Batiza, R., Storms, M.A., and Allan, J.F. (Eds.), 1995
Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 142

5. URANIUM-SERIES CHRONOLOGY OF SUBSURFACE BASALTS, 9°31′N EAST PACIFIC RISE[1]

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ABSTRACT

Mass spectrometric measurements of $^{226}Ra/^{230}Th$ and $^{231}Pa/^{235}U$ disequilibria for subsurface axial basalts recovered during Leg 142 of the Ocean Drilling Program were used to determine relative crustal residence ages for mid-ocean ridge basalt (MORB) lavas and to investigate the temporal characteristics of crustal accretion within the axial summit caldera at 9°31′N East Pacific Rise. Two core samples from the massive "ODP flow," located 0–6.6 m below surface, have lower $^{226}Ra/^{230}Th$ and $^{231}Pa/^{235}U$ activity ratios than a surface sample from this unit. The subsurface samples also have higher U, Th, and Ba concentrations, and higher Ba/Th but similar Th/U ratios relative to the surface sample. The variations in $^{226}Ra/^{230}Th$ and $^{231}Pa/^{235}U$ between the surface and subsurface samples can be attributed to differences in crustal residence age of 0.4–0.7 ± 0.3 ka and 0.3–1.3 ± 1.1 ka, respectively. Consequently, this upper extrusive unit appears to be composed of lavas with small differences in chemical composition and distinct eruption and/or magma chamber residence ages. Assuming that the oldest sample represents a stratigraphic and temporal endmember for this upper extrusive unit, a vertical accumulation rate of >10 m/ka can be estimated.

INTRODUCTION

Recent detailed geological and geophysical studies of the 9°–10° N segment of the East Pacific Rise (EPR) have revealed the diversity of crustal accretion processes at this fast-spreading ocean ridge segment (Batiza and Niu, 1992; Christeson et al., 1992; Fornari et al., 1992; Harding et al., 1993; Haymon et al., 1991, 1993; Kent et al., 1990; Perfit et al., 1991, 1994; Toomey et al., 1990). A significant step forward in understanding ocean crust formation in four dimensions occurred during Ocean Drilling Program (ODP) Leg 142 at 9°31′N EPR with the first deep-sea drilling of "zero-age" ocean crust (Batiza et al., 1992). Although initial drilling results were less than ideal due to difficulties with the diamond coring system, the first subsurface basalt samples from the axial region of an ocean ridge were obtained. Accurate isotopic dating for these samples is needed to establish a chronological framework for geochemical/petrological data and to quantify the temporal dependence of crustal processes at this site. Measurements of ^{238}U-^{230}Th (Newman et al., 1983; Goldstein et al., 1989a, 1991), ^{230}Th-^{226}Ra (Rubin and Macdougall, 1990; Volpe and Goldstein, 1993), and ^{235}U-^{231}Pa (Goldstein et al., 1993a, 1993b, 1994) disequilibria in young ocean basalts can be used to establish a precise chronology for magmatic processes at ocean ridges on a 0.1–350 ka time scale.

In this paper, I present high resolution $^{226}Ra/^{230}Th$ and $^{231}Pa/^{235}U$ isotopic data and U, Th, and Ba concentrations for three basalt samples located 0–6.6 meters below seafloor from the "ODP flow," the uppermost extrusive unit at the drill site. These data are interpreted in the context of ^{226}Ra and ^{231}Pa crustal residence ages and are used to place initial constraints on eruption ages and vertical accumulation rates for the extruded lavas.

ANALYTICAL METHODS

Procedures for mass spectrometric measurement of U, Th, and Pa isotopes in MORB are described elsewhere (Goldstein et al., 1989a, 1989b, 1991, 1993a; Pickett et al., 1994). Procedures for measurement of Ra and Ba are based on those from Volpe et al. (1991), with the following major exceptions: ^{134}Ba tracer was used to determine Ba concentrations by isotope dilution, and Ra-Ba separations were accomplished by solid-phase extraction chromatography using a crown ether (Horwitz et al., 1991). All ion exchange separations were performed under gravity flow.

Analytical accuracy was verified by measurement of a rock standard, TML, with known Th/U and $^{230}Th/^{238}U$, $^{226}Ra/^{230}Th$, and $^{231}Pa/^{235}U$ in secular equilibrium. Measured values for the TML standard agree with equilibrium or those obtained previously at Los Alamos. Procedural blanks were <1 pg for U and Th, ~10 ng for Ba, and <0.2 fg for Pa and are negligible. Blanks for Ra were ~0.4 fg and require a 1%–3% correction to the measured data.

