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Comments on 'Oxhide Ingots, Recycling and the Mediterranean Metals Trade'

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We can comment most efficiently on the analysis of the stable lead isotope ratios in Late Bronze Age oxhide ingots presented by Budd *et al.* by presenting first our own analysis of pertinent parts of these data. A preliminary observation on the data is that they divide into a number of distinctively different groups. It is true that a sizeable fraction of the ingots, from various find sites, have isotope ratios close to, or overlapping, those of Cyprus copper ores but, as Gale and Stos-Gale have pointed out, none of the oxhide ingots found on Crete has isotope ratios at all consistent with Cypriot ores. Rather they divide into three distinctly separate groups (1) specimens from Hagia Triadha with distinctly high ratios relative to ^{206}Pb, Crete 1 Ingots, (2) other specimens from Hagia Triadha and one from Tylissos with intermediate ratios, Crete 2 Ingots, and (3) four specimens from Gournia with distinctly low ratios, Crete 3 Ingots. The spread of these ingots throughout the three-dimensional isotope ratio space is shown in Figures 1 and 2. A pertinent question is how many different sources of oxhide ingots might there have been.

The stable lead isotope ratio measurements are three-dimensional data and we have always based our inference upon trivariate statistical analysis of them. Unless all three varieties are fully taken into account false matches among specimens might be inferred. It is not enough to conclude that specimens have matching isotope ratios if they appear to overlap in a two-dimensional plot of the data because they may well be separated from each other in the third dimension. When a sufficiently large group of isotopically matching specimens, about 10 or more, from related artefacts or from individual ore sources has been analyzed we usually identify other specimens that are isotopically consistent with it by means of trivariate probability calculations. Our program ADSEARCH allows us to calculate for all specimens in our database the probability of matching the core group in question and will select out, into a different file, those that match at any predetermined level of probability. We much favor these trivariate probability calculations because they not only take into account all three dimensions of the data but take fully into account the extensive correlation that exists among the variates within the groups.

