

THE PROVENANCE OF LEAD USED AT AYIA IRINI, KEOS

(PLATE 76)

IN 1980, the authors of this paper began a study of the sources of lead and litharge recovered in the University of Cincinnati excavations at Ayia Irini on the Cycladic island of Keos.¹ Our principal goal was to determine where the people of Keos obtained silver and lead in prehistoric times and to ascertain whether, over the long history of occupation at the site, there had been major changes in the sources exploited.²

¹ We owe our thanks to the late John L. Caskey for his encouragement, to the present director, Elizabeth Schofield, for her support, and to P. Spitaels for her continuing interest and enthusiasm for these studies. This paper does not give a complete presentation of lead and silver artifacts from the excavations. In our catalogue (below, pp. 401–403) we include only those finds which were analyzed by us. The contexts of the metal objects and metallurgical detritus will be described in more detail in final reports on the results of excavations at Ayia Irini (now in press or in preparation), to which, when possible, references are given in our catalogue.

We thank John C. Overbeck and E. Tucker Blackburn, for their help in choosing samples and for assistance in preparing this paper, and David Wilson and Mary Eliot, for dating the Early Cycladic samples. Samples were exported from Greece with permission of the Directorship of Conservation, The Ministry of Culture and Science. We thank H. W. Catling, Director of the British School at Athens, for obtaining the required permit on our behalf, and Mr. G. S. Dontas, General Ephor of the Akropolis, for his cooperation. M. C. Alexander, J. B. Rutter, T. M. Whitelaw, J. Bennett, J. F. Cherry, L. Morgan, J. D. Muhly, W. Rostoker, and C. N. Runnels have read the draft of this report and have provided us with useful comments. The work at Oxford is supported by the Science and Engineering Research Council, U.K., and by NATO grant 574/83.

Preliminary reports on the analyses of samples from Ayia Irini were given by Z. A. Stos-Gale and N. H. Gale ("The Minoan Thalassocracy and the Aegean Metal Trade") at the International Colloquium, "The Minoan Thalassocracy: Myth and Reality," hosted by the Swedish School at Athens, May 31—June 5, 1982, published as part of the Conference Proceedings (*Skifter Utgivna av Svenska Institutet i Athen XXXII*, R. Hägg and N. Marinatos, edd., Stockholm 1984). A preliminary version of this paper was read under the same title at the 1982 (84th) General Meeting of the Archaeological Institute of America (abstract, *AJA* 87, 1983, p. 234).

Works frequently cited will be abbreviated as follows:

Gale and Stos-Gale, = N. H. Gale and Z. A. Stos-Gale, "Cycladic Lead and Silver Metallurgy," *BSA* 76, 1981, pp. 169–224

Gale and Stos-Gale, = N. H. Gale and Z. A. Stos-Gale, "Lead and Silver in the Ancient Aegean," *Scientific SA American* 244, June 1981, pp. 176–192

Knapp and Stech = *Prehistoric Patterns of Exchange in the Aegean and Eastern Mediterranean*, A. B. Knapp and T. Stech, edd. (UCLA, Institute of Archaeology Monograph; in press).

Schofield = E. Schofield, "The Western Cyclades and Crete: A 'Special Relationship'," *Oxford Journal of Archaeology* 1, 1982, pp. 9–25.

² The analyses of lead and litharge which are reported here are not the first made of finds from Ayia Irini. Identification of litharge was made in the early years of excavation by Dr. Reuben Bullard of the Department of Geology, University of Cincinnati (unpublished manuscript on file, Ayia Irini Excavations). A sample of litharge (C-1.697) from a Period VI context was also studied by Dr. R. H. Brill of the Corning Museum of Glass, who identified it as PbO (lead oxide) and reported a 0.005% silver content (letters of January 9, 1962 and April 2, 1962 on file).

Subsequently, Brill and J. M. Wampler ("Isotope Studies of Ancient Lead," *AJA* 71, 1967, p. 77, no. 1)

Earlier studies, in particular by N. H. Gale and Z. A. Stos-Gale, had been successful in characterizing major sources of Aegean silver and lead on the basis of their typical lead-isotope ratios. By comparing isotope ratios of lead and silver from archaeological contexts with those of potential ore sources, it has been possible to assign a large number of artifacts to particular sources. These earlier studies had revealed an unexpected pattern.³ While in the Early Cycladic (EC) period Cycladic peoples seem to have depended on Siphnos as a major, perhaps even primary, source of their lead and silver, by Late Cycladic I not only had Laurion surpassed Siphnos but there is no evidence that sources other than Laurion were exploited on a large scale. From Crete, we have a similar picture. Most lead and silver from contexts later than Early Minoan is of Laurion origin,⁴ although the use of other sources appears to have continued into the Late Bronze Age to a very minor extent.

published an isotope analysis of a lead clamp for mending pottery from a Period VI–VII context at Ayia Irini (see W. W. Cummer and E. Schofield, *Keos*, III, *Ayia Irini: House A*, Mainz 1983, Room 31, Deposit A). Some years later another lead clamp (K.3791; sampled by R. Tylecote; see Cummer and Schofield, *op. cit.*, cat. no. 130, dated to [Period VI?]-Period VII) was found to be made of Laurion lead: see N. H. Gale, "Some Aspects of Aegean Lead and Silver Mining," *Thera and the Aegean World II*, C. Doumas, ed., London 1980, esp. p. 180, *s.v.* Kea.

The history of occupation at Ayia Irini has been summarized by J. L. Caskey, "Investigations in Keos, Part I: Excavations and Explorations 1966–1970," *Hesperia* 40, 1971, pp. 359–396 and "Investigations in Keos, Part II: A Conspectus of the Pottery," *Hesperia* 41, 1972, pp. 357–401. The terminology for periods of occupation which is used here was set forth by Caskey in "Ayia Irini, Keos: The Successive Periods of Occupation," *AJA* 83, 1979, p. 412.

It has sometimes been suggested that silver and lead ore were locally available on Keos. While it is true that any such ore on Keos would probably be indistinguishable from Laurion ore in terms of lead-isotope composition, it should be emphasized that there is no proof that galena was ever mined on Keos or is available. N. H. Gale and Z. A. Stos-Gale have demonstrated elsewhere that 19th-century travelers who refer to silver and lead ores on Keos may have been deceived by the presence of litharge on the surface of the site of Ayia Irini itself; the authority of such sources must, therefore, be held suspect (see Gale and Stos-Gale, *BSA*, pp. 191–192).

Moreover, recent unpublished geological mapping of Keos by V. Avdis, together with exploration of the ancient mines on Keos by Z. A. Stos-Gale, V. Avdis, N. H. Gale, and A. Papastamatakis, has shown that neither lead nor silver ores exist on Keos. The entry for Keos in the Handbook accompanying the Metallogenetic Map of Greece, Institute of Geological and Mineral Exploration, Athens 1965, has been shown to be erroneous by V. Avdis, who suggests that specular haematite was mistakenly identified as galena.

³ Results are described fully by Gale and Stos-Gale (*BSA*, pp. 169–224); see also Gale and Stos-Gale, *SA*, pp. 176–192. Cycladic chronology and nomenclature remain contentious: see R. L. N. Barber and J. A. MacGillivray, "The Early Cycladic Period: Matters of Definition and Terminology," *AJA* 84, 1980, pp. 147–157; J. B. Rutter, "Some Observations on the Cyclades in the Later Third and Early Second Millennia," *AJA* 87, 1983, pp. 69–76; R. L. N. Barber, "The Definition of the Middle Cycladic Period," *AJA* 87, 1983, pp. 76–81; J. A. MacGillivray, "On the Relative Chronologies of Early Cycladic IIIA and Early Helladic III," *AJA* 87, 1983, pp. 81–83.

Rutter has argued that there may be a gap in the Cycladic sequence (see p. 396 below) and has suggested to us that the four bracelets of Laurion silver found in Amorgos may be as late as Phylakopi I in date and might properly be considered to be Middle Bronze Age (MBA) finds. Alternatively the chronology of Barber and MacGillivray suggests that these bracelets might be assigned to Early Cycladic IIIB (EC IIIB).

