

17. LEAD AND STRONTIUM ISOTOPIC COMPOSITION OF SOME METALLIFEROUS AND PELAGIC SEDIMENTS AND BASALTS FROM THE GALAPAGOS MOUNDS AREA, DEEP SEA DRILLING PROJECT LEG 70¹

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INTRODUCTION

In recent years, metalliferous sediments have been discovered overlying newly generated oceanic crust in the East Pacific, North Atlantic, Indian Ocean, Red Sea, Gulf of Aden, and elsewhere (e.g., Boström, 1973; Lalou et al., 1977; Bischoff, 1969; Boström and Fisher, 1971; Cann et al., 1977, respectively). Such material has also been recovered by drilling from sediments lying upon older oceanic crust (Boström et al., 1972, 1976; Horowitz and Cronan, 1976).

Hydrothermal circulation of seawater at a spreading ridge results in the leaching of Fe, Mn, and possibly other elements from the basaltic volcanic layer and their transport and discharge into ocean bottom waters, whereupon fine-grained Fe-Mn-rich precipitates form and settle into the ambient sediment (cf. Corliss, 1971; Dasch et al., 1971; Spooner and Fyfe, 1973; Bischoff and Dickson, 1975; Heath and Dymond, 1977; Corliss et al., 1979, Edmond et al., 1979). Mn-rich crusts have also been recovered from active ridges and are inferred to have formed in the vicinity of hydrothermal discharge areas (Scott et al., 1974; Moore and Vogt, 1976; Corliss et al., 1978; Hoffert et al., 1978).

The source of the trace elements in the metalliferous deposits is generally not clear. They may be derived from seawater by adsorption onto the precipitates or crusts, or from hydrothermal solutions which have leached them from the basalts. Pb, however, can be used as a geochemical tracer because of the known isotopic compositional differences between oceanic basalts and seawater. Isotopic investigations of Pb in ferruginous sediments from the East Pacific have shown that it has been derived partly or mostly from a basaltic source (Bender et al., 1971; Dasch et al., 1971; Dymond et al., 1973).

In the present study, Pb isotopic analyses have been made of a suite of metalliferous sediments (nontronite, Mn-oxide crust, Mn-Fe-oxide mud), pelagic sediments, and basalts from the Galapagos mounds area. The main purposes of the Pb study were to determine the source or sources of Pb in the metalliferous sediments, and whether or not stratigraphic variations exist in the isotopic composition of Pb in the sediments.

In theory, ⁸⁷Sr/⁸⁶Sr ratios can also distinguish between seawater and basaltic sources, since they are characterized by very different ⁸⁷Sr/⁸⁶Sr ratios. However, those metalliferous sediments analyzed to date have ⁸⁷Sr/⁸⁶Sr ratios in agreement with (or very close to) the ratio for modern seawater, indicating virtually no volcanic contribution (Dasch et al., 1971; Dymond et al., 1973; O'Nions et al., 1978). Nevertheless, a number of samples were analyzed to determine whether this is also the case for metalliferous sediment forming below, as opposed to at, the sediment/seawater interface.

SAMPLES

Twenty whole sediment samples were selected for Pb isotopic analysis; five of these were also analyzed for ⁸⁷Sr/⁸⁶Sr ratios. Seventeen of the twenty samples are from mounds sites, and three are from a nonmounds pelagic site (Hole 506B). Most mounds samples were from Holes 506 and 509B (six samples from each hole). Lithologically, the samples consist of 11 nontronites, 6 pelagic oozes, 2 Mn-oxide crusts, and 1 Mn-Fe-oxide ooze. Thirteen of these samples, plus some additional ones, have also been analyzed for oxygen and hydrogen isotopes (Barrett et al., this volume).

