Πρακτικά	4ου Συνέδριου	Μάϊος 1988	
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INTERPRETATION OF LEAD-ISOTOPE DATA FROM GREEK Pb-Zn DEPOSITS, BASED ON AN EMPIRICAL TWO-STAGE MODEL

S. CHALKIAS, M. VAVELIDIS

From 128 lead-isotope ratios from lead ores we constructed an empirical two-stage lead evolution model for these Pb-Zn-deposits from Greece, because one-stage lead evolution models create only negative model ages. The first stage of our lead evolution model lasted from 4.57 to 1.36 Ga and has mantle characteristics with $^{238}U/^{204}Pb$ and $^{232}Th/^{204}Pb$ values of 8.2 and 35.45 respectively. These are nearly the same as the values for the modern mantle from ZARTMAN & DOE (1981), which are 8.35 and 29.4, respectively. The second stage of our model from which the Pb-Zn-deposits are formed, started from 1.36 Ga and lasts until the present time. Their $^{238}U/^{204}Pb$ and $^{232}Th/^{204}Pb$ values were calculated empirically to be 13.1 and 43.1 and are nearly as the same of the modern upper crust with 13.23 and 45.9, respectively. This second growth curve allows direct dating of the Greek Pb-Zn-deposits from their lead isotopic ratios.

ΣΥΝΟΨΗ

Από την έρευνα ισοτόπων μολύβδου σε 125 δείγματα από Ελληνικά κοιτάσματα μολύβδου-ψευδαργύρου προέκυψε ένα εμπειρικό μοντέλο ανάπτυξης μολύβδου δύο σταδίων για τα κοιτάσματα αυτά, επειδή η ανάπτυξη των ισοτόπων μολύβδου σε ενός σταδίου μοντέλο έδωσε αποκλειστικά αρνητικές ηλικίες. Το πρώτο στάδιο διήρκησε από 4,57 έως 1,36 δισ. χρόνια, έχει τα χαρακτηριστικά του μάνδύα και οι τιμές των σχέσεων U/Pb και Th/Pb (8,2 και 35.45 είναι όμοιες με αυτές του μανδύα από το μοντέλο του ZARTMAN and DOE (1981) που είναι 8,35 και 29,4 αντίστοιχα. Το δεύτερο στάδιο του μοντέλου μας από το οποίο και σχηματίστηκαν τα Ελληνικά μεταλλεύματα μολύβδου-ψευδαργύρου άρχισε πριν από 1,36 δισ. χρόνια και συνεχίζεται μέχρι σήμερα. Οι τιμές των σχέσεων U/P και Th/Pb υπολογίζονται εμπειρικά να είναι 13,1 και 43.1 Οι τιμές αυτές είναι κοντά με τις αντίστοιχες τιμές του ανώτερου φλοιού των ZARTAN and DOE (1981) που είναι αντίστοιχα 13,23 και 45,9. Αυτή η δεύτερη καμπύλη ανάπτυξης μας επιτρέπει τον απ΄ευθείας προσδιορισμό της ηλικίας των κοιτασμάτων μολύβδου-ψευδαργύρου από τις σχέσεις των ισοτόπων μολύβδου.

1. INTRODUCTION

In connection with provenance studies of bronze age artefacts under the guidance of the archeaometry group of the Max-Planck-Institut für Kernphysik, Heidelberg with assistance from Oxford and later from the Max-Planck-Institut für Chemie, Mainz, 128 analyses from galenas have been carried out for their lead isotopic composition (the chemical separation and cleaning procedures for the lead and also the isotopic measurements are described in detail by PERNICKA et al. 1984). The ores correspond to Pb-Zn-deposits in different geological settings in the Cyclades, the northern Aegean and the surrounding shores (Fig., 1; see Table 1).
Although the ore deposits and occurences were primarily selected for their potential importance in antiquity, their lead isotope ratios contain a wealth of geological information regarding the

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Σ. ΧΑΛΚΙΑΣ *και* Μ. ΒΑΒΕΛΙΔΗΣ - *Ερμηνεια ισοτοπων μολυμβου απο Ελληνικα κοιτασματα* Pb-Zn, *με βαση ενα εμπειρικο μοντελο δυο σταδιων.*

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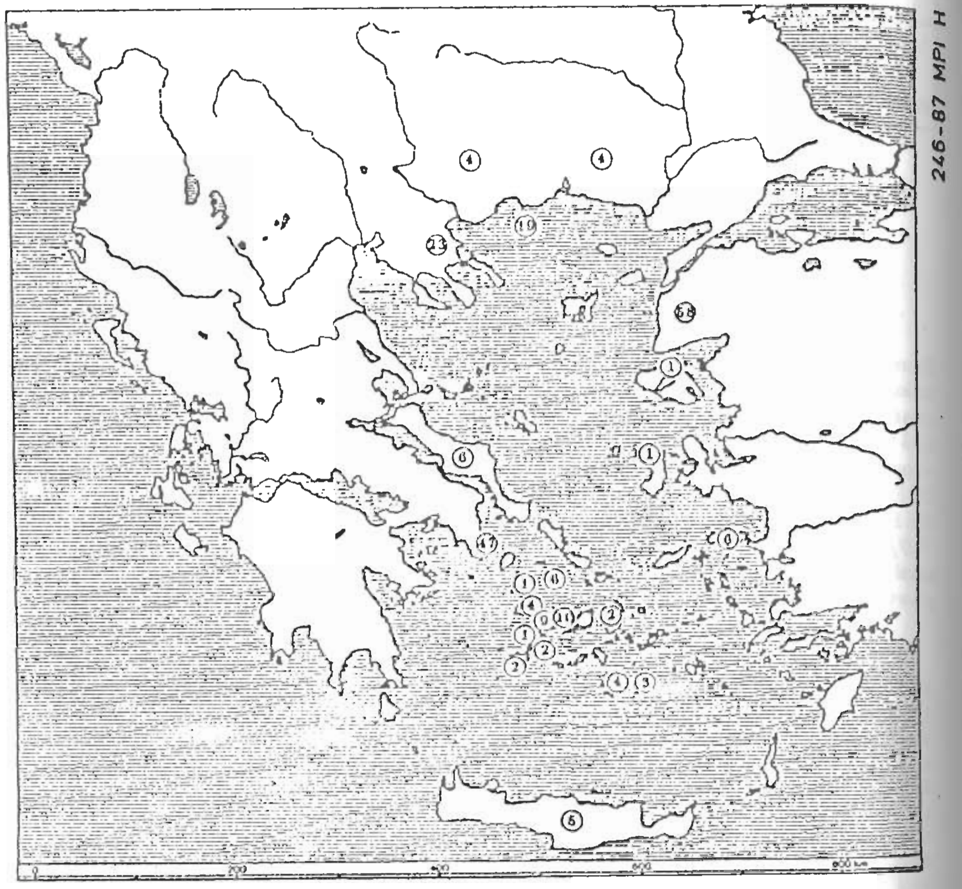


Fig. 1 :Geographical distribution of the ore occurences in the Aegean region. The number in the circles indicates the quantity of the analyzed samples.

Σχ. 1 :Γεωγραφική θέση των ερευνηθέντων κοιτασμάτων(οι αριθμοί στους κύκλους δείχνουν τον αριθμό των αναλυθέντων δειγμάτων)

source of metals and the time of ore formation. In this paper we interpret the lead isotope ratios from Greek galenas by global lead evolution models and offer an empirical two-stage model of lead evolution for Greek Pb-Zn-deposits.