⁴ For Crete, results of isotope analyses suggest that Laurion already had passed Siphnos in importance during the Middle Bronze Age. At Knossos, in the entire period from MM I through LM III, Laurion lead makes up the great majority of samples studied so far (see Gale and Stos-Gale, *BSA*, p. 185, note 123; Gale and Stos-Gale, *SA*, pp. 188–191; see also Z. A. Stos-Gale, "Sources of Lead and Silver for Bronze Age Crete," *Acts of the 5th International Congress of Cretan Studies, Agios Nikolaos, Crete, 1981* [in press]).

Analysis of samples from Ayia Irini would be worthwhile, we believed, for the following reasons:

- 1) Samples could be collected from well-dated excavation contexts covering nearly the entire Bronze Age. Occupation at Ayia Irini continued from near the beginning of the Early Cycladic period through Late Mycenaean times with few interruptions.
- 2) Samples could be taken from similar kinds of contexts for all periods. Many Early Cycladic samples which had been previously studied were from graves, while those of the later Bronze Age were mostly from settlement levels. All samples studied for this report, however, came from settlement contexts: habitation deposits, fillings, or rubbish layers. For this reason, we may be fairly certain that any changes in sources at Ayia Irini are truly a result of chronological variation and are not related to any difference in the use to which metals from various sources were put.
- 3) Because debris from lead- and silverworking, as well as lead metal, was available for analysis, conclusions could be drawn not only about sources generally available within the Cyclades in a particular period but also about the sources of metals actually worked by the inhabitants of Ayia Irini. In particular, the presence of litharge, a waste product of the cupellation of silver-rich lead to extract silver, suggested that silver had been extracted on Keos.

Forty-five artifacts were analyzed, for the most part scraps of lead, clamps for mending pottery, and chunks of litharge. Chemical analyses were made using instrumental neutron activation analysis, and lead-isotope analyses were made using thermal ionization mass spectrometry.⁵ Samples were chosen from Early, Middle, and Late Cycladic contexts. The chemical and lead-isotope analyses are given in Table 1, and the isotope analyses are given in graphic form in Figure 1.

There are a number of lead- and silver-ore deposits both in the Cyclades themselves and relatively near the coasts of the Greek and Anatolian mainland. The isotopic composition of the objects from Keos must therefore be compared with the isotopic composition of these potential ore sources in order to establish which sources were in fact supplying lead and silver to Keos in the Bronze Age. The isotopic compositions have already been reported for ore deposits from Spain, Thasos, Samos, Lesbos, and mainland Greece, from 9 Cycladic islands, and for 15 Anatolian deposits.⁶ These analyses show that lead-silver sources on Siphnos and in the Laurion have isotopic compositions different from each other and different from any other Mediterranean ore deposit yet analyzed.

Against this background the isotopic analyses of the lead and litharge from Ayia Irini (see Fig. 1) show that the ore deposits supplying this site are overwhelmingly to be identified as those on Siphnos and in the Laurion. The results confirm expectations based on earlier work: that a major change in lead and silver sources had occurred after the EC period. Laurion appears to have been a more important source for Keos than for other islands in EC times, but this is not surprising, given its proximity to the island. In Early Cycladic Keos sources were divided about equally between Siphnos and the Laurion, with possible

⁵ These procedures are fully described elsewhere: see N. H. Gale, "Lead Isotopes and Aegean Metallurgy," *Thera and the Aegean World I*, C. Doumas, ed., London 1978, pp. 529–545 and J. W. Arden and N. H. Gale, "New Electrochemical Technique for the Separation of Lead at Trace Levels from Natural Silicates," *Analytical Chemistry* 46, 1974, pp. 2–9.

⁶ See Gale, *op. cit.* (footnote 5 above); Gale and Stos-Gale, *BSA*; and Z. A. Stos-Gale and N. H. Gale, "The Sources of Mycenaean Silver and Lead," *JFA* 9, 1982, pp. 467–485.

TABLE 1: Lead-isotope and Neutron-activation Analyses of Lead and Litharge from Ayia Irini, Keos

Sample	Origin	Lead isotope ratios			Chemical analyses (ppm)				
		$^{208}\text{Pb}/^{206}\text{Pb}$	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{206}\text{Pb}/^{204}\text{Pb}$	Au	Cu	As	Sb	Ag
K1	L	2.05955	0.83149	18.900	.03	447	12	361	278
K2	L	2.06248	0.83339	18.910	.04	534	6	259	320
K3	L	2.05957	0.83159	18.881	.03	536	1	91	383
K4	L	2.05931	0.82962	18.870	.95	814	.3	39	430
K5	L	2.06572	0.83233	18.802	.82	762	.2	39	489
K6	L	2.05401	0.83136	18.846	.03	659	2	322	363
K7	L	2.05687	0.83108	18.843	.03	608	11	322	409
K8	L	2.05762	0.83125	18.841	.02	340	38	463	124
K9	L	2.05563	0.83143	18.838	.02	934	6	16	1
K10	L	2.06033	0.83198	18.808	.03	185	10	16	907
K12	L	2.06401	0.83303	18.823	.02	193	35	6	176
K13	L	2.06402	0.83118	18.819	.05	587	18	495	356
K14	L	2.06268	0.83067	18.822	.008	594	26	1001	10
K15	L	2.05687	0.83093	18.840	<.01	514	49	6435	n.m.
K16	L	2.05643	0.83099	18.837	.01	723	.5	89	153
K17					.02	1031	6	603	11
K18	?	2.06938	0.83456	18.790	.22	241	20	1	8
K19	L	2.05719	0.83113	18.838	.02	596	48	485	469
K20	L	2.05634	0.83100	18.825	.03	565	1	145	504
K21	L	2.05364	0.83076	18.854	.01	859	5	302	1
K23	L	2.06005	0.83139	18.841	.01	256	191	28	1278
K24	L	2.06572	0.83290	18.820	.42	736	3	137	321
K25	L	2.05875	0.83137	18.780	.05	454	12	435	324
K26	L	2.05941	0.83150	18.883	.02	820	2	466	393
K27	L	2.05863	0.83133	18.865	.009	632	5	283	.9
K28	S	2.07786	0.83740	18.809	.19	408	2	499	861
K29	?	2.07041	0.83348	18.881	.29	465	8	367	484
K30	S	2.07725	0.83728	18.777	.18	719	298	7313	548
K31	L?	2.06894	0.83316	18.867	.57	730	.9	92	380
K32	S	2.07710	0.83841	18.694	.11	648	10	2200	531
K33	L?	2.06820	0.83324	18.856	.75	769	1	185	494
K34	?	2.07153	0.83288	18.787	.19	588	.5	15	413
K35	S	2.07508	0.83699	18.737	.25	638	83	8053	585
K36	L	2.06028	0.83147	18.834	.06	559	3	431	631
K37	L	2.05834	0.83244	18.890	.01	135	3530	53	106
K38	L	2.05769	0.83120	18.811	.03	842	10	212	296
K39	L	2.05800	0.83117	18.843	.002	274	23	87	64
K40	L	2.05622	0.83127	18.829	.04	542	22	146	251
K41	L	2.06435	0.83178	18.905	.003	389	5	16	200
K42	L	2.05604	0.83082	18.831	.01	515	1	32	4
K44	L	2.05798	0.83158	18.826	.11	575	5	361	455
K46	S	2.07798	0.83706	18.758	.03	947	39	51	4
K47	L	2.05483	0.83102	18.828	.03	442	119	520	157
K48	L	2.06701	0.83295	18.821	.43	449	.6	72	291
K49	L	2.06021	0.83169	18.860	.01	522	33	90	29