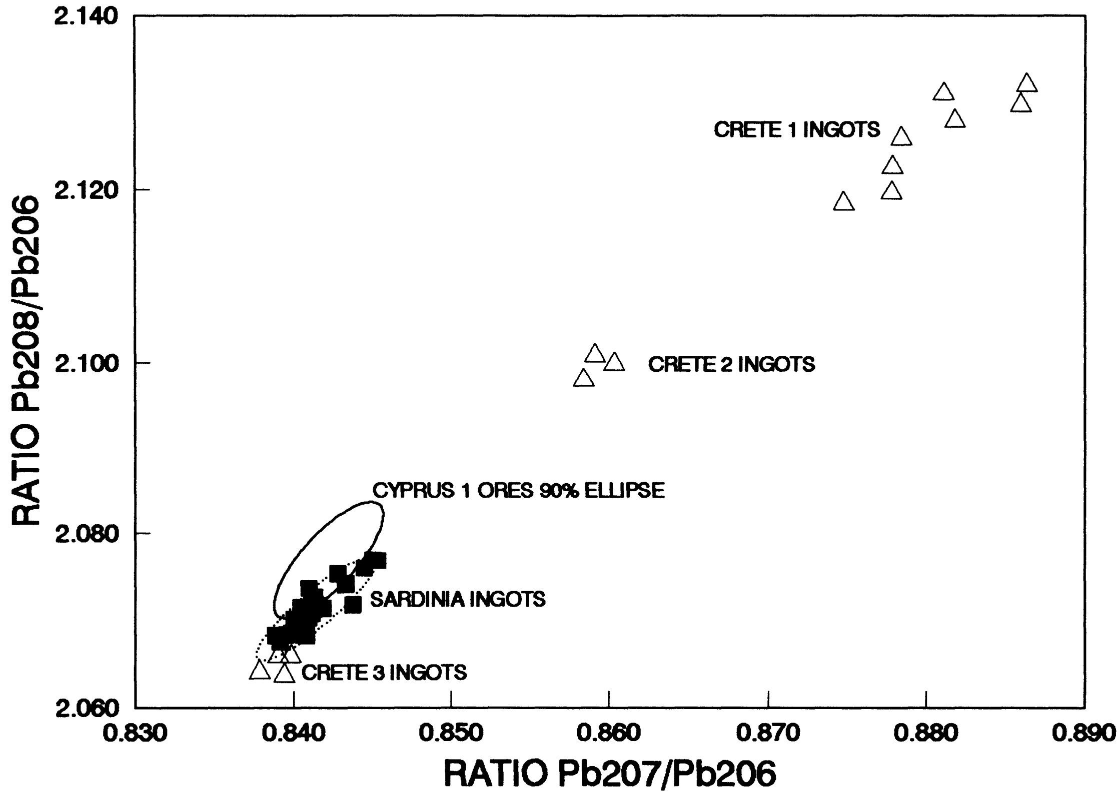

Figure 1 Comparison of groups of Oxhide Ingots from Crete and Sardinia to the Cyprus 1 ore field in $^{208}Pb/^{206}Pb$ versus $^{207}Pb/^{206}Pb$ space.

We continue to believe that the isotope data for Cypriot copper ores should be divided into two significantly separate isotopic groups, Cyprus 1 and Cyprus 2. When we determine the trivariate probabilities of the oxhide ingots matching these two ore source groups we find that none of the ingots have significant probabilities of matching Cyprus 2, but that all of the ingots from Cyprus itself and all of the ingots from the Uluburun and the Cape Gelidonya shipwrecks have significant probabilities of matching Cyprus 1. In addition, an ingot found at Mycenae and one found at Ayia Irini on Keos and about half of the ingots found on Sardinia also have significant probabilities of matching Cyprus 1. None of the ingots from Crete or from Syria matched Cyprus 1. The completeness of the match of the Cypriot and shipwreck ingots to the Cyprus 1 ore group is shown in Figures 3 and 4. It is important that the overlap is shown in more than one such two dimensional plot to confirm that it extends throughout the full three dimensions of the data. These plots show that the spread of the artefacts throughout the isotope ratio space comes close to matching fully the spread of the Cyprus 1 ore specimens. We have encountered several instances, in other isotope studies, in which a group of ore specimens and a group of artefact specimens that might relate to them nearly fully coincide in all dimensions, and we have felt that such overall coincidence strongly indicates a relationship between them. In light of the coincidence shown here we consider it highly probable that Gale and Stos-Gale's conclusion that the ingots from Cyprus and the shipwrecks were derived from Cypriot ores is correct. We also feel that the complete exclusion of Cyprus 2 ores from the match provides evidence that the division of the Cypriot ores into two groups is correct and that the production of these ingots appears to have involved only Cyprus 1 mines.

The matching group of artefacts from Cyprus and the shipwrecks is sufficiently large that we can use our program ADSEARCH to select out of our overall database of nearly 2400 ores from Europe and the Near East all other ore specimens that have trivariate probabilities of matching it. When we do this, one other sizeable ore group in addition to Cyprus 1 was found to match these artefacts, a group of ores from Bulgaria, which merit consideration as a possible source of the ingots. The 90% probability ellipses for these Bulgarian ores are also drawn in Figures 3 and 4. One can see that they form an unusually tight group to which the arte-

