

LEAD ISOTOPE CHARACTERISTICS OF THE CYPRUS COPPER ORE DEPOSITS APPLIED TO PROVENANCE STUDIES OF COPPER OXHIDE INGOTS*

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Nearly 200 new lead isotope analyses of sulphidic and oxidized ores from 26 copper mines on Cyprus show that the mines from different geological regions group in five distinctive isotopic groups, each with a substructure, related to the geological history of the ore formation. Comparison of lead isotope compositions of Bronze Age artefacts with these data can in many cases reveal the actual mines from which the copper for particular artefacts was obtained. The particular case of the provenance of the copper for 78 Late Bronze Age copper 'oxhide ingots' found in Cyprus, Crete, Greece, Sardinia, Turkey and Bulgaria is discussed. The data show that all oxhide ingots so far analysed, dating to the fourteenth century BC and later, were made of copper consistent isotopically with only one mining region in the geographical north of Cyprus, and especially the Apliki mine. The study provides further evidence which supports the validity of the conventional approach to the use of lead isotope analysis for provenancing metals; this evidence is antithetical to recent suggestions of a model for the production of copper oxhide ingots which involved widespread mixing of copper from a number of ore sources throughout the Mediterranean.

KEYWORDS: CYPRUS, BRONZE AGE, LEAD ISOTOPE ANALYSIS, COPPER OXHIDE INGOTS,
ORE DEPOSITS, COPPER, METALLOGENESIS, PROVENANCE

INTRODUCTION

The recent vigorous discussions of the lead isotope provenancing of metals may have left some archaeologists in a state of uncertainty about the subject. Budd *et al.* (1995b) claimed, as chief scientific reasons for proposing a new hypothesis about Late Bronze Age (LBA) copper oxhide ingots, that there were insufficient data properly to define the lead isotope field for Cypriot ores, that the published lead isotope data even for oxhide ingots found on Cyprus itself did not overlap convincingly with the existing isotopic data for Cypriot ores, and that the isotopic data for Cypriot ores could not be resolved from those for some other metal ore deposits. A subsequent paper (Budd *et al.* 1996), suggesting that lead isotope provenancing needed to be completely reappraised, was clearly based on these earlier doubts.

In this paper we discuss lead isotope data which increase by a factor of about five those available for Cypriot metal ores. This work was undertaken chiefly to provide a firmer basis for discussion of lead isotope analyses of LBA artefacts from Cypriot and other sites in the Mediterranean region, in particular copper oxhide ingots, for which we also report new data. It was undertaken also to investigate possible structure in the lead isotope data for Cypriot ores,

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which was tentatively suggested by the data earlier available (Gale and Stos-Gale 1992, fig. 1), and to see whether any structure which might emerge could be related to recent geological/geophysical investigations in Cyprus. The new data obtained for Cyprus could, together with new data for ores from Oman and the Tertiary Sardinian copper ores, be used also for an objective examination of possible overlaps of Cypriot lead isotope data with those for other copper ore deposits in Tuscany, Spain, Sardinia, Bulgaria and Oman, and for a reassessment of the relationship between Cypriot ore data and those for a number of copper oxhide ingots from widely dispersed findspots. As an important consequence of our research, an objective examination can be made of some of the chief foundations of a recent claim that lead isotope provenancing of metals stands in need of radical reform.

Cyprus has been a significant centre of intermittent mining activity and copper production from the Bronze Age, through the Iron Age, the Cypro-Geometric, Early Cypro-Archaic, Roman and Byzantine times (e.g., Koucky 1982) to the intensive exploitation of the pyrite deposits for sulphur in modern times (Spooner 1975), that is, from the second millennium BC to the present day. In view of this, the study of the lead isotopes of the Cypriot deposits is an important geological and archaeological topic, both for elucidating the genesis of the ores and also in provenance studies of ancient metal artefacts. Here we concentrate on the archaeological standpoint, discussing the geological aspects only insofar as is necessary to investigate whether the lead isotope data are in accord with the latest geophysical and geological research in Cyprus, in the hope that this will give the reader confidence in the basic isotopic data for ores, in terms of which the provenancing interpretation must be discussed.

The role of Cyprus in the Bronze Age metals trade in the Mediterranean has been a longstanding subject of debate (e.g., Davies 1932; Stos-Gale *et al.* 1986; Muhly *et al.* 1988). The copper oxhide ingots, usually about 25–28 kg in weight, and their provenance have played a major part in that debate. Much valuable work has been done on the metallography and chemical analysis of these ingots, principally by R. Maddin, J. Merkel, T. Stech and J. D. Muhly, but these authors have justifiably concluded in a number of their more recent papers (e.g., Muhly and Stech 1990, 203; Lo Schiavo *et al.* 1987 together with Tylecote 1987) that such analyses do not allow one to deduce the ore sources of the copper used to make the ingots. That minor or trace element chemical analyses of metal artefacts cannot, by themselves, trace the geological/geographical sources of the metal is now generally accepted (Tylecote 1987; Budd *et al.* 1996), and the geological/extractive metallurgical reasons for this to be so have been discussed in some detail (e.g., Gale and Stos-Gale 1982). That, on the other hand, trace element analyses may in some cases aid provenance studies primarily based on lead isotope analyses is fairly well accepted (Gale and Stos-Gale 1995; Pernicka 1995).

Recently it has become clear that provenancing based upon lead isotope analysis, aided by trace element analyses of gold and silver (see, e.g., Gale and Stos-Gale 1989), is so far about the only tool we have to provenance the ore source of the copper used to make copper ingots and thereby trace their movement about the Mediterranean region. The importance of this is, of course, that oxhide ingots of copper (and tin) formed an important component of the LBA metals trade in the Mediterranean, and that the unequivocal solution of this provenancing problem might then be extended to tracing the provenance of metal artefacts of other types, such as weapons and tools.

The fundamental hypothesis, at the root of all the attempts by the Philadelphia group to provenance oxhide ingots, was that these ingots were the product of a single smelt using ores from a single mine, and were therefore not subject to the confusion which might be introduced

by the mixing of metals or ores (see, e.g., Stech-Wheeler *et al.* 1975, 32). It is of course fundamental to lead isotope provenancing that the copper oxhide ingots should not have been made of mixtures of metal smelted from ores from different ore deposits having differing lead isotope compositions; this point is discussed in more detail in the section on metal recycling.

Archaeologists have long guessed Cyprus to have been a major supplier of copper in the LBA to the eastern and central Mediterranean civilizations. In principle the comparison of lead isotopic composition of Cypriot ores and copper-based archaeological metal finds should allow a scientific examination of this hypothesis. This clearly necessitates the establishing of the lead isotope composition of Cypriot copper ores to the fullest extent possible. Until now only 43 lead isotope analyses of ores from 18, not always geologically well-characterized, localities have been published. Recent geological research into the genesis of the Cypriot ore deposits suggested that there might be a much wider range of lead isotope compositions characteristic for these ores. This hypothesis has, as will be seen, been substantiated by the new analyses of samples of ores recently collected in 26 geologically well-defined copper deposits (the complete lead isotope analyses of Cypriot ores are presented in Gale *et al.* (1997, this volume).

We would like to challenge here the statement by Budd *et al.* (1995b, 26) that 'It is not meaningful, either on archaeological or geological grounds, to attempt to compare artefacts with lead isotope fields for individual mine sites'. The work to be presented here demonstrates that, with the large number of lead isotope data for ores collected under geological supervision from specific parts of the Troodos, it is possible to distinguish isotopically between a number of mines, and also that a group of 78 LBA copper oxhide ingots found in various parts of the Mediterranean is fully consistent with the lead isotope compositions of only three specific Cypriot mine sites out of the 26 investigated. By itself this would seem to indicate that it is therefore meaningful, both geologically and archaeologically, to compare artefacts with individual mine sites which are sampling different metal ore occurrences. We have many more examples of such meaningful comparisons of artefacts with individual mine sites; a recent example is a detailed examination of LBA sources of lead and silver in the Cyclades and mainland Greece (Gale *forthcoming*).

METHODOLOGY OF COLLECTING LEAD ISOTOPE DATA FOR CYPRIOT METAL ORES

The methodology of lead isotope provenance studies is not generally agreed amongst the researchers in this field. There has always been a wide discrepancy of practice between the usual Mainz-Heidelberg approach of analysing only one or two ore samples from each locality, leading to discussions in terms of the lead isotope compositions of large regions like the 'Aegean', or 'Pontides' and 'Taurides' (e.g., Pernicka *et al.* 1990), and the Oxford approach of creating a data base of numerous analyses of ores for each specific locality and then, if needed (which it is not in this paper), trying to distinguish between them using statistical methods (see, e.g., Stos-Gale 1992). The apotheosis of the statistical approach to the treatment of lead isotope data is of course that espoused by Sayre and his colleagues. The new lead isotope data on ores from Cyprus were collected in the last two years, in a continuing programme of creating an extensive as possible data base for the Mediterranean ore deposits within a NERC and INSTAP funded project. This was necessary because the Cypriot lead isotope 'field' in publications on the subject of metal provenance has been based only on 33 Oxford analyses of copper ores, sometimes of dubious provenance, collected or donated from various places (Stos-Gale *et al.* 1986; Stos-Gale and Gale 1994) together with ten analyses of ores from eight mines published

by Hamelin *et al.* (1988). Even this small group of data indicated that different mining regions might have different isotopic characteristics. The range of isotopic ratios in the Cypriot 'field' so defined was so large, about 2% ($\pm 1\%$), as to suggest it had structure, possibly folding together a number of smaller fields characteristic of individual ore deposits. Indeed Hamelin *et al.* (1988, fig. 2) showed that the lead isotope compositions for the mines of Skouriotissa + Alestos, Limni, Mathiati, Troulli, Kambia + Peristerka + Pitharochoma, fell into discrete isotopic groups, which was also demonstrated by Gale and Stos-Gale (1992, fig. 1).

Until recently there was no clear geological hypothesis to explain these detailed features of the isotopic record. Even so, until now this group of data was used to define the old overall Cypriot 'field' and was that always compared with the lead isotope composition of copper-based Bronze Age artefacts. Nevertheless, from the beginning it was known that there are sulphide minerals on Cyprus which have very different lead isotope characteristics. Lead isotope ratios for one such deposit (Mousoulos) were published by Spooner and Gale (1982) and in the last 15 years we have continually checked if these particular ratios match any of the analysed Bronze Age metals from the Aegean and eastern and central Mediterranean. So far no ancient metals from anywhere in the Mediterranean show lead isotope compositions overlapping those of these ores from Mousoulos. Moreover, the Mousoulos ore deposit is deeply buried and had no surface expression observable by the ancients, whilst its modern exploitation (by the Hellenic Mining Company Ltd. between 1967 and 1977) revealed no pre-existing galleries or other signs of previous exploitation. However, our recent work shows that there are other Cypriot ore deposits, not all deeply buried, which also have lead isotope compositions falling well outside the previous conception of the field for Cypriot ores and near the Mousoulos composition, but again there are so far no artefacts which match these isotopic compositions. Recent geophysical/geological work in Cyprus explains why it is that the ore deposits at Mousoulos and nearby are expected to have lead isotope compositions different from most other deposits on Cyprus, from which they are separated by the palaeo-transform Arapakas fault (Simonian and Gass 1978).

In earlier publications (e.g., Gale and Stos-Gale 1989, fig. 4) lead isotope compositions of umbers were also included in the overall Cypriot field but, although their inclusion makes no difference to the extent of the field (Gale and Stos-Gale 1995, fig. 1), they are not now included because there is good evidence that they did not form part of the smelting charge in the Bronze Age and their mode of formation is different from that of the sulphide ores (see the next section). The evidence that umbers were not put into Bronze Age copper smelting furnaces comes from the fact that, whilst umbers on Cyprus are manganiferous (e.g., Robertson and Hudson 1973), copper slags from Bronze Age Cypriot sites contain less than 1% Mn (usually much less), though Roman and later Cypriot slags often contain from 5% to 45% Mn (e.g., Bachmann 1982; Koucky 1982; unpublished data from the Isotracer Laboratory, Oxford).

During the last two years we have analysed another 194 ore samples, both increasing the number of samples from each mine and adding new samples from mines previously not included. These new data will provide a new background for the re-assessment of the origin of copper-based artefacts from Bronze Age Cypriot and Aegean sites which we have analysed in the last few years. For these new lead isotope data of ore samples from Cyprus special emphases were laid on knowing the exact geological/geographical provenance of mineral specimens and on high quality of measurements of lead isotope ratios—only data measured with an internal within-run precision of better than 0.01% standard error of the mean on 60 ratios are presently included. We hope that this data base will also provide a comparative background for any further

lead isotope provenance work for any group of researchers on the sources of ancient copper in the Mediterranean.

PLATE TECTONICS AND CYPRIOT ORE GENESIS

This paper is not intended as a scientific discussion of the geological origin of Cypriot ores. Nevertheless it seems essential to mention briefly the geological background to the lead isotope characteristics of Cypriot ores, because the lead isotope patterns in any mineralization reflect the history of ore formation and can not properly be discussed without an understanding of the underlying geological principles. Such a discussion is particularly appropriate here, so as to be able to emphasize how well the new lead isotope data for Cypriot ores accord with the latest geophysical and geological information for Cyprus. This may afford more confidence in the lead isotope data in their principal use in this paper, which is their application to finding the source of copper for the oxhide ingots. Some explanation is also required of geological terms used later in this paper.

In recent years there have been considerable developments in understanding the mechanism of formation of the Cypriot ores in relation to the theory of plate tectonics. According to this theory, in simplified form, the earth's crust is made up of several large plates and many smaller ones. The size and relative position of these plates is not constant but changes with time. They grow along the mid-ocean ridges where new crust is formed by the rising and solidification of magma (mobile rock material including a liquid silicate-melt phase) from deeper levels of the earth. This crustal forming process takes place along the so-called axial spreading axes, since the newly formed crustal plates on either side of each axis 'spread' away from each other. The spreading of each plate is very slow, of the order of only a few centimetres per year. An example of a mid-ocean ridge is the mid-Atlantic Ridge, which runs along the middle of the Atlantic Ocean and along which new crust is formed and spreads on either side of the spreading axis at the rate of about 2 cm per year. On the other hand, plates also collide with each other, one overriding the other, which sinks into the deeper levels of the earth, melts and gives rise to volcanic activity on the surface. These lines of collision are the so-called subduction zones, which on the earth's surface are characterized by high mountain chains and intensive volcanic and seismic activity, due to the energy released in the collision of the plates. An example of such a zone is the western coast of North and South America. (See, e.g., Windley 1984 for an account of plate tectonics.)

Detailed studies along present-day spreading axes in many parts of the oceans have revealed that these also are areas of intensive volcanic and tectonic activity with the extrusion of lavas and the formation of steep faults parallel to the line of the spreading axis and dipping to the direction of the axis; a block of rock has been downthrown along the faults relative to the rocks on either side. This tectonic picture is termed by geologists a 'graben' and is shown schematically in Figure 1 (see also Sawkins 1990, fig. 5.11, for a similar diagram for the formation environment of the Kalavassos ore deposits, Cyprus). In the text we also refer to fossil spreading axes, or fossil axes, which are the presently existing remains of previously active spreading axes.