L = Laurion

S = Siphnos

n.m. = not measured

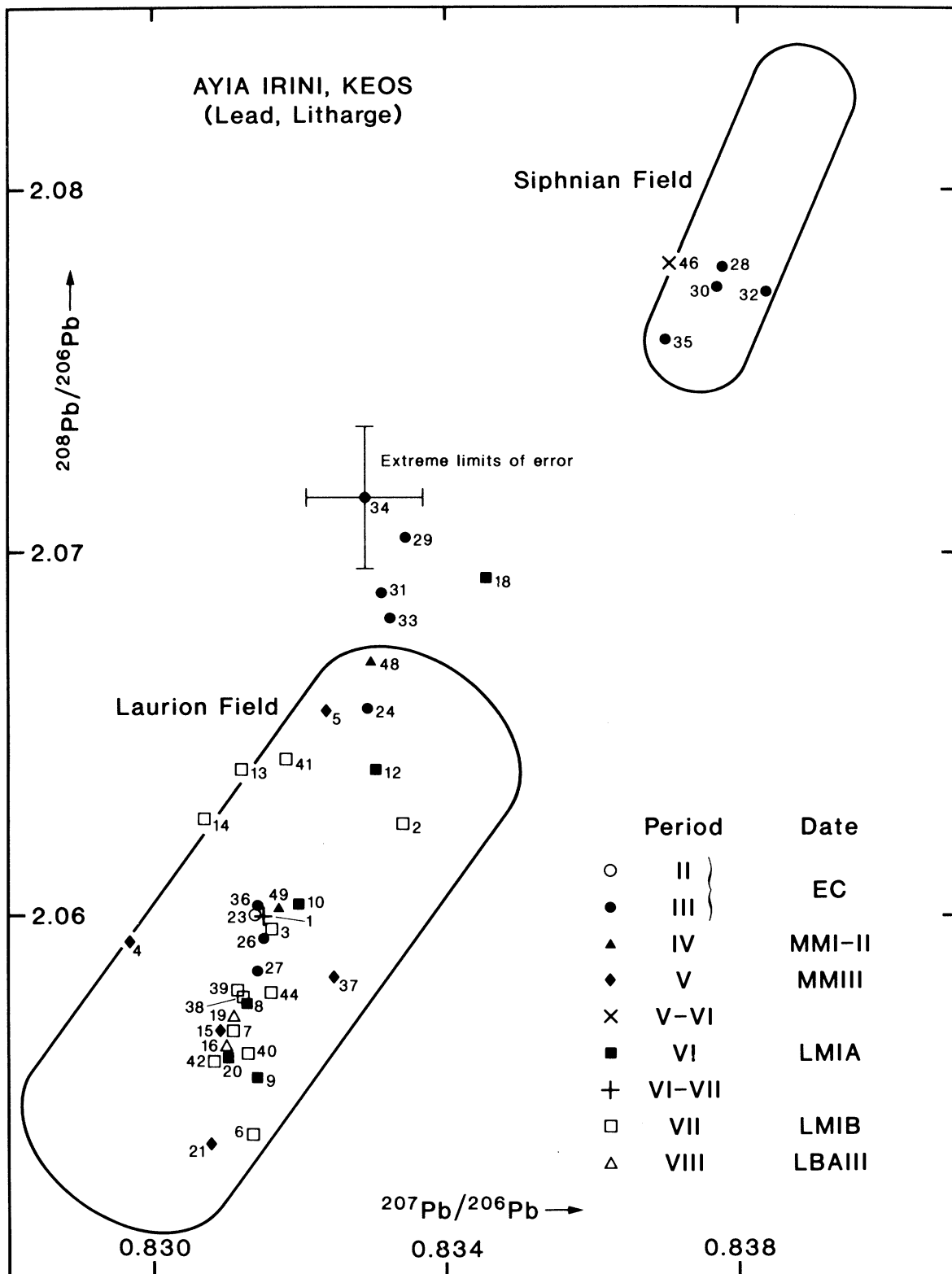


FIG. 1. Lead-isotope ratios for lead and litharge from Ayia Irini, Keos. The periods indicated for the artifacts are as defined by Caskey in *AJA* 83, 1979, p. 412. The lead isotope fields for Siphnos and Laurion have been established by isotopic analyses of lead/silver ores from these ore deposits

minor use of one other source. By LC I, just as on Thera, virtually all lead came from Laurion. At least by Period V, which should correspond in part to the end of the Old Palace Period in Crete, Laurion seems to have become the dominant source. All five samples analyzed fell within the Laurion Field. The picture for the earlier Middle Bronze Age is less clear. Few samples were available for analysis, largely because relatively few traces of local working of lead and silver have been found in strata of this period. Of the two samples analyzed, both may be assigned to Laurion. It is possible that Siphnian ores continued to be worked, albeit in small quantities, as late as the transition from the Middle to the Late Cycladic period, as evidenced by a piece of litharge (Cat. No. K46 below) from mixed Period V/Period VI levels.⁷

We digress here to discuss the “mixing problem” potentially posed by the possibility that metal artifacts from a particular site may be made from a number of remelted objects themselves made from ores from different sources, thus confusing the isotopic “fingerprint”. This is a rather unlikely possibility for lead artifacts since, as we discuss further in the technological appendix (below, p. 403), there is much evidence that in the Greek Bronze Age lead metal was a by-product of the extraction of silver from lead-silver ores. Lead metal (from the smelting of such ores) which proved to contain too little silver for its profitable extraction from the lead by cupellation was used only on rather a small scale and is likely always to have been in surplus. There was consequently little reason to melt together lead from different smelting batches and much less to melt together lead objects of different origin. Moreover, of the 27 lead objects analyzed from Ayia Irini, 9 were pottery repair clamps. Such clamps are especially unlikely to have been salvaged if the vessels which they repaired were subsequently to be broken beyond further repair.

Further, as discussed in the technological appendix (below, p. 403), litharge in the Bronze Age was always discarded and never reduced back to lead metal. Litharge, therefore, can never be the product of ores from different ore sources unless one posits the extremely unlikely situation that ores were brought from widely separated deposits to a central smelting facility. Such an operation in the Bronze Age would have been extremely disadvantageous both technically and economically. For the preceding reasons 18 litharge samples from Keos were included in this study.

The final proof that the mixing problem is unimportant for this study comes from the isotopic analyses themselves (see Fig. 1). If widespread mixing of lead from Laurion and Siphnos ore sources had occurred, the Keian analyses would scatter widely in the lead-isotope diagram, covering the whole region between the Laurion and Siphnian ore-deposit fields. If widespread use of other Cycladic, Greek, or Anatolian sources had been involved,

⁷ It is difficult to know how much importance to attach to the presence of this single Siphnian piece. EC sherds are not at all uncommon in MC and LC levels in the part of the site from which it comes; the possibility cannot be ruled out, therefore, that it is a “cast-up” from EC levels. There is very minor evidence for Siphnian and other non-Laurion artifacts on Crete in LM times: see references cited in footnote 4 above and Stos-Gale and Gale, “The Minoan Thalassocracy,” (footnote 1 above), fig. 4. We might also note that a lead object from Akrotiri has been assigned a Siphnian provenance (see Gale and Stos-Gale, *BSA*, p. 213). Clearly it is not from the destruction levels of the site but is described as from “Bronos 2, under road”. This raises the possibility that it has an MC context in view of the extensive MC layers which immediately underlie the LC I town: see C. Dumas, “The Stratigraphy of Akrotiri,” *Thera and the Aegean World I*, C. Dumas, ed., London 1978, pp. 777–782.

then the Keian isotopic analyses would tend to cluster in the region of the diagram between the Laurion and Siphnian fields, since the majority of these sources have isotopic compositions which fall in this region. In fact, the analyses cluster convincingly either in the Laurion or Siphnian field, and this is true both for lead and litharge samples. Only 5 analyses out of a total of 46 fall outside these fields, in a region which could be either the result of a mixture of Laurion and Siphnian lead or, more probably, the minor use of another ore source, perhaps on Syros. It is noteworthy, however, that each of these isotopically anomalous Keian objects is also rather high in gold content; both this and the isotopic composition are, from the purely analytical standpoint, consistent with ore deposits in the Chalkidiki, but as yet there is no evidence that these ores were exploited so early.