2. LEAD EVOLUTION MODELS

Lead isotope ratios of galenas are interpreted by lead evolution models. The earliest models, describ the lead evolution of the earth, are the single-stage models of HOLMES (1946) and HOUTERMANS (1946). They assumed a chemically closed environment in which lead was produced by uranium and thorium decay since the earth was formed and lead had the primordial composition of the troilite phase in the Canyon Diablo meteorite. The resulting lead (primordial plus radiogenic) is then separated from its parents and incorporated into ore deposits as galena. The isotope composition of lead in galena does not change because that mineral contains no U and Th.

In Fig. 2 the data are plotted with the single-stage growth curves for different $^{238}U/^{204}Pb$ and $^{232}Th/^{204}Pb$ values. Except for few points all ratios form a tight cluster with $18.65 \leq {}^{206}Pb/^{204}Pb \leq 18.95$; $15.62 \leq {}^{207}Pb/^{204}Pb \leq 15.75$ and $38.6 \leq {}^{208}Pb/^{204}Pb \leq 39.2$. It is obvious that the single-stage model cannot explain the lead evolution of these data, because all values are placed to the right of the 0-Isochrone and therefore have negative i.e. future model ages. This means that the growth of the lead due to the uranium and thorium decay could not take place in a chemically closed environment. It is likely that the $^{238}U/^{204}Pb$ ratio increased at some time.

Better knowledge of the age of the earth (TILTON et al. 1973), the composition of the primordial lead (TATSUMOTO et al. 1973), the decay constants of uranium (JAFFEY et al. 1971; ATOMIC ENERGY COMM. 1962) and thorium (LEROUX & GLENDENIN 1963), a higher accuracy of measurements of lead isotope ratios and geological evidence led to the development of new lead evolution models. These are, for instance, a two-stage evolution for terrestrial lead by STACEY & KRAMERS (1975) and a model in which a linear increase of the $^{238}U/^{204}Pb$-ratio with time was assumed (CUMMING & RICHARDS, 1975).

Plotting the data together with the evolution growth curve of STACEY & KRAMERS (1975) it is obvious that their model can describe most of the data (Fig. 3). The $^{238}U/^{204}Pb$-ratio for the first stage (4.57 - 3.7 Ga) is 7.19 and for the second stage (from 3.7 Ga to the present time) is 9.74. Model ages for ore formation can be calculated from their model even if the points do not fit their second stage curve. The reason is that the ages are calculated from the slopes of the isochrones drawn through the starting point of the second-stage and do not depend on the $^{238}U/^{204}Pb$ value of the reservoir in which it evolved.

According to their model the data have model ages ranging from 600 Ma to negative ages (-110 Ma). Most ages cluster around Jurassic/Cretacous and Tertiary dates. However, one fourth of the data cannot be explained by their model. This is evident that the lead in the ores resided in sources with different $^{238}U/^{204}Pb$ and $^{232}Th/^{204}Pb$ values then given by the model of STACEY & KRAMERS (1975).

Models including new ideas of the isotope evolution of lead in different zones of the crust and the mantle in combination with their dynamic evolution and interaction are the plumbotectonic model of ZARTMAN & DOE (1981) and the dynamic model of lead evolution by AMOV (1983a).

To find out in which tectonic settings the ores may have evolved, the data are plotted together with the growth curves from the plumbotectonic model by ZARTMAN & DOE (1981) (Fig. 4). The plot shows that all points lie above the orogene curve and around the upper crust curve with a $^{238}U/^{204}Pb$ ratio of 11 and 13, respectively. The orogene curve of the plumbotectonic model reflects the average evolution of lead in the lithosphere, while the mantle, the upper crust and the lower crust curves depict the lead evolution in the respective layers.

The data are plotted around the upper crust curve showing that the lead in the ores developed in continental environments. In these environments ore deposits enclosed in sedimentary rocks with continental affinities and ore deposits associated with igneous activity are also probable (DOE & ZARTMAN, 1979). Such

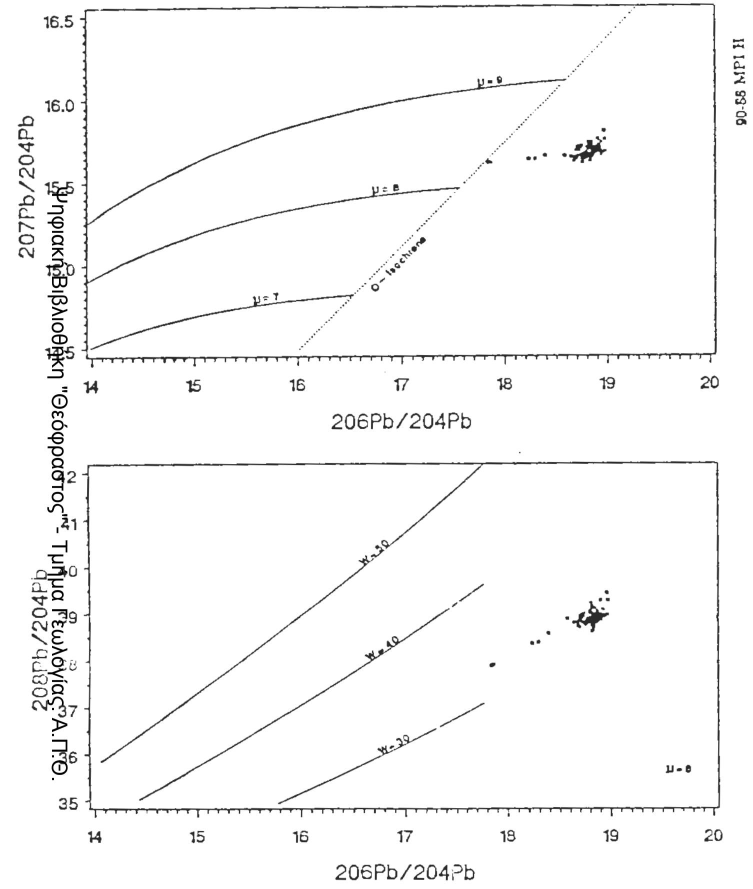


Fig. 2 :Sigle-stage evolution curves for the U-Pb-system with O-isocrone and lead isotop data.

Σχ. 2 :Καμπύλες ανάπτυξης ενός σταδίου σύστημα U -Pb μετην O-Ισόχρονο και τα σημεία προβολής των ισοτόπων μολύβδου.