Massive sulphide mineral deposits have actually been observed in the process of current formation in such sea-floor grabens in association with the faults (e.g., Goldfarb *et al.* 1983, 184–97), which act as conduits of the hydrothermal fluids which come from the deeper parts of the earth. These fluids contain various metals in solution, but when they rise to the bottom of the ocean and are discharged into cold seawater, the metal solubility in the fluid decreases as a result

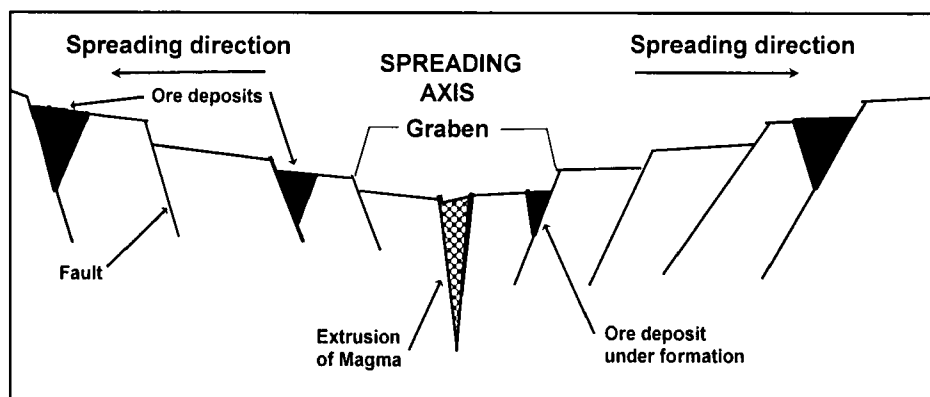


Figure 1 Schematic representation of the environment of formation of Cyprus ore deposits in relation to a sea-floor spreading axis, showing the extrusion of lavas and the formation of steep faults parallel to the line of the spreading axis and the formation of a 'graben'.

of the rapid reduction in pressure and temperature and the metals precipitate in the form of various sulphides and other ore minerals, giving rise to the ore deposits. (For more detail about such processes see, e.g., Gaskarth 1995; Cann 1995; Barnes 1988; Sawkins 1990.) In the case of Cyprus, the ore forming fluid is generally supposed to be seawater which, drawn down into the crust, reacts with basalt magmas at temperatures between 200°C and 400°C and is subsequently discharged upwards along fractures (Sawkins 1990, 207–15). Because of the spreading mechanism, at any given time, the deposits closer to the axis are younger than those further away from it, as demonstrated schematically in Figure 1. Because of the similarity of these ore deposits with those found in Cyprus, the massive sulphide deposits which are found in such spreading axis environments are often termed 'Cyprus-type' deposits in the geological literature (Sawkins 1990). In the particular case of Cyprus many geologists now believe that the Cypriot ore deposits did not form at the sort of spreading centre typified by those of the present-day large oceans, but rather at spreading axes in a subduction-related marginal sea, probably in a back-island-arc environment (e.g., Cann 1995; Sawkins 1990, 216–21; Barnes 1988, 44–8; Mitchell and Garson 1981, 176–250), but the basic mechanisms of ore formation and its tectonic setting remain those schematically illustrated in Figure 1 (and Barnes 1988, fig. 4.1).

The Cypriot ore deposits (see Bear 1963 for a descriptive account of these deposits) belong to the Troodos ophiolite complex, which is one of the best studied and documented of such complexes in the world. The so-called ophiolite complexes are considered to be fragments of the oceanic crust formed as explained above and elevated above sea level by later large-scale tectonic movements. Troodos is a well-preserved and well-exposed complex which exhibits the typical ophiolitic suite, comprising a Plutonic complex at the bottom, the Sheeted Dyke complex, and at the top the Pillow Lava Sequence. The latter is divided into the Upper (UPL) and Lower (LPL) units and hosts the sulphide ore deposits, which overlay the LPL and were preserved from being completely eroded away by post-depositional seawater interactions by being overlaid by the UPL. The Troodos ophiolite complex was originally formed at submarine spreading centres during Late Cretaceous times at close to 90 Ma (Mukasa and Ludden 1987), being uplifted to its present position in Late Maestrichtian (Searle and Panayiotou 1980) times (about 70 Ma).

Recent geophysical, geochemical and geological data suggest that Troodos evolved in a suboceanic environment, at several spreading axes. In the northern Troodos region it is believed that there existed two major spreading axes, the Solea axis to the west and the Larnaca axis to the east, which are believed to have been formed by the progressive eastward jump of a spreading centre (Varga and Moores 1985; Allerton and Vine 1987; Cooper 1993). In the southern Troodos region, Adamides (1975 and 1980) implied the existence of another two such fossil axial spreading centres in the Kalavassos and Limni regions which are referred to as the Kalavassos axis and the Limni axis. The location of these axes in the Troodos complex are shown in Figure 2.

The occurrence of the sulphide ore deposits in the Troodos complex appears to be related to the spreading axes which are described above. They were formed by hydrothermal processes which take place in such axial environments. Similar ore deposits have been and are presently being studied at active oceanic axial regions in the East Pacific Rise (e.g., CYAMEX 1979; Goldfarb *et al.* 1983, 184–97) and elsewhere, but Cyprus presents a unique opportunity to make systematic comparisons of the isotopic compositions from various ore deposits on the large scale of the Troodos massif (about 90×30 km). Adamides (1975 and 1980), on the basis of geological and structural evidence, has related the genesis of the ore deposits in the Limni and the Kalavassos mining areas to the Limni and the Kalavassos axes. Recent geological and geophysical studies (Cooper 1993 and Maliotis 1995) revealed that the ore deposits and occurrences in the northern parts of the Troodos complex are structurally controlled by faults which are associated with the Larnaca and Solea axes. Figure 2 depicts the location of the different ore deposits in relation to the respective spreading axes.

On the basis of the spreading mechanism which was briefly described above, ore deposits now located at different distances from a given spreading axis are inferred to have been formed at the axis at different times, transported to their present locations by sea floor spreading, where they were preserved in particular environments (Hall and Yang 1994) before subsequent uplift of their ophiolite host rocks, which left the ore deposits in place. Consequently, on this model it is expected that mineral deposits now located further from a fossil spreading axis must be older than those nearer to the axis. Furthermore, groups of mineral deposits associated with different spreading axes which were active at different times are expected to have different ages, and different lead isotope compositions.

Typically, the Troodos sulphide ore deposits consist of a layer of massive sulphide ore, predominantly of pyrite with lesser amounts of chalcopyrite. This is underlain by a pipe-shaped stockwork zone (the remains of feeder veins) consisting of veined sulphide ore in brecciated, altered and silicified rock (Adamides 1984). As described above, these sulphide ore deposits are related to the spreading axes, are located stratigraphically in the Lower unit of the Pillow Lava sequence and are classified amongst the 'Cyprus-type' sulphide deposits. In addition to these, however, there are a number of other sulphide deposits which are located in the Upper unit of the Pillow Lava sequence and are believed to have resulted from later magmatic activity not directly related with the spreading axis activity (Maliotis 1995).

THE LEAD ISOTOPE DATA FOR CYPRIOT COPPER ORE DEPOSITS

The copper ore deposits which were sampled and analysed during the present study are listed in Table 1; their localities are given in Figure 2. All new lead isotope data (including some remeasured samples), together with the reliable analyses published by Stos-Gale and Gale (1994), are listed in Gale *et al.* 1997. The data are plotted in Figures 3 to 6 in groups according to

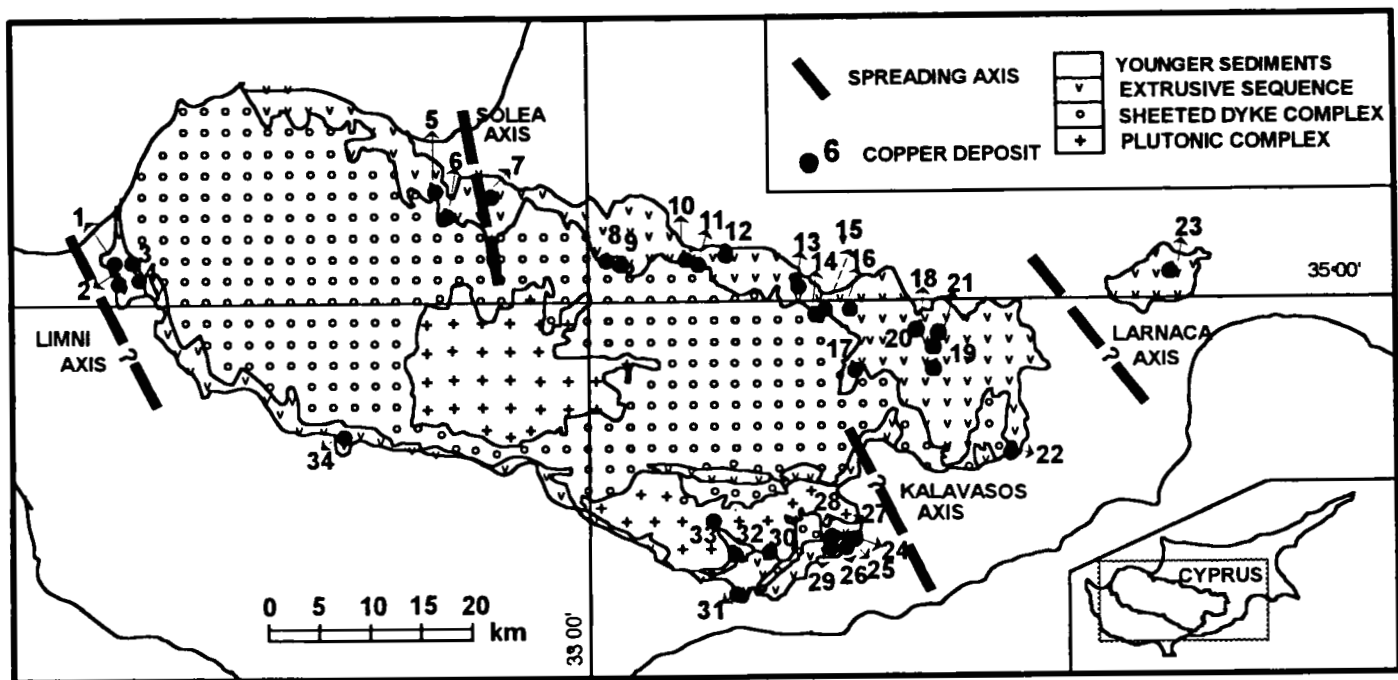


Figure 2 Geological map of the Troodos ophiolite complex showing the position of the identified fossil sea-floor spreading axes and the major copper ore occurrences. *Limni axis*: (1) Limni; (2) Evloymeni; (3) Kinousa; (4) Uncle Charles. *Solea axis*: (5) Mavrovouni; (6) Apliki; (7) Skouriotissa; (8) Alestos; (9) Memi. *Larnaca axis*: (10) Kokkinoyia; (11) Kokkinopezoula; (12) Agrokippia; (13) Klirou; (14) Pitharochoma; (15) Peristerka; (16) Kambia; (17) Kapedhes; (18) Mathiati; (19) Sha; (20) New Sha; (21) Strongyli; (22) Anglisidhes; (23) Troulli. *Kalavassos axis*: (24) Petra; (25) Mousoulos; (26) Mavridhia; (27) Landaria; (28) Mavri Sykia; (29) Platies; (30) Mazokambos; (31) Mangaleni. Other occurrences: (32) Pevkos; (33) Laxia tou Mavrou; (34) Perevasa.

Table 1 The copper deposits studied for this paper, giving the number of samples analysed from each deposit and the spreading axis environment to which they belong. The numerical lead isotope data are reported in Gale *et al.* (1997, this volume), together with the specification in each case of the minerals analysed

Copper deposit and (in parentheses) no. of samples analysed	Spreading axis
Evloymeni (6), Kinousa (7), Limni (22)	Limni axis (west)
Alestos (3), Apliki (30), Mavrovouni (4), Memi (5), Skouriotissa (10)	Solea axis (central)
Agrokipia (4), Kambia (6), Kokkinopezoula (4), Kokkinoyia (8), Mathiati (8), Peristerka (10), Pitharochoma (13), Sha (14), Troulli (6)	Larnaca axis (east)
Landaria (3), Mangaleni (3), Mavri Sykia (5), Mavridhia (2), Mousoulos (7), Petra (4), Platies (3)	Kalavasos axis (south-east)
Laxia tou Mavrou (9), Pevkos (14)	Limassol Forest, complex Fe-Ni-Cu-As ores (south)
Totals: 26 deposits and 210 samples	

the fossil spreading axis to which they belong, as revealed by the recent geological and geophysical studies mentioned above. To facilitate comparisons of these new data with our old diagrams we have included on Figures 3–6 the 95% confidence ellipses which were used on all diagrams in the most recent previous publication (Stos-Gale and Gale 1994); these ellipses were computed around the 33 data from Oxford (Stos-Gale and Gale 1994, table 9) plus ten data from Hamelin *et al.* (1988). The three lead isotope ratios are plotted here on two two-dimensional diagrams, which are sections through the complete groups of points in three-dimensional space. This method of presentation seems at present the most appropriate and has been that most used in most archaeological applications. As will appear, we believe that graphical comparison of the lead isotope data for Cypriot ores with those for copper oxide ingots is sufficient, and that the application of multivariate statistical treatments is not necessary for this case, and indeed that such a statistical approach may well obscure rather than help the discussion. In the plots we have used, geologically older ores will have higher $^{208}\text{Pb}/^{206}\text{Pb}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ ratios (and, respectively, lower $^{206}\text{Pb}/^{204}\text{Pb}$ ratios).

Inspection of Figures 3–6 shows clearly that the lead isotope analyses of the samples of sulphidic ores from different deposits, when grouped according to their associated fossil spreading axes, plot in relatively tight groups which largely have the character of linear arrays of limited range. The majority of the lead isotope data in these groups from the major copper mines also fall into the old Cypriot 'field'. However, each group occupies only a part of this field and the lead isotope ratios for each geological group are distinctive. The increased number of analytical data for each mine demonstrate, with augmented evidence, the point made in our earlier work (Gale and Stos-Gale 1992, fig. 1) that it is possible to distinguish ores from different mines on the basis of their lead isotope composition. By this we do not mean that the lead isotope composition of each mine on Cyprus can be distinguished from every other one. The overall pattern of lead isotope compositions consists of smaller fields characteristic of different mines, but in some parts of isotopic space some of these smaller fields overlap to a greater or lesser extent.

The new data show also that there are some deposits of the Troodos ophiolite which have lead isotope compositions which fall far outside the old Cypriot field. From the investigations carried out so far these deposits are only from the Kalavasos and Larnaca fossil spreading axis groups;