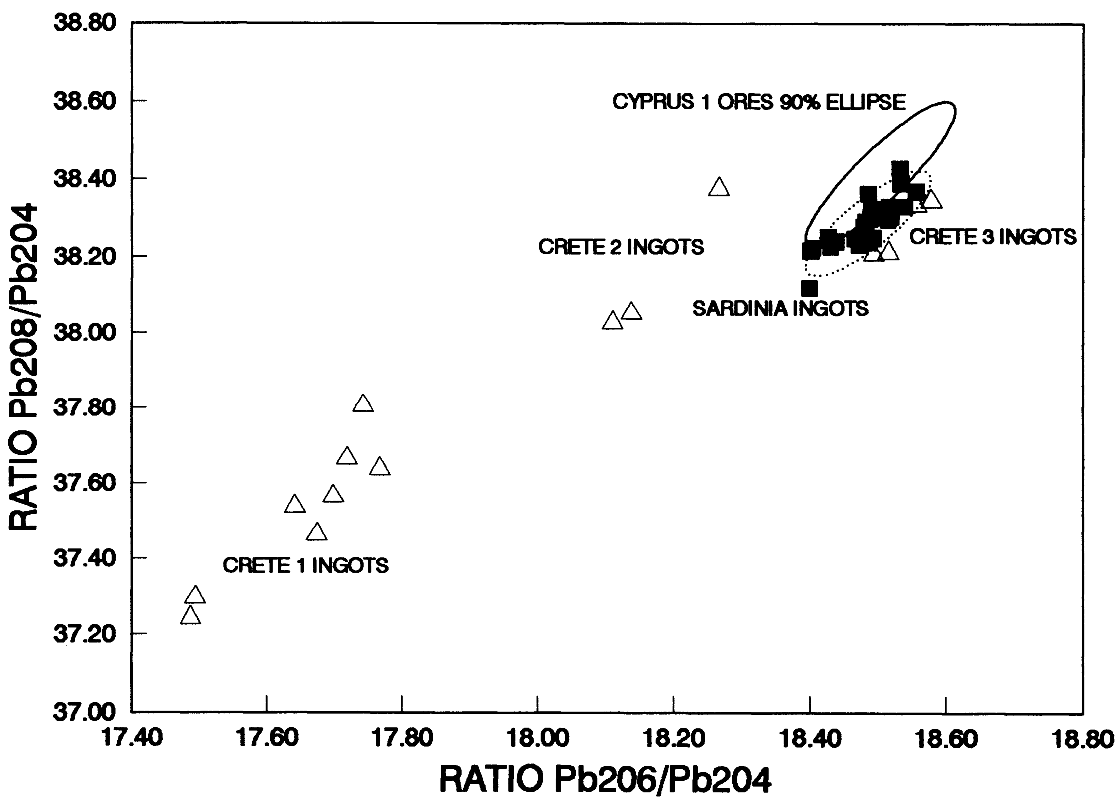

Figure 2 Comparison of groups of Oxhide Ingots from Crete and Sardinia to the Cyprus 1 ore field in $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ space.

facts, in general, do not conform as they do to the Cyprus 1 group. The Bulgarian ore source is reasonably well defined by 26 specimens, but it is possible that further sampling of this source would extend it more over the range of the ingots. As it now stands, it would seem to be a far less probable source of these ingots than Cyprus 1. There are also a few matching single ore specimens from such remote sites as France, England, Germany and Holland, which do not merit consideration as potential sources. A pair of ore specimens from Thrace matched but they are peripheral members of a large, self-consistent group of ores from Thrace and nearby Chalcidice, most of which are well offset from the ingots in question. The same is true of a pair of matching specimens from the eastern Black Sea shore of Turkey. Single, individual specimens from northern Thrace, the Taurus mountains and Egypt match but, we feel offer little evidence of probable alternative sources. The restrictions on the length of these comments prohibit more comment on this scatter of conceivably related ores and on the possible sources of the oxhide ingot groups found on Crete, which a complete analysis would, of course, require.