With one exception, all nontronite samples are granular (granules typically 2–10 mm in diameter) and were taken from sections of the core where the nontronite was homogeneous in appearance; the exception is a sample from a transitional, nontronitic mud layer. Smear slides and XRD analyses indicate that the nontronitic samples are lithologically pure, containing less than 1% biogenic material and/or volcanic glass shards. Five of the six pelagic sediment samples are foraminifer nanofossil oozes containing about 5 to 10% clays. Of these five, one sample contains about 20% siliceous microfossils; the other four contain less than 10% siliceous microfossils. The sixth pelagic sample is of the oxidized brownish surface sediment which is present in a thin (<50 cm) layer at the top of all holes. The two Mn-oxide crust samples each consist of several hard metallic plates (up to 20 × 10 × 5 mm in size); soft black porous sediment about 1 mm thick is commonly present on one or both sides of the plates. One sample is from the middle of the main unit of Mn crust recovered, near the top of Hole 509B; this unit consisted of 1.4 meters of Mn-oxide crust fragments. The other sample is from a 30-cm interval near the top of Hole 506C, over which Mn-oxide fragments are intermixed with nontronite granules, probably as a result of drilling disturbance. Mn-Fe-

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oxide mud, present only in Hole 509B, occurs as two fairly well-defined layers about 10 cm thick near the top of the hole, just above and just below the main interval of Mn-oxide crust.

Five basalts were selected for Pb-, Sr-, and O-isotopic analysis, four of which are from the Galapagos mounds area (Sites 506, 507, and 508). The other basalt sample is from older, nonmounds crust (Site 510) lying about 100 km north of the Galapagos mounds area. All samples are from depths in the crust of less than 15 meters, as a result of limited drill penetration in the basalts.

ANALYTICAL TECHNIQUES

In the case of sediments, 20 to 30 g of material were powdered using an agate mortar and pestle, and rinsed in distilled water. In the case of the basalts, 60- to 70-g samples were broken into cm-size fragments, rinsed in distilled water, crushed to sand size in a stainless steel mortar and pestle, then ground to a fine powder in an agate planetary ball mill.

Pb was extracted from whole-rock powder splits by dissolution followed by electrodeposition, following the technique of Arden and Gale (1974). Cathodic electrodeposition was carried out twice, prior to anodic electrodeposition, in order to ensure removal of all Fe prior to analysis. Samples were mounted on a single Re filament, using a silica gel-phosphoric acid activator, and the analyses were made on the Oxford 12-in. solid source mass spectrometer designed by Dr. N. H. Gale. Pb isotope data have been corrected for mass fractionation by comparison with results on standard NBS 981. Typical errors on Pb isotopic ratios are 0.1 to 0.15% (2 σ).

Sr was extracted from powder splits by standard ion-exchange methods (cf. O'Nions and Pankhurst, 1973), and analyzed on a V.G. MM-30 mass spectrometer at Oxford. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios have been normalized to a value of 0.70800 for the Eimer and Amend Sr standard. Typical errors on $^{87}\text{Sr}/^{86}\text{Sr}$ measurements are 0.01%. Sr and Rb contents of basalts were determined by X-ray fluorescence. The errors in Sr concentration are not more than $\pm 5\%$; the Rb data, however, should be considered semiquantitative because of the low concentration levels.

Oxygen isotopic measurements were carried out at the University of Tübingen, using splits of the whole-rock basalt powders analyzed for Pb and Sr. Oxygen was extracted using the bromine pentafluoride procedure (Clayton and Mayeda, 1963). Oxygen isotopic compositions are reported using common δ -notation relative to SMOW (Standard Mean Ocean Water). Routine reproducibility of $\delta^{18}\text{O}$ values is 0.15‰.

LEAD ISOTOPES

Results

Lead isotopic ratios of the 20 sediment samples are given in Table 1, together with the Sr isotopic ratios of five of the samples. Table 2 lists the Pb-, Sr-, and O-isotopic composition of the basalts. The Pb isotopic data are plotted in Figure 1. The most important aspects of these data are:

1) The sediments define approximately linear arrays, which result mainly from variation in the Pb isotopic