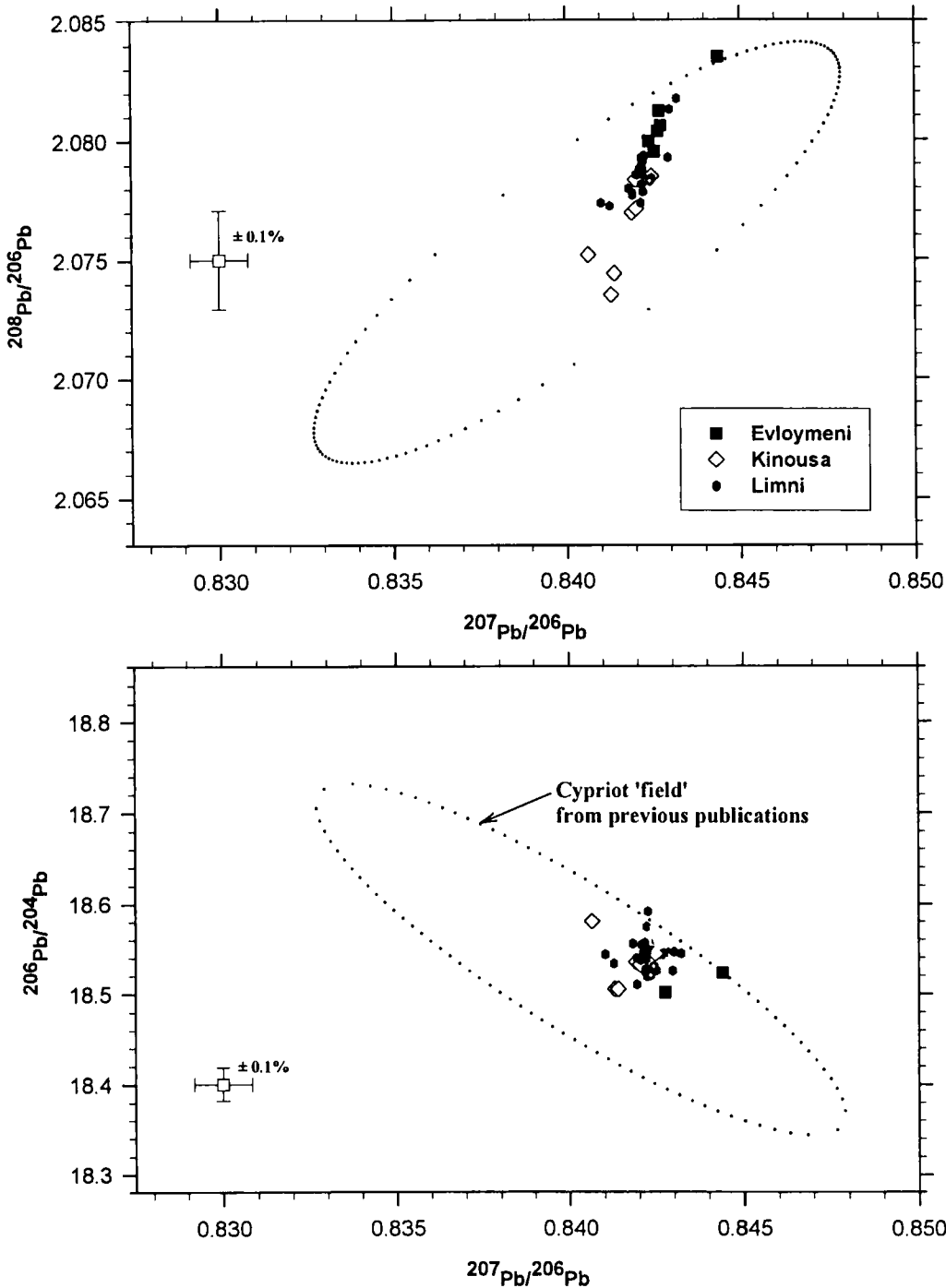
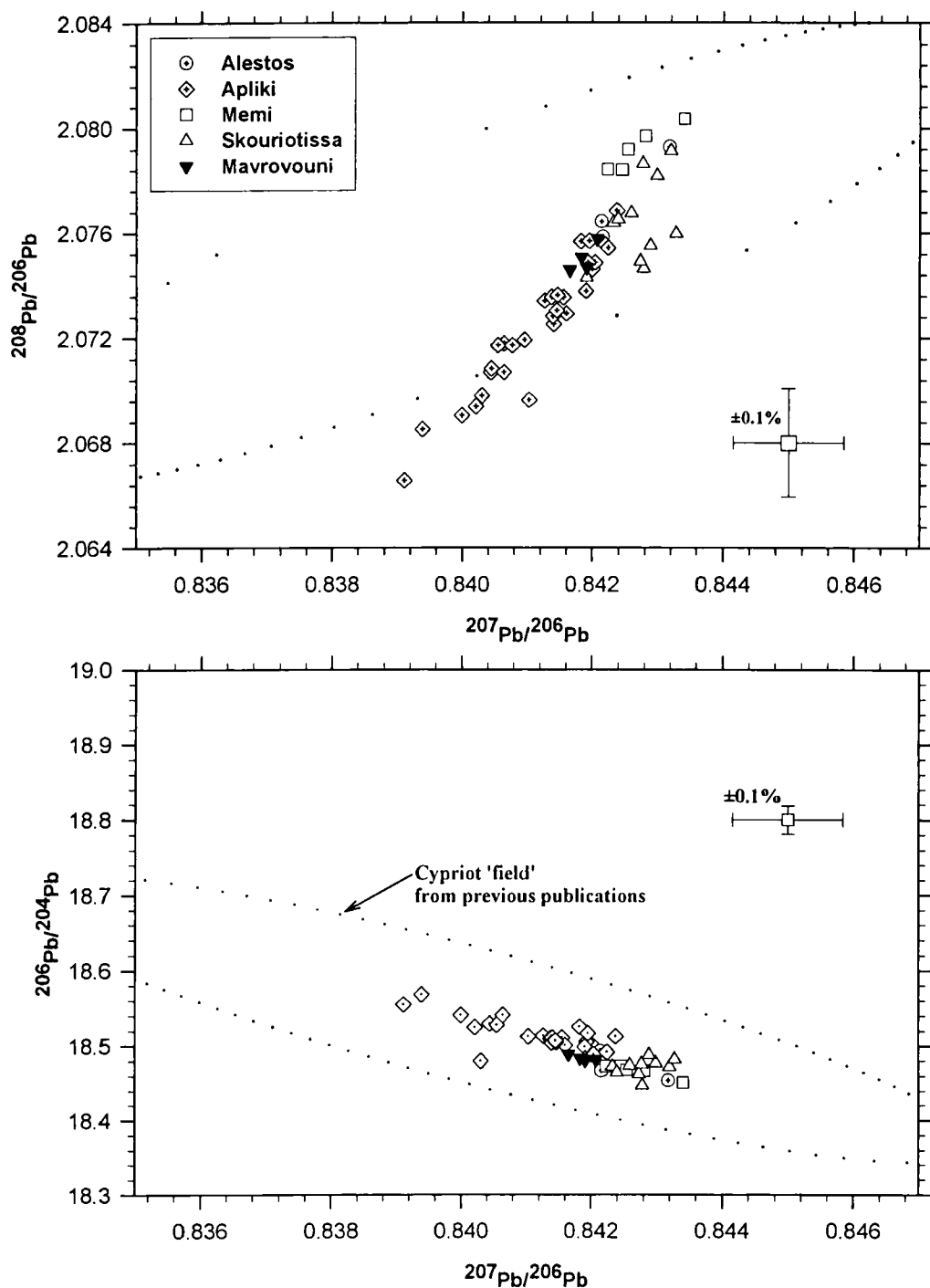


Figure 3 Plot of the lead isotope data for ores associated, by independent geophysical/geological evidence, with the Limni fossil spreading axis (two data are included for the Limni mine from Hamelin et al. 1988).

Figure 4 Plot of the lead isotope data for ores associated with the *Solea* fossil spreading axis.

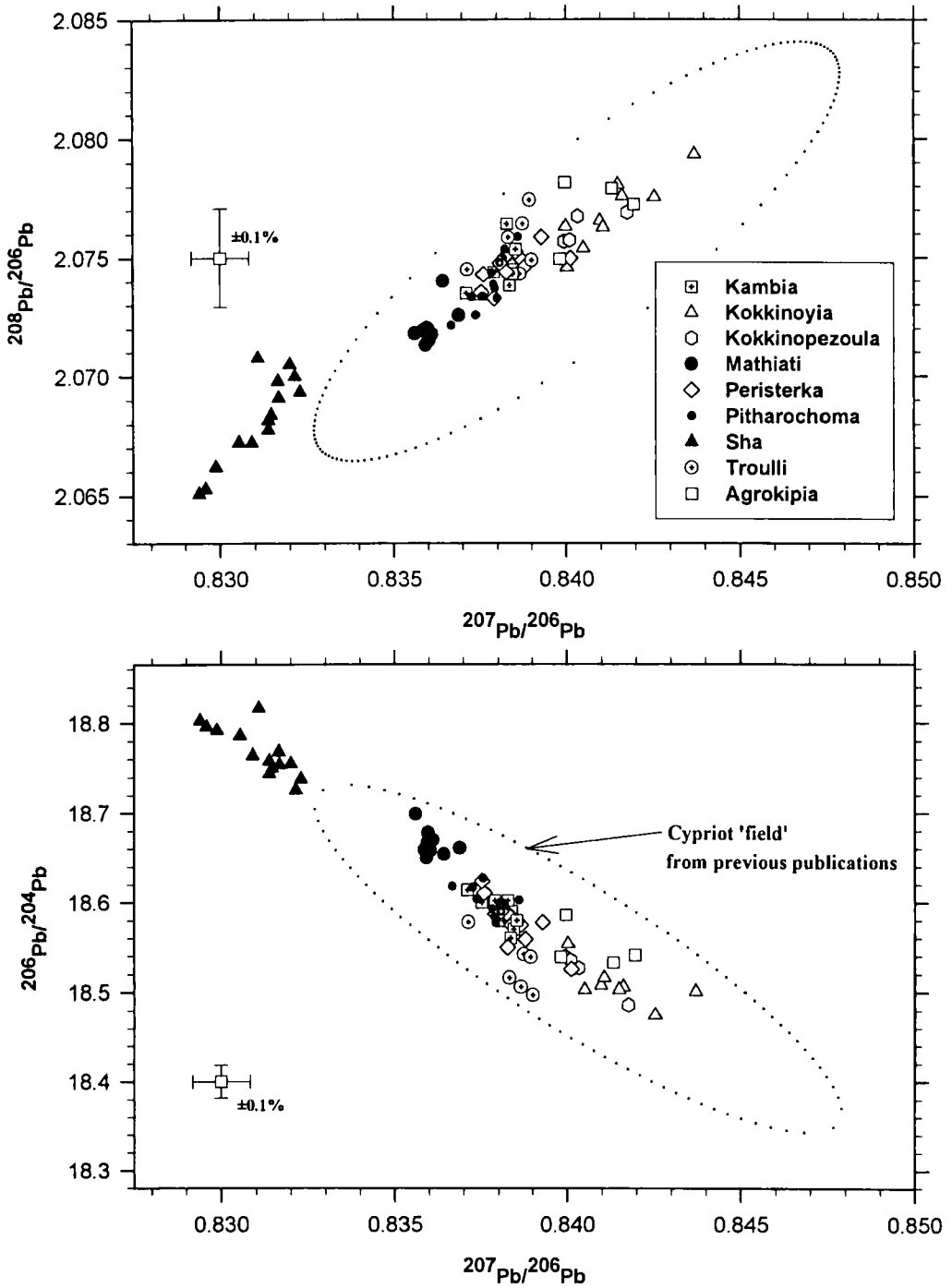


Figure 5 Plot of the lead isotope data for ores associated with the Larnaca fossil spreading axis (including also data from Hamelin et al. 1988).

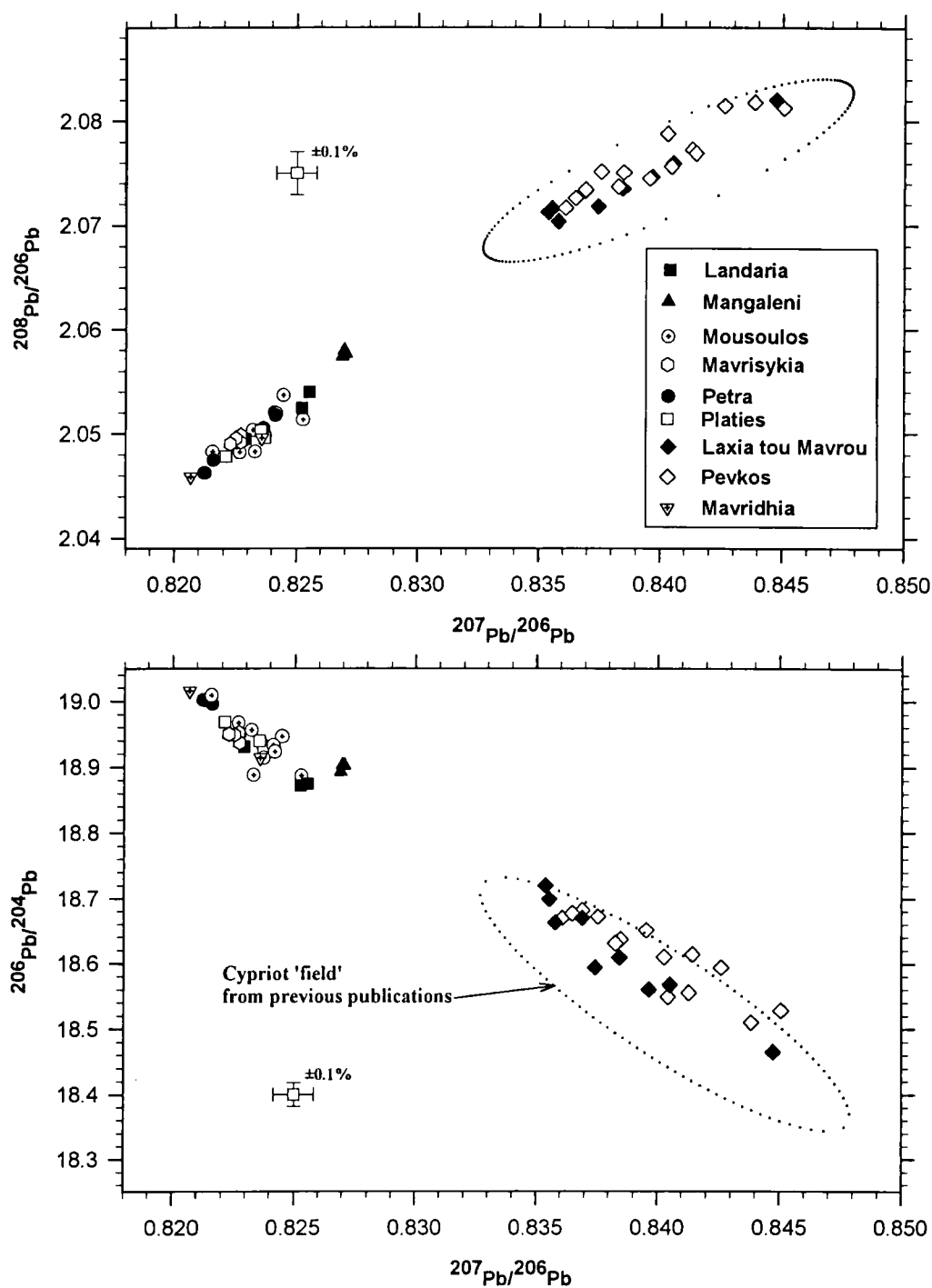


Figure 6 Plot of the lead isotope data for ores associated with the Kalavassos fossil spreading axis and for the Limassol Forest complex ores.

they show generally lower $^{208}\text{Pb}/^{206}\text{Pb}$ ratios which suggests that these ores are younger than the main groups of the Troodos deposits.

The overall distribution of lead isotope data for ore deposits from the Larnaca, Limni and Solea axes is not bivariate normal in a mathematical sense, and therefore does not justify the use of a 95% confidence ellipse for delineation of an overall Cypriot field. It would also be wrong to draw closed curves enclosing all the isotope data for Cypriot ores presented in Figures 3–6, and call that the ‘Cypriot lead isotope field’, since such bounding curves would also enclose parts of lead isotope space not populated by data for any Cypriot ores. It was part of our case for rejecting the so-called ‘Aegean lead isotope field’ proposed by Pernicka and his colleagues (Seeliger *et al.* 1985) that this field also enclosed parts of lead isotope space not populated by data for any Aegean ores. A similar situation has been known for a long time for Sardinia. With its complex geology, resulting in widely different lead isotope compositions between the ores of Cambrian and Tertiary age, it was never correct to speak of an overall Sardinian lead isotope field. Clearly our earlier concept of an all-embracing lead isotope field for Cyprus must now be discarded, as is shown from the plots of the new data given in Figures 3–6. A quotation from the Cambridge

Table 2 Mean lead isotope ratios for individual ore deposits, grouped according to the fossil spreading axes with which they are associated by independent geophysical and structural geological data; for each axis the ore deposits are listed in the order of increasing distance from the assumed positions of the fossil spreading axes

Fossil axis	Ore deposit (no. *)	$^{208}\text{Pb}/^{206}\text{Pb}$	95% error	$^{207}\text{Pb}/^{206}\text{Pb}$	95% error	$^{206}\text{Pb}/^{204}\text{Pb}$	95% error
Limni	Kinousa (7)	2.07626	.00179	.84168	.00056	18.534	.024
	Limni (22)	2.07854	.00065	.84219	.00021	18.542	.008
	Evloymeni (6)	2.08082	.00148	.84290	.00078	18.535	.021
Solea	Apliki (30)	2.07250	.00093	.84115	.00031	18.514	.008
	Mavrovouni (4)	2.07503	.00086	.84186	.00028	18.484	.006
	Skouriotissa (10)	2.07636	.00109	.84273	.00042	18.472	.008
	Alestos (3)	2.07718	.00456	.84249	.00136	18.471	.049
	Memi (5)	2.07921	.00104	.84269	.00056	18.466	.011
Kalavassos	Mavridhia (2)	2.04772	.02358	.82214	.01848	18.965	.051
	Petra (4)	2.04899	.00407	.82267	.00232	18.965	.062
	Platies (3)	2.04922	.00315	.82313	.00218	18.944	.055
	Mavri Sykia (5)	2.04936	.00040	.82256	.00022	18.947	.007
	Mousoulos (7)	2.05060	.00187	.82344	.00095	18.950	.030
	Landaria (3)	2.05196	.00565	.82457	.00353	18.893	.082
	Mangaleni (3)	2.05765	.00077	.82698	.00020	18.899	.014
Larnaca	Sha (14)	2.06820	.00106	.83117	.00061	18.765	.018
	Mathiati (8)	2.07220	.00066	.83609	.00033	18.668	.012
	Kambia (6)	2.07455	.00115	.83789	.00052	18.598	.013
	Peristerka (10)	2.07461	.00057	.83851	.00056	18.580	.019
	Pitharochoma (13)	2.07407	.00066	.83782	.00030	18.600	.009
	Troulli (6)	2.07556	.00128	.83847	.00073	18.530	.031
	Agrokippia (4)	2.07706	.00233	.84077	.00167	18.550	.039
	Kokkinopezoula (4)	2.07626	.00102	.84054	.00133	18.522	.039
	Kokkinoyia (8)	2.07631	.00129	.84103	.00073	18.513	.020

* No. of samples analysed for the particular specified mine.

economist, John Maynard Keynes, may be appropriate here: 'When the facts change, I change my mind. What do you do, Sir?'