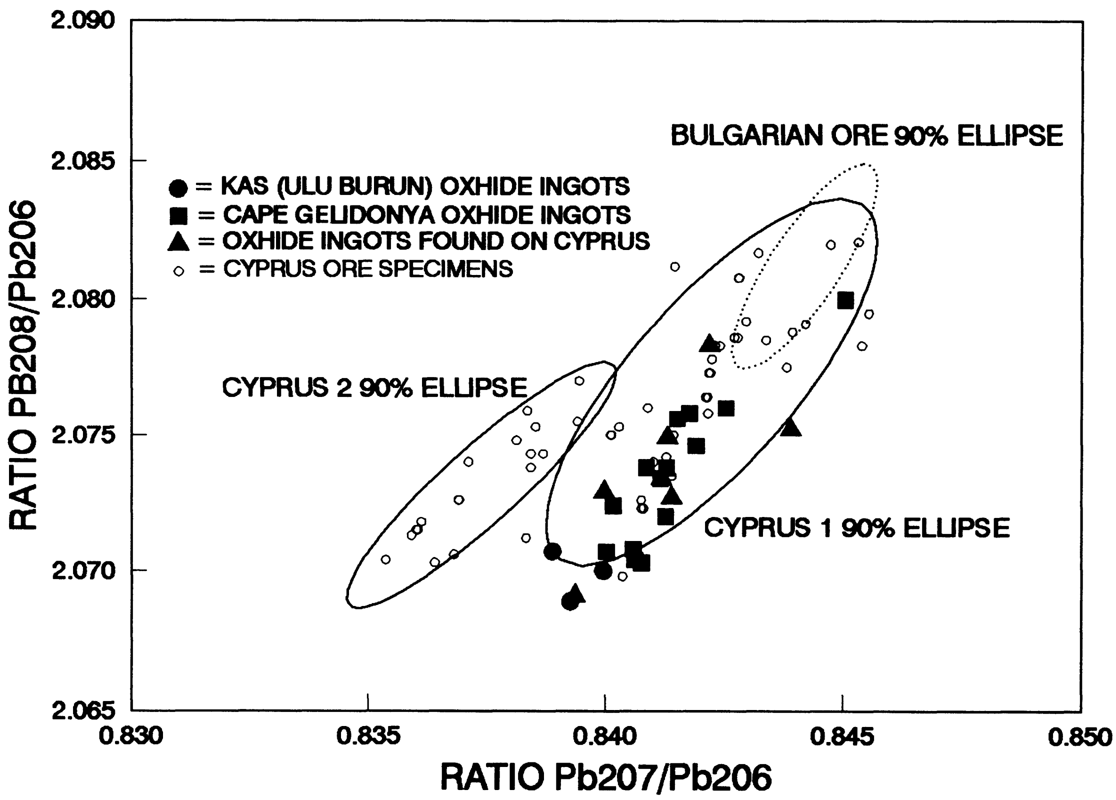

Figure 3 Comparison of Oxhide Ingots found on Cyprus and the Uluburun and Gelidonya shipwrecks to the Cyprus 1, Cyprus 2 and Bulgarian ore fields in $^{208}Pb/^{206}Pb$ versus $^{207}Pb/^{206}Pb$ space.

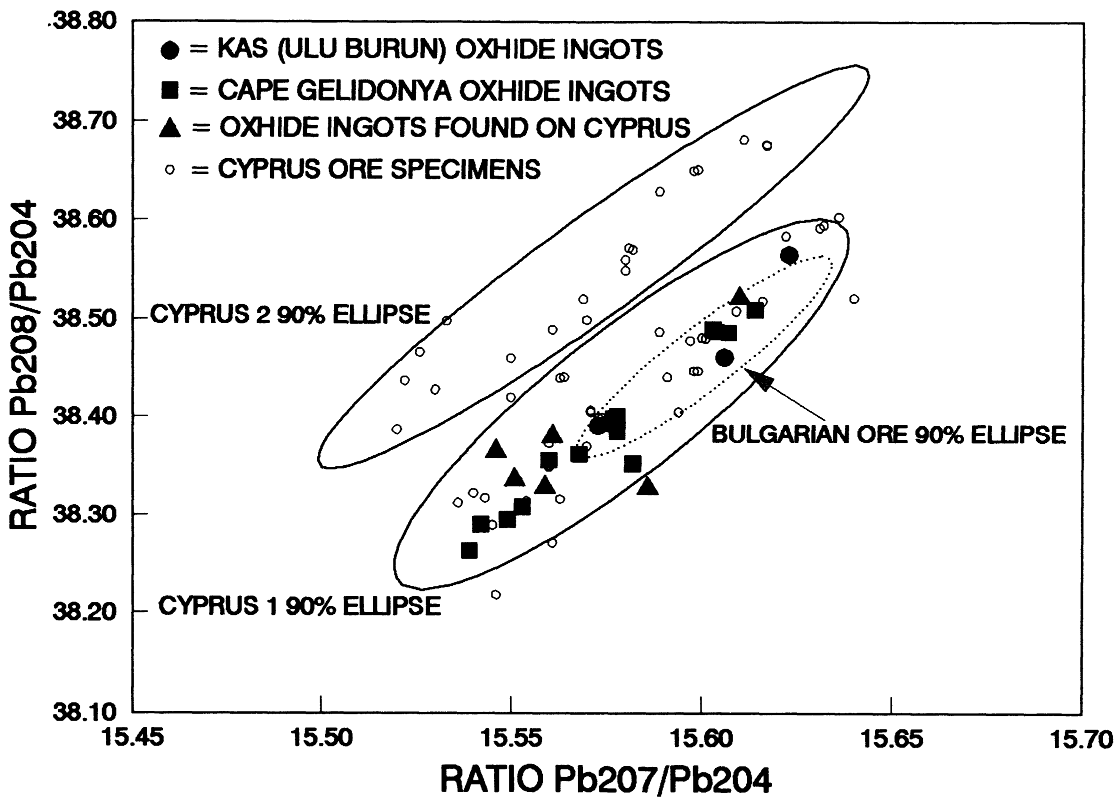

Figure 4 Comparison of Oxhide Ingots found on Cyprus and the Uluburun and Gelidonya shipwrecks to the Cyprus 1, Cyprus 2 and Bulgarian ore fields in $^{208}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ space.