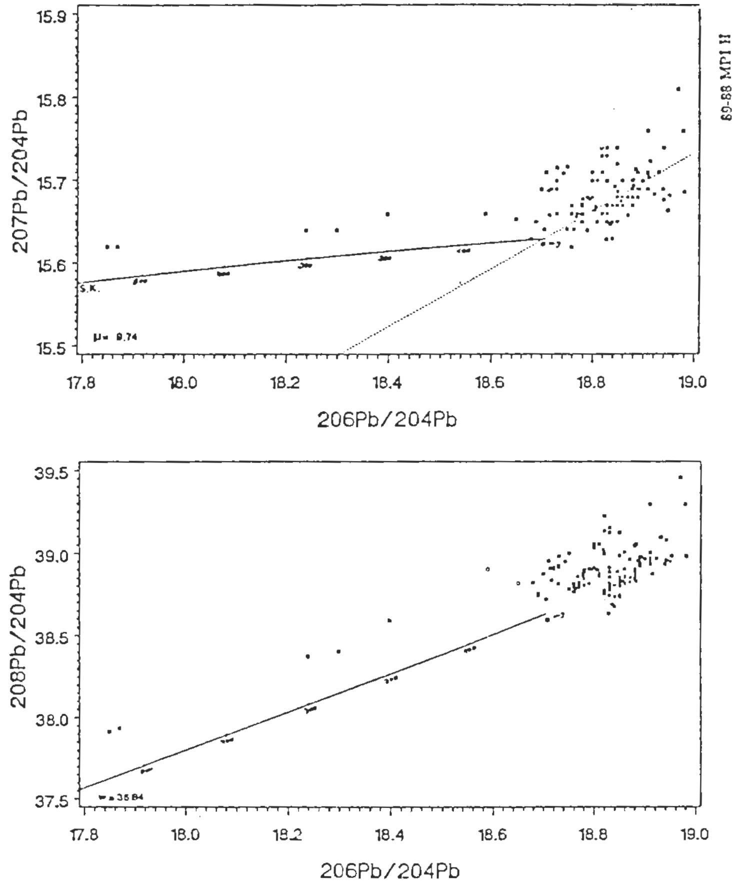


Fig. 3 :Two-stage evolution curves from STACEY & KRAMERS(1975) and lead isotope data.

Σχ. 3 :Καμπύλες ανάπτυξης δύο σταδίων απο τους STACEY & KRAMERS(1975) και σημεία προβολής των ισοτόπων μολύβδου.

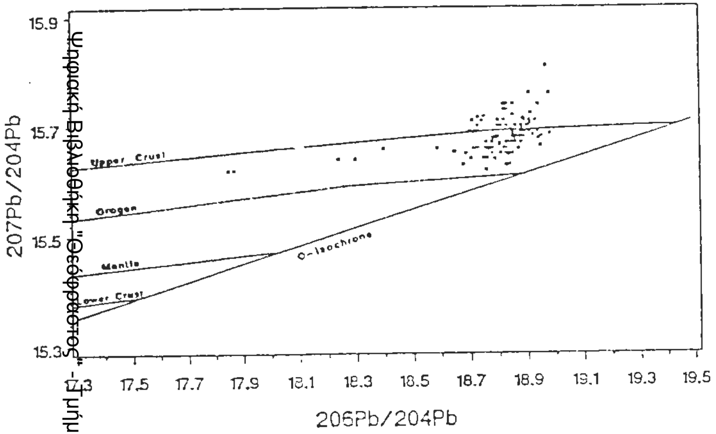


Fig. 4 Plumpotectonic model of ZARTMAN & DOE(1981) and lead isotop data.

Σχ. 4 Μοντέλο ισοτόπων κατα ZARTMAN & DOE(1981) και σημεία προβολής

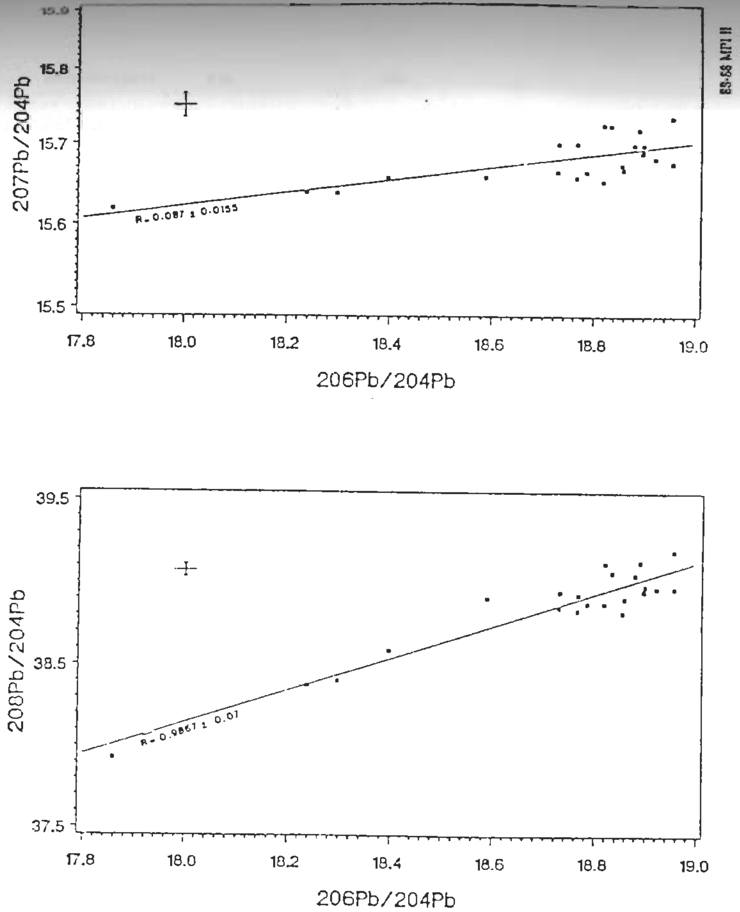


Fig. 5 :Linear relation of the mean points of each deposits or region indicate a common source of the reservoir of the Pb-Zn-ores

Σχ. 5 :Η γραμμική συσχέτιση των μέσων τιμών απο κάθε εμφάνιση ή περιοχή δείχνει μια κοινή προέλευση του μεταλλευματος Pb-Zn.

Table 1 :Measured lead isotope ratios and calculate model from STACEY & KRAMERS(1975) and empirical two-stage model

Πιν. 1' :Αναλογίες ισοτόπων μολύβδου, υπολογισθέντες ηλικίες μοντέλου κατα STACEY & KRAMERS(1975) και εμπειρικό δύο σταδίων μοντέλο.