The correct approach to evaluating whether artefacts were made from Cypriot copper, now that we know the true complexity of the lead isotope compositions of Cypriot ore deposits and that this is soundly based on geophysical/geological evidence, is to compare the lead isotope compositions of particular Bronze Age copper alloy artefacts with relevant parts of the lead isotope data for Cypriot ores. In this paper it is sufficient to do this visually from plots of the data.

In each of the groups listed in Table 1, Figures 3–6 show that the ore deposits within a given spreading axis group show a slight shift in their lead isotope ratio data which is linked to the geographical distance of a particular deposit from the axis with which it is associated by independent geophysical and structural geological research. Table 2 lists the mean lead isotope ratios (with the associated 95% errors) for each deposit. In this table the ore deposits are grouped with their associated fossil spreading axes; for each axis the ore deposits are listed in the order of increasing distance from the assumed positions of the fossil spreading axes. In general there is a satisfactory monotonic progression of the mean isotope ratios, within error, as a function of distance from the appropriate fossil axis.

This shift of isotopic composition is, as mentioned earlier, attributed to the respective time of formation of a particular deposit during the spreading activity. The fact that we observe these differences in lead isotope composition, even for deposits genetically related to the same spreading axis, indicates the scale at which 'disconnected', successive, hydrothermal cells operated in generating the Cyprus sulphide ore deposits, demonstrated by the lack of Pb isotopic homogenization between deposits. The fact that these marked isotopic differences between different deposits are observed for the sulphide ores, but not for the umbers (Gale *et al.* 1981; Hamelin *et al.* 1988), is in good agreement with the hypothesis that the sulphides were rapidly precipitated on emergence of hot metalliferous fluids from the different subaqueous vent exits, whereas metalliferous sediments (umbers) resulted from dispersion and re-deposition of hydrothermal products on a larger scale, thus allowing for further mixing of lead (it should be reiterated that the isotopic compositions of the umbers analysed in Oxford fall within and spread through the old field which has, up until this paper, been used to characterize the Cypriot ores overall; see Gale and Stos-Gale 1995, fig. 1). Short descriptions of each spreading axis and the major characteristics of copper deposits which are associated with it, as well as the known periods of mining activities, are given in the next paragraphs.

The Limni axis

The Limni axis is situated in the furthest western part of the Troodos mountains and includes three known deposits: Limni, Kinousa (which includes Kinousa Underground and Uncle Charles opencast) and Evloymeni. These are cupriferous pyritic deposits which were extensively mined during the period from 1937 to 1978. Of these three mines Limni was by far the largest, at about 8.1 million tonnes. The small Evloymeni deposit was less than one million tonnes and was only partly mined in the early 1970s. It is situated to the south of Limni, being apparently on the same structural lineament. The Kinousa deposit occurs to the east of the Limni deposit along a parallel structure; it has a total reserve of about half a million tonnes. It was mined by both underground (Kinousa Underground mine) and opencast pit workings (the Uncle Charles mine); we took samples from both mines. All lead isotope ratios for these four mines plot in the upper part of the old Cypriot field (Fig. 3) forming together an elongated group, with the lead isotope ratios of pyrites from Kinousa falling lowest in the $^{208}\text{Pb}/^{206}\text{Pb}$ versus $^{207}\text{Pb}/^{206}\text{Pb}$ diagram. These lead

isotope data suggest that the mineralization in Kinousa is the youngest formation and Evloymeni the oldest, but that Evloymeni and Limni are of practically the same geological age. All three deposits taken together show a very small range of lead isotope ratios (less than 0.5% for all three ratios), which is perhaps consistent with their rather close geographical proximity. A sizeable, thus far undated (Koucky 1982), slag heap occurs in the coastal area to the west of the Limni mines.

The Solea axis

The Solea axis is situated in the central northern parts of the Troodos ophiolite. The known deposits related to this axis include Mavrovouni, Apliki, Skouriotissa, Alestos and Memi. Mavrovouni was 16 million tonnes, being the largest copper deposit found in Cyprus, Skouriotissa was six million tonnes and Apliki about three million tonnes. The Memi deposit was about 4.5 million tonnes, whereas the Alestos deposit is the smallest, holding about half a million tonnes.

The broad Skouriotissa region, which was the basis of the revival of mining/metallurgy in Cyprus by the fledgling Cyprus Mines Corporation in the early decades of this century, must also have been important in antiquity, as is testified by the imposing slag heaps at Skouriotissa and Apliki which are estimated to be about a million tonnes (Lavender 1962, 63). Radiocarbon dates of slag samples collected from the surface of the large slag heaps at Skouriotissa (Zwicker 1986) are AD 310 ± 50 and AD 260 ± 50 , but radiocarbon dates of timbering from the Skouriotissa mines gave much earlier dates of 580 ± 60 BC and 485 ± 50 BC (all radiocarbon dates in this paper quoted from Zwicker 1986 are calibrated ages converted to the AD/BC system by subtracting 1950 years, as described by Gillespie 1984, 32–3). It was also in this region where Joan du Plat Taylor (1952) discovered the first Bronze Age settlement situated in a mining district in Cyprus. Small-scale mining carried out by the Hellenic Mining Company in the 1950s at the Ambelikou mineral occurrence, which is situated about three kilometres to the west of Mavrovouni mine, revealed small-scale ancient workings (Merrillees 1984), as evidenced by the presence of Red Polished III pottery. The average copper content of the Skouriotissa and Mavrovouni deposits was fairly high, about 2.5% and 4.5% respectively.

The lead isotope ratios of samples of ores from this group form, regarded as a whole, an elongated array across the old Cypriot field (Fig. 4). The Memi and Alestos ores show the highest $^{208}\text{Pb}/^{206}\text{Pb}$ ratios (older formations) and the ores from Apliki the lowest (younger). In fact many samples of ores from Apliki (collected from the mine by the authors) fall below, in the $^{208}\text{Pb}/^{206}\text{Pb}$ versus $^{207}\text{Pb}/^{206}\text{Pb}$ diagram, the old 95% confidence ellipse for the earlier published 43 ore samples, as was already hinted at by the first measurements of Apliki ores published by Stos-Gale and Gale (1994).

The Larnaca axis

This axis (see Fig. 2) is situated in the central part of Cyprus, at the north-eastern edge of Troodos and includes a large number of deposits. Of these, the most important ones were sampled and analysed for their Pb isotope ratios during the present study. These deposits are, from west to east: Kokkinoyia, Kokkinopezoula, Agrokippia, Pitharochoma, Peristerka, Kambia, Mathiati, Sha, Troulli. Another deposit which belongs to the Larnaca axis is Anglisidhes (not yet analysed) which, though at some distance to the south from the other mines, is believed from the geophysical/geological evidence to relate to this axis.

Most of these mines were extensively mined in the last forty years to provide cupreous and pyritic concentrates. In some occurrences the oxidized cappings of the deposits were exploited for their gold and silver contents, in the late 1930s and early 1940s, by small-scale selective mining. It must be emphasized though that in all cases the detailed records of the Hellenic Mining Co. show that the gold- and silver-rich parts of these deposits were found intact, without any evidence of ancient mining. In relation to this it should be stated that gold and silver in this type of mineralization are invisible to the naked eye, and could only be concentrated efficiently in modern times by cyanidation techniques. The copper values in the orebodies which are genetically related with the Larnaca axis are in general lower than those of the Solea axis. An exception is the Kokkinoyia deposit where the uppermost parts were substantially rich in copper. In those copper-rich levels of Kokkinoyia, modern mining during 1971–9 by the Hellenic Mining Co. encountered ancient workings of unknown age. Ancient slag heaps are very common throughout the region of the Larnaca axis and in proximity to the different sulphide deposits. Few of these slag heaps or mines have been dated, though the Kambia I and II mines have radiocarbon dates, on gallery timbers, of 660 ± 110 BC, 460 ± 30 BC and 640 ± 50 BC, whilst the Kapedhes slag heap yielded a radiocarbon date of AD 450 ± 90 , the Mitsero slag heap AD 470 ± 150 and the Mathiati slag heap AD 270 ± 60 (Zwicker 1986).

The lead isotope compositions of ores from Kokkinoyia, Kokkinopezoula and Agrokipia are very similar (Fig. 5), in accordance with their geographical proximity to each other which indicates that they were formed at the spreading axis close together in time. A similar conclusion applies to the ores from Kambia, Peristerka and Pitharochoma, which are geographically close together and have similar isotopic compositions, though as a group they have $^{208}\text{Pb}/^{206}\text{Pb}$ ratios lower than the Kokkinoyia-Kokkinopezoula-Agrokipia group, which accords with the positions of these two groups relative to the Larnaca fossil spreading axis. The Mathiati ores seem somewhat younger still, again in accordance with their position closer yet to the fossil spreading axis. All lead isotope compositions measured for these mines fall, in both lead isotope diagrams, comfortably into the old Cypriot lead isotope field.

Very different isotopic compositions were revealed when we analysed a series of pyritic ores from Sha (see Fig. 5). The lead isotope ratios of the group of 14 recently collected samples of pyrite from Sha fall outside the old Cypriot field. Whilst all lead isotope ratios of other mines in this group form a sort of continuum, suggesting their evolution to have been rather close in time, the minerals from Sha stand entirely separately, as if the process of the ore formation at Sha followed the others after a certain lapse of time. During the course of mining of the Sha deposit by the Hellenic Mining Co. in the 1960s, it was discovered that the higher parts of the sulphide ore were rich in copper and on many occasions there were discovered ancient, but as yet undated, workings. Copper values in the recently mined ore were as much as 4% copper suggesting that the ancients should have mined much higher grades. But as yet there is no indication of any specific period when this mining activity took place. Perhaps lead isotope analyses of copper-based Cypriot artefacts from a wide time-span could answer this question. So far there are no Bronze Age metals matching the lead isotope composition of ores from Sha.

The exceptional character of the Sha deposit (and possibly its neighbour, New Sha) was suspected earlier during the interpretation of a low altitude aeromagnetic survey (Huntings 1969), in which these two deposits do not appear to be related to a definite axis-parallel fault. Instead an inferred structure was assumed to be responsible for their origin (Cooper 1993; Maliotis 1995). At the same time, it was observed that the Sha deposits are at the centre of a prominent high altitude magnetic anomaly (Huntings 1970) which was interpreted as being

caused by a high level intrusive body (Maliotis 1995), the presence of which was suggested earlier by a gravity survey (Swift 1990). Such intrusive bodies are believed to be later stage phenomena than the actual axis spreading mechanism; consequently the lead isotope data for Sha are in excellent accord with the earlier inferences from geophysical investigations, and suggest that it may be legitimate to interpret the lead isotope data for Cypriot ores as linked at least with the relative chronology of ore formation.

The Kalavassos axis

This spreading axis is situated in the region of Kalavassos village near the southern coast, east of Limassol. The mines which belong to this axis are potentially of great archaeological interest, because of the recently excavated neighbouring Bronze Age sites of Ayios Dhimitrios-Kalavassos (South 1989) and Maroni (Cadogan 1989). It has seemed reasonable to expect that any copper metallurgy carried out on these sites would have relied on the ores from the Kalavassos region mines (e.g., Cadogan 1989).

The Kalavassos mining region, situated west of Kalavassos village, includes a number of closely located deposits whose genesis appears to be related to a series of axis-parallel faults. These deposits are, from east to west: Petra, Mousoulos, Mavridhia, Landaria, Mavri Sykia, Platies. According to Adamides (1984) who studied these deposits in detail, an associated fossil spreading axis should have been located to the east of the mining area. The Kalavassos deposits were generally small in tonnage, but their higher parts were notably rich in copper, and mining in this century encountered evidence for prior exploitation at some as yet undated period. Relevant radiocarbon dates for this region are: 225 ± 150 BC and 430 ± 85 BC for the large Kalavassos slag heap, 450 ± 40 BC for the Kalavassos-Platies slag heap and 480 ± 60 BC for the Mazokambos slag heap (Zwicker 1986).

Other occurrences of sulphide mineralization are found to the south-west of the Kalavassos mining region, running along the lava terrain which extends in that direction. Of these, the most important are the Mazokambos and the Mangaleni mineralizations, which were rich in copper. The latter was mined in both ancient (undated) times, and recently by Hellenic Mining Co. Indeed all these deposits, except Mousoulos, are shallow seated and have evidence of ancient, but undated, exploitation. From Adamides's (1984) work, in which the related spreading axis is located to the east of Kalavassos, it may be concluded that the Mangaleni mineralization is the furthest from the spreading axis and is therefore older than the Kalavassos region ore deposits. Table 2 shows that the lead isotope compositions are fully consistent with these conclusions, which were based on independent geological evidence.

Before the present study only a few samples from the Mousoulos modern underground mine had been analysed (Spoonner and Gale 1982); their lead isotope compositions were very different from all the other Cypriot ores analysed at that time and do not match the lead isotope compositions of any analysed Bronze Age copper artefacts from any part of the Mediterranean. To supplement the lead isotope data for this region, samples of minerals were collected in the summer of 1995 from the other mines in the Kalavassos region: Landaria, Mavri Sykia, Mavridhia, Platies and Petra. Some samples of good pyrite from Mangaleni mine were donated to us by Professor Zwicker, and samples from Mazokambos were collected in early 1996.

It was found that minerals from all of these mines show lead isotope ratios very different to any of those which were included in the old Cypriot field (Fig. 6). From the geological point of view the lead isotope compositions of these minerals suggest ore forming processes of much younger age than the main group of Cypriot ores, and younger also than the ores from the Sha

mine. Within the group the ores from the mines of Mavri Sykia, Platies, Petra, Mousoulos and perhaps Landaria seem to have an identical history, as if they belonged to virtually the same ore body. This appears to be reasonable in view of the fact that all these deposits occur very close to each other. Only the Mangaleni ores were formed at an earlier stage, which agrees with the fact that this ore deposit is the most distal from the assumed axis.

Again, as with the Sha mine, no analysed Bronze Age copper artefacts from Cyprus, or elsewhere in the Mediterranean, have lead isotope compositions corresponding to those characterizing these mines of the Kalavassos axis.