All of the 30 ingots from Sardinia analyzed by Gale (Gale 1989), with the exception of two, numbers 34 and 59 which are nonmatching outliers, form a consistent group that has very nearly the same shape and spread as the Cyprus 1 group. They overlap the Cyprus 1 group in part, but are definitely offset from it in all dimensions, as is shown in Figures 1 and 2. Figure 5 compares the ingots from Cyprus and the shipwrecks directly to the ingots from Sardinia with the 90 percent probability ellipses that would relate to them as separate groups. The relation between these two groups is one that we often encounter in otherwise unrelated groups of specimens, e.g. ore source specimens from geographically widely separated sites that partially overlap each other without being totally coincident. Certainly some of the Sardinian ingots are fully consistent with Cyprus 1 and the Cypriot ingots, but if one considers them to be a single group of artefacts originating from a different ore source, which we believe is very probable considering the geographically separate region in which they were found, it would appear that this ore source was significantly offset from Cyprus 1. Our present data provides no indication of the location of this probable source, since within the entire database only four Cyprus 1 ore specimens and a single specimen for a mine in Great Britain, have 2 percent or more probability of matching the proposed Sardinian ingot group. These probability calculations of course, exclude the Sardinian ores as possible sources of the Sardinian ingots, a relationship that we shall discuss in more detail later.

Figures 1 and 2 show that the Crete 3 ingots are isotopically close to the Sardinian ingots. However, they are consistently offset from them. They have probabilities of matching the Sardinian ingot group that only range from less than 0.05% to 3.7 percent. It is quite possible they might have come from the same source as the Sardinian ingots, but it seems more likely to us that they relate to a different source. Thus, we believe that Figures 1 and 2 indicate that there were at least five isotopically different groups of oxhide ingots which probably came from different sources, the three Crete groups, the Sardinian group, and the group from Cyprus and the shipwrecks that nearly coincide with the Cyprus 1 ores. Not shown on these graphs are two specimens from Ras bin Hani in Syria and one from Emporio on Chios which have high probabilities of matching the Sardinian ingots, a specimen from Mycenae that matches well both the Sardinian ingots and the Cyprus 1 ores, a specimen from Ayia Trini on Keos which has a 4.4 percent probability of matching the Cyprus 1 ores, and the two outlying Sardinian ingots, which, if they are not in error, might indicate yet two additional sources for oxhide ingots. Each of the five possible ingot groups has distributions that are of a size and nature similar to what one normally encounters in ores from a single source. This leads us to believe that each of them probably was derived from a single source, rather than being the product of mixing metals from two or more sources. Isotope ratios of a group of artefacts produced by mixed alloying of metals from two isotopically separate sources would, in all probability, be rather widely spread out in the isotope space between the two groups because it is unlikely that the fraction of the two metals being mixed would be the same in all artefacts. If one were arbitrarily to assume that the ingots from Cyprus, Sardinia, the shipwrecks and possibly Gournia on Crete were all from a common source then the combined specimen group would have the spread out distribution that might indicate metal source mixing. We see no *a priori* justification for such an assumption but would not rule it out as a possibility.

Figure 6 is a $^{207}Pb/^{204}Pb$ versus $^{208}Pb/^{204}Pb$ plot comparing the Sardinian ingot group to all of the Sardinian ore specimens and ore fields of Cartagena in Spain and Tuscany in Italy, which have been considered as possible sources of the Sardinian ingots. This plot shows that when one takes into account ratios involving ^{204}Pb the ingots are distinctly separate from these ores. This explains why when one uses the ingot group as a core group one finds that none of the Sardinian ore specimens have significant probabilities of matching it. Conversely, there are no Sardinian ingots with significant probabilities of matching any of the three groups of Sardinian ores or the Cartagena or Tuscan ores. We feel that the isotopic data, when considered in its full three dimensions, confirms the opinion of Gale and Stos-Gale, that the probability that the ingots were derived from any of these sources is extremely low. Budd *et al.* conclude, on the basis of a $^{207}Pb/^{206}Pb$ versus $^{208}Pb/^{206}Pb$ plot (their Figure 4), that "on the basis of lead isotope data it is not possible to rule out northwest Sardinia as a potential source of copper for the oxhide ingots". However such plots, being two dimensional, are inadequate to determine whether the ingots might indeed be well resolved from the Sardinian ores in the full three dimensions of the isotope data. Until Budd *et al.* are willing to take the ^{204}Pb data fully into account they will continue to make inaccurate judgements as to whether different groups of specimens are isotopically coincident. We believe that the generally negative attitude they express toward lead isotope data stems, to a great extent, upon the inadequacy of the methods they use to analyze these data, methods that leave all of their conclusions in doubt.