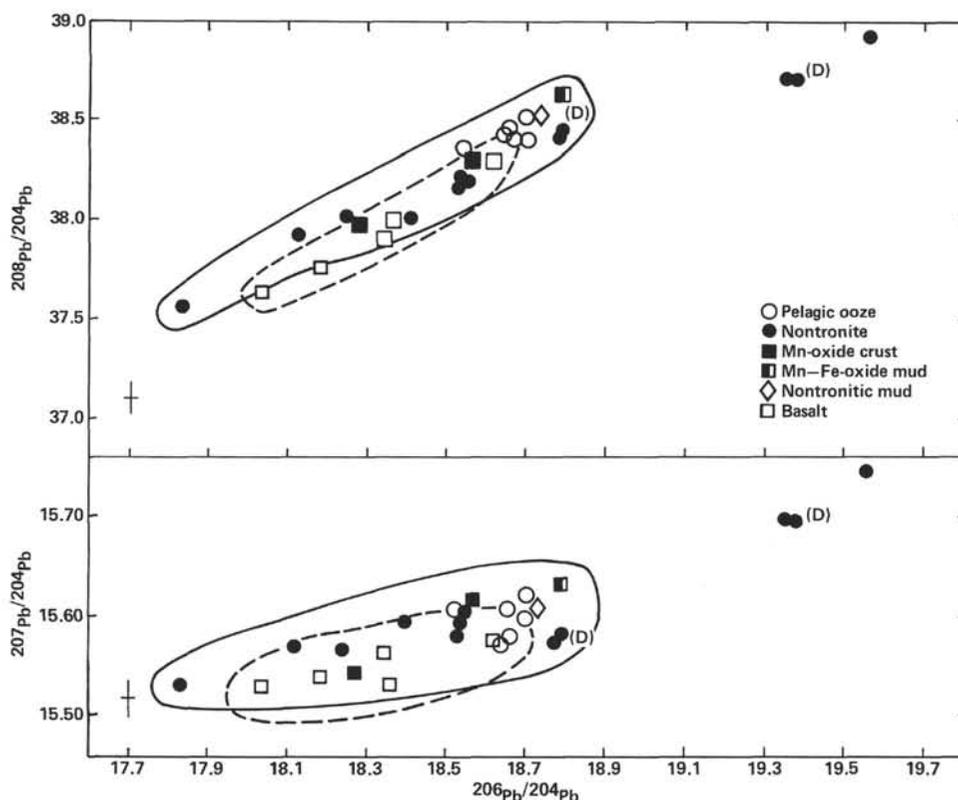


Figure 1. $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ for sediments and basalts from the Galapagos mounds area (Sites 506, 507, and 509). Solid lines enclose the sediment data arrays, and dashed lines the basalt data arrays (Table 1). Samples 12 and 17 were analyzed in duplicate (D). Samples 13 and 17 were not included in the sediment arrays because their Pb isotopic ratios are more radiogenic than seawater and mid-ocean ridge basalts (see text for discussion). Error bars give 2 σ errors.

composition of nontronite. Although data are limited, there are no obvious trends in Pb isotopic composition of the nontronites with increasing stratigraphic depth at mound sites.

2) The nontronite arrays are directed toward and closely approach the composition of average Mn nodules, which is considered representative of the Pb isotopic composition of seawater (average pelagic sediment also approximates the Pb isotopic composition of seawater).

3) Two nontronite samples have a very unusual isotopic composition, far more radiogenic than seawater (they are not included in the encircled arrays in Figs. 1 and 2).

4) The five pelagic sediment samples plot very closely together. Their average composition is slightly less radiogenic than average Mn nodules and average oceanic sediment. Brownish oxidized surface sediment (Sample 8) is somewhat less radiogenic than the average pelagic sediment in the Galapagos mounds area.

5) One sample, the Mn-Fe-oxide mud, has the composition of average Mn nodules and oceanic sediment.

6) One of the Mn-oxide crusts, from Hole 509B, is slightly less radiogenic than the average pelagic sediment of the Galapagos area and is in fact identical in composition to the sample of brownish oxidized surface sediment. The other Mn crust, from Hole 506C, plots near the middle of the nontronite array.

7) The basalts define approximately linear arrays which are mostly contained within the sediment arrays.

Discussion

The data on the nontronites (excluding Samples 13 and 17, which will be discussed separately) can be interpreted as the result of mixing, in varying proportions, Pb derived from basaltic and seawater sources. The isotopic composition of the basement-derived Pb should be some average of the range in Pb isotopic composition displayed by individual basalt samples. The average proportion of this Pb to normal seawater Pb in the sedi-