Ores from the Limassol Forest

About 20 kilometres from Kalavassos, near the village of Dhierona, at the locality Laxia tou Mavrou, and to the north of Parekklishia village, at the locality Pevkos (see Fig. 2), both localities falling in the Limassol Forest area, there are small occurrences of sulphide mineralization of a quite different type. According to Panayiotou (1980) these sulphides were formed by segregation during magmatic differentiation rather than by a hydrothermal process (though see Thalhammer *et al.* 1986). These two occurrences are of particular interest because the minerals found there contain arsenic and therefore might in principal have been a convenient source of raw material for producing the arsenical copper used in the Early and Middle Cypriot periods. Typical chemical compositions of ores containing copper minerals from the region of Pevkos and collected by us are presented in Table 3. It should be noted that the copper content of the massive ores from the Limassol Forest area ranges up to 20%, with the mean of 199 analyses being 3.32% Cu (Panayiotou 1980), so that from the standpoint of copper values alone these ores contain sufficient copper for ancient exploitation. The comparison of their chemical composition with other copper ores from various Cypriot mines (see, e.g., Gale *et al.* in press) shows that these ores, apart from the arsenic content, have also much higher concentrations of iron, nickel,

Table 3 Neutron activation analyses of ores from the Limassol Forest: Laxia tou Mavrou (LTM), Pevkos (PEV)

Sample no.	Au (ppm)	As (%)	Sb (ppm)	Ag (ppm)	Cr (%)	Zn (ppm)	Co (%)	Ni (%)	Fe (%)	Cu (%)
LTM 11	3.13	0.001	<1	2.2	0.039	91.3	.234	0.199	58.73	0.847
LTM 12	1.16	0.045	3.6	<1	0.216	<50	.130	0.172	56.72	0.349
LTM 13	1.43	0.559	1.7	1.9	0.175	253	.028	0.151	52.5	1.99
LTM 14	1.73	0.023	<1	2.5	0.421	113.5	.047	0.198	60.26	0.478
LTM 15	1.46	0.293	<1	5.2	0.154	74	.029	0.137	51.66	0.452
LTM 2b	3.99	0.001	<1	1.2	0.172	67.9	.124	0.246	59.90	0.604
LTM 2c	1.19	0.016	1.7	<1.5	0.233	112.0	.173	0.149	52.25	0.511
CY 620c Pevkos	0.24	0.340	<2	1.6	0.022	251	.007	0.050	40.57	1.53
CY 621a Pevkos	0.46	0.478	6.2	1.7	1.15	163	.077	0.527	58.64	1.13
PEV 100A	0.05	0.068	<1	2.1	0.125	91	.179	1.08	57.69	0.567
PEV 100B/2	2.04	0.199	<5	3.3	0.799	699	.193	0.706	55.5	2.95
PEV 100D	14.92	3.96	104.3	6.4	0.740	206	.326	6.65	48.50	1.14
PEV 100E	0.14	0.172	11.0	1.9	0.344	122	.199	1.10	57.25	0.449
PEV 100F	2.11	0.699	1.4	7.3	0.640	718	.233	1.26	53.73	6.31
PEV 17/94	0.05	0.009	0.6	3.7	0.650	387	.076	0.281	6.77	15.26
PEV 18/94	0.70	4.01	71.4	5.6	4.76	323	.269	10.06	4.75	1.01

cobalt and chromium. It seems that smelting copper from such complex ores might have been rather difficult in the Bronze Age. Apparently Zwicker (1986) failed to find a way to smelt copper from the Limassol Forest ores though, in a complicated process unlikely to be the way in which arsenical copper was commonly produced in Bronze Age Cyprus, he did manage to transfer arsenic from Pevkos ore to molten copper with the addition of 50% CaO under a charcoal cover in a crucible at 1250 °C.

It should be pointed out that during the course of the intensive exploration of these mineral occurrences in the Limassol Forest area with hundreds of metres of adits and pits within the narrow sulphide mineralization, which was carried out in the early 1950s by the Hellenic Mining Co., there was not found any sign whatsoever of pre-existing ancient workings. In addition to this, all veins were intact up to the surface, indicating that no exploitation has taken place. Furthermore, there are no known slag heaps in proximity to these localities.

All the copper ore samples from these two localities analysed so far have lead isotope compositions within a range similar to ores from the Larnaca axis, excluding Sha (Fig. 6). This is not too surprising because, if they are indeed the result of magmatic segregation, this may have taken place at the time of spreading and would then correspond to one of the spreading periods, in this case that of the Larnaca axis. The lead isotope data may have implications, which it is inappropriate to discuss here, for the alternative hypotheses about the genesis of the Limassol Forest ores presented by Panayiotou (1980) and Thalhammer *et al.* (1986).

COMPARISON OF LEAD ISOTOPE COMPOSITIONS OF CYPRIOT ORES WITH OTHER DEPOSITS

If the lead isotope data for Cypriot ore deposits are to be used for comparison with metal artefacts for the purpose of finding the latter's origin, then one has to be reasonably sure that there are no other deposits of copper minerals with the same lead isotope characteristics as the Cypriot ores. It has been stated by Budd *et al.* (1995b) that there is overlap between the lead isotope compositions for ores from Cyprus and Sardinia, which makes it impossible to decide whether copper oxhide ingots are made from copper from Cyprus or Sardinia. First, one should stress that about 90% of the data available for Sardinia are for ores from Pb/Zn deposits which contain no copper ores and are therefore totally irrelevant to the discussion about possible copper sources. Second, all ores from the ore deposits in the south-west of Sardinia, and from the copper deposit of Funtana Raminosa in central Sardinia, have lead isotope compositions very different from those of Cypriot ores (Stos-Gale and Gale 1992; Sayre *et al.* 1995; Pernicka 1995), since they are of Cambrian to Devonian geological age, as opposed to the much younger Cretaceous ores of Cyprus. Only the Tertiary copper deposits of north-west Sardinia have lead isotope compositions in any way comparable with those of Cyprus; for these we have already shown (Gale and Stos-Gale 1995, fig. 2) that the Tertiary Sardinian copper ores do not at all overlap with the isotopic compositions of copper oxhide ingots from Cyprus, and overlap only marginally with the edges of the old 'Cypriot field'. Note that it is sufficient, in determining that two sets of lead isotope data distributions do not overlap in three-dimensional space, for any two-dimensional cross-sectional view to show a separation (as in Sayre *et al.* 1995, fig. 6). That no Sardinian ores considered by Budd *et al.* (1995b) have lead isotope compositions which overlap the isotopic compositions of copper oxhide ingots found on Sardinia was elegantly shown by Sayre *et al.* (1995, fig. 6). Since there were rather few available data for north-west Sardinian copper ores in 1995 we have analysed more (the data are given in Table 4); the data are

Table 4 Lead isotope analyses of ores from the north-west Sardinian deposit of Capo Marargiu and two different deposits near Castello di Bonvei

Capo Marargiu ores	CPM5	2.08575	.84345	18.572
	CPM6	2.08411	.84270	18.588
	CMCP	2.08491	.84346	18.585
	CPM7	2.08869	.84385	18.576
	CPM8	2.08889	.84399	18.576
	CPM9	2.08876	.84393	18.573
	CPM10	2.08438	.84255	18.597
	CPM11	2.08823	.84331	18.631
	CPM12	2.08437	.84255	18.594
Castello di Bonvei schist ores	CB5	2.07779	.83771	18.742
	CB6	2.07475	.83710	18.713
	CB7	2.07766	.83710	18.741
	CB8	2.07638	.83739	18.729
	CB9	2.07521	.83722	18.723
	CB10	2.07476	.83716	18.715
Castello di Bonvei pellet ores	CSB6	2.06561	.83325	18.810
	CSB4	2.06575	.83340	18.815
	CDB100	2.06674	.83374	18.809
	CSB14	2.06552	.83302	18.823
	CSB10	2.06504	.83306	18.821
	CSB11	2.06636	.83362	18.804
	CSB12	2.06637	.83356	18.807
	CSB13	2.06731	.83393	18.807

Data for samples CPM5, CPM6, CMCP, CSB4, CSB6, CSB7 have been remeasured and replace formerly published data (from which they differ usually by less than 0.1%, rarely by 0.3%); other data are new for this paper. The set of data in this table is the reliable data set at present available for north-west Sardinian ores.

plotted in Figure 7 relative to reliable data for Sardinian copper oxide ingots and confirm that these Sardinian copper deposits were not the source of the copper for any analysed oxide ingots found on Sardinia.

It has also been suggested (Muhly 1991; Knapp and Cherry 1994; Budd *et al.* 1995b) that there are overlaps of lead isotope compositions of the Cypriot ores with the Spanish Cartagena ore deposit, Tuscan deposits, ore deposits in the Negev Desert (Timna and Feinan?—no other copper ore deposits are known in this region) and Oman. Gale (1991) presented lead isotope evidence for Tuscan deposits and Cartagena which demonstrated that there are no overlaps with the Cypriot ores, whilst Sayre *et al.* (1995, fig. 6) elegantly reinforce this conclusion. For Feinan the lead isotope data of Hauptmann *et al.* (1992) show that there is no overlap with Cypriot ores, and the same is true for copper ores from Timna (Gale *et al.* 1990). The first lead isotope data for ores from the copper deposits of Oman are given in Table 5; inspection shows that the lead isotope data for the Oman ores are very different from those for Cypriot ores; there is no overlap here. The ores analysed are from three of the Omani mines with evidence for ancient activity as described by Berthoud *et al.* (1978) and Hauptmann (1985). The ores analysed were pyrite ores associated with the copper mineralization.

A comparison of published lead isotope data for the Anatolian copper ores and the Cypriot data was discussed at some length in an earlier publication (Stos-Gale and Gale 1994). The

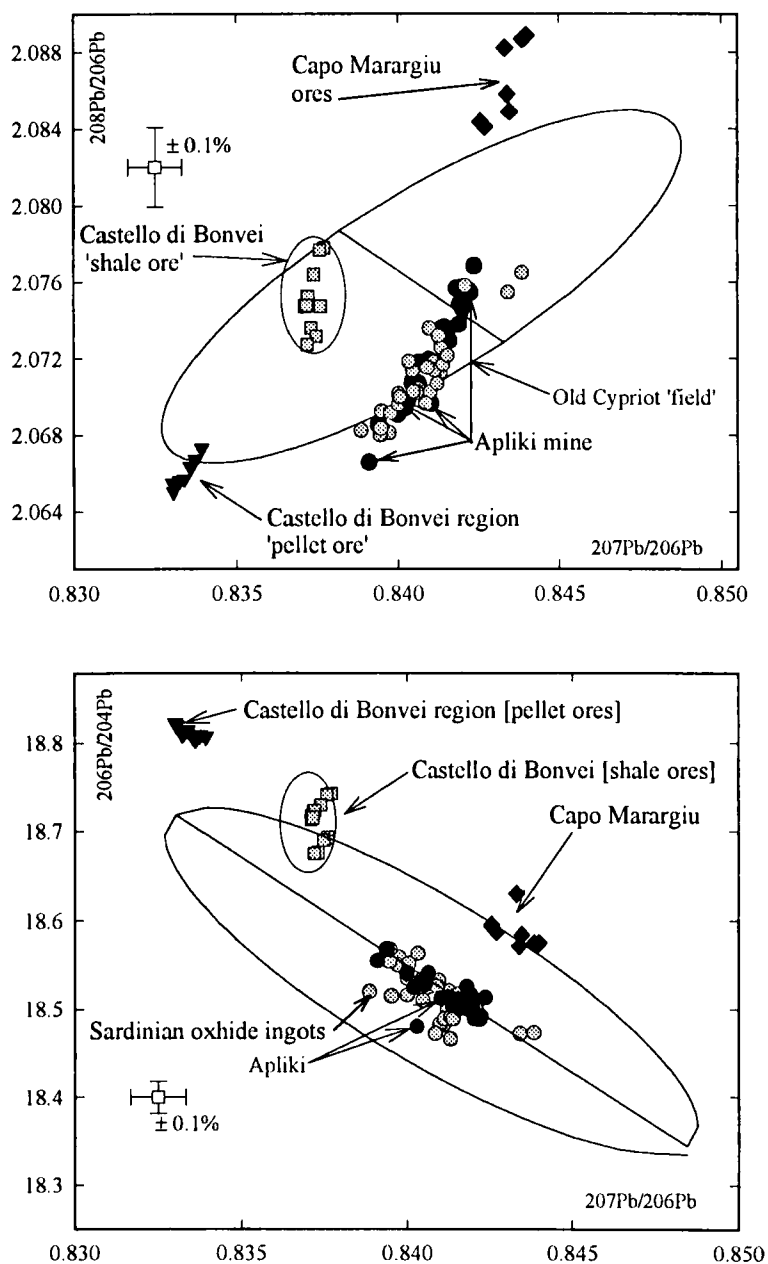


Figure 7 Old Cypriot lead isotope 'field' for 43 ores from Cyprus compared with some ores from Apliki, north-west Sardinian Tertiary copper ores from Capo Marargiu and two different deposits in the region of Castello di Bonvei, and with oxhide copper ingots found on Sardinia.

Table 5 Lead isotope analyses of ore samples from Oman

Sample no.	Site	Mineral	$^{208}\text{Pb}/^{206}\text{Pb}$	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{206}\text{Pb}/^{204}\text{Pb}$
AAR 17	Aarja J1	Pyrite	2.10791	.86250	17.901
AAR 48	Aarja J4	Pyrite	2.10653	.86031	17.968
AAR 83	Aarja J8	Pyrite	2.10583	.86010	17.981
AAR 85	Aarja J8	Pyrite	2.10709	.86310	17.879
BAY 87	Bayda J8	Pyrite	2.10411	.85944	17.985
LAS 26a	Lasail J1	Pyrite	2.10479	.85999	17.968

significantly increased number of data which we now have for Cypriot ores essentially do not change the situation, beyond a slight improvement in their separation from the ores of the Black Sea region. However, it should be cautioned that though the Heidelberg team visited and sampled about 85 ore deposits in Turkey, they have published only about 150 lead isotope analyses of them. Consequently most ore deposits have but one or two isotopic analyses available, so our knowledge of the lead isotope characterization of these ore deposits remains fragmentary. Undoubtedly, many more analyses of copper ores from Turkey are needed. So far there is only an indication of possible partial overlap of some of the Black Sea ore deposits with the ores from the Limassol Forest and some of the mines from the Larnaca axis. There are not enough data at present to use discriminant analysis to see if they can be distinguished from each other, but if more data on Turkish ores were available then the statistical approach might be required. Finally, and of most importance for this paper, there is no overlap in lead isotope composition between ores from the Cypriot mine of Apliki with any published data for Anatolian copper ores.

Another 'overlap' has been pointed out by Sayre *et al.* (1995) between the Cypriot ores and the lead isotope compositions of the ores from the Chalcolithic mine of Ai Bunar in Bulgaria published in 1991 (Gale *et al.* 1991). The overlap between the ores from Ai Bunar and Cyprus is in fact of very limited extent: the Ai Bunar ores plot in a very tight group in the upper right-hand corner of the old Cypriot field ($^{208}\text{Pb}/^{206}\text{Pb}$ diagram), and plot well away from the isotopic compositions of the LBA copper oxhide ingots, as shown in Figure 8. Moreover the mineralization in Ai Bunar is of relatively small importance. The only activity in copper mining claimed for this small occurrence is for the Bulgarian Eneolithic period (Chernykh 1978). There are no slags in the vicinity of this mine, or in the whole region of Stara Zagora. There is no indication of any later mining in Ai Bunar, so that it is not relevant as a source of copper for any part of the Mediterranean Bronze Age.

COPPER OXIDE INGOTS AND COPPER PRODUCTION IN LATE BRONZE AGE CYPRUS

The new, greatly improved information about the lead isotope compositions of ores from different Cypriot mines allows us to take a fresh look at the development of Cypriot copper metallurgy based on the lead isotope compositions of metals excavated on Cyprus. A large part of the lead isotope data for the Bronze Age metals from Cyprus was published two years ago (Stos-Gale and Gale 1994). Since this publication we have analysed nearly 100 more artefacts and we hope soon to publish these new data in a series of archaeological papers. Here we would like to discuss briefly only one, very important, group of LBA artefacts—the copper oxhide ingots.

