^{226}Ra and ^{231}Pa systematics of axial morb, crustal residence ages, and magma chamber characteristics at 9–10°N East Pacific Rise

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Introduction

Mass spectrometric measurements of ^{230}Th-^{226}Ra and ^{235}U-^{231}Pa disequilibria for axial basalts are used to determine crustal residence ages for MORB magma and investigate the temporal and spatial characteristics of axial magma chambers (AMC) at 9–10°N East Pacific Rise (EPR). Relative crustal residence ages (eruption + magma chamber residence ages) can be calculated from variations in ^{226}Ra/^{230}Th and ^{231}Pa/^{235}U activity ratios for axial lavas, if 1) mantle sources and melting are uniform, and mantle transfer times are constant or rapid for axial N-MORB, and 2) ^{231}Pa/^{235}U and ^{226}Ra/^{230}Th in the melt are unaffected by shallow level fractional crystallization. Uniform Th, Sr, and Nd isotopic systematics and incompatible element ratios for N-MORB along the 9–10°N segment (Goldstein *et al.*, 1993; Harpp *et al.*, 1990; Batiza and Niu, 1992; Perfit *et al.*, 1991) indicate that mantle sources and transfer times are similar. In addition, estimated bulk solid/melt partition coefficients for U, Th, and Pa are small, hence effects of fractional crystallization on ^{231}Pa/^{235}U ratios for the melt are expected to be negligible. However, fractional crystallization of plagioclase in the AMC would lower ^{226}Ra/^{230}Th ratios in the melt and produce a positive bias in ^{226}Ra crustal residence ages for fractionated lavas.

Results

Based on initial data, ^{226}Ra/^{230}Th activity ratios for N-MORB recovered from along the axial summit caldera range from ~2.8 to 2.0. Highest ^{226}Ra/^{230}Th (2.8) and ^{231}Pa/^{235}U (2.71) activity ratios are found for relatively mafic lavas (Mg# = 64) at the recently erupted tubeworm BBQ site at 9°50′N, whereas lower ^{226}Ra/^{230}Th (2.0-2.2) and ^{231}Pa/^{235}U (2.54-2.64) activity ratios are characteristic of more fractionated samples (Mg# = 58-62) from the remainder of the segment. The variations among axial samples correspond to crustal residence age differences of 0-1.4 ± 0.2 ka for ^{226}Ra and 0–5 ± 2 ka for ^{231}Pa.

Two subsurface (0-6.6m deep) samples from the ODP Leg 142 site (9°31′N) have progressively lower ^{226}Ra/^{230}Th and ^{231}Pa/^{235}U ratios than surface samples at this location. The variations between surface and sub-surface samples of the 'ODP flow' correspond to differences in crustal residence age of up to 0.7 ka for ^{226}Ra and 1 ka for ^{231}Pa. These results indicate that this relatively chemically homogeneous unit is composed of lavas with distinct eruption and/or magma chamber residence ages. Because the exact depth of the subsurface samples is not known, and only a few samples from a very limited depth range were analyzed, only a rough estimate for the vertical accumulation rate (> ~10 m/ka) can be obtained from these data. In comparison, a steady-state value of 30 m/ka can be calculated based on the present width of the axial summit caldera and estimates of the thickness of seismic layer 2A (Christeson *et al.*, 1992).

Discussion

In comparing ^{226}Ra and ^{231}Pa crustal residence ages, it is apparent that ^{226}Ra ages are about an order of magnitude more precise. This reflects the more appropriate half-life of ^{226}Ra (1.6 ka) relative to ^{231}Pa (33 ka) for dating axial magmatic processes. Differences between ^{226}Ra and ^{231}Pa crustal residence ages for surface lavas are small, but lie slightly outside estimated errors at the 2-sigma level. These slightly discordant ages are most likely due to subtle variations in initial $^{231}Pa/^{235}U$ along axis, but could also reflect additional processes fractionating $^{226}Ra/^{230}Th$ or $^{231}Pa/^{235}U$ in magma chambers. On this time scale, ^{226}Ra ages are much less sensitive to small source variations or magma chamber fractionations, and so ^{226}Ra ages should generally be more accurate than ^{231}Pa ages. However, effects of plagioclase crystallization on ^{226}Ra ages can be significant, and so ^{226}Ra age differences are likely an upper limit.