The confirmation of the pattern suspected from earlier analyses challenges us to attempt to explain why and how Laurion became the dominant supplier of lead and silver to the Cyclado-Minoan world and why Siphnos eventually ceased to be a major source, or perhaps even a source at all, when it lay much closer to Crete than Laurion. It does not appear that the exhaustion of all available ores on Siphnos or elsewhere in the Cyclades, closer to Crete than Laurion, is an adequate explanation since, in addition to Siphnos, accessible lead ores still occur today on Kythnos, Syros, Seriphos, Melos, Polyaigos, Antiparos, Thera, and Anaphi while silver-bearing ores occur on Syros, Antiparos, Seriphos, Melos, and Thera.⁸ It seems that these deposits were just not discovered in the Bronze Age; certainly our own exploration has revealed no evidence that they were. In the Archaic period, however, the Siphnian mines are attested to have been an important source of silver by the historical record (for instance, Herodotos, III.57–59), by scientific analyses of Greek silver coins,⁹ and by direct dating of levels underground in the Siphnian mines.¹⁰ Nor does it appear that Siphnos after the Early Bronze Age was cut off from the rest of the Aegean, owing, for example, to its incorporation into an economic sphere to which its former trading partners did not belong.¹¹ What little is known about Siphnos in the Middle Cycladic and early Late Cycladic periods does not suggest that the island was in any way isolated from Crete or other Cycladic islands.¹²

Some additional explanation seems to be needed, therefore, if this paradox is to be understood: in particular, why by MC III/LC I did Crete and Thera come to draw the bulk of their silver and lead from the Laurion, when clearly Siphnos was much closer and had in

⁸ Gale and Stos-Gale, *BSA*, pp. 185–203. Insufficient attention was paid in this paper to the silver ores on Melos, which are well described by M. L. de Launay, "Les minerais d'argent de Milo," *Annales des Mines* VI, 1894, pp. 345–353; there is not yet any evidence, however, for Bronze Age exploitation of these silver ores.

⁹ See N. H. Gale, "Lead Isotopes and Archaic Greek Silver Coins," *Archaeo-Physika* 10, 1979, pp. 194–208; also N. H. Gale, W. Gentner, and G. A. Wagner, "Mineralogical and Geographical Sources of Archaic Greek Coinage," *Metallurgy in Numismatics* I (Royal Numismatic Society), D. M. Metcalf, ed., London 1980, pp. 3–54.

¹⁰ Gale and Stos-Gale, *BSA*, pp. 200–202.

¹¹ Cf. the Mesoamerican case studies described by R. Zeitlin, "Toward a More Comprehensive Model of Interregional Commodity Distribution: Political Variables and Prehistoric Obsidian Procurement in Mesoamerica," *American Antiquity* 47, 1982, pp. 260–275, where consumers appear to have been isolated from sources formerly available to them.

¹² See Schofield, pp. 12–13. In addition to the finds at Kastro, MC sherds (of Phylakopi II type) and buildings are said to have been found at Ayios Andreas on Siphnos; cf. B. Philippaki, «'Η ἀκρόπολις τοῦ Ἀγίου Ἀνδρέου Σίφνου», *AAA* 6, 1973, p. 101.

earlier times provided them with metals? The answer may, we believe, be partly technological and may lie partly in the fundamental restructuring of Cretan and Cycladic economies which occurred in the course of the Middle and Late Bronze Ages. It would appear that the popularity of Laurion as a source coincided roughly with the growth of Cretan trade in the Cyclades, and we suspect that the two events were not unconnected.

Let us, therefore, summarize the evolution of regional exchange systems in the prehistoric Cyclades, with special attention to developments in the MC and earlier LC periods. By the middle phase of the Early Cycladic period, there is plentiful evidence for inter-regional contact, but the precise nature of what Renfrew has called the "international spirit" of EC II is still far from clear. After such promising beginnings, there followed a phase at the end of the Early Cycladic period when the islands may have been relatively isolated from the rest of the Aegean world, perhaps even deserted (although this is a view not accepted by all Aegean archaeologists).¹³ With the advent of the Middle Bronze Age, "inter-regional" trade began to increase once more, although the earliest stages in the growth of Cretan trade with the Cyclades are not well known, largely because there are few published data from the earlier stages of the Middle Cycladic period. It seems, on the basis of evidence from Ayia Irini, that exchange between Crete and the Cyclades in early MC times was not nearly so frequent as it became later.

By Middle Cycladic III—Late Cycladic II trade in the Aegean had reached new heights, not only in the volume and diversity of goods being traded but also, it seems, in the distances over which they were regularly transported. By this time there had been established a trade route through the Cyclades, linking Crete, the Cyclades, and the Greek mainland. Furthermore, common systems of measurement may have been used throughout the

¹³ For interregional exchange in the Early Cycladic period, see C. Renfrew, *The Emergence of Civilisation: the Cyclades and the Aegean in the Third Millennium B.C.*, London 1972; for doubts about the scale of trade, see G. Cadogan, "The Beginnings of the Minoan Palaces," *BICS* 28, 1981, pp. 164–165 and J. F. Cherry, "Evolution, Revolution, and the Origins of Complex Society in Minoan Crete," *Minoan Society: Proceedings of the Cambridge Colloquium 1981*, O. Krzyszkowska and L. Nixon, ed., Bristol 1983, pp. 33–45.

For the suggested period of isolation and desertion between Early and Middle Cycladic times see Rutter, *op. cit.* (footnote 3 above); for the contrary view see Barber and MacGillivray, *op. cit.* (footnote 3 above). Rutter has suggested that events in the Cyclades during his "gap" in the Cycladic sequence may have led to the demise of Siphnos as a supplier of ores and metals to Crete (*op. cit.*, p. 76; Rutter and C. W. Zerner, "Early Hellado-Minoan Contacts," [proceedings of the conference "The Minoan Thalassocracy: Myth and Reality," (footnote 1 above), pp. 75–83]; and Rutter, "The 'Early Cycladic III Gap': What It Is and How to Go About Filling It Without Making It Go Away," in press in the proceedings of the London Conference on Cycladic chronology, June 1983): *viz.*, as a result of disturbances in the islands, the Minoans were denied access to Siphnos and, consequently, turned to Laurion, at first reaching it by a route which passed through western Crete, Kythera, and the Argolid; in the MBA, with the resumption of business as usual in the Cyclades, the Minoans will have turned to a more direct route up the "Western String" of Cycladic islands to eastern Attica.

Although it is reasonable to suggest that the supply of metals from Siphnos to Crete was disrupted at this time and that the Minoans looked to Laurion as a replacement for Siphnos, such a scenario fails to explain a continued dominance of Laurion over Siphnos in the Middle and Late Bronze Ages: i.e., after trade between Crete and the Cyclades had been re-established, why did Siphnos not regain its position as a major supplier? Moreover (see above, p. 394), it is not entirely certain that Laurion had become the major supplier of silver and lead to the Aegean already by the earlier MC period (i.e., in the years immediately following the "gap") or that Siphnos had actually ceased production by MC times. We clearly need a program of isotope analysis concentrating on samples of the later EBA and earlier MBA on Crete, on the mainland, and in the islands, if we are to resolve these issues.

Cyclado-Minoan world.¹⁴ In short, interregional trade appears to have been better organized and more frequent than ever before.