LOCATION	SAMPLE-NUMBER	206/204	207/204	208/204	ORE-TYPE	REFERENCE	MODEL AGES FROM THE MODEL OF STACEY & KRAMERS ± 45 m.y.	MODEL AGES FROM THE EMPIRICAL TWO-STAGE MODEL ± 20 m.y.
ANAFI								
.	ANA.1	18.89	15.69	38.98	Pb	GALE (1981)	-10	6
.	ANA1	18.90	15.70	38.97	Pb	GALE (1981)	0	1
.	ANA2	18.91	15.71	39.01	Pb	GALE (1981)	20	-4
ANTIPAROS								
.	AP1	18.80	15.70	39.04	Pb	GALE (1981)	80	50
.	AP2	18.80	15.71	39.06	Pb	GALE (1981)	100	50
.	AP3	18.82	15.73	39.14	Pb	GALE (1981)	120	41
.	AP4	18.80	15.70	39.05	Pb	GALE (1981)	80	50
.	AP6	18.81	15.70	39.06	Pb	GALE (1981)	70	46
.	AP7	18.82	15.74	39.23	Pb	GALE (1981)	140	41
.	AP8	18.83	15.74	39.16	Pb	GALE (1981)	140	36
.	AP9	18.83	15.73	39.13	Pb	GALE (1981)	120	36
.	SA23A	18.97	15.81	39.46	Pb	GALE (1978)	180	-34
.	SA23B	18.73	15.70	38.93	Pb	GALE (1981)	130	85
CHALKIDIKE								
ASPRES GOUVES	111 A-1	18.73	15.66	38.82	Pb	VAVEL.(1985)	40	85
KOLOMPOUNI	107 B-1	18.79	15.64	38.82	Pb	VAVEL.(1985)	-50	55
MADEM LAKKOS	38 C	18.77	15.66	38.86	Pb	GALE (1978)	10	66
MADEM LAKKOS	GRL1	18.78	15.66	38.88	Pb	WAGNER(1986)	10	61
MADEM LAKKOS	GRL3	18.78	15.66	38.91	Pb	WAGNER(1986)	10	60
MAVRES PETRES	38 A-8	18.76	15.62	38.77	Pb	VAVEL.(1985)	-70	70
MAVRES PETRES	GRL4	18.81	15.67	38.90	Pb	WAGNER(1986)	0	47
MAVRES PETRES	GRL5	18.81	15.66	38.90	Pb	WAGNER(1986)	0	48
OLIMPIAS	GRL6	18.78	15.68	38.90	Pb	WAGNER(1986)	40	60
OLIMPIAS	GRL7	18.79	15.68	38.91	Pb	WAGNER(1986)	30	53
OLIMPIAS	GRL8	18.78	15.67	38.89	Pb	WAGNER(1986)	30	60
OLIMPIAS	39 A-2	18.77	15.66	38.80	Pb	VAVEL.(1985)	10	65
OLIMPIAS	39 E	18.77	15.66	38.82	Pb	VAVEL.(1985)	10	65
OLIMPIAS	40	18.78	15.67	38.85	Pb	VAVEL.(1985)	30	60
OLIMPIAS	40	18.76	15.66	38.82	Pb	GALE (1979)	20	70
OLIMPIAS	109 B-1	18.76	15.66	38.80	Pb	VAVEL.(1985)	20	70
PIAVITZA	106 A-1	18.76	15.67	38.81	Pb	VAVEL.(1985)	40	70
PIAVITZA	106 A-2	18.77	15.66	38.83	Pb	VAVEL.(1985)	10	65
PIAVITZA	106 B	18.78	15.65	38.81	Pb	VAVEL.(1985)	-20	60
SIKEA	42 A	18.69	15.65	38.76	Pb	VAVEL.(1985)	50	104
SIKEA	42 B	18.69	15.65	38.75	Pb	VAVEL.(1985)	50	104
ZEPKO	114	18.77	15.66	38.81	Pb	VAVEL.(1985)	10	65
CHIOS								
AGRILIA	**157 A-3**	**18.24**	**15.64**	**38.38**	**Pb**	**WAGNER(1985)**	**370**	**320**

Table 1 :

Πιν. 1 :

LOCATION	SAMPLE-NUMBER	206/204	207/204	208/204	ORE-TYPE	REFERENCE	MODEL AGES FROM THE MODEL OF STACEY & KRAMERS ± 45 m.y.	MODEL AGES FROM THE EMPIRICAL TWO-STAGE MODEL ± 20 m.y.
LAURION								
PLAKA	A6	18.85	15.69	38.89	Pb	GALE (1980)	30	28
PLAKA	B2	18.88	15.69	38.84	Pb	GALE (1980)	0	10
PLAKA	B5	18.86	15.68	38.84	Pb	GALE (1980)	-20	22
PLAKA	C3	18.91	15.70	38.94	Pb	GALE (1980)	0	-5
.	PB-77	18.88	15.68	38.89	Pb	BRILL (1970)	-30	11
LESBOS								
ARGENOS	51	18.59	15.66	38.91	Pb	VAVEL.(1985)	150	153
MAZEDONIEN								
DAFNOUDI	30	18.82	15.74	39.03	Pb	GALE (1978)	140	42
METALLIKON	37	18.30	15.64	38.41	Pb	WAGNER(1985)	320	291
PONTEKERASIA	34 B-1	18.81	15.65	38.87	Pb	VAVEL.(1985)	-40	45
PONTEKERASIA	34 B-3	18.83	15.66	38.89	Pb	VAVEL.(1985)	-30	36
MILOS								
.	IGMRPi	18.88	15.70	39.06	Pb	GALE (1978)	20	10
TRIDES	44 -7.1	18.86	15.70	39.05	Pb	VAVEL.(1985)	20	11
NAXOS								
.	491 B	18.93	15.71	39.10	Pb	GALE (1978)	0	-15
.	491 C	18.98	15.76	39.30	Pb	GALE (1981)	70	-39
POLIEGOS								
.	45	18.91	15.76	39.30	Pb	GALE (1978)	120	-4
TRIS-PANAGIES	45 2.1	18.87	15.68	38.97	Pb	VAVEL.(1985)	-20	16
SAMOS								
AMPELOS	49	18.91	15.69	38.96	Pb	WAGNER(1985)	-30	-4
DRAKEI	50 A	18.94	15.69	38.94	Pb	WAGNER(1985)	-50	-19
DRAKEI-KALIVES	50 B	18.86	15.70	39.01	Pb	VAVEL.(1985)	30	21
SIKIA	47	17.85	15.62	37.92	Pb	WAGNER(1985)	620	501
SPATHAREI	46	17.87	15.62	37.94	Pb	WAGNER(1985)	600	492
ZESTOR	48	18.88	15.68	38.91	Pb	WAGNER(1985)	-30	11
SERIFOS								
MOUTOULA	52 A-7	18.89	15.68	38.93	Pb	VAVEL.(1985)	-30	6
.	52 A	18.87	15.66	38.86	Pb	GALE (1978)	-70	15
.	52 A	18.94	15.74	39.09	Pb	GALE (1978)	50	-20
.	52 B	18.89	15.69	38.98	Pb	GALE (1978)	-10	5

Table 1 :
Πιν 1 :