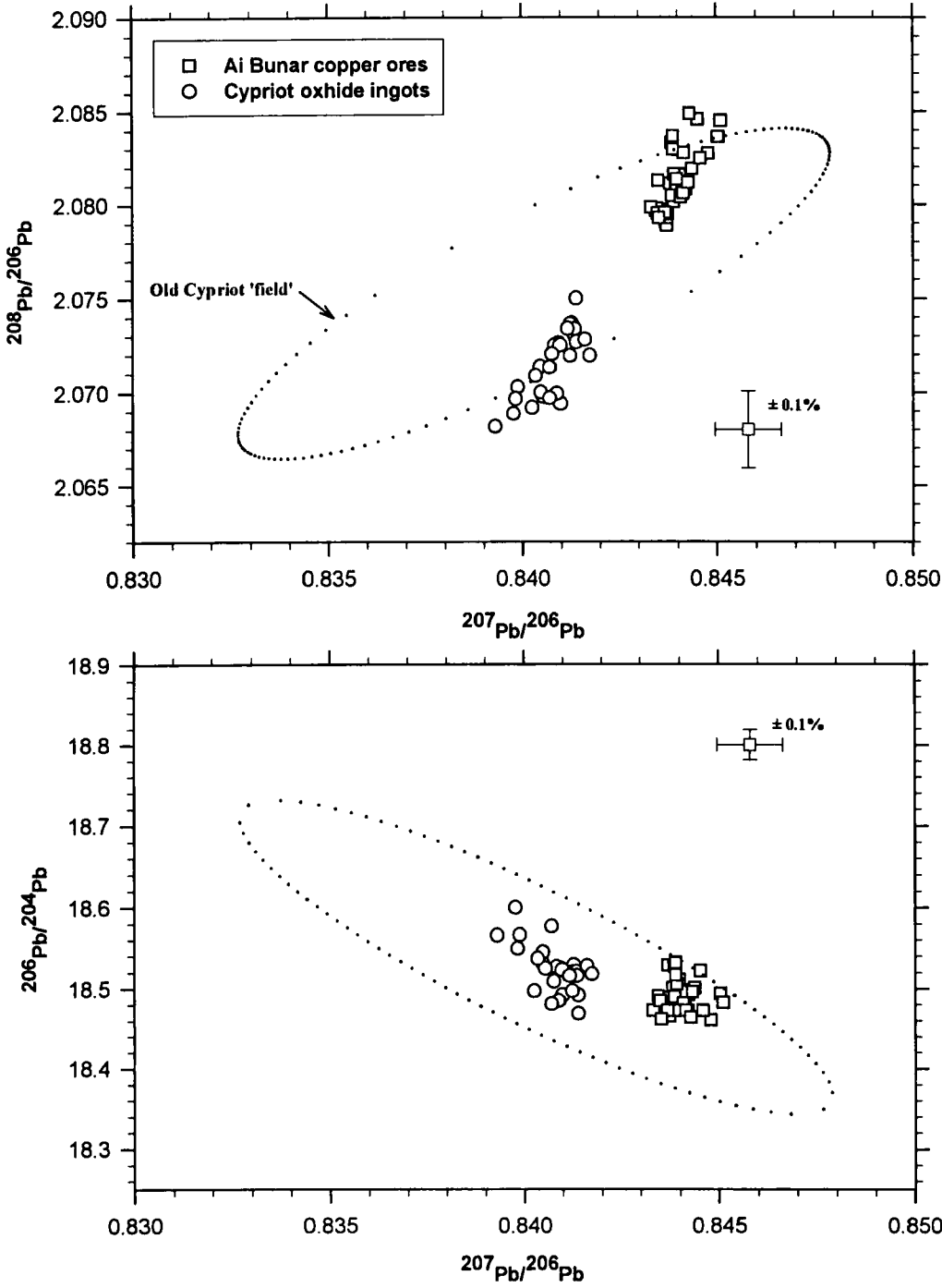


Figure 8 Lead isotope data for copper ores from the Bulgarian ore deposit of Ai Bunar compared with those for Cypriot copper oxide ingots.

Copper oxide ingots (known also as *talenta*, *keftiubarren*, *kissenbarren*, double-axe ingots, etc.) have been most comprehensively discussed by Buchholz (1959), Bass (1967), Gale (1989), Muhly *et al.* (1988) and Gale (1991). These ingots, apparently confined to the LBA (in the Aegean sense), are found on land all over the Mediterranean, approximately from Cyprus through Crete and Greece to Sardinia and Sicily, with a distribution given by maps in Muhly *et al.* (1988, 282, fig. 1) and in Gale (1991, 201, fig. 2). The large number of such ingots found in the two LBA shipwrecks of Cape Gelidonya (Bass 1967) and Ulu Burun (Bass 1986 and 1987; Pulak 1988) corroborate the assumption, from the distribution of land-based finds, that oxhide ingots were traded by sea. The find spots on land are dominated by those on the three great islands of the Mediterranean: Cyprus, Crete and Sardinia; the earliest, dating to LM I times (about 1550 to 1450 BC), have so far been found only in Crete, though they are depicted also in contemporary Egyptian tomb paintings (Bass 1967, 62–3). It has been claimed, on the basis chiefly of lead isotope analyses, that all examined oxhide ingots dated to the later part of the Aegean LBA have been proven to have been made of copper extracted from Cypriot copper ores including, unsurprisingly, those ingots found on Cyprus itself (Gale and Stos-Gale 1986; Gale 1989 and 1991). On the other hand the earlier LM I copper oxhide ingots found on Crete at Hagia Triadha and Tylissos have been suggested not to have been made of copper from Cyprus; these LM I oxhide ingots have Palaeozoic, especially Precambrian, lead isotope ratios which it does not at present seem possible to relate to the younger copper ore deposits of the Mediterranean or Turkey, but point probably to ore sources in Afghanistan, Iran or central Asia (Gale and Stos-Gale 1986; Gale 1991) (the same is true of the geologically old lead found in many EB II bronzes from Troy IIg and Kastri in Syros: Stos-Gale *et al.* 1984; Gale *et al.* 1985). That the ingots excavated in Crete are not made from copper ore deposits in Crete itself is no surprise, since copper ores are rare and scanty in Crete (Stech-Wheeler *et al.* 1975; Gale and Stos-Gale 1986).

Until recently no oxhide ingots found on Cyprus, either whole or fragmentary, have had sound archaeological contexts. The only whole oxhide ingot at present in Cyprus is held in the Cyprus Museum (Nicosia) and is said to be from the Ingot hoard (clandestinely excavated, therefore not datable, but perhaps about 1200 BC: Catling 1964, 282), Enkomi (Catling 1964, 267–8, pl. 49a, b); another thought to be from this hoard was in a private collection in Los Angeles (Catling 1964, 268; Muhly *et al.* 1977, 359–60). From something resembling an excavation (Murray 1990, 15, 17) comes the whole ingot (1897/4-1, 1535) from the Enkomi Foundry hoard (Catling 1964, 267; Matthäus and Schumacher-Matthäus 1986) held in the British Museum, together with six fragments (1897/4-1: 12, 13, 14, 15, 33, 36) from the same hoard, all dating to about 1200 BC (see Muhly *et al.* 1988, 285, for the date of the whole ingot). Other oxhide ingot fragments without archaeological context held in Nicosia include 11 fragments from the poorly recorded Mathiati hoard (Catling 1964, 282–5, pl. 49 g, 1936/VII-17/9) and at least seven fragments (1976-I-20) apparently with no proper record at all, but loosely associated with the Skouriotissa mine region. The Mathiati hoard (which included about 66 objects, embracing also smithy, carpenter's and agricultural tools and some weapons and scrap) was found in a shallow excavation, not more than two feet below the ground surface, whilst the Cyprus Mines Corporation was removing soil at North Mathiati, prior to mining the unusual gold occurrence there (Catling 1964, 283). The fragments of oxhide ingot said to be from Skouriotissa are kept, in the Nicosia Museum, in a box with a large tuyère with adhering slag, fragments of three others, a large piece of black slag and another of reddish slag, and two stones with adhering slag, but the records do not prove that all these were found together. The find spots give no reason to associate either the Mathiati or Skouriotissa oxhide ingot fragments with nearby copper

mining; from this evidence alone these ingots could have been made of copper from any ore deposit in Cyprus.

Recent archaeological excavations in Cyprus have transformed this situation, so that now there are a number of oxhide ingot fragments from secure, comparatively well-dated, contexts. Dating from the mid-thirteenth century BC (LC IIC) are some four fragments from Kalavassos-Ayios Dhimitrios (South-Todd 1985, 119); also from LC IIC are four unpublished fragments excavated by Cadogan at Maroni-Vournes. From the end of LC IIC come oxhide ingot fragments excavated from Maa-Palaeokastro (Demas 1984) and Pyla-Kokkinokremos (Karageorghis and Demas 1984).

METAL RECYCLING

That some recycling and mixing of metals used for tools, weapons, and so forth, may have occurred in the LBA Mediterranean is not questioned here, but there is no archaeological evidence that this was a large-scale phenomenon in this region. The assumption made by Maddin, Muhly and Stech that copper oxhide ingots were the product of one smelt of a charge containing ores from one ore deposit has recently been called into question by Budd *et al.* (1995b), partly on the basis that modern work attempting to reconstruct ancient smelting has failed to smelt, from one furnace charge, as much as the 28–30 kg of copper metal needed to make one ingot (e.g., Merkel 1990). Budd *et al.* (1995b) suggested that the remelting and mixing of metals was widespread in the LBA Mediterranean, that the oxhide ingots were made from mixing copper from many sources and that bronze scrap was mixed into at least some oxhide copper ingots. Gale *et al.* (forthcoming) discuss several grave difficulties inherent in this model for production of oxhide ingots. Gale and Stos-Gale (1995) showed that the tin content in all analysed oxhide ingots was so low as to preclude the addition of bronze scrap to these ingots, and pointed to evidence (Zwicker 1986) for large LBA smelting crucibles/furnaces from Enkomi and Kition which, in a small part of their total volume, very easily hold 30 kg of copper metal. Merkel (pers. comm. 1996) opines that, even if oxhide ingots were made by remelting a number of bun ingots followed by casting an oxhide ingot from the resulting mixture, it is likely that the bun ingots contributing to a particular oxhide ingot were all smelted on site from ores from the same ore deposit. Pernicka (1995, 63) states that: 'Even if it is possible that oxhide ingots do not represent the product of one smelting charge, they are likely to be made of copper from one source, according to the present evidence, and their purity still favours their interpretation as primary products (i.e., copper that was smelted and possibly refined, but not alloyed).' Sayre *et al.* (1995, 52–3) state that '... source mixing in the ingots does not seem to us to be supported by the lead isotope data', and again 'Ingots are a primary form of metal produced at production sources, which logically would most probably be located near the sources of metal in them ...', whilst 'Alloying of metals from different sources is much more likely to have occurred at these secondary artefact-producing sites than at the primary ingot-producing sites.' Relevant to this discussion is the proposal (Budd *et al.* 1995a) that fairly large changes of the isotopic composition of tin in ancient bronzes could identify bronze samples which had resulted from remelting and mixing together different samples of bronze. If this is so, large differences in the isotopic composition of tin should be common for bronzes sampled from the LBA Mediterranean, a region in which Budd *et al.* (1995b) claim that mixing of metals, in both artefacts and ingots, was very common. In fact a recent study of the isotopic composition of tin in a selection of LBA bronzes from this region failed to reveal any difference from the natural

composition in the isotopic composition of tin within these bronzes (Gale 1997, this volume), throwing some further doubt on the Bradford concept that the practice of mixing and recycling metals was widespread in this *koine*.

TRACE ELEMENTS IN THE OXHIDE INGOTS

In discussing the scientific data for the copper oxhide ingots we start with the analyses of their content of gold and silver. First, we restate here our position about the Au-Ag field characteristic of post-LC IIB copper/bronze (it is the same for both alloys) produced in Cyprus from Cypriot ores (this characteristic Au-Ag field was discussed by Gale 1989). Our position is that if, and only if, some LC IIC (in date, not typology) or later artefact found outside Cyprus has a lead isotope composition which links it to Cypriot copper ores and LBA Cypriot copper-alloy artefacts, then if it also falls into the Au-Ag field characteristic of post-LC IIC Cypriot artefacts, this provides additional evidence that it was produced from Cypriot copper smelted on Cyprus in LBA times. This is a position in which we have recently received support from Pernicka (1995, 61–2).

We do not assume that one can apply gold and silver contents alone to source metal artefacts, or that 'copper ores from particular deposits or geographical regions have uniform gold and silver ratios and that these differ significantly from each other' (Budd *et al.* 1995b). On the contrary we have consistently stated that trace element analyses alone do not allow one to link copper-alloy artefacts with copper ores (e.g., Gale and Stos-Gale 1982; Gale 1991, 204–5). Moreover we specifically drew attention (Gale 1989, 252, fig. 29.12) to the fact that the gold-silver concentrations of sulphidic and oxidized Cypriot copper ores scatter widely and do not fall in the restricted field characteristic of post-LC IIC Cypriot artefacts, and suggested (Gale 1989, 252–4) that the restricted field into which stratified LBA (not EC or MC) Cypriot copper/bronze objects fall may reflect a change in copper production technology or type of ores used in Cyprus at around 1325 BC. Further technical discussion of these and other relevant points appears in Pernicka (1995) and Gale and Stos-Gale (1995).

Table 6 presents the presently available data for gold and silver concentrations in the oxhide ingots discussed in this paper, together with lead isotope data. The gold and silver contents data for copper oxhide ingots are plotted in Figure 9 in relation to data from well-stratified copper/bronze objects from Cypriot excavations dating within the periods LC IIC to LC III. Clearly all oxhide ingots discussed in this paper have gold and silver contents consistent with them having been made from copper smelted from Cypriot copper ores in this time period. This is, of course, by itself not conclusive proof that this is so; for definite indications we turn to the lead isotope analyses.

THE LEAD ISOTOPE COMPOSITIONS OF COPPER OXHIDE INGOTS

Cypriot oxhide ingots

The latest lead isotope analyses for oxhide ingots found on Cyprus listed in Table 6 are graphed in Figure 10 in relation to the ores related to the Solea spreading axis. Clearly all these oxhide ingots match very well indeed the lead isotope compositions of ores from the Apliki mine, with but one fragment (of the ingots linked in the Nicosia Museum with 'Skouriotissa') plotting in such a position that it might have been made of copper from the Mavrovouni or Skouriotissa

Table 6 *Reliable lead isotope data and gold and silver content for oxhide ingots discussed in this paper*

<i>Ingot</i>	<i>Site</i>	$^{208}\text{Pb}/^{206}\text{Pb}$	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{206}\text{Pb}/^{204}\text{Pb}$	<i>Au (ppm)</i>	<i>Ag (ppm)</i>
<i>Bulgaria</i>						
84.74	Tcherkovo	2.07404	.84111	18.528	nm	nm
<i>Crete</i>						
GMS A	Gournia	2.06802	.83984	18.562	4.5	27
GMS B	Gournia	2.06947	.84001	18.530	2.2	12
GMS C	Gournia	2.06677	.83907	18.547	4.3	27.3
GMS D	Gournia	2.06584	.83900	18.556	4.2	26.1
KOM 82	Kommos	2.07491	.84135	18.531	5.5	36
<i>Cyprus</i>						
E12	Enkomi	2.06940	.84099	18.492	5.3	27.5
E14	Enkomi	2.06919	.84026	18.497	23.6	142
E15	Enkomi	2.07195	.84123	18.497	26.0	177
E1535	Enkomi	2.06993	.84089	18.485	18.6	109
E33	Enkomi	2.07134	.84071	18.577	12.5	66
E36	Enkomi	2.06969	.84071	18.481	15.3	89
KAD X	Kalavassos	2.06909	.83967	18.556	nm	nm
KAD1000	Kalavassos	2.07231	.84073	18.554	15.7	106
KAD468	Kalavassos	2.07205	.84077	18.509	12.4	74
KAD471	Kalavassos	2.07583	.84257	18.506	15.4	115
Maa LN526	Maa	2.06887	.83978	18.605	2.2	18
MV/M 201	Maroni	2.07262	.84094	18.525	22.3	96.2
MV/M 210	Maroni	2.06818	.83930	18.566	8.2	44.6
MV/M 216A	Maroni	2.07029	.83989	18.566	3.8	15.1
MV/M 216B	Maroni	2.07366	.84127	18.529	33.2	239
MV/M181	Maroni	2.07137	.84047	18.532	nm	nm
Mat 1	Mathiati	2.07088	.84053	18.537	24.3	140
Mat 2	Mathiati	2.07267	.84139	18.492	14.9	158
Mat 3	Mathiati	2.07337	.84135	18.516	22.3	103
Mat 4	Mathiati	2.07338	.84117	18.516	9.7	75
1982: 65(L)	Pyla	2.07281	.84162	18.528	nm	nm
1982: 65(S)	Pyla	2.07196	.84174	18.518	6.7	45.3
SK6	Skouriotissa	2.07250	.84084	18.527	21.4	129.7
SK7A	Skouriotissa	2.07364	.84123	18.520	25.9	162.2
SK7B	Skouriotissa	2.07251	.84098	18.523	23.8	122
SK7C	Skouriotissa	2.06977	.84055	18.525	1.7	13
SK7D	Skouriotissa	2.07500	.84139	18.471	3.95	35.3
SK7E	Skouriotissa	2.06731	.84134	18.521	2.8	15.6
SK7F	Skouriotissa	2.07001	.84049	18.545	2.8	22.5
<i>Greece</i>						
CEAC/54/164	Chios, Emporio	2.06897	.84061	18.509	4.9	34
KYME 4	Kyme	2.07439	.84228	18.505	4.2	39
KYME 12	Kyme	2.07290	.84183	18.525	2.0	18
7664.1	Mycenae	2.06841	.84039	18.496	15.4	102
7664.10	Mycenae	2.06849	.84045	18.501	13.7	85
7664.11	Mycenae	2.07326	.84100	18.560	8.2	30
7664.2	Mycenae	2.06976	.84037	18.494	29.0	163
7664.3	Mycenae	2.06976	.84010	18.529	24.8	172
7664.4	Mycenae	2.07171	.84125	18.503	22.7	113
7664.6	Mycenae	2.07089	.84049	18.520	41.1	141