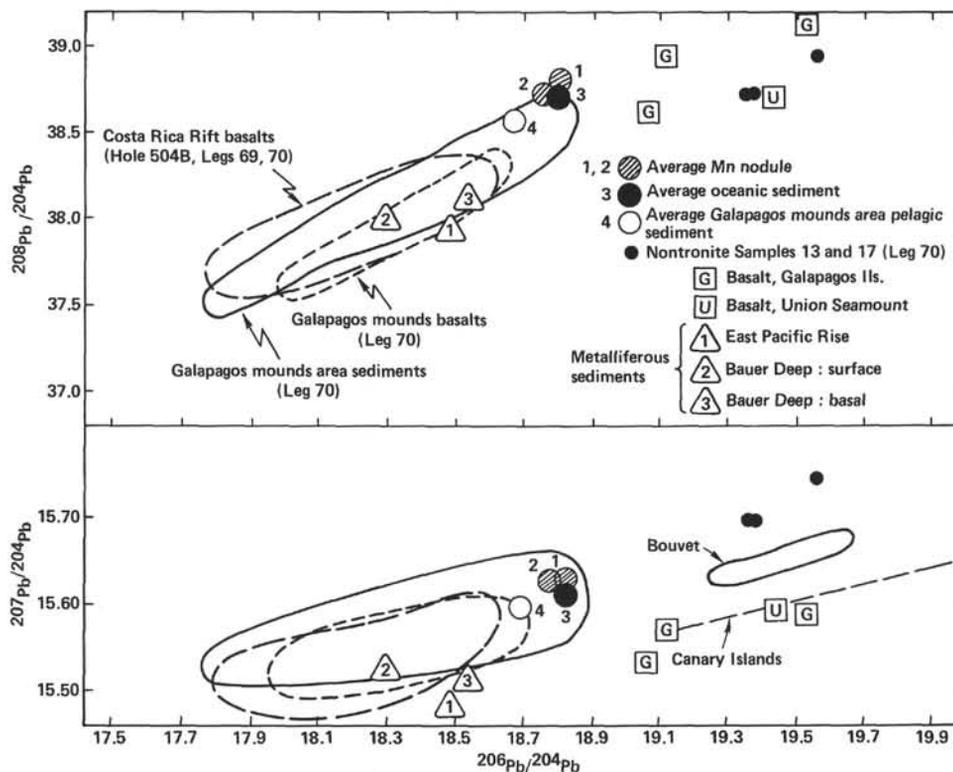


Figure 2. $^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ for sediments and basalts from the Galapagos mounds area (Sites 506, 507 and 509; data from Fig. 1), and basalts from the Costa Rica Rift (Hole 504B, Barrett, Leg 69). Also shown are the average Pb isotopic compositions of Mn nodules (1: Reynolds and Dasch, 1971; 2: Stacey and Kramers, 1975), oceanic sediment (Stacey and Kramers, 1975), Galapagos mounds area pelagic sediment (average of Samples 6, 7, 9, 10, and 14, Table 1), and the compositions of three metalliferous sediments from the east Pacific (1: East Pacific Rise crest core V19-54, O'Nions et al., 1978; 2: Bauer Deep surface sediment, corrected value from Dasch et al., 1971, in Dymond et al., 1973; 3: Bauer Deep basal sediment [15 m.y. old]). Overlying tholeiite, DSDP Hole 319, Unruh and Tatsumoto, 1976). Nontronite Samples 12 and 17 (Fig. 1), three selected basalts from the Galapagos Island (White, 1979) and basalt from the Union Seamount (Church and Tatsumoto, 1975) are also shown in the upper and lower diagrams. The arrays of volcanic rocks from Bouvet and the Canary Islands (fig. 5, Sun et al., 1975) are plotted in the lower diagram.

ment pore waters during the period of nontronite formation will then determine where the nontronitic Pb will plot on a mixing line. It is reasonable to expect that if the discharge rate of basement solutions through the mounds sediments is relatively high, normal seawater occupying the pore spaces will be gradually flushed out, and the nontronite will grow in the presence of solutions dominated by basaltic Pb. It should be noted that basement-derived Pb could dominate sediment pore waters even if fairly substantial mixing with normal seawater takes place. For example, consider a volume of basalt which is leached by ten volumes of seawater. Leaching of 1% of the average amount of Pb in this basalt (~1 ppm; Church and Tatsumoto, 1975; Unruh and Tatsumoto, 1976) would produce a concentration of Pb in basement solutions (10^{-3} ppm) at least one order of magnitude greater than the Pb concentration of normal seawater (3×10^{-5} ppm to 2×10^{-6} ppm; Goldberg, 1965; C. C. Patterson, in Tatsumoto, 1978).

