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Co- and post-magmatic modifications of the oceanic crust: lead isotope evidences

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Abstract: The Pb-isotopic analysis of the basalt-/basalt-andesitic rocks of the drill hole CY-4 in the Troodos-Ophiolite in Cyprus shows that the postmagmatic alteration by sea water has produced a $^{206}Pb/^{204}Pb$-increase, and to a lesser extent, $^{208}Pb/^{204}Pb$-raising, especially about the hydrothermal root-zone. The primary origin of the radiogenic Pb must refer to the continental Pb, instead of to the fresh Cretaceous ocean water. The average $^{206}Pb/^{204}Pb$ (18.589), $^{207}Pb/^{204}Pb$ (15.642) and $^{208}Pb/^{204}Pb$ (38.508) are almost identical with the crust-lead of Stacey and Kramers and suggest an island arc environment. The Pb-residence time in the source region comes to 0.62 Ga and the corresponding $^{232}Th/^{238}U = 2.88$. This time is probably an intermediate value in a certain variation range with a continuously varying Th/U-ratio. Pb-isotopically, the Troodos-Ophiolite deviates strongly from the oceanic composition and shows an unequivocal affinity to sediments and continental basalts. The radiogenic $(^{208}Pb/^{206}Pb)^*$ lie in a range from 0.952 to 0.996 and $(^{207}Pb/^{206}Pb)^*$ from 0.549 to 0.607 and, therefore, fall into the typical MORB-domain. The $\Delta(^{208}Pb/^{204}Pb)$-value varies between 10 and 60 and locates immediately at the boundary of DUPAL-zone. The Troodos-Ophiolite originates from the complex primary and secondary as well as binary and ternary mixings of the depleted (DMM), the enriched (EMII) and the HIMU mantle components. DMM is the main component (up to 70%), which was strongly and non-uniformly contaminated by enriched materials from EMII. HIMU appears not to be the immediate source and had previously mixed with DMM to have formed a secondary source for Troodos-Ophiolite.

INTRODUCTION

Variations of Pb-isotopic compositions as well as U/Pb- and Th/Pb-ratios of the oceanic magmatic rocks can result from fractionation of U and Th, from mixings and contaminations of magmas, from fractional crystallization and from hydrothermal activities. Investigations of Pb-isotopes of the oceanic basalts (Gast *et al.*, 1964; Tatsumoto, 1978; Tilton, 1983; Hart, 1984; Zindler and Hart, 1986; White *et al.*, 1993, Vroon *et al.*, 1995) have greatly contributed to modeling of the circulation of the mantle, to locating of the chemical and isotopic mantle domains and to constraint of the temporal and spatial dimensions of the development of the crust/mantle-system. After the discovery of the DUPAL-anomaly (Dupre and Allegre, 1983), Zindler and Hart (1986) as well as Hart (1988) have tried to establish a heterogeneous mantle model with several independent mantle end-members. In our discussion, the following nomenclatures will be used (Hart, 1988): DMM *(Depleted MORB-Mantle)*, HIMU *(High* $\mu = {}^{238}U/{}^{204}Pb$*)* and EMI and EMII *(Enriched Mantle)*.

The previous Pb-isotopic studies of the oceanic rocks were mostly limited to *young extrusive rocks from the modern seafloor*. The depth of sampling is only slightly more than 1000 m under the ocean floor. The ophiolites, as the oceanic crust on land, have rarely been Pb-isotopically analyzed (Chou *et al.*, 1978; Saleeby and Chen, 1978; Chen and Pallister, 1981).

In the frame of *Cyprus Crustal Study Projects* (CCSP), five deep drill holes have been set in the well-known Troodos-Ophiolite of Cyprus, in which CY-4 is the most deep one (2,263 m) (Fig. 1) and has given us a favourable opportunity to study the Pb-isotopic distributions in all the important layers (dikes/gabbros/ultrabasites) of the oceanic crust in detail.

Purposes of this study are: to characterize the co- and postmagmatic isotopic variations; to calculate the Th/U- and $^{238}Pb/^{204}Pb$-ratios as well as the Pb-residence time in the sources; to find the relations of mantle sources to the different mantle components; to recognize the oceanic and continental affinity of the ophiolite and to discuss the Pb-isotopic development with relation to the provenance of the ophiolite.

GEOLOGICAL SUMMARY

The Troodos-Ophiolite builds the central upland of Cyprus and locates at the northwestern end of a cretaceous ophiolite-belt that lies partly along the margin of the Arabic plate (Moores *et al.*, 1984).

The ophiolite is regarded as the oceanic crust of the neotethyic ocean from the later Cretaceous (ca. 60–90 Ma) (Gass, 1979; Blome and Irvin, 1985; Mukasa and Ludden, 1987; Gee *et al.*, 1993).

The deepest layer of the ophiolite is exposed in the core of the massif and is composed of the deformed and serpentinized harzburgite and dunite. This layer is overlain by the interbedding of the ultramafic cumulates (dunite, wehrlite and websterite) which was separated from one or more former magma chambers (Greenbaum, 1972; Malpas *et al.*, 1989a, b). From roof of the magma chamber, the gabbroic rocks began to crystallize out, whose lower part is banded and whose upper section is structureless and was cut partly by plagioclase-rich granitic rocks.