Estimates of eruption age based on sediment cover and lava appearance are mostly < 100 a for the axial lavas (Haymon *et al.*, 1991), consequently most of the variation in ^{226}Ra and ^{231}Pa crustal residence age for surface samples can be attributed to differences in AMC residence time. Absolute AMC residence ages for MORB lavas can be calculated by extrapolation of the $^{226}Ra/^{230}Th$ and $^{231}Pa/^{235}U$ data to zero crystallization at Mg# = 71. Assuming a linear relationship between melt residence time and extent of crystallization, initial $^{226}Ra/^{230}Th$ and $^{231}Pa/^{235}U$ activity ratios for unfractionated lavas are 3.6 and 2.9, respectively. Based on these initial activity ratios, AMC melt residence times for the axial lavas range from 0.9-2.3 ka for ^{226}Ra and 4–9 ka for ^{231}Pa, with typical values of 2 ka for ^{226}Ra and 6 ka for ^{231}Pa. If crystallization rates increase with extent of crystallization and AMC age, then initial $^{226}Ra/^{230}Th$ and $^{231}Pa/^{235}U$ ratios and AMC melt ages will be greater than those determined for the linear crystallization model.

Average crystallization and cooling rates from the ^{231}Pa and ^{226}Ra data are 6–24%/ka and 8-30°C/ka, respectively. The crystallization rates are consistent with crystal growth rates on the order of 10^{-13} cm/s, at least 2 orders of magnitude smaller than values measured for Hawaiian lava lakes (Kirkpatrick, 1981; Cashman and Marsh, 1988). Using the lava lake crystal growth rates, AMC melt residence times of < 2 a are obtained from plagioclase phenocryst zonation for lavas at 9°31′N EPR (Brophy and Allan, 1993). However, AMC residence times of ~10 ka have been estimated based on thermal modeling of a large, hydrothermally cooled AMC (Lister, 1983). Model ^{226}Ra and ^{231}Pa AMC residence times are similar to ^{226}Ra dates of ~ 3 ka for recently erupted plagioclase phenocrysts from continental calc-alkaline magmatic systems such as Mt. Erebus (Reagan *et al.*, 1992) and Mt. St. Helens (Volpe and Hammond, 1991).

Melt volumes can also be approximated from this model, assuming a steady-state AMC. For typical melt residence times of 2 ka for ^{226}Ra and 6 ka for ^{231}Pa, average steady state AMC melt volumes are 1 and 4 km^3/km ridge, respectively. These estimated steady-state melt volumes are smaller than estimated melt volumes for the entire AMC (melt lens + mush zone + transition zone) of ~4–6 km^3/km ridge based on recent seismic/petrologic (Sinton and Detrick, 1992) and ophiolitic models (Nicolas *et al.*, 1993). However, they are larger than estimated volumes of ~0.5 km^3/km ridge for the melt lens alone. These differences in melt volume may indicate limited mixing between the melt lens and mush/transition zones of the AMC, with erupted lavas derived primarily from the melt lens. Inefficient mixing between different parts of the AMC is also suggested by the variation in crustal residence ages along axis as well as seismic and geochemical data. The ^{226}Ra data, and to a larger extent the ^{231}Pa data, are broadly consistent with a segmented magma chamber and crustal accretion model in which highest supply rates and lowest crustal residence times are found at bathymetric minima.

References

Batiza, R., and Niu, Y. (1992) *J. Geophys. Res.*, **97**, 6779–97.

Brophy, J.G., and Allan, J.F. (1993) *Trans. AGU, Fall Meeting Suppl.*, **74**, 644.

Cashman, K.V., and Marsh, B.D. (1988) *Contrib. Mineral. Petrol.*, **99**, 292–305.

Christeson, G.L., Purdy, G.M., and Fryer, G.J. (1992) *Geophys. Res. Lett.*, **19**, 1045–8.

Goldstein, S.J., Murrell, M.T., and Williams, R.W. (1993) *Earth Planet. Sci. Lett.*, **115**, 151–9.

Harpp, K., White, W.M., and Batiza, R. (1990) *EOS*, **71**, 658.

Haymon, R.M., Fornari, D.J., Edwards, M.H., Carbotte, S.C., Wright, D., and Macdonald, K.C. (1991) *Earth Planet. Sci. Lett.*, **104**, 513–34.

Kirkpatrick, R.J. (1981) In *Kinetics of Geochemical Processes* (Lasaga, A.C. and Kirkpatrick, R.J., eds.), Reviews in Mineralogy, 8, Mineralogical Society of America, pp. 321–98.

Lister, C.R.B. (1983) *Geophys. J. R. Astr. Soc.*, **73**, 351–65.

Nicolas, A., Freydier, Cl., Godard, M., and Vauchez, A. (1993) *Geology*, **21**, 53–6.

Perfit, M.R., Fornari, D.J., Smith, M., Langmuir, C., Bender, J., and Haymon, R. (1991) *EOS*, **72**, 491.

Reagan, M.K., Volpe, A.M., and Cashman, K. (1992) *Geochim. Cosmochim. Acta*, **56**, 1401–7.

Sinton, J.M., and Detrick, R.S. (1992) *J. Geophys. Res.*, **97**, 197–216.

Volpe, A.M., and Hammond, P.E. (1991) *Earth Planet. Sci. Lett.*, **107**, 475–86.