While we know much about the trade between the Cyclades and Crete, we know relatively little about contacts between the Cyclado-Minoan world and Laurion, other than through lead-isotope analysis. It is clear, however, that by the end of the Middle Bronze Age, pottery from the Cyclado-Minoan world was reaching the site of Thorikos at Laurion, and by the Late Bronze Age, the discovery of disk weights of the type common in the Cyclades, and perhaps on a Minoan standard of measurement, suggests regular exchange with the Minoan world.¹⁵

It is within the context of the development of the state in Crete that one should view the development of regular organized overseas Minoan trade, namely, as a response to the increased energy requirements of an increasingly complex Minoan society.¹⁶ Moreover, it is likely that increased trade through the Cyclades between Crete and the mainland was the result of increased demand in Crete for products not available on the island itself.¹⁷ It is unlikely to be coincidental that Cretan trade with the Cyclades began in earnest soon after the foundation of the Old Palaces and increased dramatically after the building of the New Palaces. Furthermore, as Schofield has recently noted, it is highly likely that much Cretan trade with the islands was under the control of the Palaces.¹⁸ Not only does a more politically complex polity have greater needs but it also has greater resources at its disposal to attempt to satisfy them. The palatial elite could have both afforded costly investments in ships and supplied necessary goods to exchange for increased imports.¹⁹ It might also, with

¹⁴ The best survey of the evidence for Cretan-Cycladic trade is by Schofield, pp. 9–25. See also J. F. Cherry and J. L. Davis, “The Cyclades and the Greek Mainland in LC I: The Evidence of the Pottery,” *AJA* 86, 1982, pp. 333–341.

¹⁵ See H. D. Mussche *et al.*, *Thorikos* 3, 1966, p. 23, figs. 18, 19 and B. Kaiser, *CVA*, Bonn 2 [Germany 40], 21 [1947]:5, for pottery imports. For lead weights see K. M. Petruso, *Systems of Weight in the Bronze Age Aegean*, diss. Indiana University 1978, cat. no. 386; H.-G. Buchholz, “Das Blei in der mykenischen Kultur und in der bronzzeitlichen Metallurgie Zyperns,” *JdI* 87, 1972, p. 35, cat. nos. 201, 202. N.B. The context and date of these weights are far from clear; associated pottery is as late as LH IIIB.

¹⁶ Certainly lead and silver were not available, although P. Faure (“Les minerais de la Crète antique,” *RA*, ser. 8, 1, 1966, pp. 45–78) has suggested that there are on Crete several deposits of argenteiferous lead ore. In fact, all these occurrences, except that at Ano Varsamonero, are minuscule. That at Ano Varsamonero has very little silver, while the lead-isotope composition of none of these sources is represented amongst analyzed Cretan or Cycladic artifacts. P. Warren has recently commented on the increased needs for foreign goods apparent in particular during the period of the New Palaces: “The Stone Vessels from the Bronze Age Settlement at Akrotiri, Thera,” *’Αρχ’Εφ*, 1979, p. 108.

¹⁷ J. Cherry has discussed the general concepts of “Energy Trends” and has examined the relationship between the rise of palatial civilization in Crete and increased energy needs and expenditures: cf. “Generalization and the Archaeology of the State,” in *Social Organisation and Settlement: Contributions from Anthropology, Archaeology, and Geography* (*British Archaeological Reports International Series* 47), D. Green, C. Haselgrove, and M. Spriggs, edd., Oxford 1978, pp. 411–437.

¹⁸ See Schofield, pp. 19–20.

¹⁹ T. K. Earle (“Prehistoric Economy and the Evolution of Social Complexity,” in Knapp and Stech has discussed in some detail how an elite invests in mercantilism and especially their role in improving boats. Similar elite-encouraged production beyond subsistence level is also discussed at length by C. Gamble, “Animal Husbandry, Population, and Urbanism,” *An Island Polity: The Archaeology of Exploitation in Melos*, C. Renfrew and M. Wagstaff, edd., Cambridge 1982, pp. 161–171; by C. Renfrew, “Polity and Power: Interaction, Intensification and Exploitation,” *ibid.*, pp. 264–290; and by C. Gamble, “Social Control and the

the resources of the state behind it, at times have undertaken greater risks in the pursuit of gain than private merchants would have dared.

It is, unfortunately, difficult to say much at present about the relationship between the actual emergence of the Cretan palaces and the metals trade specifically, since so little is known about the use of lead and silver on Crete in Old Palace times. Few lead artifacts from Middle Minoan Crete have been published, and even fewer silver objects are known.²⁰ Some have interpreted this evidence to mean that lead and silver were very scarce,²¹ one possible explanation for the rarity of lead and silver in earlier MC contexts at Ayia Irini. To the contrary, others have argued that in MM I–II metals, including silver, were very familiar to the Minoans, even though archaeological finds in Crete are rare, and that they had become much more common by MM III.²² The recent discovery that Laurion silver was apparently reaching Egypt perhaps as early as prepalatial times may, if it was traded by way of Crete, point to an otherwise unattested familiarity with the metal on the part of the Minoans.²³ Our picture of the scale of silver and lead consumption in the Old Palace period may, in fact, be grossly distorted by a lack of any excavated royal tombs and a scarcity of destruction deposits in buildings which were subsequently abandoned. It therefore seems reasonable to suggest as a working hypothesis that increased demand from Crete was the major factor behind the rise of Laurion as the primary source of Aegean lead and silver.

In times of increased demand for metals, Laurion, we believe, had distinct natural advantages over other Aegean sources of lead and silver, advantages which can be seen most clearly if viewed from the perspective of formal economics. The formalist approach of economic anthropology emphasizes economizing decisions in economic behavior.²⁴ Its

Economy,” in *Economic Archaeology: Towards an Integration of Ecological and Social Approaches* (British Archaeological Reports International Series 96), A. Sheridan and G. Bailey, edd., Oxford 1981, pp. 215–229. Ships used in the Cyclades in Middle Minoan and early Late Minoan times may indeed have been rather more sophisticated than EC ships: see Renfrew, *op. cit.* (footnote 13 above), pp. 354–358 and P. F. Johnston, “Bronze Age Cycladic Ships: An Overview,” *Temple University Aegean Symposium* 7, 1982, pp. 1–8, where EC ships are contrasted with those represented in the Ship Fresco from Akrotiri. For the broader context of Cretan ships and sailing, see P. Johnstone, *The Sea-Craft of Prehistory*, London 1980.

²⁰ For the most recent comprehensive catalogue of published lead objects from the entire Aegean area, cf. H.-G. Buchholz, *op. cit.* (footnote 15 above), pp. 1–59; for a more recent catalogue of *Cycladic* lead and silver, cf. Gale and Stos-Gale, *BSA*, pp. 222–224. For Crete a partial catalogue appears in K. Branigan, “Silver and Lead in Prepalatial Crete,” *AJA* 72, 1968, pp. 219–229. Silver vessels from Crete have been catalogued and discussed in detail by E. N. Davis, *The Vapheio Cups and Aegean Gold and Silver Ware*, New York 1977, pp. 66–123; P. Warren clarifies the contexts and chronology of a few pieces in his review of her book, *CR* 30, 1980, pp. 104–106. Cf. also F. Vandenabile, “Vases de metal,” *Le quartier mu (Études cretoises XXVI)*, Paris 1980, pp. 71–89.

²¹ Cf. especially E. N. Davis, *op. cit.*, pp. 94–99; see also J. D. Muhly’s comments on the scarcity of metals in the Middle Bronze Age Aegean, “Metals and Metallurgy in Crete and the Aegean at the Beginning of the Late Bronze Age,” *Temple University Aegean Symposium* 5, 1980, pp. 25–36.

²² See, e.g., S. Hood, *The Arts in Prehistoric Greece*, New York 1978, pp. 153–167.

²³ Cf. Gale and Stos-Gale, *SA*, p. 191.