The ca. 1.5 km thick *sheeted-dike-complex* lies above the gabbros. These dikes consist of subvertically standing and parallel constructed basaltic dikes that are nearly trend N-S. They have typically diabasic components and structures that formed when the magma moved temporally and spatially one after another from the magma chamber upwards and extruded as lava.

Pillow lava builds the uppermost magmatic layer (1.3 km) of the ophiolite and is composed of the strongly silicificated lower and the SiO_2-undersaturated upper dikes, sills and lava streams. This pillow lava is covered by the Fe-Mn-containing sediments, clays and radiolarites of the Campanian formation.

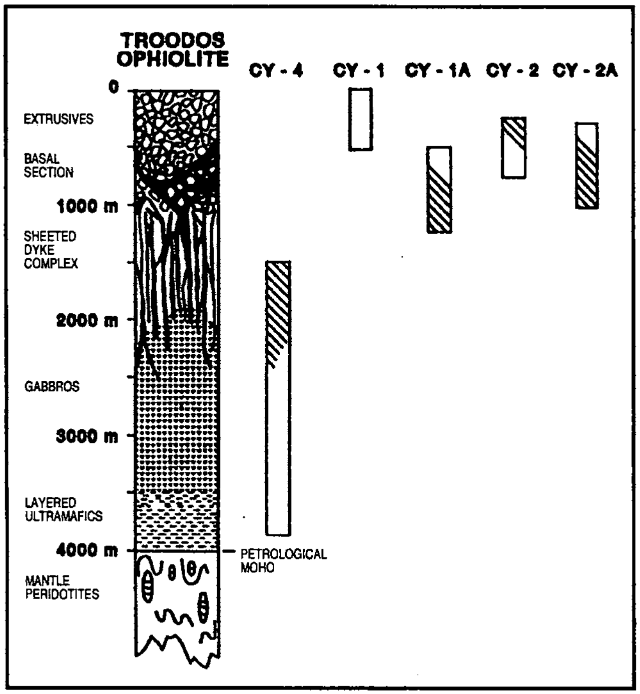

Figure 1. The schematic profile of the hole CY-4 in comparison with positions of the other drill holes of CCSP (Cyprus Crustal Study Project).

The famous (already in the prehistoric time) massive sulphide-deposition laying in the lava on the northern margin of the complex was produced by hydrothermal processes being active in the former oceanic crust (Coleman, 1977; Schiffman and Smith, 1988).

SAMPLES AND DATA

The rock powder produced in a disk vibratory mill was used for RFA and mass spectrometric measurements. The mineral samples were obtained only through hand picking. The purity of the mineral preparations was tested by X-ray diffractometry. The analyses were carried out in Institute for Mineralogy, Free University of Berlin. The contents of the main and trace elements were determined by the sequence X-ray spectrometer SRS 300 (Rh-tube/V = 60 kV/I = 46 mA). The isotope ratios were measured on a solid mass spectrometer (FINNIGAN MAT 261, 90° magnet sector field, extended geometry, thermionic source, variable multiple collector).

Considering the possible postmagmatic disturbance of the primary Pb-isotopic distributions, the small Th/Pb- and U/Pb-ratios as well as young age (90 Ma) of the rock, the measured Pb-isotope ratios were directly used as the initial values.

For instance, we take a typical Th/Pb-ratio of 0.32 and an U/Pb-ratio of 0.18 (Nebe, 1990, unpublished). Then, we obtain the corresponding radiogenic growth since the crystallization of the ophiolite is as follows: $^{206}Pb/^{204}Pb = 0.156$, $^{207}Pb/^{204}Pb = 0.007$ and $^{208}Pb/^{204}Pb = 0.088$. The radiogenic contribution for $^{207}Pb/^{204}Pb$ is smaller than the analytical errors of most samples (0.01–0.03), whereas the growth of $^{208}Pb/^{204}Pb$ is lower than the largest error of the measurements (0.106). The uncertainty for $^{206}Pb/^{204}Pb$ is somewhat larger (measuring error for $^{206}Pb/^{204}Pb \leq 0.051$). However, this growth of 0.156 for $^{206}Pb/^{204}Pb$ is 8 times smaller than the variance of $^{206}Pb/^{204}Pb$-ratios (1.37).

PB-ISOTOPIC DISTRIBUTION

The $^{206}Pb/^{204}Pb$- and $^{208}Pb/^{204}Pb$-ratios show an approximately synchronous variation (Fig. 2) and reflect the geochemical coherence between U and Th with respect to their similar ionic radii (1.05 Å for U^{+4} and 1.10 Å for Th^{+4}). The fluctuation of Pb-isotope ratios is strong and their variances exhibit the following sequence: $^{206}Pb > ^{208}Pb > ^{207}Pb$.