In several instances Budd *et al.* appear to quite misunderstand the data analysis methods we are using. For example, they describe the probability calculations we used in Sayre *et al.* 1992 as being based on discriminant function analysis. The probabilities calculated in DFA are the relative probabilities that a specimen might match two or more arbitrarily selected population groups. These probabilities are entirely different from the probabilities we

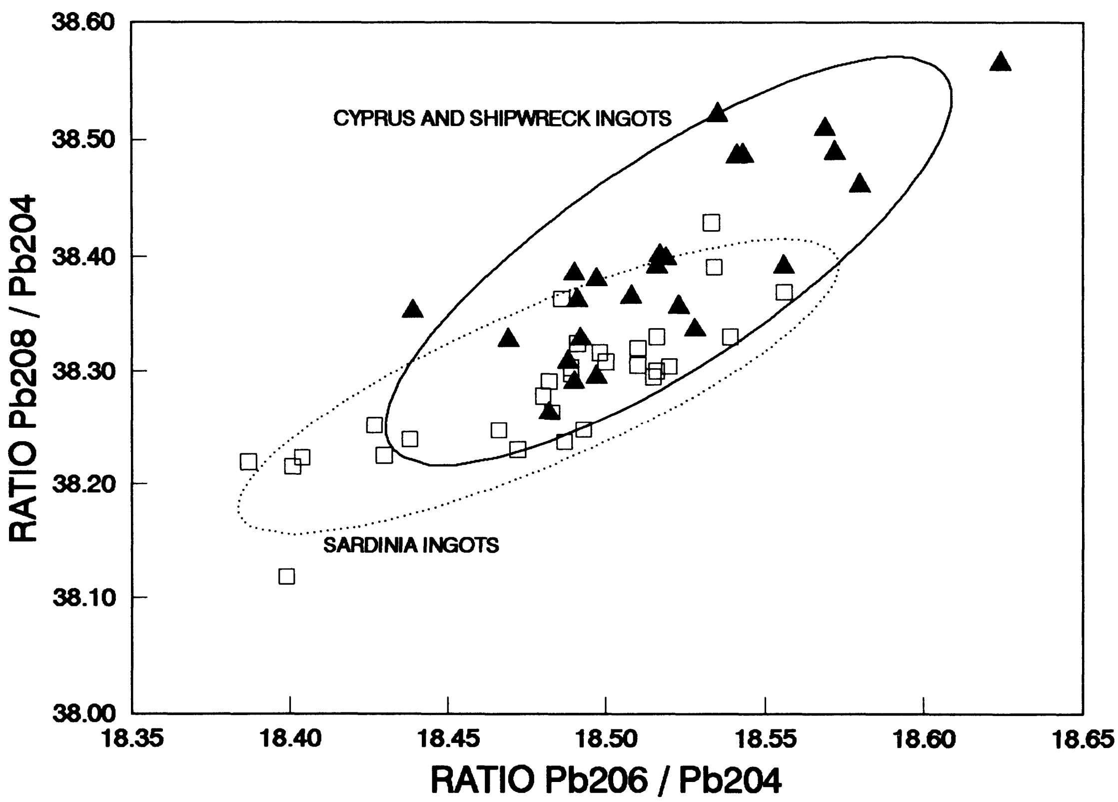

Figure 5 Comparison of Oxhide Ingots found on Sardinia to those found on Cyprus and the Uluburun and Gelidonya shipwrecks in $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ space.