LOCATION	SAMPLE-NUMBER	206/204	207/204	208/204	ORE-TYPE	REFERENCE	MODEL AGES FROM THE MODEL OF STACEY & KRAMERS ± 45 m.y.	MODEL AGES FROM THE EMPIRICAL TWO-STAGE MODEL ± 20 m.y.
EUBOA								
ALMIROPOTAMOS	56	18.83	15.70	38.92	Pb	VAVEL.(1985)	50	36
ALMIROPOTAMOS	56 A	18.85	15.72	38.99	Pb	VAVEL.(1985)	80	26
ALMIROPOTAMOS	56 B-2	18.80	15.70	38.92	Pb	VAVEL.(1985)	80	50
KALLIANOU	58	18.72	15.69	38.92	Pb	VAVEL.(1985)	110	90
KALLIANOU	59 C	18.71	15.71	38.96	Pb	VAVEL.(1985)	160	94
KALLIANOU	59 E	18.70	15.69	38.88	Pb	VAVEL.(1985)	130	99
KIMOLOS								
VESTURIS	99 -3	18.86	15.67	38.91	Pb	VAVEL.(1985)	-30	21
KRETA								
RETHIMNIS		18.40	15.66	38.60	Pb	GALE (1978)	290	244
KYTHNOS								
		18.92	15.68	38.97	Pb	GALE (1978)	-50	-10
LAURION								
CAP-SOUNION	S12	18.91	15.71	38.98	Pb	GALE (1980)	10	-4
ESPERANCE	854	18.83	15.67	38.82	Pb	BARNES(1974)	-10	36
ESPERANCE	856	18.85	15.67	38.82	Pb	BARNES(1974)	-20	26
ESPARANCE	857	18.85	15.67	38.84	Pb	BARNES(1974)	-20	26
KAMAREZA	KK1	18.83	15.67	38.75	Pb	STOS (1986)	-10	36
KAMAREZA	KK10	18.84	15.63	38.68	Pb	STOS (1986)	-110	31
KAMAREZA	KK10/A	18.85	15.65	38.74	Pb	STOS (1986)	-70	26
KAMAREZA	KK2	18.85	15.67	38.75	Pb	STOS (1986)	-20	26
KAMAREZA	KK2/C	18.87	15.68	38.83	Pb	STOS (1986)	-20	16
KAMAREZA	KK8	18.89	15.71	38.95	Pb	STOS (1986)	30	6
KAMAREZA	KK9	18.84	15.65	38.74	Pb	STOS (1986)	-60	31
KAMAREZA	863	18.82	15.66	38.76	Pb	BARNES(1974)	-20	41
KAMAREZA	864	18.84	15.67	38.81	Pb	BARNES(1974)	-20	31
KAMAREZA	865	18.88	15.70	38.85	Pb	BARNES(1974)	20	11
KAMAREZA	866	18.86	15.67	38.82	Pb	BARNES(1974)	-30	21
KAMAREZA	D1	18.85	15.69	38.81	Pb	GALE (1980)	10	25
KAMAREZA	60 A-1	18.84	15.65	38.69	Pb	GALE (1980)	-60	33
KAMAREZA	60 A-2	18.83	15.63	38.64	Pb	GALE (1980)	-100	33
KAMAREZA	60 A-3	18.92	15.72	38.88	Pb	GALE (1980)	40	-7
PLAKA	850	18.86	15.68	38.86	Pb	BARNES(1974)	-10	21
PLAKA	851	18.83	15.66	38.80	Pb	BARNES(1974)	-30	36
PLAKA	852	18.83	15.67	38.80	Pb	BARNES(1974)	-10	36
PLAKA	853	18.82	15.66	38.78	Pb	BARNES(1974)	-20	41
PLAKA	855	18.83	15.67	38.86	Pb	BARNES(1974	-10	36
PLAKA	858	18.86	15.67	38.87	Pb	BARNES(1974	-30	21
PLAKA	859	18.88	15.67	38.87	Pb	BARNES(197	-50	11
PLAKA	860	18.88	15.69	38.88	Pb	BARNES(197	0	11
PLAKA	861	18.85	15.67	38.81	Pb	BARNES(1974	-20	26
PLAKA	862	18.85	15.68	38.86	Pb	BARNES(1974)	0	26
PLAKA	A5	18.89	15.71	38.96	Pb	GALE (1980)	40	8

Table 1 :
Πιν. 1 :

LOCATION	SAMPLE-NUMBER	206/204	207/204	208/204	ORE-TYPE	REFERENCE	MODEL AGES FROM THE MODEL OF STACEY & KRAMERS ± 45 m.y.	MODEL AGES FROM THE EMPIRICAL TWO-STAGE MODEL ± 20 m.y.
SIFNOS								
AGIOS-SOSTIS	43 -9	18.71	15.69	38.91	Pb	GALE (1978)	120	93
AGIOS-SOSTIS	43 -10	18.75	15.72	39.00	Pb	GALE (1978)	150	74
AGIOS-SOSTIS	43 -12	18.73	15.72	38.99	Pb	GALE (1978)	160	84
AGIOS-SOSTIS	43 -36	18.74	15.71	38.96	Pb	GALE (1978)	140	78
VORINI	54 -4.2	18.72	15.69	38.91	Pb	VAVEL.(1985)	110	90
ΞEROXYLON	69 -6	18.73	15.69	38.92	Pb	VAVEL.(1985)	110	85
SYROS								
.	SY1	18.85	15.74	39.13	Pb	GALE (1981)	120	26
.	SY2	18.82	15.71	39.01	Pb	GALE (1981)	80	41
THASOS								
AGIOS-ELEFTHERIOS	25	18.75	15.64	38.79	Pb	GALE (1978)	-10	74
KALIRACHI	27	18.76	15.64	38.79	Pb	GALE (1978)	-20	68
KOUMARIA	26 -10	18.78	15.67	38.89	Pb	VAVEL.(1985)	30	60
MARLOU	74 -A6	18.80	15.68	38.92	Pb	VAVEL.(1985)	30	50
MARLOU	74 -A7	18.79	15.68	38.91	Pb	VAVEL.(1985)	40	55
RACHONI	104	18.81	15.65	38.88	Pb	VAVEL.(1985)	-40	46
SOTIROS	28	18.78	15.66	38.87	Pb	GALE (1978)	10	61
VOUVES	24 -21	18.82	15.71	39.00	Pb	VAVEL.(1985)	80	41
THERA								
.	360B	18.98	15.69	38.99	Pb	GALE (1978)	-90	-40
.	CX	18.94	15.68	38.96	Pb	GALE (1978)	-80	-20
.	PH30	18.95	15.66	38.96	Pb	GALE (1978)	-110	-24
.	PH91	18.95	15.68	38.99	Pb	GALE (1978)	-80	-25
THRAZIEN								
FARASINION	67	18.68	15.63	38.83	Pb	GALE (1978)	20	109
IASMOS	66	18.72	15.66	38.84	Pb	GALE (1978)	50	92
KALOTICHON	65	18.65	15.65	38.82	Pb	GALE (1978)	90	124
PHILIPPI	61	18.71	15.64	38.73	Pb	GALE (1978)	20	96

Pb = Galenite;

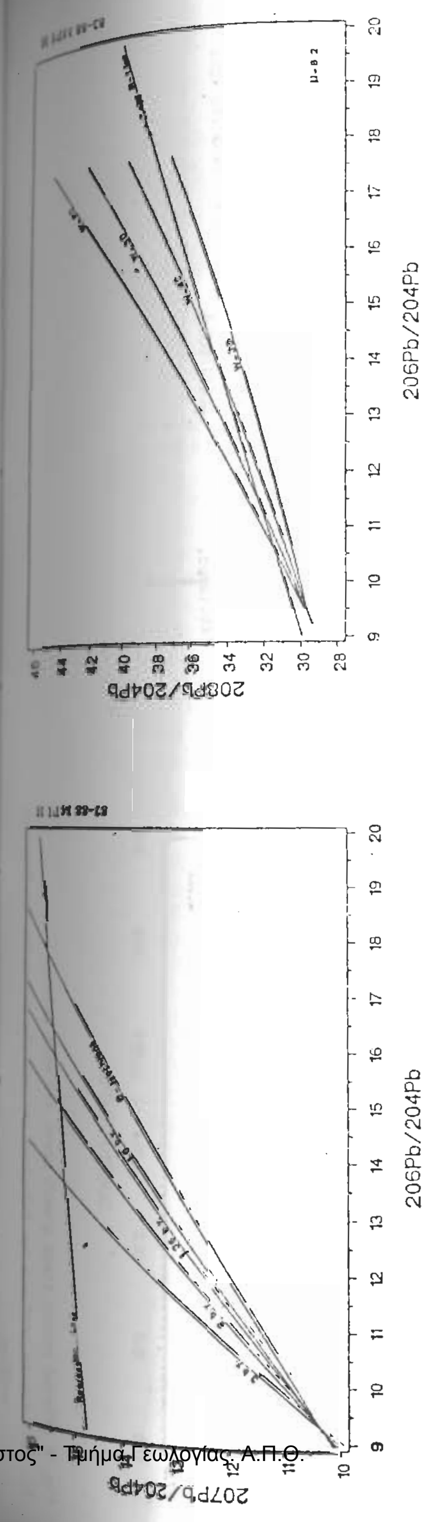
deposits are mainly formed in intracratonic basins and marginal seas. There is no evidence of of mantle origin in the lead of the Greek ores.