^{207}Pb exhibits the largest constancy. Its mother-isotope ^{235}U has a very small half-life time (0.7 Ga) compared to ^{238}U (4.468 Ga) and ^{232}Th (14.01 Ga). The rapid decay of ^{235}U had led to an almost complete exhaustion of ^{235}U reserve (ca. 98%) from formation of the Earth to crystallization of the Troodos-Ophiolite. The differences of the variances between ^{206}Pb and ^{208}Pb result mainly from the higher mobility of U^{+6} relative to Th^{+4} in the source region of CY-4.

The causes for the observed Pb-isotopic variations are, in the first place, the heterogeneity of the magma source, the fractional crystallization and the hydrothermal alteration by sea water.

It is noticeable that the maximum of ^{206}Pb/^{204}Pb-ratios (Fig. 2-a) lies about the transition zone from dikes to gabbros around the depth of 600 m i.e. in the hydrothermal root-zone, as called by Nehlig (1994). Right here, there is a higher water/rock-ratio and a abrupt increasing of ^{87}Sr/^{86}Sr-ratios (Sun, 1995), which was caused by the intensive exchange between sea water and rock. This suggests that the contribution of sea water alteration to the ^{206}Pb/^{204}Pb-increase can not be excluded.

From Figure 2 it is recognizable that the strongly altered samples concentrate in the rocks over 1,200 m and possess higher ^{206}Pb- and ^{208}Pb-contents than the samples from the lower layers. This distribution has contributed to the general decreasing of ^{206}Pb/^{204}Pb- and ^{208}Pb/^{204}Pb-ratios with increasing depth and is in accordance with the tendency of the changes of the alteration degree of the rocks (Sun, 1995).

Because of the extreme low lead concentrations, Pb is not detectable in several samples such as calcite and pyroxene as well as the plagioclase of the sample S.126. The primary plagioclase of the sample S.110 shows the identical ^{206}Pb/^{204}Pb and ^{207}Pb/^{204}Pb with their whole rock within error, whereas ^{208}Pb/^{204}Pb in the plagioclase is clearly smaller. ^{208}Pb/^{204}Pb and ^{207}Pb/^{204}Pb of epidote are somewhat lower than those of the whole rock, while ^{206}Pb/^{204}Pb strongly increases (19.045 ± 0.018) compared to the whole rock. Moreover, laumontites exhibit the unusually high ^{207}Pb/^{204}Pb-ratios (15.792 ± 0.062 – 15.894 ± 0.155).

However, it is difficult to say whether the high ^{207}Pb/^{204}Pb of laumontite, high ^{206}Pb/^{204}Pb of epidote and the ^{206}Pb/^{204}Pb-increasing of the whole rocks above 1200 m depth, and especially about the transition zone from dikes to gabbros, result from exchange with *fresh* sea water. The reason is that Pb has a very short residence time in ocean water (ca. 100 years, O'Nions *et al.*, 1978; Abouchami and Goldstein, 1995) and its isotope ratios are strongly variable and source-dependent. Sr- and Nd-isotopically (Sun, 1995), the ^{87}Sr/^{86}Sr- and ^{143}Nd/^{144}Nd-ratios of the circulating phase have fairly been changed. For lead, it is also possible that the excess radiogenic ^{206}Pb and ^{208}Pb derived from the circulated enriched materials e.g. from the continent i.e. from the oceanic sediments (D^{207}Pb/^{204}Pb up to 20 and ^{206}Pb/^{204}Pb up to 19, White and Dupre, 1986). On this theme, it will be later further discussed.

The fractional crystallization is capable to arrange the Pb-isotopic profile in such a way that the Pb-isotope ratios (mainly ^{206}Pb/^{204}Pb and ^{208}Pb/^{204}Pb) increase regularly upwards, since U and Th