SAMPLES

Sample A2358-4 was collected from the surface of the massive "ODP flow" during site surveys by ALVIN in 1991. The two core samples represent a mixture of material from 0–6.6 m below the seafloor. Exact locations of these samples are unknown, but since mixing of material within the core was probably incomplete, Sample 142-864A-1M-6 likely consists of deeper material than Sample 142-864A-1M-3 (R. Batiza, pers. comm., 1993).

RESULTS

U, Th, and Ba concentration data are presented in Table 1, and $^{226}Ra/^{230}Th$ and $^{231}Pa/^{235}U$ activity ratios and crustal residence ages are presented in Table 2. U, Th, and Ba concentrations, Th/U and Ba/Th ratios, and $^{226}Ra/^{230}Th$ and $^{231}Pa/^{235}U$ activity ratios are typical of axial N-MORB from 9°–10°N EPR (Goldstein et al., 1993a; Volpe

[1] Batiza, R., Storms, M.A., and Allan, J.F. (Eds.), 1995. *Proc. ODP, Sci. Results*, 142: College Station, TX (Ocean Drilling Program).

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Table 1. U-Th-Ba concentrations and ratios.[a]

Sample	U (ppb)	Th (ppb)	Ba (ppm)	Th/U (wt)	Ba/Th (wt)
A2358-4[b]	68.00	168.8	10.24	2.482	60.67
142-864A-					
1M-3, 35–55 cm	68.23	169.7	10.69	2.487	63.00
1M-6, 0–75 cm	68.89	171.3	10.91	2.486	63.72

[a] 2-sigma errors in U, Th, and Ba concentrations <0.5%, and errors in Th/U and Ba/Th = 0.4%. Blanks for U, Th, and Ba are <1 pg, <1 pg, and ~10 ng, respectively, and are negligible.
[b] U-Th data for A2358-4 from Goldstein et al. (1993a).

Table 2. $^{226}Ra/^{230}Th$ and $^{231}Pa/^{235}U$ activity ratios and ages.[a]

Sample	$(^{226}Ra)/(^{230}Th)$[b] (activity)	$(^{231}Pa)/(^{235}U)$ (activity)	^{226}Ra age (ka)	^{231}Pa age (ka)
A2358-4[c]	2.249 ± 0.077	2.539 ± 0.030	0	0
142-864A-				
1M-3, 35–54 cm	2.068 ± 0.051	2.531 ± 0.019	0.4 ± 0.3	0.2 ± 1.1
1M-6, 0–75 cm	1.910 ± 0.057	2.498 ± 0.018	0.7 ± 0.3	1.3 ± 1.1

[a] Ages for core samples calculated relative to surface sample A2358-4. Blanks for ^{231}Pa and ^{226}Ra are <.1 fg and ~0.4 fg, respectively. All errors are 2-sigma.
[b] Calculated using a $^{230}Th/^{238}U$ activity ratio of 1.14 ± 0.02 as measured by mass spectrometry.
[c] $^{231}Pa/^{235}U$ data for A2358-4 from Goldstein et al. (1993a).

and Goldstein, 1993). The two subsurface samples have higher U, Th, and Ba concentrations and lower $^{226}Ra/^{230}Th$ and $^{231}Pa/^{235}U$ ratios than the surface sample. Th/U ratios for the subsurface samples are identical within error of the surface sample, whereas the two core samples have higher Ba/Th than the surface sample. Differences between surface and subsurface samples are generally small, ranging from 0.4%–1.3% for U, 0.5%–1.4% for Th, 4.4%–6.6% for Ba, 0.2% for Th/U, 3.8%–5.0% for Ba/Th, 0.3%–1.6% for $^{231}Pa/^{235}U$, and 8.0%–15.1% for $^{226}Ra/^{230}Th$. However, when compared to estimated errors of <0.5% for U, Th, Ba, Th/U, and Ba/Th, ~1% for $^{231}Pa/^{235}U$, and ~3% for $^{226}Ra/^{230}Th$, it is apparent that at least part of the variations between the surface and subsurface samples are statistically significant for all parameters except Th/U and possibly $^{231}Pa/^{235}U$.

DISCUSSION

The uniform Th/U ratios and large ^{226}Ra and ^{231}Pa activity excesses for these samples permit determination of relative crustal residence ages for these lavas with relatively high resolution (Goldstein et al., 1993a, 1993b, 1994). Based on their constant Th/U ratios, all three samples are inferred to have been derived from a uniform source, and the initial $^{226}Ra/^{230}Th$ and $^{231}Pa/^{235}U$ ratios upon melting and transport to the crust should be similar for all of the samples. If initial $^{226}Ra/^{230}Th$ and $^{231}Pa/^{235}U$ ratios are uniform, the variations in $^{231}Pa/^{235}U$ and $^{226}Ra/^{230}Th$ can be attributed to differences in crustal residence age, which is the sum of the magma chamber residence age and eruption age (Goldstein et al., 1994).