3. CONSTRUCTION OF A TWO STAGE MODEL

By plotting the average ratios of each deposit or region (done to suppress the outliers in a deposit) it is evident that the data are linearly related (Fig. 5). This linear relation can either be the result of incomplete mixing of two different types of lead. Hence the slope through the points has no age significance; or the lead can be formed by a two stage process and the slope can be a secondary isochrone. Assuming there is a two stage evolution of the lead in the ores, the regression line cuts a primary growth curve at two points. t_1, the age of the source from which the ores derived and t_2, the age of mineralization of the deposit. If the age of mineralization is known approximately, the age of the source material can be calculated, and vice versa. By using this slope ($R_{Data} = 0.087 \pm 0.015$) one can calculate an age of the second stage using the equation (1), assuming $t_2 = 0$. This equation is solved for t_1 by interpolation and yields $t_1 = 1.36 \pm 0.3$ Ga. This date represents the time when the ${}^{238}U/{}^{204}Pb$ value of the first stage diversified to produce a set of secondary growth curves that now form the secondary isochrone. To calculate the lead isotope ratios at 1.36 Ga we defined the intersection point of the regression line ($R_{Data} = y = 0.087x + 14.04$) and the 1.36 Ga isochrone ($R_{Isochrone} = y = 0.785x + 2.98$) as a starting point of the second stage (Fig. 6). The values are 15.84 for the ${}^{206}Pb/{}^{204}Pb$ and 15.42 for the ${}^{207}Pb/{}^{204}$ ratio. The ${}^{238}U/{}^{204}Pb$ value at 1.36 Ga is calculated using equation (2), giving a value of 8.2 for the first stage. The ${}^{238}Th/{}^{204}Pb$ value at that time can be determined to any desired level of accuracy using a graphical method. By plotting the ${}^{208}Pb/{}^{204}Pb$ versus the ${}^{206}Pb/{}^{204}Pb$ ratios one obtains the regression line through the points ($R_{Data} = 0.9867$). This regression line intresects only one growth curve at 1.36 Ga with the previous ${}^{238}U/{}^{204}Pb$ value of 8.2 (Fig. 7). The ${}^{232}Th/{}^{204}Pb$ value for the first stage is determined to be 35.45. Therefore the ${}^{232}Th/{}^{238}U$ value is 4.32. Using equation (4) the ${}^{208}Pb/{}^{204}Pb$ ratio is 36.00.
The lead isotope ratios at 1.36 Ga enable us to define second stage evolution curves for lead in the Aegean region. ${}^{238}U/{}^{204}Pb$ and ${}^{232}Th/{}^{204}Pb$ values for distinct growth curves can be calculated from equations (5), (6) and (7) knowing geological ages of the ores, or the ratios of lead isotope evolution in the Aegean region today. One possible growth curve can be calculated from lead isotope ratios in galenas from very young and recent volcanic tuffs on the Aegean islands of Milos, Thera, Poliegos and Kimolos. As the volcanism on these islands is less than 2.5 Ma (SCHRÖDER,1981) we estimate a $t_2 \approx 0$. From the average ratios of these islands we obtain a ${}^{238}U/{}^{204}Pb$ value of 13.1 and a ${}^{232}Th/{}^{204}Pb$ value of 43.1 (${}^{232}Th/{}^{238}U = 3.29$) (see Table 2). In Fig. 8 this second stage growth curve is plotted together with the data.

4. DISCUSSION

The first stage of the model lasted from 4.57 to 1.36 Ga with ${}^{238}U/{}^{204}Pb$ and ${}^{232}Th/{}^{204}Pb$ values of 8.2 and 35.45, respectively. These values are nearly the same as for the modern mantle with 8.35 and 29.4, respectively (ZARTMAN & DOE 1981). The second stage during which the Greek Pb-Zn-deposits were formed, started 1.36 Ga ago and still lasts. The ${}^{238}U/{}^{204}Pb$ and ${}^{232}Th/{}^{204}Pb$ values are 13.1 and 43.1 respectively, which are similar to ${}^{238}U/{}^{204}Pb$ and ${}^{232}Th/{}^{204}Pb$ values of the modern crust, with values of 13.23 and 45.9, respectively. From this second stage growth curve the Greek Pb-Zn-deposits can be dated directly from their lead isotope ratios, provided that their metals derive from sialic upper crust sources. The error of the model ages depends on the accuracy of the measurements and lies at ±10 Ma for the ${}^{206}Pb/{}^{204}Pb$, ±150 for the ${}^{207}Pb/{}^{204}Pb$ and ±20 for the ${}^{208}Pb/{}^{204}Pb$ ratio. The most accurate and meaningful ages are calculated from the ${}^{206}Pb/{}^{204}Pb$ and ${}^{208}Pb/{}^{204}Pb$ ratios and range from 500 to −30 Ma and from 500 to −100 Ma, respectively. Most ages cluster around 30 for the ${}^{206}Pb/{}^{204}Pb$ and around 40 Ma for the ${}^{208}Pb/{}^{204}Pb$ ratio. The model ages are plotted as histograms in Fig. 9. It is obvious that the clustering of the ages around the Tertiary, the Cretaceous and Jurassic



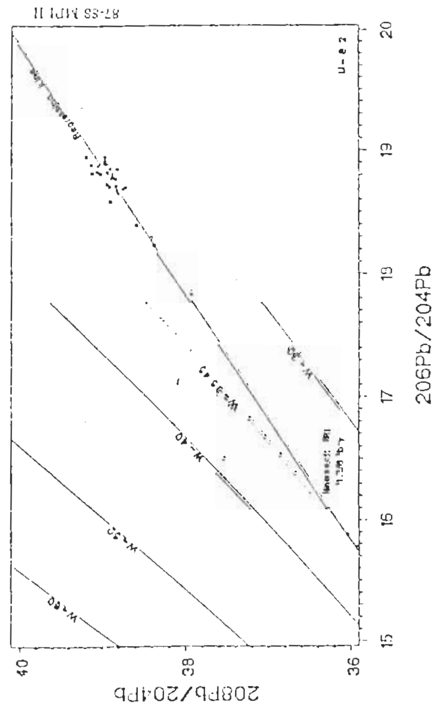


Fig. 7 :Regression line of the data ploted in the ${}^{208}Pb/{}^{204}Pb$ versus ${}^{206}Pb/{}^{204}Pb$ diagram intersects only one growth curve at 1.36 b.y. with initial ${}^{238}U/{}^{204}Pb$ value of 8.2.

Σχ. 7 :Ευθεία παλινδρόμησης των δεδομένων στο διάγραμμα ${}^{208}Pb/{}^{204}Pb$ προς ${}^{206}Pb/{}^{204}Pb$.