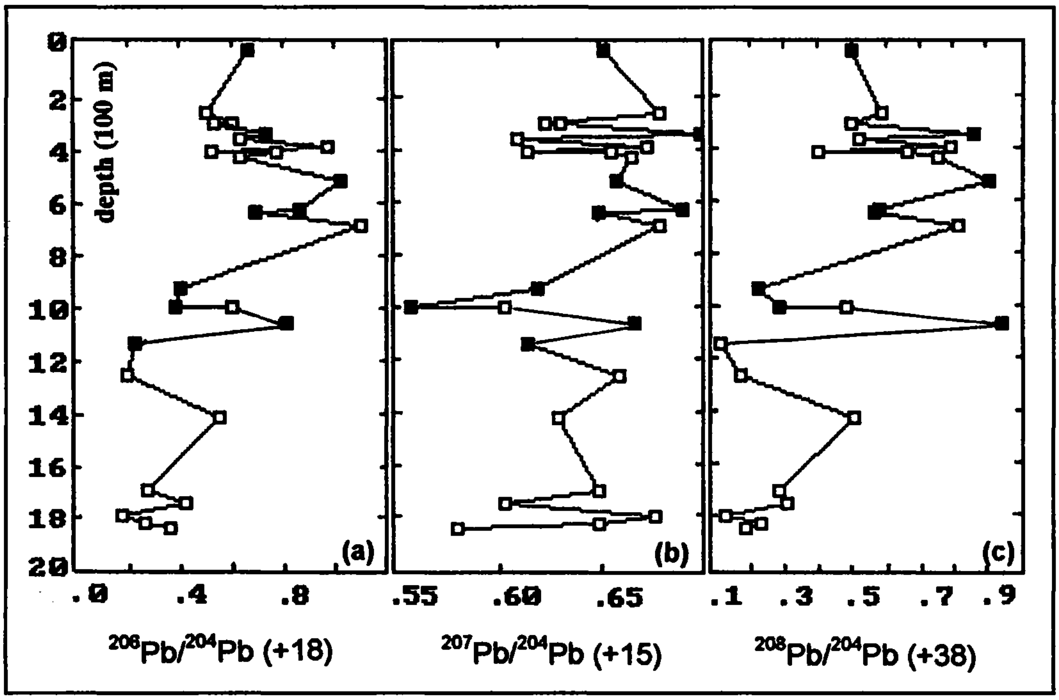

Figure 2. Pb-isotopic profile of the whole rocks of hole CY-4. The black blocks represent the strongly altered samples.

belong to the highly incompatible elements (HIE, distribution coefficients in form of solid/liquid in most of minerals of basalts < 0.01, Saunders, 1986). However, this modification has probably not or only slightly changed the Pb-isotope ratios in CY-4 as a whole, if we consider the relative young rock age of 90 Ma.

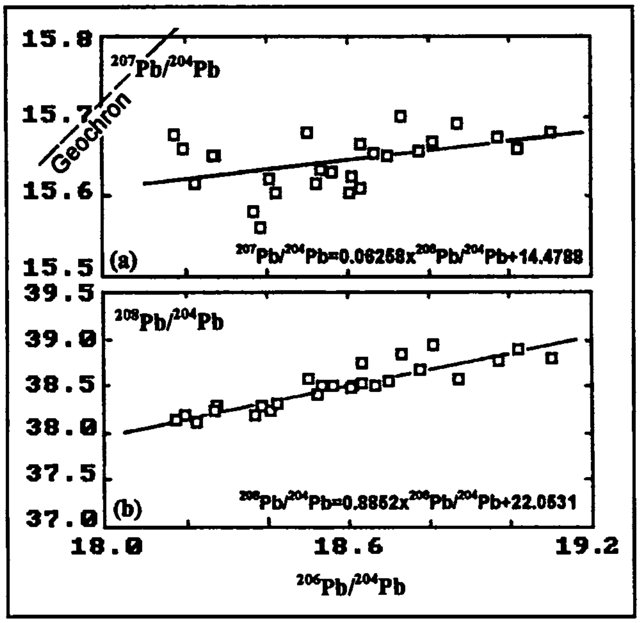

Figure 3. Linear regressions of $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$, respectively. Regarding the regression line of Fig. (a) as secondary isochron, the Pb-residence time can be calculated (= 0.62E + 9 y). The corresponding $^{232}Th/^{238}U$ is 2.88 for the mantle-source from which the CY-4-magma was diversified and/or separated ca. 0.71E + 9 years ago.

The strongly altered whole rock samples show an irregular and nearly random scatter. Thus, it can be assumed that the hydrothermal metasomatosis has probably not falsified the primary distribution of Pb-isotopes systematically and severely. The clearness of the linear correlations between $^{208}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ as well as between $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ (see below) are also in agreement with this suggestion. Consequently, we regard the properties of the *whole* Pb-isotopic distribution after alteration as unchanged. Therefore, the Pb-isotopic variations in CY-4 should result *mainly* from the processes, which had modified the magma before it solidified, e.g. mixings between two or more components and/ or assimilations of the rocks with different Th/Pb, U/Pb and Pb-isotope ratios originally derived from diverse sources.

In addition, it is noteworthy that the Pb-isotope ratios of the measured plagiogranites show no differences to the surrounding dikes. Consequently, plagiogranite in CY-4 could only be separated from the same magma as the gabbros and dikes and not be formed by melting of any old sialic basement.

PB-ISOTOPIC CORRELATIONS

For the linear correlations between $^{208}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ (correlation coefficient r = 0.8999, Fig. 3-b) as well as between $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ (r = 0.4441, Fig. 3-a), there are four possible interpretations: *a)* accidental and meaningless, *b)* isochrones, *c)* binary mixing lines and *d)* isochrones which were modified by later mixing. Although the