Crustal processes that fractionate parent/daughter abundances may also complicate the crustal age modeling and interpretations of the data. For example, variations of ~5% for Ba and Ba/Th are greater than expected based on the more uniform Th, U, and Th/U data, if Ba, Th, and U behave as highly incompatible elements during petrogenesis. Decoupling of Ba/Th and Ba concentrations from the Th/U, Th, and U data may be due to plagioclase fractionation in axial magma chambers, since plagioclase contains significant amounts of the alkaline earths Ba and Ra but negligible amounts of the actinides U, Th, and Pa. The varying Ba/Th but constant Th/U for these lavas may reflect small differences in plagioclase abundance in the erupted lavas and/or variations in plagioclase crystallization and retention in the axial magma chamber(s) from which the lavas were derived.

If differences in Ba/Th are due to plagioclase fractionation in the axial magma chamber, $^{226}Ra/^{230}Th$ ratios would also be affected. Assuming similar partition coefficients for Ba and Ra, $^{226}Ra/^{230}Th$ would increase by ~5% for the subsurface samples relative to the surface sample. After correction for plagioclase fractionation, variations in $^{226}Ra/^{230}Th$ of the lavas would then be slightly (~5%) greater than indicated by the measurements. Hence, crustal age differences between surface and subsurface samples based on the measured $^{226}Ra/^{230}Th$ data may underestimate the real age differences by a small extent (~0.2 ka).

^{226}Ra and ^{231}Pa crustal residence age differences between the subsurface and surface samples are 0.4 and 0.2 ka for Sample 142-864A-1M-3 and 0.7 and 1.3 ka for Sample 142-864A-1M-6. Estimated 2-sigma errors in ages are 0.3 ka for ^{226}Ra and 1.1 ka for ^{231}Pa, so most of the age differences are statistically significant. Although assumptions of uniform initial $^{226}Ra/^{230}Th$ and $^{231}Pa/^{235}U$ are important in the crustal age modeling, the uniform Th/U ratios and agreement between ^{226}Ra and ^{231}Pa ages provide support for the existence of small age differences between the samples. Consequently, this upper extrusive unit appears to be composed of lavas with slight variations in chemical composition and small but significant differences in eruption and/or magma chamber residence age.

Assuming that the oldest sample (142-864A-1M-6) represents a stratigraphic and temporal endmember within this upper extrusive unit, a vertical accumulation rate of ~10 m/ka can be estimated based on the ^{226}Ra ages. Because part of the age differences can be attributed to varying magma chamber residence times, this estimated accumulation rate is likely a lower limit. In comparison, a mean accumulation rate of 30 m/ka is calculated assuming a 60-m-deep extrusive layer (Christeson et al., 1992), a 200-m-wide zone of emplacement corresponding to the width of the axial summit caldera, and a mean half spreading rate of 5.5 cm/yr. This may indicate that the eruption interval for this unit is less than 0.7 ka (i.e., 0.2 ka), the accumulation rate for the upper unit is not the steady-state rate, or the recent spreading rate is lower than the steady-state rate. More data from subsurface samples are needed to more accurately determine long-term accumulation rates and distinguish among these possible explanations.

CONCLUSIONS

Two subsurface samples from the massive "ODP flow" have progressively lower $^{226}Ra/^{230}Th$ and $^{231}Pa/^{235}U$ activity ratios than a surface sample from this unit. The subsurface samples also have higher U, Th, and Ba concentrations, and higher Ba/Th but similar Th/U ratios relative to the surface sample. The apparent decoupling of Ba/Th and Th/U variations in these samples may be due to effects of plagioclase crystallization and fractionation in the axial magma chamber.

The variations in $^{226}Ra/^{230}Th$ and $^{231}Pa/^{235}U$ between the surface and subsurface samples can be explained by differences in crustal residence age of up to 0.7 ka for ^{226}Ra and 1.3 ka for ^{231}Pa. Although numerous assumptions are involved in determining crustal residence ages on a ~1 ka time scale, uniform Th/U ratios and agreement between ^{226}Ra and ^{231}Pa ages provide support for the accuracy of the model. Consequently, the "ODP flow" appears to be composed of lavas with small variations in chemical composition and distinct eruption and/or magma chamber residence ages. Assuming that the oldest sample represents a stratigraphic and temporal endmember for this upper extrusive unit, a vertical accumulation rate of >10 m/ka can be estimated.

ACKNOWLEDGMENTS

I thank D. Pickett and M. Murrell for laboratory assistance, R. Batiza and M. Perfit for helpful discussions, and NSF-JOI-USSAC for financial support.

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Date of initial receipt: 1 October 1993
Date of acceptance: 11 August 1994
Ms 142SR-115

*Abbreviations for names of organizations and publications in ODP reference lists follow the style given in *Chemical Abstracts Service Source Index* (published by American Chemical Society).