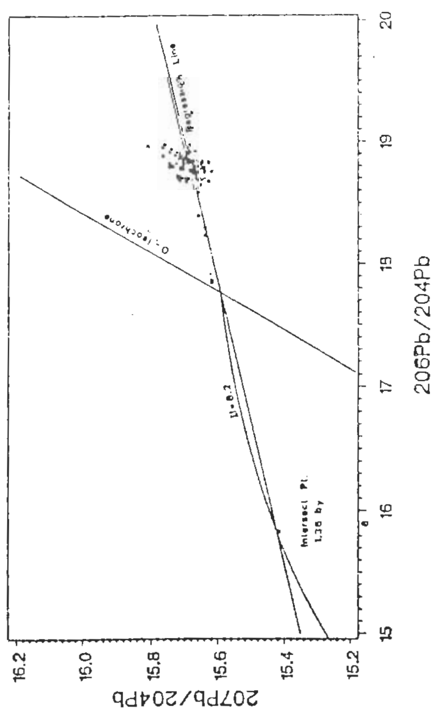


Fig. 6 :The intersection point of the slope of the regression line of the data and the slope of the 1.36 b.y. Isochrone gives a ${}^{238}U/{}^{204}Pb$ ratio of 8.2 for the first stage and the initial ratios of the second stage.

Σχ. 6 :Σημείο τομής της ισόχρονης των 1,36 δισ. χρ. και της ευθείας παλινδρόμησης των δεδομένων.

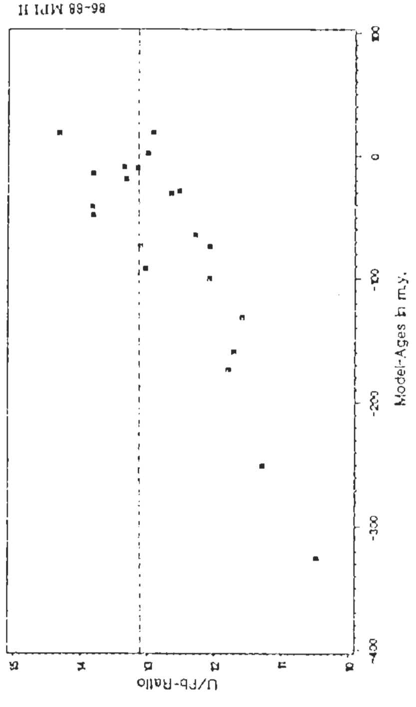


Fig. 10 : The average $^{238}U/^{204}Pb$ values the average model age from each deposit shows that there is a linearly increasing of the $^{238}U/^{204}Pb$ ratio as the model age decreases.

Σχ. 10 : Οι μέσες τιμές $^{238}U/^{204}Pb$ προς την μέση ηλικία για κάθε κοίτασμα.

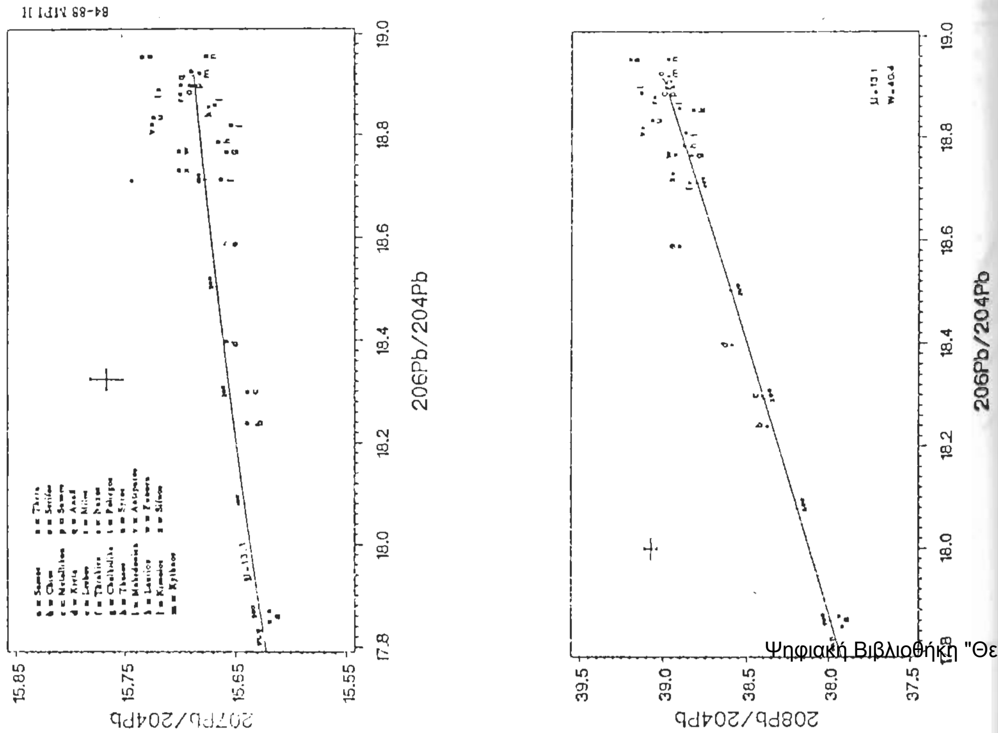


Fig. [illegible]: Ploted second stage growth curve and data points.

Σχ. [illegible]

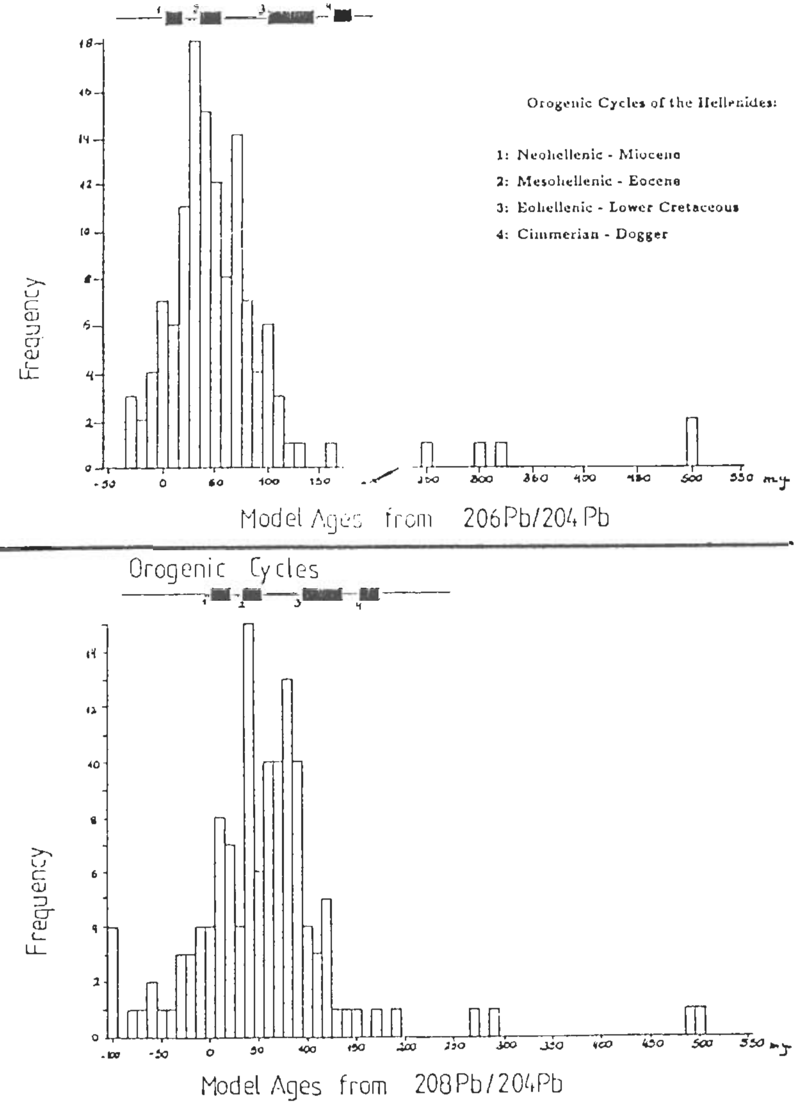


Fig. 9 : Histogramm of the model ages in m.y.