A Mn-oxide crust from Hole 509B (Sample 15) contains essentially seawater Pb, although a small basaltic contribution is possible. (The uppermost nontronite in this hole [Sample 16], located only 50 cm below the analyzed Mn-oxide crust, has an almost identical Pb isotopic composition.) By contrast, the other Mn-oxide crust (Sample 11) contains considerable basaltic Pb. This indicates that Mn-oxide crusts, although formed at or near the surface of mounds, can also be influenced by basement-derived solutions during their growth.

Some Mn-oxide crusts are laminated on a millimeter scale, clearly visible in reflected light. Electron-microprobe analysis has shown that in one of the two cases investigated, layers with low Pb contents (<100 ppm) are present together with occasional layers of high Pb content (~1000 ppm). Although errors of $\pm 100\%$ can be expected for Pb contents of less than 200 ppm, the recorded variation is sufficient to indicate that it is real. The difference in Pb-concentration suggests that the two types of layers have grown at different rates. Mn crusts which have grown in the presence of discharging hydrothermal solutions have very low Pb contents (generally <20 ppm), and have grown relatively quickly (Toth, 1980). Manganese nodules and ferromanganese crusts forming in areas where bottom waters probably carry a hydrothermal component, such as on the East Pacific Rise and in the Bauer Deep (O'Nions et al., 1978; Dasch et al., 1971), typically contain 180 to 260 ppm Pb (Toth, 1980). By contrast, Mn nodules formed away from spreading axes as strictly hydrogenous deposits growing from normal seawater have very high Pb concentrations of 800 to 2500 ppm Pb (Mero, 1965; Toth, 1980). Galapagos mounds area Mn-oxide crusts have average Pb contents of about 56 ppm (Moorby and Cronan, this volume), which is intermediate between the first two types of Mn deposit described above. It is possible that such crusts contain rapidly formed layers with a high isotopic component but low concentration of basaltic Pb, and occasional more slowly formed layers with a relatively high isotopic component and high concentration of normal seawater Pb. The net result would

be a crust with a relatively low Pb content, but a predominantly seawater Pb isotopic composition. Crusts which are relatively enriched in basaltic Pb, as in Sample 11, would require a greater or perhaps more continuous influence from basement-derived solution.

Oxidized surface pelagic ooze (Sample 8, Hole 506B) has a Pb isotopic composition distinct from the typical pelagic sediments of the Galapagos mounds area, but identical to the Sample 15 Mn-oxide crust. It also differs from typical Galapagos pelagic ooze in containing a significantly higher concentration (~2%) of Mn, mainly as micronodules. Possibly the small contribution of basaltic Pb in the oxidized ooze is associated in part with the Mn micronodules. Although no nontronite or Mn-oxide fragments are present in this hole, it is situated only 50 meters from Hole 506, located on a mound. A small component of basement-derived solutions could conceivably be present in the pore waters of off-mound sites, and Pb could be precipitated with Mn as upward-moving solutions pass through the oxidized surface layer.

Mn-Fe-oxide mud, found only as two 10-cm-thick layers in Cores 1 and 2 of Hole 509B, is brownish black and has a rather gelatinous appearance. The ooze consists dominantly of black Mn-oxide microaggregates, with lesser amounts of orangish-brown microaggregates, which are probably Fe oxide-hydroxides. This is the only sample in which the Pb isotopic composition corresponds to the average seawater value, indicating no basaltic contribution. It is possible that the two Mn-Fe mud layers formed at the sediment surface following discharge of Mn-Fe-rich solutions directly into seawater, rather than within the mound itself. Nevertheless, the absence of basaltic Pb is rather unexpected.

Two extraordinary Pb isotopic compositions were measured for nontronites from Core 507F-2 (Sample 13) and Core 509B-2 (Sample 17). These samples have not been included in the sediment array in Figure 1 because their Pb is too radiogenic to have been derived from midocean ridge basalts or seawater. A duplicate of Sample 17, prepared by a different analyst in the same laboratory, produced identical results. Recently, a sample from 4 cm below Sample 13 yielded a Pb composition approximately intermediate between those of Samples 13 and 17 (P. Taylor, personal communication, 1981).