²⁴ See H. K. Schneider, *Economic Man*, New York 1974. For a case study in an Aegean prehistoric context, cf. C. N. Runnels, *A Diachronic Study and Economic Analysis of Millstones from the Argolid, Greece*, diss. Indiana University 1981. The usefulness of the approach has also been demonstrated in a number of case studies from the Eastern Mediterranean (Knapp and Stech).

fundamental assumption is that individuals will seek out maximum benefits at the least cost. They may be assumed to “choose what to produce, how to produce it, the means of transport, whom to exchange with, and what to obtain for consumption, based on a rational evaluation of their goals and the alternative possibilities.”²⁵ Recent studies of pottery trade between Crete, the mainland, and the Cyclades have shown that this approach is an effective way to understand at least some aspects of Middle and Late Bronze Age trade. Cherry and Davis have argued that the distribution of Helladic pottery in the Cyclades in LC I may best be understood if it was being traded by middlemen capitalizing on differences in value of particular kinds of pottery in different parts of their trading sphere.²⁶ Davis and Lewis, moreover, have shown that many changes which have been observed in Cycladic pottery of the later Middle and early Late Bronze Ages can be best explained as attempts to make Cycladic pottery more marketable in the face of competition from Crete.²⁷

From such a perspective, it is likely that the very abundance of Laurion’s metal resources would have been its major advantage, since it is unlikely that Siphnos, although its ore was of high quality, could have produced large quantities of ore as easily as was possible at Laurion.²⁸ It should here be emphasized that the lead-silver ore on Siphnos, although rich in silver, seems to have been disseminated rather sparsely in the host iron ore. Moreover, although the ore outcrops at seven places, six of these are inland, some hundreds of meters above sea level, and generally rather inaccessible. Only at Ayios Sostis, at sea level on the northeast coast, has evidence so far been found for Bronze Age working. In Laurion, on the other hand, there were incomparably greater and more easily worked reserves of silver-rich galena in thick veins, and at Thorikos the ore occurs conveniently near the sea in considerably larger quantities than at Ayios Sostis.

The inability of Siphnos to supply large quantities of ore easily may occasionally have forced traders who could not find adequate supplies closer to Crete to travel to Laurion. Laurion may even have become a preferred source because of the abundance and accessibility of its ores. This preference, as soon as the scale of production at Laurion had surpassed that in the Cyclades, may have been reinforced by the greater agglomeration of traders drawn to its ports, who would find there opportunities for trade at a central location in goods other than metals.

Much also depends on how politically and economically developed the settlements in the Laurion were at the time when the area was first becoming the major source of lead and silver for the Minoan world. If, in the Middle Bronze Age, Thorikos, for example, was relatively less developed than were Cycladic settlements, then traders attempting to escape stiff competition closer to Crete may have been attracted there.²⁹ In addition, in a region like Thorikos where Minoan goods were probably not common, some Cretan trade items may

²⁵ Quoted from Earle, *op. cit.* (footnote 19 above).

²⁶ See Cherry and Davis, *op. cit.* (footnote 14 above).

²⁷ See J. L. Davis and H. B. Lewis, “Mechanization of Pottery Production: A Case Study from the Cycladic Islands,” in Knapp and Stech.

²⁸ See Gale and Stos-Gale, *BSA*, pp. 195–203.

²⁹ For the expansion of trade into underdeveloped markets, see R. Bradley, “Trade Competition and Artefact Distribution,” *World Archaeology* 2, 1970–1971, pp. 347–352.

have acquired a prestige value both for their artistry and simply by virtue of being exotic. There may have been more opportunity than was available closer to home to exchange items which were fairly inexpensive to produce, such as fine Minoan pottery, for metals and other products scarce in Crete.

Laurion had still another advantage over Siphnos and other Cycladic sources as we now know: the availability of copper ore. Recent analyses by Gale and Stos-Gale of copper artifacts found on Crete suggest that already by MM I much of the copper of Crete may have come from Laurion.³⁰ Analyses of slag from Ayia Irini in Keos by W. Rostoker and by Gale and Stos-Gale in addition suggest that Laurion copper was being smelted on Keos by the later Middle Bronze Age.³¹ The quest for copper, an ore which does not occur on Siphnos, may have been important in promoting regular trade with Laurion and, in so doing, would also have helped to erode the major advantage which Siphnos had as a silver source: its proximity to Crete.

It should be noted that the same increased Cretan demand which we suggest to have encouraged growth of the Laurion mining industry may well have encouraged the demise of industries on Cycladic islands. For example, although increased demand for Siphnian ore might initially have led to accelerated production, the end result of such demand may have been that the time was quickly reached when the best known and accessible veins of ore had been exhausted and the amount of effort which would have been needed to develop new mines did not show promise of being repaid. As long as the supply of lead and silver from Laurion continued uninterrupted, such a trend would have been irreversible and would have been reinforced once abundant copper was discovered also in the Laurion.

We have suggested that the dominance of Laurion as a source of Aegean lead and silver can be seen as a consequence of the emergence of greater social complexity in Crete and of the increased demand for metals by the Minoan palaces. Laurion would have been favored over Siphnos and other Cycladic sources because of its more abundant resources. In this way the demand for metals promoted increasing trading missions to Laurion and was probably a major factor in the establishment of a trading network through the Cyclades. Prospects of greater profits may have encouraged the Cretan elite to invest their resources in increased production of goods for trade or in the construction of improved ships. This, in turn, would have led to even easier and more frequent communication within the Western String and more exchange with Laurion as the importance of distance as a deterrent to trade was diminished. This is not, of course, to exclude the possibility that trade was also carried out in Cycladic³² or even Helladic ships.

What effects did the emergence of Laurion as the dominant source of Aegean lead and silver have on the development of Aegean civilization? First, Ayia Irini and other Cycladic centers may have profited considerably from increased trade in metals, notably, as Schofield

³⁰ Cf. N. H. Gale and Z. A. Stos-Gale, "Bronze Age Copper Sources in the Mediterranean: A New Approach," *Science* 216, 2 April 1982, pp. 11–19; also *idem*, "Cyprus and the Bronze Age Metals Trade," *Acts of the Second International Congress of Cypriot Studies*, Nicosia 1982 (in press).

³¹ These analyses are not yet published.

³² See C. Doumas, *Thera*, London 1983, pp. 130–131.

has recently suggested, through the imposition of duties on foreign traders passing through their ports, although we need not assume that Ayia Irini in any way monopolized access to the Laurion sources.³³ Another source of profit may have been through trade in metals extracted locally from Laurion ores. When demand was sufficiently high, it might have been profitable to trade for unprocessed or partly processed ore or metal, to finish the processing locally, and then to use the processed metals in further barter. For example, on Thera local production of silver that derived ultimately from Laurion is proved by lead-isotope analyses of litharge found at Akrotiri.³⁴ Since no lead-smelting slag was found, it is most probable that richly argentiferous lead metal was taken from Laurion to Thera and processed on the island for silver.

We should not assume, however, that because evidence of metalworking has been found at Ayia Irini, Phylakopi, and Akrotiri they were particularly important suppliers of metals. We obviously need a way to judge the size and scale of production at a site. Since most metallurgical activities were no doubt conducted away from the settlement and therefore out of the area of most excavations, to detect them we will need special techniques, such as intensive surveys with magnetometers, perhaps accompanied by supplementary excavations.

Additional wealth may have been derived through trade in manufactured goods. Certain kinds of metal objects may have been manufactured at Ayia Irini since we have considerable evidence for the remelting of bronze and copper.³⁵ It has also been suggested that the lead weights so common in the islands at this time were cast in Keos.³⁶ All those so far analyzed prove to have been made of Laurion lead, but there is no evidence that they were actually made at Ayia Irini.

In addition to bringing wealth to certain Cycladic centers, the establishment of Laurion as the major source of silver and lead in the Aegean and as an important source of copper may have had important consequences for the evolution of complex society in the Aegean. When an important resource is concentrated at a single location it becomes easier to control access to it; moreover, if access can be controlled, it is possible for an elite class to use the resource to build or extend its power base.³⁷ For example, it has been suggested that Mykenai during the period of the Shaft Graves gained power through its control over the Aegean tin, and perhaps copper, supply.³⁸

³³ See Schofield, pp. 18–19.

³⁴ For analyses of LC I lead and litharge from Akrotiri, see Gale and Stos-Gale, *BSA*, pp. 213–223.

³⁵ See Schofield, p. 18; full analyses of crucibles used for remelting copper and bronze at Ayia Irini will be published by J. D. Muhly and colleagues; preliminary analyses by C. E. Conophagos of crucible slags show that some crucibles were used to melt copper, some to melt bronze.