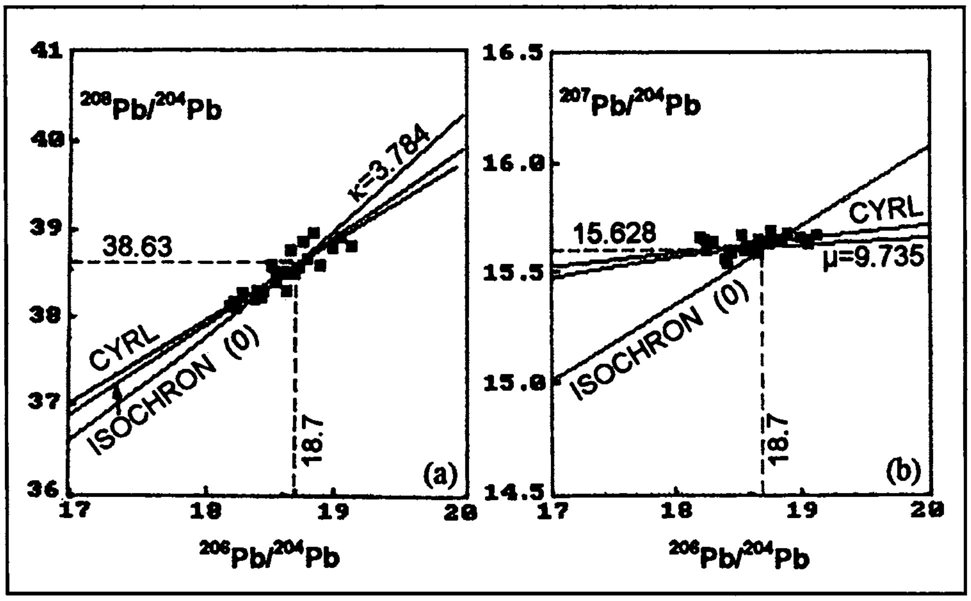

Figure 4. Comparison of Pb-isotope ratios in CY-4 and those in the Two-stage-model of Stacey and Kramers (1975). The drawn Isochron has the time 0. CYRLs are the regression lines of CY-4.

rocks have suffered pervasive alteration, we have obtained the fairly good correlations. Thus, we are allowed to exclude the first possibility at first.

It is remarkable that *all the data points lie on the right side of the geochron* (Fig. 3-a) and require a negative age. Clearly, CY-4 contains excess radiogenic Pb, compared to the classic one-stage model (Chen and Wasserburg, 1983). Consequently, the Pb-isotopic distribution cannot be explained by this model and must be caused by secondary events. This Pb was separated from its source(s) at a certain time before the crystallization of Troodos-Ophiolite and has later redistributed on the secondary isochron. The calculation with the slope of the isochron (0.06258) yields a time (= 0.6227 Ga) which can be understood as the residence time of this lead in the immediate source of CY-4.

According to the model of Galer and O'Nions (1985), the average residence time of the lead, which streamed together with other incompatible elements from the primitive lower mantle towards the depleted upper mantle, is ca. 0.6 Ga and is identical with that of CY-4 within error. Thus, the magma of CY-4 could contain the lead that was supplied ca. 0.6 Ga before the crystallization of the magma.

In Figure 3, ^{208}Pb/^{204}Pb-ratios correlate with ^{206}Pb/^{204}Pb-ratios linearly ($r = 0.9$) and yield a slope of 0.8852. Through the above calculated time (0.6227 Ga) and this slope, the ratio ^{232}Th/^{238}U (k) = 2.88 can be deduced. This k-value lies at the upper end of the recent oceanic basalts (mostly 0.65–3.0, Tatsumoto, 1978; Allègre *et al.*, 1986). Compared to the *recent* Pacific-MORB ($k = 2.57$, Newman *et al.*, 1983; $k = 2.6$, White *et al.*, 1987), our k is slightly larger. This signifies that either k has become smaller with the decreased ages (Allegre *et al.*, 1986) or CY-4-source restrains some *exogenous* lead which derived not from the normal MORB-mantle.

Taking note of the strong and convergent scattering of the data points towards the radiogenic direction in Fig. 3-a, as well as the small correlation coefficient between ^{207}Pb/^{204}Pb and ^{206}Pb/^{204}Pb, we may think that the above calculated Pb-residence time of 0.62 Ga is probably only a intermediate value within a certain space of time, which is determined by a series of secondary stages. Consequently, the k-value must also vary with time (Tatsumoto, 1978; Allegre *et al.*, 1986). This means that the direct source(s) of the ophiolite in the upper mantle was *extremely heterogeneous in terms of Pb-isotopes*. This source could contain the Pb that was differentiated possibly in different times continuously and has built a bundle of secondary isochrones.

Another interpretation is that the characteristic data spreading in Fig. 3-a signifies the Pb-isotopic variations between several end members. Since the radiogenic corner of the triangle built by the scattering of the data points lies within the domain of ^{207}Pb/^{204}Pb- and ^{206}Pb/^{204}Pb-ratios of the modern Atlantic sediments and mantle component EMII, it is very likely that the Pb-isotopic composition of CY-4 has evolved in some complicated mixing processes (see the later discussions).