In Figure 2, the Pb isotopic compositions of selected oceanic basalts and sediments are shown, together with a summary of the data in Figure 1. The two radiogenic nontronite samples are also plotted. The only plausible source for such radiogenic Pb appears to be intraplate oceanic island volcanics. Some Galapagos Island basalts (the more radiogenic of those reported by White, 1979) have ^{208}Pb and ^{206}Pb isotopic compositions similar to those of the radiogenic nontronite samples. The ^{207}Pb isotopic composition of these Galapagos Island basalts is, however, lower than that of the nontronite samples. The same observations can be made for a basalt sample from the Union Seamount in the northeast Pacific (Church and Tatsumoto, 1975). Easter Island volcanics (not shown) have a $^{208}\text{Pb}/^{204}\text{Pb}$ ratio quite similar to that of Sample 13, but both of the other isotopic ratios

are lower (Tatsumoto, 1966). Island arc or continental margin arc volcanics are not likely to have supplied ash of the appropriate composition for either of Samples 13 and 17, as such volcanics have $^{206}\text{Pb}/^{204}\text{Pb}$ ratios less than 19.1 (Doe and Stacey, 1974; Kay et al., 1978; McHugh, 1980).

Ocean island volcanics conceivably could be erupted as pyroclastic ash which could be transported by winds over long distances. Three ash layers, from 2 to 5 cm thick, have been found in Hole 158, located 550 km north of the Galapagos mounds area, at subsurface depths of 2, 15, and 20 meters (Yeats, 1973). Ash layers have been recorded from Hole 504B, Leg 69, 200 km east of the Galapagos mounds area, at subsurface depths of about 12 and 17 meters (the uppermost 10 m of sediment were not recovered) (J. Cann and M. Langseth, personal communication, 1981). In the Galapagos area, ash is present in Hole 509B at a depth of 6.3 meters, in Hole 507D at a depth of 6.5 meters and in Hole 509 at a depth of 12.0 meters. No ash was observed at depths shallower than 6.3 meters in Hole 509B or 6.5 meters in Hole 507D; however, Mn-oxide-rich and nontronitic sediments occupy most of these intervals. The radiogenic nontronite from Hole 509B (Sample 17) occurs at a depth of approximately 3.5 meters, whereas the other radiogenic nontronite, from Hole 507F (Sample 13), is from a depth of 4.0 meters. (It should be noted that the exact depth of an ash layer deposited over a large area could vary significantly, depending on the local rate of pelagic sedimentation.)

The absence of recognizable ash in other sites in the mounds area could be the result of bioturbation, as it would be expected that ash layers (as in Hole 509B) which are deposited at least 300 km from the nearest probable source area also should be deposited at the other drilled sites, which are all located within 5 km of each other. Although no ocean island volcanic rocks have been reported in the literature with isotopic values matching perfectly those of the radiogenic nontronites (particularly with respect to the $^{207}\text{Pb}/^{204}\text{Pb}$ ratio), the only mechanism which at present can be invoked to explain their composition would seem to be replacement of an ocean island-derived ash band originally contained within pelagic sediment. This proposal could be tested by Pb isotopic analysis of ash bands from near-surface sediments in the east Pacific.

The range in Pb isotopic composition of Galapagos mounds area sediments overlaps the basalt arrays from the mounds area and from the Costa Rica Rift (also part of the Galapagos spreading axis). Both the sediment and the basalt arrays are positioned slightly "higher" than some other midocean ridge basalts on the conventional isotopic plots (cf. Church and Tatsumoto, 1975; Tatsumoto, 1978).

STRONTIUM ISOTOPES

Results and Discussion

The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for five sediments and three basalts from the Galapagos mounds area are listed in Tables 1 and 2, respectively. One basalt from Site 510 was also analyzed.

Table 1. Pb and Sr isotopic composition of selected samples of nontronite, Mn-oxide crust, Mn-Fe-oxide mud, and pelagic sediments from the Galapagos mounds area, Leg 70.