³⁶ See G. Cadogan, "Cyprus and Crete c. 2000–1400 B.C.," *Acts of the International Archaeological Symposium on the Relations Between Cyprus and Crete ca. 2000–500 B.C.*, Nicosia 1978, p. 66.

³⁷ See, for example C. Renfrew, "Trade as Action at a Distance," *Ancient Civilization and Trade*, J. Sabloff and C. C. Lamberg-Karlovsky, edd., Albuquerque 1975, p. 35; J. W. Pires-Ferreira and K. V. Flannery, "Ethnographic Models for Formative Exchange," *The Mesoamerican Village*, K. V. Flannery, ed., New York 1976, esp. pp. 291–292; and J. Haas, *The Evolution of the Prehistoric State*, New York 1982, pp. 40–41, 140–146.

³⁸ See O. T. P. K. Dickinson, *The Origins of Mycenaean Civilization (SIMA XLIX)*, Göteborg 1977, p. 55 and J. D. Muhly, *op. cit.* (footnote 21 above), pp. 25–36.

Although it is at present far from clear who controlled the mines, we should certainly consider the importance that control of access to the metals of Laurion may have had for the elite of Crete, the islands, or the mainland. Might not, for example, the importance of Thorikos in early Mycenaean times (if Thorikos controlled the mines) have come from its control of Laurion resources? If an elite class in Laurion increased production in response to increased demand, this increased production may have resulted in specialization and elaboration of the administrative hierarchies within Laurion.³⁹

The value of continued research into intra-Aegean exchange in metals seems clear. The hypothesis advanced in this paper can and certainly needs to be tested further. In this regard, detailed examination of the relationship between increased demand for silver and lead (perhaps measured as an index of several factors including their frequency, amounts of metallurgical debris, and the degree to which they are dispersed outside central places) and the percentage of lead and silver with a Laurion provenance would be an extremely useful next step. Isotope analysis offers us the tool to answer questions which only a few years ago we could scarcely formulate, but in such studies may lie answers to questions about the rise of civilization which are of interest not only to Aegean archaeologists but to all students of prehistory.

³⁹ Thorikos appears to have been a large community in the Middle Bronze and early Late Bronze Ages. We know that silver was being cupeled at Thorikos at least by the end of the Middle Bronze Age, and P. Spitaels (see below) has shown that galena was being mined from at least as early as the final phases of the Early Bronze Age in mine No. 3 at Thorikos. There are signs that Thorikos was also prosperous and developed a stratified society rather early in Mycenaean times: it has some of the earliest tholos tombs on the mainland. For references to Thorikos and the earliest evidence for metalworking in the Laurion area, see R. Hope Simpson and O. T. P. K. Dickinson, *A Gazetteer of Mycenaean Civilization in the Bronze Age*, I, *The Mainland and the Islands* (SIMA LII), p. 209; N. H. Gale and Z. A. Stos-Gale, "Thorikos, Perati, and Bronze Age Silver Production in the Laurion, Attica," *Miscellanea Graeca* 5, 1982, pp. 97–103; Stos-Gale and Gale, *op. cit.* (footnote 6 above); and P. Spitaels, "The Dawn of Silver Metallurgy in Greece," *Archaeology* 2994, *Illustrated London News* 271, July 1983, p. 63.

With reference to trade between the Graeco-Etruscan World and Iron Age Europe, P. S. Wells outlines a model which may be relevant in the present case. See *Culture Contact and Culture Change: Early Iron Age Central Europe and the Mediterranean World*, Cambridge 1980; see also S. Frankenstein and M. J. Rowlands, "The Internal Structure and Regional Context of Early Iron Age Society in South-Western Germany," *Bulletin of the Institute of Archaeology* 15, 1978, pp. 73–112.

CATALOGUE

The contexts of many of the objects in this catalogue have already been described in volumes of the final publication of excavations at Ayia Irini; some of the objects will themselves be published in more detail. We have made reference to the volume in which they will be presented or their context discussed. References to House A catalogues or Rooms are to W. W. Cummer and E. Schofield, *Keos*, III, *Ayia Irini: House A*; references to Period V catalogues are to J. L. Davis, *Keos*, VI, *Ayia Irini: Period V* (forthcoming); and references to Period IV catalogues are to J. C. Overbeck, *Keos*, VII, *Ayia Irini: Period IV* (forthcoming). For each entry in our catalogue, the date (based on analysis of pottery) is given when the stratum containing the sample is most likely to have been laid down. In parentheses following this date are given the dates of any intrusive pottery found in the stratum, of both earlier and later date. In the case of periods for which the final publication is not yet completed (*viz.*, all EC periods, Period VI, Period VII outside House A, and Period VIII), all dates should be considered provisional and may be subject to slight revision in final publications. Samples K11, K22, K43, K45, and K50 are omitted; analysis showed them to have no connection with lead or silver metallurgy.

K1. Clamp for mending pottery (K1.597). Pl. 76:a. Period VI/VII. Attached sherd datable to Period VII on stylistic grounds: from a small closed vessel with scale pattern.

K2. Clamp for mending pottery (K1.1032). Pl. 76:b. Period VII/LH III. Attached sherd datable to Period VII on stylistic grounds: from a large closed vessel.

K3. Clamp for mending pottery (K.1482). Pl. 76:c. Period VII (post main destruction). Attached sherd datable to Period VII on stylistic grounds: from a beaked jug with marine-style decoration, including argonauts and seaweed.

K4. Small bar of lead (K4.506). Period V (some earlier MC, EC, and a couple of LC sherds). Period V, cat. no. U-111.

K5. Clamp for mending pottery (K4.505). Period V (several EC; two Period VII sherds). Period V, cat. no. R-5.

K6. Lead spoon (K1.567). Period VII (several intrusive Late Roman sherds). House A, cat. no. 1459.

K7. Clamp for mending pottery (K4.139). Period VII. House A, cat. no. 973.

K8. Litharge (A-4.114). Period VI. House A, Room 39, Deposit C.

K9. Litharge (A-4.110). Period VI. House A, Room 39, Deposit C.

K10. Litharge (A-4.111). Period VI. House A, Room 39, Deposit C.

K12. Litharge (A-4.93). Period VI. House A, Room 39, Deposit C.

K13. Strip of lead (A-0.41). Period VII (one LH IIIB sherd and one or two Late Roman). House A, Room 22, Deposit B.

K14. Litharge (A-1.924). Period VII (a few Late Roman sherds). House A, Room 30, Deposit A.

K15. Litharge (C-1.785). Period V (several Period VII sherds). Period V, cat. no. N-7.

K16. Litharge (M-4.251). Period VIII.

K17. Litharge (M-7.109). Period VI (several MC and EC sherds).

K18. Litharge (L-3.639). Period VI.

K19. Piece of lead (G-6.7). Period VIII.

K20. Piece of lead (L-3.227). Period VI.

K21. Litharge (N-74.5). Period V (several sherds of earlier MC and EC). Period V, cat. no. AB-3.

K23. Litharge (C-71.21). Period II.

K24. Piece of lead (C-9.55). Period III.

K25. Piece of lead (C-8.146). Context uncertain.

K26. Large piece of lead (F-9.60). Period III.

K27. Litharge (F-9.75). Period III.

K28. Piece of lead (F-9.108). Period III.

K29. Clamp for mending pottery (F-9.86). Period III.

- K30. Piece of lead (F-9.72). Period III.
- K31. Pieces of lead (F-9.120). Period III.
- K32. Lead cylinder (F-9.90). Period III.
- K33. Piece of lead (F-9.90). Period III.
- K34. Clamp for mending pottery (F-9.93). Period III.
- K35. Clamp for mending pottery (F-9.71). Period III.
- K36. Clamp for mending pottery (F-9.102). Period III.
- K37. Litharge (A-3.239). Period V (several LC sherds). Period V, cat. no. AP-15.
- K38. Piece of lead (C-8.234). Period VII (probably early). House A, Room 7, Deposit A.
- K39. Litharge (L162). Period VII.
- K40. Piece of lead (C-1.841). Period VII (perhaps post main destruction).
- K41. Litharge (R-7.98). Period VII.
- K42. Litharge and weathered products (C-1.1009). Period VII (perhaps post main destruction).
- K44. Piece of lead (M-6.66). Period VII.
- K46. Litharge (J-7.74). Period V-VI.
- K47. Lead metal (G-8.9). Context uncertain.
- K48. Piece of lead (A-4.507). Period IV mid to late. Period IV, Deposit CI.
- K49. Litharge (C-9.32). Period IV late (much earlier MC). Period IV, Deposit AE.