AN AVERAGE CRUST-LEAD

Comparing the Pb-isotopic distribution as a whole with the S/K-model (two stage model of Stacey and Kramers, 1975) (Fig. 4), it is clear that our data points concentrate densely about the radiogenic end of the Pb-growth curve of the second stage ($\mu = 9.735$) (Fig. 4-a). The average ^{206}Pb/^{204}Pb (18.589), ^{207}Pb/^{204}Pb (15.642) and ^{208}Pb/^{204}Pb (38.508) are almost identical with the so-called crust-lead with the corresponding isotope ratios of 18.700, 15.628 and 38.630, respectively. In comparison to ^{207}Pb, ^{208}Pb shows stronger approach to S/K-model (Fig. 3-b). CYRL (the regression lines of CY-4) is approximately identical with the zero-time-isochron of S/K.

This kind of Pb-isotopic distribution around the crust-lead is typical for basalts of many recent island arcs (Amstrong and Cooper, 1971; Tilton, 1983, Vroon *et al.*, 1993), where the Pb-isotopes were imprinted by the characteristic features of the radiogenic composition from the continental crust with higher U/Pb-ratios (Allegre *et al.*, 1995) in the past.

DEVIATION FROM THE OCEANIC ROCKS

Sr- and Nd-isotopic analyses (Sun, 1995) have lead to an obviously oceanic origin of the Troodos massif. Pb-isotopically, CY-4 shows, however, a strong deviation from the oceanic domain (Zindler *et al.*, 1982). Figure 5 illustrates the large portions of the radiogenic ^{207}Pb and ^{208}Pb from CY-4 relative to NHRL on which the MORBs lie. Most samples depart from area of the oceanic basalts and show the evident affinity to modern marine sediments and the continental basalts.

D(^{208}Pb/^{204}Pb)-values of CY-4 lie about 40 and fall in the typical oceanic area (from −120 to 140). It is interesting that there is a free zone around D(^{208}Pb/^{204}Pb) = 40 that has not been covered by the Pb-isotope data up to now. Most of samples of CY-4 in the coordinates of ^{208}Pb/^{204}Pb and ^{206}Pb/^{204}Pb (Fig. 5-A) accumulate then just side by side within this gap. This special feature indicates that the CY-4-magma can be a mixing of some components of both inside and outside the oceanic region.

In diagram $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ (Fig. 5-B), it is very clear that almost all the samples from CY-4 lie outside of the oceanic area and fall into or even out of the fields of sediments. Certainly, the CY-4-magma contains a considerable amount of Pb from the continental crust. This is just the reason why the average Pb-isotopic composition of CY-4 is, as above mentioned, very similar to the terrestrial lead obtained by the summarizing of the Pb-isotopic compositions of oceanic sediments and the old sialic rocks (Stacey and Kramers, 1975) (see also Fig. 4).

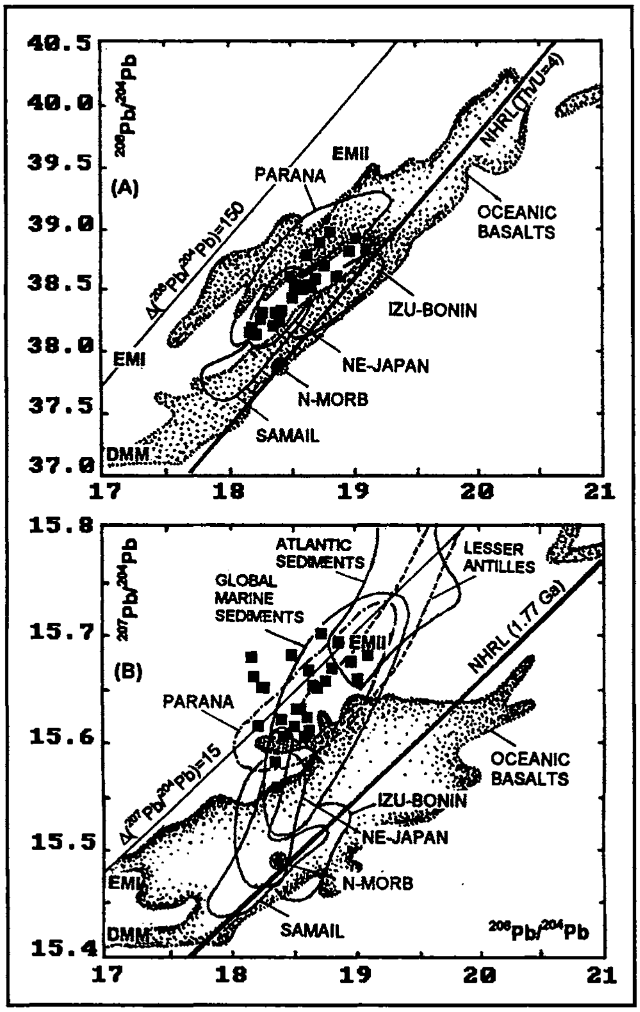

Figure 5. Pb-isotopic deviation of CY-4 from oceanic region and approach to the marine sediments and to the continental flood basalts. Data sources: oceanic basalts (Hart, 1988; Vital, 1992; Mahoney *et al.*, 1992; White *et al.*, 1993); definitions of EMI, EMII, DMM, NHRL and N-MORB (Hart, 1984, 1988); continental flood basalts from Parana (LPT, Südbrazil, Hawkesworth *et al.*, 1986); basalts from Lesser Antilles, global marine and Atlantic sediments (White and Dupre, 1986); ophiolite from Samail (Oman, Chen and Pallister, 1981); basalt from NE-Japan (Tatsumoto and Nacamura, 1991); boninite from Izu-Bonin (Mariana-Arc, Pearce *et al.*, 1992).