Sample No.	DSDP Sample (interval in cm)	Lithology	^{206}Pb	^{207}Pb	^{208}Pb	^{87}Sr
			^{204}Pb	^{204}Pb	^{204}Pb	^{86}Sr
1	506-2-2, 69-71	Granular nontronite	18.405	15.597	38.030	0.70891 ± 4
2	506-3-1, 45-47	Granular nontronite	17.836	15.532	37.569	
3	506-4-2, 45-47	Granular nontronite	18.545	15.606	38.211	
4	506-6-2, 125-127	Granular nontronite	18.244	15.569	38.039	
5	506-6-3, 39-41	Foraminifer nannofossil ooze	18.659	15.608	38.455	
6	506-8-1, 86-88	Foraminifer nannofossil ooze	18.663	15.579	38.427	0.70909 ± 5
7	506B-1-1, 21-23	Diatomaceous nannofossil ooze	18.539	15.606	38.356	
8	506B-2-3, 12-14	Foraminifer diatom nannofossil ooze	18.700	15.595	38.522	
9	506B-5-1, 94-96	Foraminifer nannofossil ooze	18.706	15.623	38.406	
10	506C-2-1, 67-69	Mn-oxide crust	18.273	15.545	37.984	
11	506C-4-3, 40-42	Compact nontronite	18.731	15.607	38.516	
12a	507D-2-1, 52-54	Granular nontronite	18.791	15.584	38.453	
12b	Duplicate		18.776	15.576	38.416	
13	507F-2-2, 6-8	Granular nontronite	19.563	15.752	38.917	
14	507F-7-1, 77-79	Foraminifer nannofossil ooze	18.647	15.573	38.420	
15	509B-1-2, 85-90	Mn-oxide crust	18.564	15.620	38.310	0.70908 ± 6
16	509B-1-2, 133-135	Granular nontronite	18.540	15.598	38.223	
17a	509B-2-1, 44-48	Granular nontronite	19.358	15.699	38.722	0.70909 ± 4
17b	Duplicate		19.376	15.691	38.718	
18	509B-2-1, 114-118	Mn-Fe-oxide mud	18.790	15.633	38.651	0.70896 ± 7
19	509B-3-1, 100-102	Granular nontronite	18.536	15.584	38.173	
20	509B-4-3, 37-39	Granular nontronite	18.124	15.570	37.920	

In the case of the sediments, the pelagic ooze, the Mn crust, and one of the nontronites (Sample 17, 3.5 m subsurface) have identical $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.70909, 0.70908, and 0.70909. These values are equivalent to the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of modern seawater (0.70910 ± 6 ; Veizer and Compston, 1974). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for the Mn-oxide ooze is just marginally lower, while the ratio for the other nontronite (Sample 2, 6.5 m subsurface) is 0.70891. This latter value appears to be statistically distinguishable from seawater and would imply an ~3% contribution of basaltic Sr to the nontronite, given an average initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for fresh basalt of 0.70265 (see below).

It should be noted that the reason a given nontronite or manganiferous sediment can contain a distinct basaltic Pb component, but only seawater-derived Sr, is related to the relative abundances of these elements in seawater and basalt. Although the basalts contain two orders of magnitude more Sr than Pb (~120 ppm vs. ~1 ppm, Hart, 1976; Yamaguchi et al., 1977; Church and Tatsumoto, 1975; Unruh and Tatsumoto, 1976), seawater contains about six orders of magnitude more Sr than Pb (~8 ppm vs. 3×10^{-5} to 2×10^{-6} ppm, Veizer and Compston, 1974; Goldberg, 1965; C. C. Pat-

Table 2. Pb-, Sr- and O-isotopic compositions, and Rb and Sr contents of basalts from the Galapagos mounds area, Leg 70.

Sample No	DSDP Sample (interval in cm)	Lithology	Alteration ^a	$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{204}\text{Pb}}$	$\frac{^{208}\text{Pb}}{^{204}\text{Pb}}$	Rb (ppm)	Sr (ppm)	$\frac{^{87}\text{Sr}}{^{86}\text{Sr}}$	$\delta^{18}\text{O}$
1	506G-2-1, 30-33 (Piece 4)	Fine-grained sparsely Pl-Cpx phyric basalt; margin of pillow	G	18.187	15.520	37.763	0.6	60.4	0.70275 ± 5	5.8
2	507B-1-1, 46-50 (Piece 24)	Coarse-grained subophitic basalt; thin flow (~50 cm) thick; sample from middle	Nil	18.621	15.578	38.097	0.3	63.6	0.70256 ± 5	5.9
3	507F-9, CC	Glass fragments, presumably from pillow margin	Nil	18.366	15.532	38.018	1.3	59.6	—	5.7
4	508B-4-1, 3-6 (Piece 44)	Fine-grained aphyric basalt; probably margin of pillow	G	18.348	15.565	37.904	4.1	60.0	0.70278 ± 7	—
5	510-11-1, 66-70 (Piece 128)	Medium-grained moderately Pl phyric basalt; sample from ~25 cm below flow top	G	18.035	15.529	37.653	0.0	46.2	0.70263 ± 6	5.8

^a G = greenish to brownish to near-colorless smectites replacing olivine and glass, and as vesicle fillings.