TECHNOLOGICAL APPENDIX

The neutron activation chemical analyses of the lead and litharge from Ayia Irini add an important body of material confirming deductions that Gale and Stos-Gale had previously made about the technology of lead and silver production in the Bronze Age.⁴⁰ They had deduced that, in the Bronze Age, lead metal was not produced by reducing back to the metal the litharge produced as a waste product in cupeling for silver⁴¹ but that lead metal used for its own sake was taken from a batch of smelted lead which had, in a test cupellation on a sample in a small crucible, been found to contain too little silver for economic recovery by large-scale cupellation. They had further deduced that the lowest level of silver in lead necessary for economic recovery in EC times in the Cyclades was about 700–800 g. per tonne but, on the basis of analyses of lead artifacts from Thera, Mykenai, Menidi, Vapheio, Thorikos, and Perati,⁴² that this had dropped to a figure of about 400–600 g. per tonne by the Middle and Late Bronze Ages.

The chemical analyses given in Table 1 show that the average silver (Ag) content of ten samples of litharge (K9, 14, 17, 18, 21, 27, 39, 42, 46, 49) is 13 ppm, while only one sample of lead metal contains less than 250 ppm Ag (K47, with 157 ppm Ag). It is again clear that lead metal at Ayia Irini was not obtained by reducing litharge.⁴³ It is most likely that here, as elsewhere in the Aegean, a test cupellation was made on each fresh batch of smelted lead and that lead containing too little silver was set aside to be used as lead metal, the silver-rich lead being instead cupeled on a large scale for its silver and the litharge thrown away. If timber was in relatively short supply,⁴⁴ it would not be

⁴⁰ See Gale and Stos-Gale, *BSA*, pp. 215, 217; Stos-Gale and Gale, *op. cit.* (footnote 6 above), pp. 483–484.

⁴¹ Silver was produced in a two-step process. Silver-rich lead ores were first smelted in a furnace to produce silver-rich lead metal, which was then cupeled to liberate the silver from the lead. In the process of cupellation silver was recovered from the lead by oxidizing the lead to litharge (PbO) by blowing currents of air over the lead kept molten in a crucible at a temperature of about 1100°C. Impurities like Cu, Sn, Sb, As are largely oxidized with the lead, but the silver is not oxidized and is left behind as a molten globule of silver metal when the molten litharge is removed by mechanical means or by absorption into the wall of the crucible.

⁴² The arguments are given at length in the references quoted in footnote 40 above.

⁴³ Some samples of litharge from Ayia Irini (K8, 10, 12, 16, 23, 37, and 41) do contain high over-all amounts of silver, but it is not situated in the litharge matrix. In these samples the silver is concentrated in small droplets of highly argentiferous lead entrapped in the litharge, a phenomenon noted also in litharge from Laurion by C. E. Conophagos, "Une méthode ignorée de coupellation du plomb argentifère utilisée par les anciens Grecs," *Annales géologiques de pays helléniques* II, 1959, pp. 137–149. This involves a loss of silver and occurs when the litharge is carelessly removed from the surface of the bath of molten argentiferous lead; the relatively high incidence of such litharge at Ayia Irini perhaps reflects a carelessness induced by the ready availability of rich silver ore in the Laurion.

⁴⁴ We should not forget that large quantities of fuel are needed to smelt metals. This point has been well made (with reference to ironworking) by W. Rostoker in a paper read to the 1982 (84th) General Meeting of the Archaeological Institute of America: "Iron and Steel in Greece and the Aegean," abstract, *AJA* 87, 1983, p. 225. See also L. Horne, "Fuel for the Metalworker: The Role of Charcoal and Charcoal Production in Ancient Metallurgy," *Expedition* 25, 1982, pp. 6–15 and J. Ramin, *La technique minière et métallurgique des anciens* (*Collections Latomus* 153), Brussels 1977, pp. 125–127. We thank Prof. A. M. Snodgrass for the last reference.

Just how well forested each of the Cycladic islands was in prehistoric times is a matter of considerable uncertainty. There does seem to be general agreement, however, that by the later Bronze Age none is likely to have had abundant supplies of timber. See O. Rackham, "The Flora and Vegetation of Thera and Crete before and after the Great Eruption," *Thera and the Aegean World* (footnote 5 above), pp. 755–764; J. L. Bintliff, *Natural Environment and Human Settlement in Prehistoric Greece* (*British Archaeological Reports, International Series* 28), Oxford 1977, p. 73; and M. Wagstaff and C. Gamble, "Island Resources and their Limitations," *An Island Polity* (footnote 19 above), pp. 95–105.

The lack of timber on the Cycladic islands in the later Bronze Age is another factor which may have

likely that it would be expended in reducing litharge to lead; sufficient directly smelted, silver-poor lead would always have been available to meet the rather small demand for this metal in the Bronze Age Aegean. On the other hand, the fact that we never find lead artifacts containing silver above about 800 g. per tonne of lead (most Keian lead artifacts cluster around silver levels of about 300–500 g. per tonne), whereas Laurion galena commonly contains 4000–8000 g. per tonne of silver, suggests that silver was the metal chiefly sought, that highly argentiiferous smelted lead was always cupeled to extract the silver, and that lead containing lower amounts of silver was used when lead metal was needed.

One final point is that, unlike the situation elsewhere in the Cyclades, at Ayia Irini the silver content of EC lead is not markedly higher than that of lead from later periods. Perhaps this marks a higher standard of expertise in silver metallurgy, gained earlier at Ayia Irini because it had ready access to the rich silver ores of the Laurion. It may also reflect better access to supplies of timber, which allowed from early times the expenditure of the larger amounts of fuel necessary to cupel lead poorer in silver than it was economical to process elsewhere in the Cyclades.

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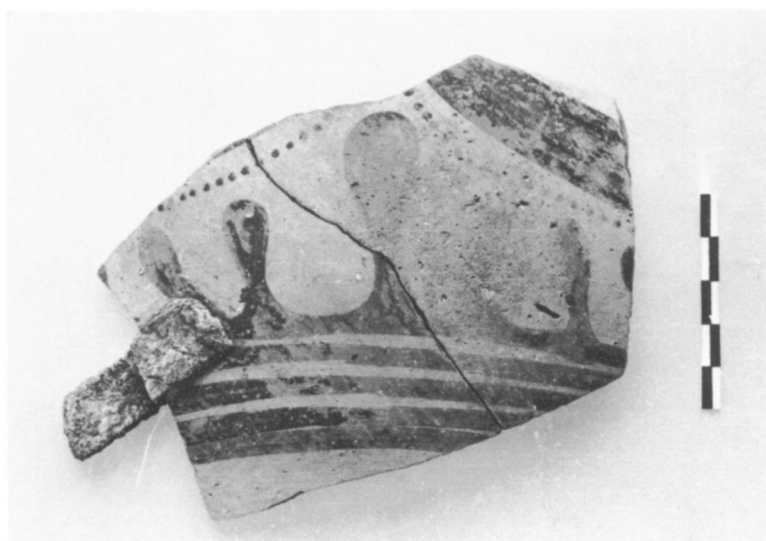
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discouraged the development of major metal-smelting industries even on those islands where metals were available. By the end of the Early Cycladic period it may be that an island such as Siphnos had been extensively deforested and that fuel supplies from neighboring islands were also in short supply. The conjunction at Laurion of more abundant ores and fuel to smelt them may have been a decisive factor in the swing from Siphnos to Laurion as a silver source in the late Bronze Age.



a. K1



b. K2



c. K3