Compared to boninite from Mariana-arc (Pearce *et al.*, 1992), CY-4 is clearly more radiogenic in terms of ^{208}Pb and ^{207}Pb. The former has typical oceanic Pb-isotope composition. The island arc basalts from NE-Japan that was a part of the old eurasic continental margin (Tatsumoto *et al.*, 1991) have the similar $^{208}Pb/^{204}Pb$- and $^{206}Pb/^{204}Pb$-ratios with the nonradiogenic part of CY-4, whereas CY-4 shows a obviously higher $^{207}Pb/^{204}Pb$. Moreover, the Samail-Ophiolite (Chen and Pallister, 1981), Taiwan-Ophiolite (Chou *et al.*, 1978) and Kings-Kaweah-Ophiolite (Saleeby and Chen, 1978) deviate clearly from the sediment-area and show a strong affinity to the normal MORB. Consequently, such ophiolites should have formed in the *normal middle* oceanic spreading centers (Chen and Pallister, 1981; McCulloch *et al.*, 1981; Nehlig, 1994) whereas the Troodos-Ophiolite must petrogenetically closely relate to the so-called suprasubduction (e.g. Malpas *et al.*, 1989a, b). For instance, the IAB from the Lesser Antilles, a typical example for contamination with sedimentary Pb (White and Dupre, 1986, Fig. 5-B), shows a obvious similarity with the drifting tendency of CY-4, not only Sr- and Nd- isotopically (Sun, 1995) but also Pb-isotopically.

CONNECTION TO THE DUPAL-ANOMALY

From Figure 6, it is clear that CY-4 has higher $^{208}Pb/^{204}Pb$- and $^{207}Pb/^{204}Pb$-ratios relative to NHRL [$\Delta(^{208}Pb/^{204}Pb) = 10–60$ and $\Delta(^{207}Pb/^{204}Pb) = 7.3–18.3$]. Thus, the data points lie just on the boundary of the DUPAL-anomaly ($^{87}Sr/^{86}Sr > 0.705$ and $\Delta(^{208}Pb/^{204}Pb) \geq 60$).

The basalts from Izu-Bonin (Pearce *et al.*, 1992), from the Samail-Ophiolite (Chen and Pallister, 1981) and from the northeastern Japan (Tatsumoto and Nacamura, 1991) lie along a path between the normal MORB and the terrigenous and pelagic sediments. However, the data points of CY-4 move strongly away from N-MORB and fall almost completely into the sediment domains. This deviation from normal MORB, accession to the DUPAL-zone and the strong data spreading signify, as we will see below, a very complicated mixing scheme with different components.

TERNARY MIXINGS OF PB-ISOTOPES

In the diagrams of $^{207}Pb/^{204}Pb$, $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ vs. $(^{208}Pb/^{206}Pb)^*$, respectively (Fig. 7), the characteristic distributions of the data points are conspicuous: they concentrate within the triangles formed by the three mantle components. Clearly, this can be explained by a mixing scheme with three end members.

The fractions of the components in every sample can be read out directly from the mixing triangles. For each concrete sample, there is three percentages, each of which refers to one of the three end components and the sum of the three percentages comes to 100. The relative positions of the samples are independent on the scales of axes or forms of the triangles. The percentage of a component can be measured as man sets a line parallel to the reverse side of an angle at whose vertex this component lies. The percentage on the reverse side is 0 and comes to 100 at the vertex.

For comparison, the variation ranges of the portions of all three Pb-isotope ratios relating to the three end members have been listed in Table 1. Compared to DMM and EMII, the HIMU has a relatively small and stable portion. In the cases of ^{208}Pb and ^{206}Pb, HIMU appears not to be the direct source of the CY-4-magma since the two side-bisectors through EMII in Figure 7-a and 7-c lie parallel to the upper sides of the triangles, as to speak, formed by the data points. These bisectors separate all of the samples under them. This means that there is an intermediate component between HIMU and DMM for the source in terms of ^{208}Pb and ^{206}Pb. This secondary component was formed by binary mixing of the two components HIMU and DMM with the same portion. In the case of ^{207}Pb/^{204}Pb vs. (^{208}Pb/^{206}Pb)* there is no visible evidence for such secondary source. It indicates the dependence of the mixing between DMM and HIMU on the Th/Pb- and ^{238}U/^{204}Pb-ratios as well as on time (Vidal, 1992).

In terms of ^{208}Pb/^{204}Pb and ^{206}Pb/^{204}Pb, the CY-4-magma contains a large contribution from the depleted MORB-mantle (up to 70%). It signifies the forming of the ophiolite in a oceanic spreading

Table 1. Variation ranges of percentages of the mantle-components in CY-4-source in consideration of Pb-isotopic mixing model with three end members.