Table 6 (continued)

<i>Ingot</i>	<i>Site</i>	$^{208}\text{Pb}/^{206}\text{Pb}$	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{206}\text{Pb}/^{204}\text{Pb}$	<i>Au (ppm)</i>	<i>Ag (ppm)</i>
7664.7	Mycenae	2.06716	.83942	18.555	8.6	34
7664.8	Mycenae	2.06826	.83946	18.532	20.5	121
<i>Sardinia</i>						
20969	Arzachena	2.06848	.83987	18.516	9.9	57
20970	Arzachena	2.06922	.83950	18.559	nm	nm
BELV1	Belvi	2.06962	.84086	18.472	18.8	52
A1048	Cagliari Museum	2.07214	.84155	18.517	9.5	59
CAP	Capoterra	2.07184	.84033	18.563	7.7	61
60495	Ittireddu	2.06811	.83972	18.550	nm	nm
60496	Ittireddu	2.07122	.84132	18.466	nm	nm
38477	Lanusei	2.06834	.83953	18.515	nm	nm
38478	Lanusei	2.06913	.83976	18.559	23.8	159
38478b	Lanusei	2.07181	.84112	18.482	nm	nm
38478c	Lanusei	2.07578	.84210	18.502	nm	nm
38479	Nuoro Museum	2.07022	.84100	18.483	19.9	138
60498	Ortueri	2.06798	.83946	18.554	6.1	36
60499	Ortueri	2.06834	.83948	18.568	nm	nm
10622	Ossi	2.06940	.84027	18.510	13.9	94
SI A CA2	Serra Ilixi	2.06846	.83956	18.524	8.2	55
SI C CA1	Serra Ilixi	2.08049	.84168	18.605	3.6	22
10231	Tertenia	2.07357	.84097	18.533	15.5	78
CA4	Teti Abini	2.07068	.84122	18.500	6.0	43
VDI	Valle D'Isalle	2.07153	.84091	18.526	9.1	69
BS1	Villanovaforru	2.07138	.84114	18.489	nm	nm
BS10	Villanovaforru	2.07545	.84342	18.472	nm	nm
BS11	Villanovaforru	2.07169	.84141	18.489	19.6	98
BS2	Villanovaforru	2.07258	.84134	18.491	nm	nm
BS3	Villanovaforru	2.07395	.84329	18.483	16.4	88
BS4	Villanovaforru	2.07021	.84059	18.534	nm	nm
BS5	Villanovaforru	2.07025	.84048	18.510	5.8	30
BS7	Villanovaforru	2.07318	.84127	18.521	nm	nm
BS9	Villanovaforru	2.07649	.84385	18.473	nm	nm
<i>Turkey</i>						
ANT 1	Antalya	2.07201	.84089	18.523	2.4	14.9
TU 274	Bogazkoy	2.06955	.83977	18.525	6.2	35
Sarkoy	Sarkoy	2.06970	.84019	18.535	nm	nm

Objects with the prefix 7644. are from the Poros Wall hoard, Mycenae. Some samples with previous less precise data have been reanalysed for this paper: GMS B; GMS C; Mat 1; Mat 3; SK7A; SK7B; SK7D; CA1; CA2; VDI; CAP; 60495; 38478; 38478c; 60498; 60499; BS4; BS7; BS9; BS10.

nm: not measured.

mines. Ingot fragments plotting in the upper diagram slightly below our old Cypriot field are now seen to match ores from Apliki plotting also in this region. A close examination of the positions in which lead isotope data plot from other Cypriot mines (see Figs. 3–6; Gale *et al.* 1997, this volume) reveals that data for no other mine or deposit as yet analysed overlap with any of the Cypriot oxhide ingots found on Cyprus. We thus have a situation where all analysed copper oxhide ingots found or excavated in Cyprus, dating from the mid-thirteenth century BC

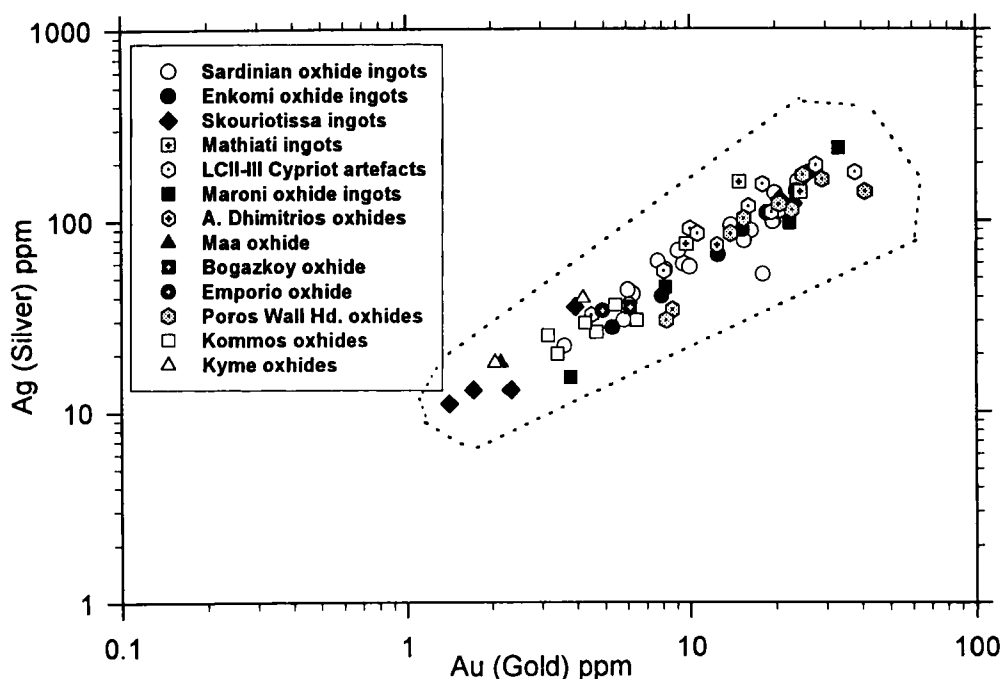


Figure 9 Gold and silver concentrations in Late Bronze Age 'bronze' artefacts from the Cypriot archaeological sites of Ayios Dhimitrios, Maa, Pyla, Hala Sultan Tekke, and for oxhide copper ingots found in various countries.

to about 1200 BC, have lead isotope compositions which match perfectly Cypriot ores from the Apliki mine.

Miscellaneous copper oxhide ingots

We have also analysed a number of copper oxhide ingots from various sites around the Mediterranean. Table 6 presents the lead isotope data for these oxhide ingots; the data are plotted in Figure 11. From Crete the Gournia ingots date most probably to LM IB (about 1500–1450 BC), whilst the Kommos ingots date to LM IIIA2–IIIB (about 1350–1200 BC). The Mycenaean ingot fragment from Emporio, Chios, comes from an LH IIIC context (about 1200–1150 BC), whilst those from the Poros Wall hoard at Mycenae (Wace 1959) are of probable LH IIIB date (about 1340–1200 BC). The oxide ingots from Kyme (Euboea) and Bulgaria (not, as previously reported, from the sea off Sozopol, but from a single-period Bronze Age site at Tcherkovo: see Karaitov 1978), and that in the Metropolitan Museum attributed to Antalya, are all of uncertain date, whilst that from Sarkoy, on the northern shore of the Sea of Marmara is also of dubious chronology, but probably dates to about the twelfth to eleventh centuries BC (Harmankaya 1994). As Figure 11 demonstrates, all these oxhide ingots, of different dates and found over a considerable geographical range, match closely the lead isotope compositions of ores from Apliki in Cyprus. The ingot from Bulgaria does have an isotopic composition falling in the region where ores from both Apliki and Mavrovouni fall, as does one from Kommos, but otherwise the match is with Apliki alone.

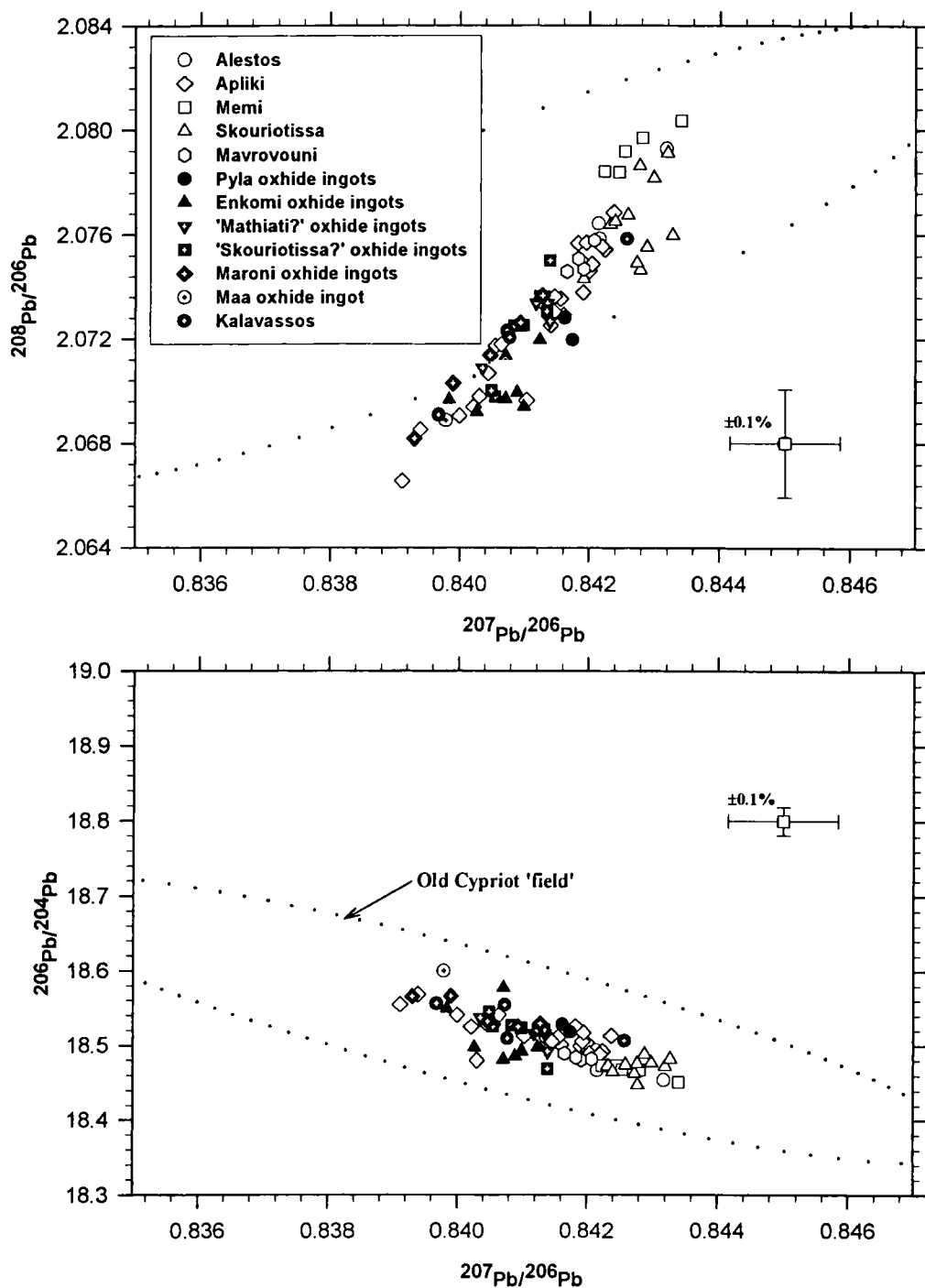


Figure 10 Comparison of lead isotope data for ores from the mines of the Solea spreading axis with those for copper oxhide ingots excavated from Cypriot Late Bronze Age sites.

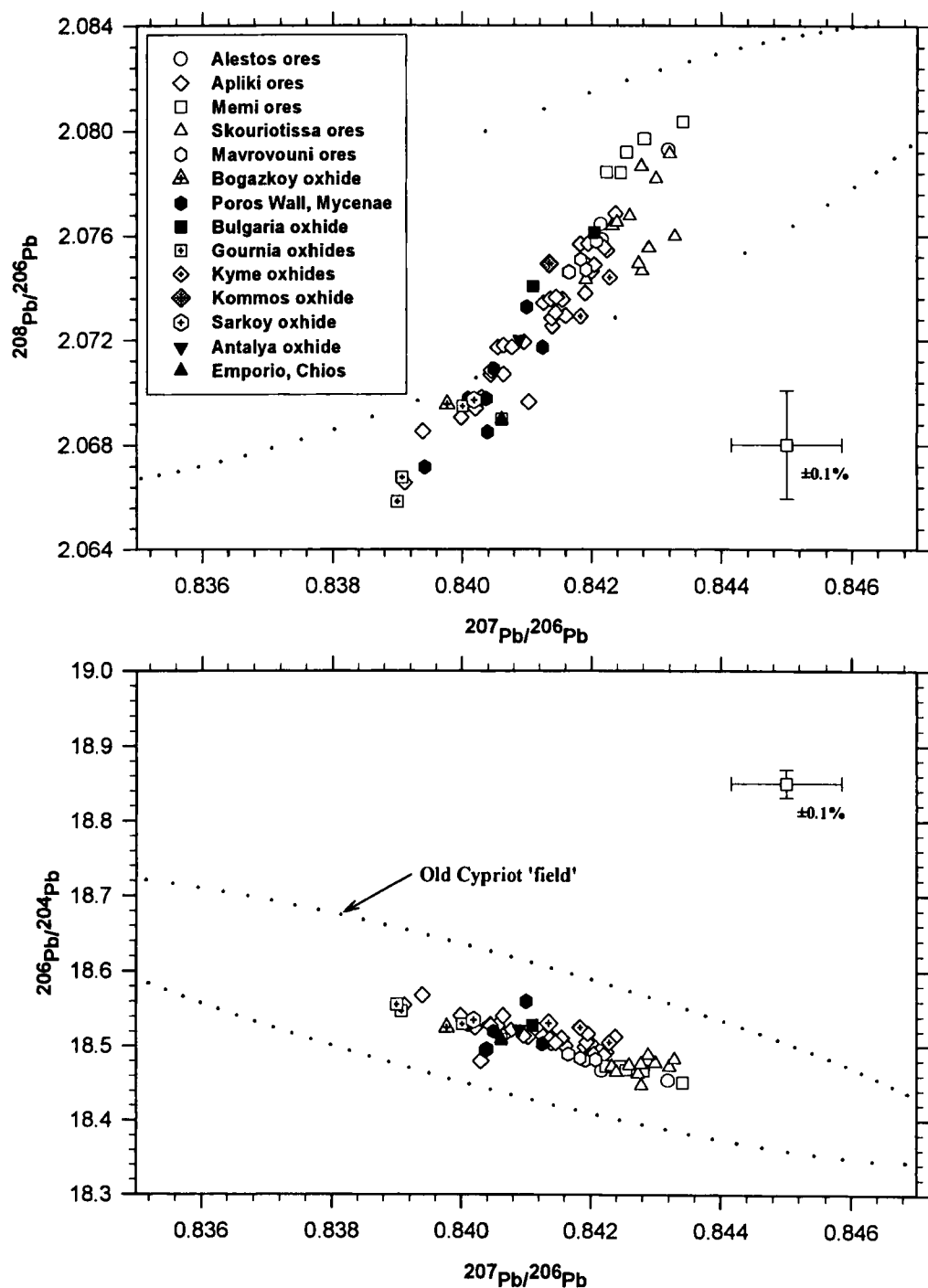


Figure 11 Comparison of lead isotope data for copper oxide ingots from Greece, Turkey and Bulgaria with those for ores from mines associated with the Solea fossil spreading axis.