^b Average $^{87}\text{Sr}/^{86}\text{Sr}$ for samples 1, 2, 4 and 5: 0.70268. Errors are 2 standard errors of the mean. Average Rb and Sr values for all 5 samples are 1.1 ppm and 58.2 ppm, respectively.

terson, in Tatsumoto, 1978). A given volume of discharging solution which had leached (or isotopically exchanged with) 1% of the Sr and Pb from an equal volume of basement would contain ~1 ppm basaltic Sr and ~0.01 ppm basaltic Pb. Mixture with an equal volume of normal seawater (or even 10 volumes of seawater) would then produce a solution dominated by seawater Sr and basaltic Pb.

The four analyzed basalts have tightly grouped $^{87}\text{Sr}/^{86}\text{Sr}$ ratios ranging from values of 0.70256 to 0.70278, with a mean of 0.70268 (Table 2). The range is outside of analytical error and may be the result of limited amounts of primary magmatic variation and/or limited seawater alteration. The mean value of 0.70268 is, however, almost indistinguishable from the mean value for fresh midocean ridge basalts of 0.70265 (Hart, 1976). The basalts also have tightly grouped oxygen isotope ratios, with a mean $\delta^{18}\text{O}$ value of $5.8 \pm 0.1\%$ (Table 2). This value is statistically indistinguishable from the average value for fresh midocean ridge basalts of $5.8 \pm 0.3\%$ (Taylor, 1968; Muehlenbachs and Clayton, 1972). The Sr- and O-isotopic data, taken together, indicate that the analyzed samples have not been affected isotopically by seawater contamination during low-temperature alteration. Therefore, the overall water/rock ratio must have been very low. By contrast, basalts recovered by the DSDP from oceanic crust of age 3.5 to 110 m.y. typically show Sr- and O-isotopic evidence of seawater alteration (cf. Yamaguchi et al., 1977; Gray et al., 1977; Hoernes and Friedrichsen, 1979; Hoernes et al., 1979; Muehlenbachs, 1979; Staudigel et al., 1979). The virtual lack of isotopic alteration of the three mounds area basalts is rather surprising, given the fact that the area represents sites of discharging/recharging solutions which have circulated through the underlying basement. One reason may be that the circulation zones are very localized, for example along certain basement fractures; the drilled sites could have been slightly removed from these zones. Another factor may be related to the young age

of the basalts. The basalts in the Galapagos mounds area are less than 1 m.y. old, and could conceivably undergo future isotopic alteration. Convective seawater circulation within the basaltic basement on the Costa Rica Rift is known to continue for up to about 5 m.y. (Anderson and Hobart, 1976).

SUMMARY

The Pb isotopic compositions of metalliferous sediments from the Galapagos mounds area define approximately linear arrays in conventional isotopic ratio plots. The arrays, which result mainly from variation in the Pb isotopic composition of nontronite, overlap the fields defined by basalts from the Galapagos mounds area and the Costa Rica Rift and are directed toward and closely approach the average Pb isotopic composition of Mn nodules. These relations indicate that the metalliferous sediments formed from solutions which contained variable proportions of basaltic Pb, introduced into pore waters by basement-derived solutions, and of normal seawater Pb.

Two nontronite samples have highly radiogenic Pb isotopic compositions which are not readily explained; a possibility may be that they represent the alteration products of volcanic ash, derived from an oceanic island. A sample of Mn-Fe-oxide mud contains only seawater Pb. One Mn-oxide crust and an oxidized surface pelagic ooze appear to contain a small contribution of basaltic Pb, while a second Mn-oxide crust contains a significant component of basaltic Pb.

The Sr isotopic compositions of the metalliferous and pelagic sediments from the Galapagos mounds area are essentially indistinguishable from the value for modern seawater. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of four basalts from sub-basement depths of <15 meters display a small range of 0.70256 to 0.70278 with an average of 0.70268, almost identical to the average value of 0.70265 for fresh midocean ridge basalts. Oxygen isotope ratios of four Galapagos area basalts have a mean $\delta^{18}\text{O}$ value of $5.8 \pm$

0.1%, also characteristic of fresh midocean ridge basalts. The Sr- and O-isotopic data indicate that the overall water/rock ratio within the uppermost basalts has been very limited.

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