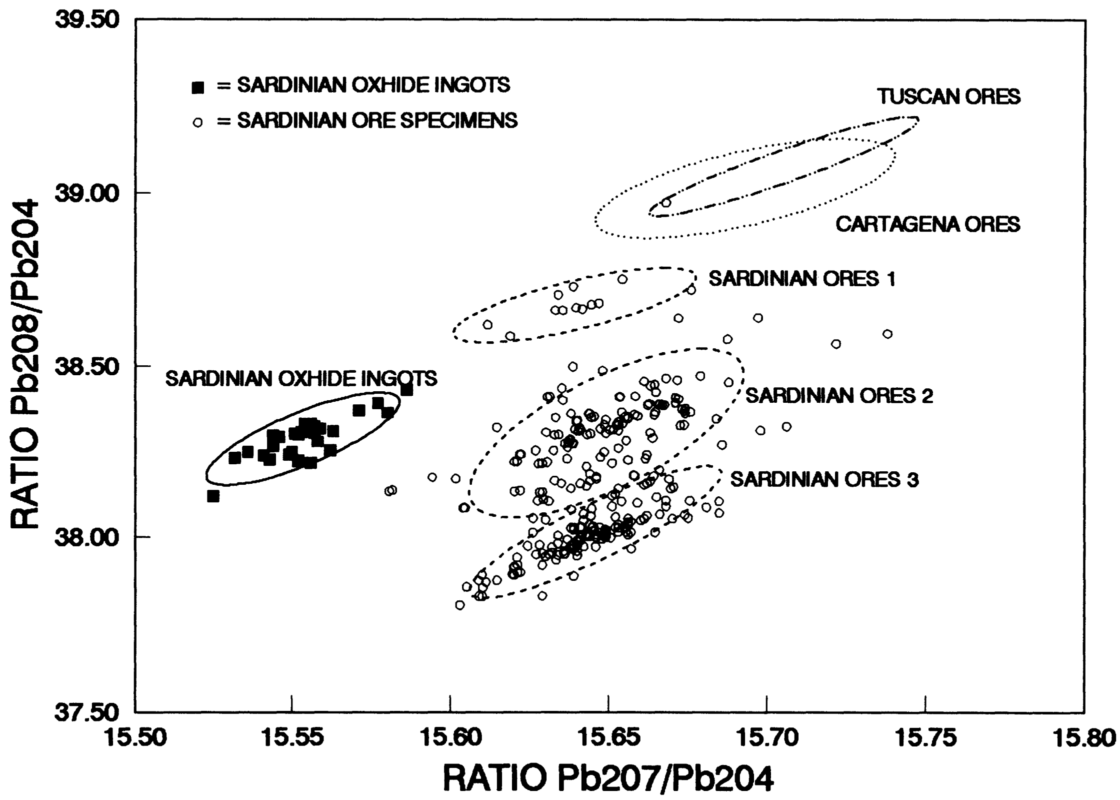

Figure 6 Comparison of Oxhide Ingots found on Sardinia to Sardinian ore specimens and the Cartagena and Tuscan ore fields in $^{208}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ space.

use, which are the absolute probabilities that individual specimens match single population samples. Although DFA can be a useful and highly dependable tool in certain applications we seldom use it, as it is highly dependent on *a priori* assumptions that can sometimes lead to questionable conclusions. We are also puzzled by their statement that "there is no evidence that multivariate statistics are helpful in the description of lead isotope data" because "with only three independent variables lead isotope data can be fully expressed in three dimensions". The data analysis methods we use, and recommend to others, are all conventional multivariate statistical procedures *applied in three dimensions*. Why they regard trivariate analysis as something separate from multivariate analysis we do not understand.

The proposal of Budd *et al.* that there might have been extensive mixing of metals from different sources in the production of the ingots is worthy of consideration. One should always be concerned with the possibility that isotope ratios in specimens may have been affected by contamination or alloying, but for reasons presented above source mixing in the ingots does not seem to us to be supported by the lead isotope data. It is, we believe, much more probable that the ingots were fabricated at a number of different sites but cast into a commonly accepted, convenient form. Ingots are a primary form of metal produced at production sites, which logically would most probably be located near the sources of the metal in them, for distribution to locations where they would have been used to fabricate artefacts. 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. Secondary recasting of ingots would have been a useless complication in metal handling, and we fail to see that Budd *et al.* have produced any convincing evidence that it indeed existed. Implicit in their proposal is the moot assumption that the ingots from Cyprus and the shipwrecks and those found on Sardinia had a common source. If that were true one would expect them to overlap fully, not partially as they are shown to do in Figure 5.

Note

The term we use for simplicity of expression — the probability that an individual specimen matches a single population sample — is more precisely defined as the probability that specimens might deviate from the centroid of the population sample by the extent to which the individual specimen does, or more. This is logically a measure of the likelihood of the specimen matching the population but is not precisely the probability of its doing so. The full definition is, we believe, too complicated for common use and the term we have used seems to us to be an acceptable approximation to it.