Ratios	^{207}Pb/^{204}Pb		^{206}Pb/^{204}Pb		^{208}Pb/^{204}Pb	
Variation	min.	max.	min.	max.	min.	max
HIMU	20	50	15	40	13	40
EMII	15	65	5	55	7	55
DMM	10	60	30	70	28	67

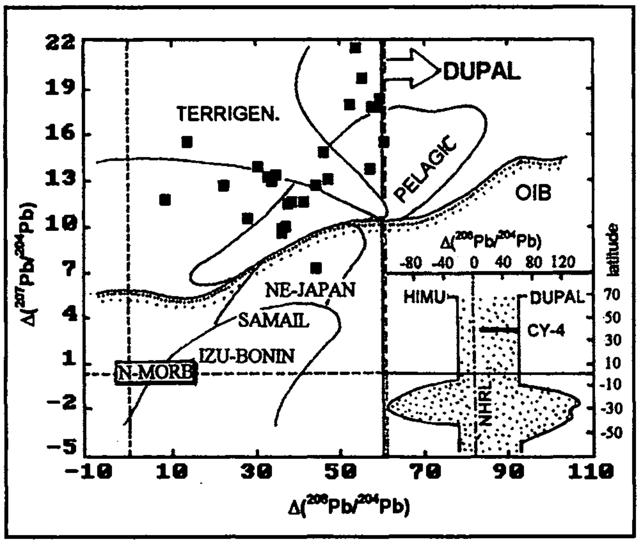

Figure 6. Pb-isotopic distribution of CY-4 and DUPAL-anomaly (Dupre and Allegre, 1983; Hart, 1984). Note the deviation of CY-4 from MORB and OIB as well as the affinity to the terrigene/pelagic sediments (Hart, 1988) and the connection to the DUPAL-zone. For comparison, data of the arc-basalts from NE-Japan (Tatsumoto and Nacamura, 1991), Samiail-Ophiolite from Oman (Chen and Pallister, 1981), boninite from Izu-Bonin (Pearce *et al.*, 1992) and the latitudinal location of CY-4 are also schematically illustrated.

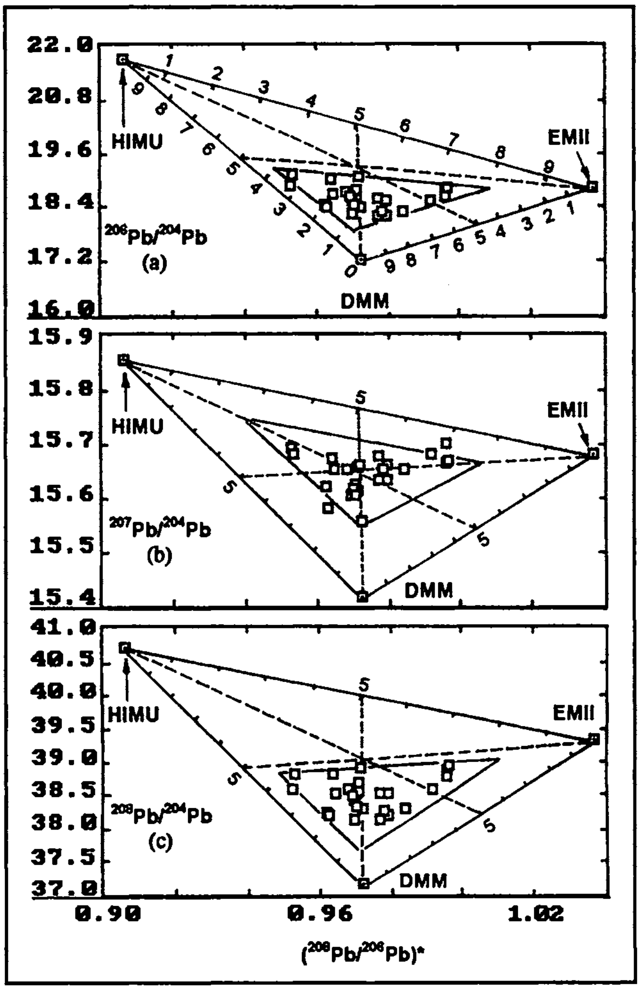

Figure 7. Ternary mixings of Pb-isotopes in the CY-4-sources based on the correlations of ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb vs. (^{208}Pb/^{206}Pb)* [=(^{208}Pb/^{204}Pb-29.475)/(^{206}Pb/^{204}Pb-9.3066)]. For definitions of DMM, HIMU and EMII, see Hart (1988).

ridge. Considering the strongly variable and higher portions (compared to HIMU) of EMII, it can be true that the source of Troodos-Ophiolite has derived from a depleted region of the mantle which was later contaminated by enriched materials. This conception can be explained by an island arc environment whereby the materials withdrawn from the depleted upper mantle have mixed with the enriched oceanic sediments. This contamination must be very heterogeneous so that the observed large variation of the portions of EMII has occurred in the source region of CY-4.

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