Σχ. 9 : Χιστόγραμμα ηλικιών μοντέλου σε εκατομμύρια χρόνια.

Table 2 Average values of the lead ratios from Aegean islands and from these calculated average, $^{238}U/^{204}Pb$ and $^{232}Th/^{204}Pb$. Values of the first and second stage growth curves of the Aegean region.

Πιν. 2: Μέσες τιμές των σχέσεων των ισοτόπων μολύβδου από τα νησιά του Αιγαίου, υπολογισθείσες μέσες τιμές μ και w και παράμετροι της καμπύλης ανάπτυξης του πρώτου και δεύτερου σταδίου.

Location	206/204	207/204	208/204
Kimolos	18.86	15.67	38.91
Milos	18.881	15.7005	39.0557
Poliegos	18.89	15.72	39.135
Thera	18.9554	15.6739	38.971
Average	18.8996	15.6911	39.01
Rounded	18.90	15.69	39.00

Calculated average values for $^{238}U/^{204}Pb$ and $^{232}Th/^{204}Pb$:

$^{238}U/^{204}Pb = 13.01$ from the $^{206}Pb/^{204}Pb$-ratio;

$^{238}U/^{204}Pb = 13.21$ from the $^{207}Pb/^{204}Pb$-ratio;

Mean $= 13.1$ for $^{238}U/^{204}Pb$;

$^{232}Th/^{204}Pb = 43.1$ from the $^{208}Pb/^{204}Pb$-ratio;

$^{232}Th/^{238}U = 3.29$

Start of 1.system	End of 1.system	start of 2.system	End of 2 system
$t_0 = 4.57$ b.y.		$t_1 = 1.36 \pm 0,3$ b.y.	
$x_0 = 9.307$	$x = 17.77$	$x_1 = 15.84$	$x_2 = 18.92$
$y_0 = 10.294$	$y = 15.59$	$y_1 = 15.42$	$y_2 = 15.69$
$z_0 = 29.487$	$z = 37.71$	$z_1 = 36.00$	$z_2 = 39.00$
$^{238}U/^{204}Pb = \mu_1 = 8.2$		$\mu_2 = 13.1$	
$^{232}Th/^{204}Pb = W_1 = 35.45$		$W_2 = 43.1$	
$^{232}Th/^{238} = \varkappa_1 = 4.32$		$\varkappa_2 = 3.29$	

time corresponds well with the orogenic cycles of the Hellenides (JACOBSHAGEN, 1986).

When comparing the model ages of the ores with the geological data it is obvious that they agree well. For example, the paleozoic model ages of the galena from Chios (320 Ma) fall well within the age of the paleozoic sequences of the non-metamorphic host rocks in which they occur. The same is true for the paleozoic model age from the galena of Metallikon in Mazedonia (300 Ma) which occurs in metamorphic schists of paleozoic age.

Relationships between magmatic and metamorphic events can also be distinguished by the model ages of the ores. For example, the Pb-Zn-deposits by Stratonion and Olimpias at Chalkidike Peninsula. The ores are located between the paleozoic marbles and schists. The nearby plutonic rocks are related to the Eocene/Oligocene period (K-Ar isotope measurements of the magmatic rocks gave ages between 29.6 and 48 Ma, MEYER & KOCKEL, 1986). The model ages from the ores range between 50 and 80 Ma with an average of 70 Ma, showing that the ores can be related to the Tertiary magmatism.

The Pb-Zn-ores from Euboea are situated in two different tectonic units (KATZIKATZOS, 1978; DÜRR, 1986). It is assumed that the upper unit is thrusted over the lower unit. Radiometric measurements show that there was a high pressure metamorphic event at 120 - 110 Ma in the upper unit and a greenschist metamorphic event at 50 and 45 Ma for the upper and the lower unit. The model ages of the ores from the upper unit are about 100 Ma and that from the lower unit around 40 Ma. Both model ages fall together with the metamorphic events of their units. The overthrust hypothesis provides a good explanation for the Cretaceous model ages of the upper unit and the Tertiary ages of the lower unit.

By plotting the average $^{238}U/^{204}Pb$ values for each deposit or region versus the average model age it is obvious that the $^{238}U/^{204}Pb$ values increase as the model age decreases (Fig. 10). Consequently, a single increase of the $^{238}U/^{204}Pb$ value from 8.2 to 13.1, as shown in this model, cannot explain the Greek Pb-Zn-deposits exactly.

Nevertheless, the two stage model given here can be a useful tool for determining the model ages of the Greek Pb-Zn-deposits, for distinquishing epigenetic from syngenetic mineralization as well as for finding relationships of the ores with magmatic or tectonic events. This feature of the model is important for exploration.

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Appendix : Used parameters and equations
Παράμετροι και εξισώσεις που χρησιμοποιήθηκαν

Nuclide	*Decay constant*	*Symbol*	*Reference*
^{238}U	$0.155125 \times 10^{9} a^{-1}$	λ_1	Jaffey et al. (1971)
^{235}U	$0.98485 \times 10^{9} a^{-1}$	λ_2	"
^{232}Th	$0.049475 \times 10^{9} a^{-1}$	λ_3	LeRoux & Glendenin (1963)
Present	day ratio $^{238}U/^{235}U$	$= 137.88.$	Atom.Energ.(1962)
Isotopic	composition of Canyon Diablo troilite lead		Tatsumoto et al. (1973)

$$x_0 = (^{206}Pb/^{204}Pb)_{t_0} = 9.307$$
$$y_0 = (^{207}Pb/^{204}Pb)_{t_0} = 10.294$$
$$z_0 = (^{208}Pb/^{204}Pb)_{t_0} = 29.476$$

Meteoritic isochrone Tilton (1973)

$^{207}Pb/^{204}Pb,^{206}Pb/^{204}Pb$ — Steigung $= R_0 = 0.626208$
R_0 defines the age of the earth, $t_0 = 4.57$ b.y.

$$R_1 = \frac{1}{137.88}\left(\frac{e^{\lambda_2 t_1} - 1}{e^{\lambda_1 t_1} - 1}\right) \quad (1)$$

$$x_1 = x_0 + \mu_1 \left(e^{\lambda_1 t_0} - e^{\lambda_1 t_1}\right) \quad (2)$$

$$y_1 = y_0 + \frac{\mu_1}{137.88}\left(e^{\lambda_2 t_0} - e^{\lambda_2 t_1}\right) \quad (3)$$

$$z_1 = z_0 + (W_1)\left(e^{\lambda_3 t_0} - e^{\lambda_3 t_1}\right) \quad (4)$$

$$x_2 = x_1 + \mu_2 \left(e^{\lambda_1 t_1} - e^{\lambda_1 t_2}\right) \quad (5)$$

$$y_2 = y_1 + \frac{\mu_2}{137.88}\left(e^{\lambda_2 t_1} - e^{\lambda_2 t_2}\right) \quad (6)$$

$$z_2 = z_1 + (W_2)\left(e^{\lambda_3 t_1} - e^{\lambda_3 t_2}\right) \quad (7)$$