Oxhide ingots from Sardinia

The analytical data for some of the oxhide ingot fragments found on Sardinia include some from the hoard of Villanovaforru (CA), Baccu Simeone, which possibly (the evidence is not conclusive) date to the end of the Italian LBA (Lo Schiavo *et al.* 1990) (c. end of the tenth century BC). Ingot fragments from Nuraghe Albucciu (Arzachena, Sassari) may also date to the end of the LBA (Lo Schiavo 1980). Other Sardinian oxhide ingot fragments for which data are discussed here come from Nuraghe Nastasi (Tertenia, NU), Perda 'e Floris (Lanusei, Nuoro), Nuraghe Funtana (Ittireddu, Sassari); their apparently tenuous chronology is discussed by Lo Schiavo (1980). The lead isotope data for the oxhide ingot fragments appear in Table 6 and are plotted in Figure 12. Again the data for the oxhide ingot fragments plot together with the lead isotope data for the Cypriot copper ores from the Apliki mine; moreover the gold and silver contents of these Sardinian ingots fall with those found on Cyprus. We still would like to withhold final judgement about the origin of the copper used to make these oxhide ingots found on Sardinia until we have analysed Sardinian copper ores from the Calabona deposit in north-west Sardinia, but it does look increasingly that the source may be the Apliki ores of Cyprus.

In view of the consistency of the Sardinian ingots with the ores from Apliki it should be remembered that (as discussed at length by Gale 1991, 219–24) many LBA copper-based artefacts found in Sardinia were asserted by Lo Schiavo *et al.* (1985) to be of Cypriot manufacture, and both Cypriot and Minoan sherds have been excavated in Sardinian coastal sites, so there seems no archaeological reason against the oxhide ingots also having come from Cyprus. Indeed Muhly and Stech (1990, 205–17) have seriously discussed the possibility that Cypriot copper came to Sardinia in exchange for Sardinian iron. It has been suggested (*ibid.*) that there may be a chronological difficulty in that oxhide ingots ascribed to the Italian LBA are found in Sardinia, whereas none so late as that have been found in Cyprus. But ingots have been found in good archaeological contexts only recently in Cyprus, where excavated LBA and Early Iron Age sites are still rare, and the Italian LBA extends from about the thirteenth century to the tenth century BC, with but exiguous evidence that even one Sardinian ingot belongs to the end of this period.

The conclusion that the majority of analysed oxhide ingots are consistent with having been made of copper from the Cypriot Apliki ore deposit (perhaps also Skouriotissa and Mavrovouni to a minor extent) shows the mining operations in the vicinity of Morphou Bay in a new light. Each oxhide ingot weighs nearly 30 kg. The number of these ingots produced particularly in the thirteenth and twelfth centuries BC must have been considerable, judging from the fact that only two ships, Cape Gelidonya and Ulu Burun, carried between them more than 400 whole ingots and many fragments. If indeed all of these oxhide ingots were smelted in the region of Apliki-Skouriotissa then the production of copper there must have been organized with professional efficiency.

INDEPENDENT ARCHAEOLOGICAL EVIDENCE FOR ANCIENT
MINING/METALLURGY IN NORTH-WEST CYPRUS

What direct evidence is there for ancient mining of the ores in the Apliki/Skouriotissa region? Most Cypriot scholars are familiar with the extremely large copper smelting slag heaps at Skouriotissa; these are so large that no-one would associate them with the Bronze Age, and the three radiocarbon dates reported by Zwicker (1986) are AD 310, 260 and 310. However, Zwicker also reports that wood from timbered, and therefore late, galleries in the Skouriotissa

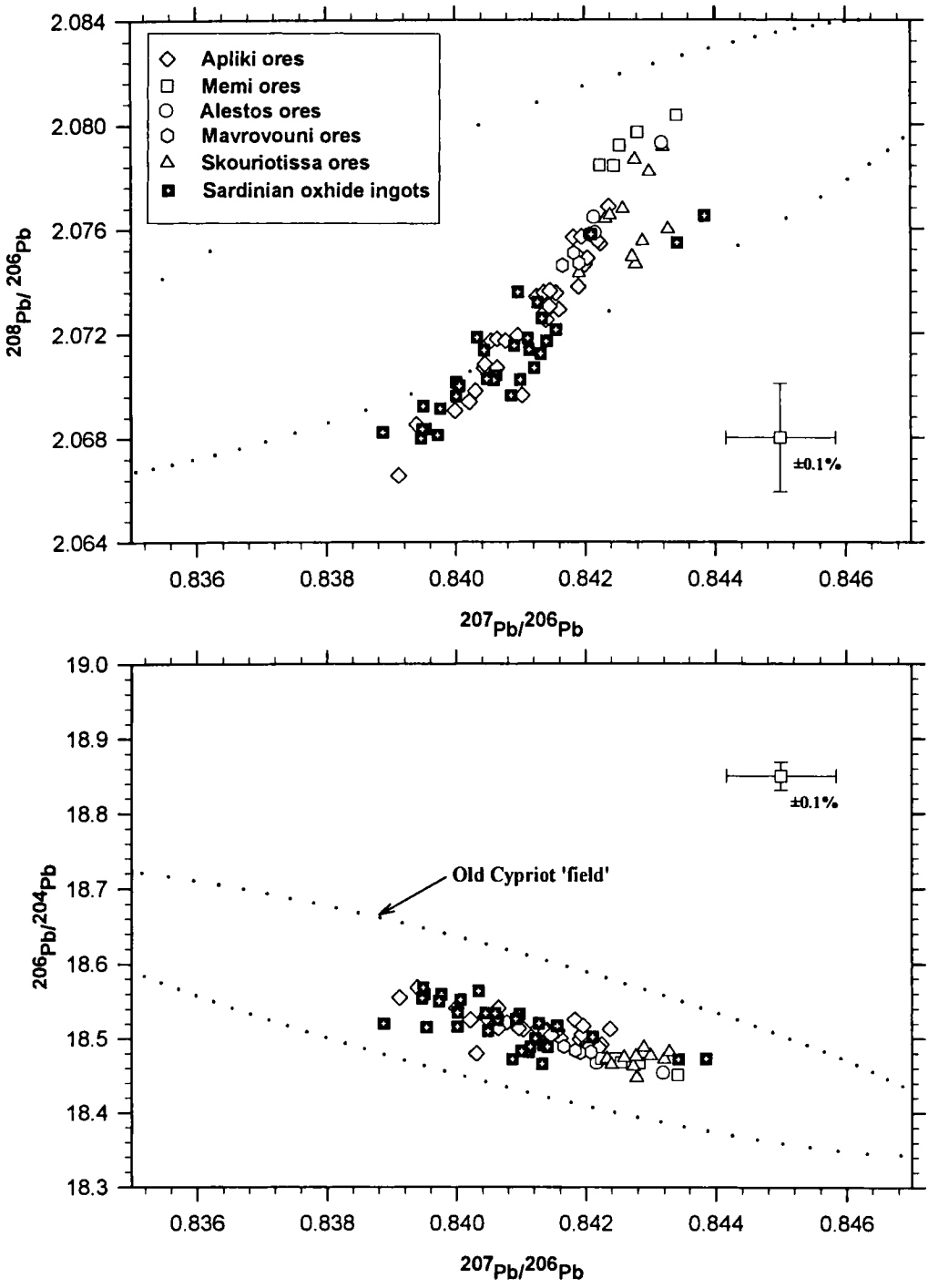


Figure 12 Comparison of lead isotope data for copper oxhide ingots from Sardinian sites with those for ores from mines associated with the Solea fossil spreading axis.

mine has radiocarbon dates of 580 and 485 BC. Shaft timberwork from the Apliki mine itself, now in the Deutsches Bergbau-Museum at Bochum (Weisgerber 1982, pls. I–III), has been radiocarbon-dated to 410 BC. Thus we have direct evidence for fairly early, Cypro-Archaic to Classical, 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 archaeological evidence for Middle Cypriot I mining in the much smaller Ambelikou mine in the same region (Merrillees 1984). There is definite evidence at the Middle Cypriot I site of Ambelikou-Aletri, near the Ambelikou mine, for crucible copper smelting (Merrillees 1984, 7–8; Zwicker 1982). A little later there is the possible evidence for Minoan and Mycenaean interest in north-west Cyprus of Mycenaean I pottery from Ayia Irini and of LM I pottery both from Ayia Irini and from Toumba tou Skourou (see Catling 1980). Muhly (1989, 301) has drawn attention to the fact that, though Toumba tou Skourou is often described as strictly a ceramic production centre, primary copper smelting slag has been found on the site.

Most persuasive of all is the evidence from the Bronze Age miners' settlement of Apliki-Karamallos, which had apparently lasted from the beginning of the fourteenth century BC to the first half of the twelfth century BC (LC IIC into LC IIIA: du Plat Taylor 1952). Muhly (1989) has further discussed the finds from this site, which included a number of massive D-shaped and elbow tuyères, much larger than those found at Enkomi. There were also large amounts of massive black copper slag (see Muhly 1989, 307, fig. 35.1), especially in House A; the slag was found under the floors of rooms filled with Mycenaean and Cypriot pottery of the thirteenth and twelfth centuries BC. As recorded in her report of the 1939 season to the Cyprus Mines Corporation (du Plat Taylor 1939), in the neighbourhood of the site the excavator found several remnants of ancient mining galleries, including one connected with a waste ore/gangue dump containing pottery contemporaneous with the Bronze Age settlement. Muhly (1989, 309) has written: 'we need have no difficulty in seeing Apliki as a LBA mining and smelting site.' The evidence presented in this paper now links the Apliki copper deposits and the production of copper oxhide ingots which found their way to LBA Bogazkoy, Bulgaria, Egypt, Chios, Crete, Keos, mainland Greece and Sardinia.

CONCLUSIONS

This article has principally a dual purpose: one is to present, in support of the validity of the new lead isotope data, the geological background for the new 194 lead isotope analyses of Cypriot ores, which form a contribution to the data base of isotopic 'fingerprints' of ore deposits used in antiquity. The second purpose of this article is to present the evidence that a large number of analyses of ores from the same deposit can lead to the identification of structure in the data which allows the identification of specific mine sites which produced copper in specific periods. This case is illustrated by the comparison of lead isotope compositions of a number of copper oxhide ingots with the ores from Cyprus, which isolates the Apliki mine as the chief source within Cyprus of copper for the production of these ingots.

The sulphide ore deposits which were analysed for their lead isotopes include most of the major deposits of the Troodos ophiolite complex. The deductions from geological/geophysical work which relate particular deposits to particular fossil spreading axes are verified by the isotopic results, which show that when the lead isotope data for deposits assumed to be related to

a given axis are plotted on the same graph, they group together and demonstrate a specific trend of isotopic data, with older model ages for deposits further away from the fossil axis. The relative lead isotope data for the Larnaca and Solea axes support the suggestion that the Larnaca axis is younger than the Solea axis, as has already been proposed from geological/geophysical evidence. The Limni axis appears to be of the same age as the Solea one, though no comparison was previously made from the geological point of view. Similarly, the ores associated with the Kalavassos axis appear to have their own distinctly different age which is younger than for the other fossil spreading axes. As was stated above, the Limassol Forest results generally support that the mineralization there could be the result of magmatic segregation at the time of spreading of the Larnaca axis, rather than a separate hydrothermal phenomenon, as proposed earlier by Panayiotou (1980).

For the purposes of provenancing the sources of copper for LBA Mediterranean artefacts the lead isotope compositions of Cypriot ores are now much better defined, and prove to be complex. In this regard the suggestion (Budd *et al.* 1995b, 26) that there is a lead isotope field for the whole of Cyprus which must be drawn so that a bounding line encloses all the data for all the deposits must be regarded as erroneous (since such a line will enclose also regions of isotopic space unpopulated by ore data), as was the even less tenable suggestion of Pernicka that an all-encompassing lead isotope field can be envisaged for the whole Aegean. Nor are Budd *et al.* (1995b, 26) correct to assert (based on no discussion of actual data) that it is not meaningful, either on archaeological or geological grounds, to compare artefacts with lead isotope data for individual mine sites. This paper demonstrates, based on a discussion of concrete evidence, that on both grounds the opposite is true. It is of course correct that overlaps between isotopic data for some Cypriot mines mean that some artefacts will be assignable only to a group of mines but others may be assignable to a particular mine, as we have seen is true for copper oxhide ingots.

In that regard it seems clear that all of the copper oxhide ingots for which data are presented in this paper have lead isotope compositions which link them firmly with the lead isotope compositions of the Apliki ores (perhaps also the Skouriotissa and Mavrovouni ores) in Cyprus, with which at present there are no known overlaps of isotopic composition with any other Mediterranean ore deposits. An examination of the new data for Cypriot ores and Figures 3–12 will convince the reader that the lead isotope data for copper oxhide ingots presented here do not overlap with Cypriot ores associated with any fossil spreading axis other than the Solea axis; this point is emphasized in Gale *et al.* (forthcoming, fig. 6). Ongoing analyses in Oxford of several hundred oxhide and other ingots from the Ulu Burun and Gelidonya shipwrecks will most likely provide crucial evidence about copper production and 'trade' in the eastern Mediterranean in the thirteenth to twelfth centuries BC. We will see then if the supremacy of Skouriotissa and Apliki holds as sources of copper for the oxhide ingots.

Budd *et al.* (1995c, 72) recently suggested a very unlikely new recycling hypothesis for the origin of copper oxhide ingots. Budd *et al.* (1995b) concluded that no Mediterranean ore deposit will ever be found which has lead isotope compositions which exactly match those of the oxhide ingots. They were in large part prompted to propose their recycling hypothesis as a result of their attempt to argue that the lead isotope compositions of the oxhide ingots 'cluster in a three dimensional plot in a pattern that does not fit any of the fields of the Mediterranean, including Cyprus! The offset position of the [lead isotope compositions of the] ingots within the Cypriot [lead isotope] source [field] means that the ingots could not have derived solely from the ore bodies of that island.' This was not completely true even for the data available in 1994, for which we (Stos-Gale and Gale 1994, 105–8, fig. 3.38; Gale and Stos-Gale 1995, fig. 2; Gale and Stos-

Gale forthcoming) had pointed out that the tendency for oxhide ingots found on Cyprus to plot towards and slightly below the bottom edge of the overall Cypriot field in one diagram was in fact matched by the lead isotope composition of the two analysed ores from the Cypriot Apliki mine then made.

The new data which we have accumulated both for Cypriot ores and for oxhide ingots show, not an offset from, but a perfect match between the lead isotope compositions of the ingots and particular Cypriot ore bodies. Those who, basing themselves largely on the view that there is no such match, have recently written about a postulated crisis in lead isotope and metal provenancing studies no longer seem to have grounds for this gloomy assessment (it is noteworthy that no support was forthcoming from Sayre *et al.* (1995) or Pernicka (1995) for the nihilistic model of oxhide ingot production proposed by Budd *et al.* (1995b)). On the contrary, the present work seems to give confidence that, with sufficient well-controlled data acquisition, the field of lead isotope metal provenancing is one of the more successful fields of science-aided archaeology, with much further potential for a direct input to solving important archaeological questions.

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