA of slags at Kalavasos-*Ayios Dhimitrios* show use of various ore deposits, including Apliki, but no use whatsoever of ores from the Kalavasos ore deposits. LIA of artefacts at Kalavasos show that they also were not made of copper from Kalavasos ore deposits.
7) In consequence LIA support a model where in Cyprus 'world bulk metal' (as defined by Hauptmann) for export as oxhide ingots was made from copper smelted from Apliki ores, but that Cypriot LBA artefacts were made both from 'Apliki copper' and from copper smelted from other ore deposits around the Troodos at smelting sites such as Politiko-*Phorades*.
8) It seems probable that at Apliki rich ores from the cementation zone were exploited, leading to mass production and an 'imprinting phase' of metal production as described by Stöllner (2003) and Hauptmann (2009). The cementation zone at Apliki was favoured for discovery since it lay near the surface and above the water table.
9) It is a matter of chance when or where, in the Bronze Age, the really rich, supergene, copper ores will have been discovered in Cyprus, but once such a source was discovered it is likely to have been exploited intensively to supply the need for copper exports, as ingots in a convenient form.

Notes

1 Formerly we referred to the oxhide ingots with Apliki lead isotope compositions as being post 1250 BC, since the great majority of such ingots (from Greece, Cyprus, Turkey, Bulgaria, Sardinia, Cape Gelidonya, etc.) did date after approximately 1250 BC. However our later work showed that LM IB oxhide ingots from both Gournia and Mochlos were made of copper from the Apliki deposit. Absolute dates for LM IB remain controversial (Manning *et al.* 2006), but may perhaps be taken as approximately 1550–1400 BC, though Manning (2009) has recently suggested the approximate range of *c.* 1600 to *c.* 1470/60 BC. Conservatively we may perhaps therefore refer to the ingots with lead isotope compositions matching the Apliki compositions as post *c.*1400 BC.

2 The axes mentioned in this figure are spreading axes, explained in Stos-Gale *et al.* (1997).

3 The English translations quoted are from Ü. Yalçin (ed.), Handouts, Uluburun Workshop, Deutsches Bergbau-Museum, April 2006.

4 In this regard a completely independent appraisal of the present situation will be found within Hauptmann (2009).

5 The location of the Calabona copper ore deposit is conveniently given by Frenzel *et al.* 1975, who also give a sketch map of the Calabona mining area showing the locations of ore samples mentioned in Table 8.2.

6 There is no evidence that this slag heap is Roman; it might be earlier.

7 Held in the collections of the Institute of Archaeology, UCL, London.

8 These gossans often also contained precipitated and disseminated gold and silver, as *e.g.* at Skouriotissa, Apliki, Limni, Mathiati, but there is no evidence that these precious metals were recognized or worked in Cyprus before the 20th century AD (Bear 1963, 185–189; Constantinou 1992).

9 In contrast with the 0.5% to 4.5% copper content of the primary sulphide ores.

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