Radioactive disequilibria from two-dimensional models of melt generation in plumes and ridges

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Introduction

The half-lives of ^{230}Th, ^{226}Ra and ^{231}Pa are 75400 years, 1600 years, and 33000 years respectively, compared to mantle convection timescales of millions of years. The systems ^{238}U-^{230}Th-^{226}Ra and ^{235}U-^{231}Pa are thus in secular equilibrium in mantle material which has remained unmelted for this time. The relative concentrations of ^{238}U, ^{230}Th and ^{226}Ra, ^{235}U and ^{231}Pa can be calculated from their half-lives, and provide an important constraint on source geochemistry. The activity ratio (Daughter/Parent)$= \lambda_d C_d/\lambda_p C_p$, where $\lambda = \ln(2)/t_{\frac{1}{2}}$, and C_d, C_p are daughter and parent concentrations. Thus the activity ratios (^{230}Th/^{238}U), (^{226}Ra/^{230}Th) and (^{231}Pa/^{235}U) are all one in such a closed system.

Recent observations of (^{230}Th/^{238}U) are usually > 1 for recent lavas. Measurements of (^{226}Ra/^{230}Th) and(^{231}Pa/^{235}U) are strikingly high in some cases. The accuracy of these measurements has increased dramatically recently with the use of mass spectrometry.

The excess daughter isotope is explained by the longer residence time of the parent in the matrix, compared to that of the daughter. If the parent has a higher partition coefficient than the daughter, its extraction from the matrix is retarded, and the (Daughter/Parent) activity ratio in the melt can be > 1. The total extent of melting becomes irrelevant, (provided it is greater than the partition coefficients) and the important factor is the melting rate. Experiments [1,2,3,4] have shown that $D_U > D_{Th}$ for garnet peridotite, but not for spinel peridotite. Therefore, beneath mid-ocean ridges, some melting must occur in the garnet peridotite field, otherwise the (^{238}U/^{230}Th) ratio of MORB would be < 1 [1,4]. D_{Ra} and D_{Pa} are not known, due to experimental difficulties. However, extrapolation from other group II elements suggests D_{Ra} is very small ($\sim 10^{-6}$). D_{Pa} is also expected to be small ($\sim 10^{-5}$).

Models to date [5,6,7,8,9], have dealt with one dimensional systems. In this study, the activity ratios for melts produced in the garnet peridotite stability field are calculated for two dimensional models of plumes and ridges, using a simplified model of melt extraction. The results show that it

is possible to reproduce the values of (^{226}Ra/^{230}Th) and (^{230}Th/^{238}U) observed in recently erupted basalt from Hawaii with this simple model. Melting at the periphery of a plume structure is very slow, and can result in melts with high (Daughter/Parent) activity ratios. Two dimensional models of mid-ocean ridges with several variable parameters (angle, spreading rate, melt gradient) show that the activity ratio is largely determined by the mean melting rate, Γ.

Simple two-Dimensional models

The melting regions beneath ridges and plumes can be approximated more accurately in two dimensions than in one. An important feature of both ridges and plumes is that the mantle upwelling velocity decreases away from the centre. Simple one dimensional melting models often use an average upwelling velocity to evaluate radioactive excesses. Without calculating the 2D solution, it is not clear whether using the average upwelling velocity in a 1D solution gives the correct results. In the case of plumes, the average upwelling velocity is not as easily defined as it is for ridges. Therefore 2D calculations are required. In order to calculate melt compositions, 2D temperature and velocity fields for the region of interest are needed. These can be analytic, or obtained from numerical experiments. For plumes, the flow and temperature fields used were those of Watson and McKenzie [10], chosen by them as the best model fits to melt production, residual depth anomaly and geoid. These were generated by a two-dimensional axisymmetric convection code [11]. For mid-ocean ridges, the flow-field used was an analytic solution for corner flow, with variable angle and spreading rate [12]. The temperature field chosen for ridges had a constant potential temperature of 1280°C.

A simplified extraction model was used, similar to that of McKenzie [5]. No extraction of melt occurs until the melt fraction exceeds some small amount ϕ_0. Above that amount, extraction takes place via a channel where there is no chemical equilibration with the matrix. All melt in the channel is assumed to be well mixed, and to have

negligible transit time to the surface. The two-dimension model can thus be reduced to a number of one dimensional problems which involve solving the equations for chemical equilibrium and radioactive decay, given melt fraction as a function of pressure and temperature on streamlines. For a radiogenic isotope, the expressions are complicated, because its concentration depends on the melting history.

Results

Extensive geochemical observations are available from Hawaii. Recent measurements of $(^{226}Ra/^{230}Th)$ and $(^{230}Th/^{238}U)$ by mass spectrometry give values of 1.1–1.2 and 0.98–1.02 respectively, for historical eruptions of Kilauea [13]. We used the same parameterization of melt fraction with pressure and temperature as Watson & McKenzie to calculate the activity ratios for $(^{226}Ra/^{230}Th)$ and $(^{230}Th/^{238}U)$. The predicted $(^{230}Th/^{238}U)$ lies between 1.02 and 1.04 and varies little with ϕ_0. It is close to unity because the melting rate is fast compared to the decay rate of ^{230}Th. In contrast, $(^{226}Ra/^{230}Th)$ reaches values of up to 1.5, indicating slow melting compared to ^{226}Ra decay. The observed activity ratios are consistent with our calculations if the separation melt fraction, $\phi_0 \sim 0.1\%$. Even if the melting rate is much slower, ϕ_0 must be less than 0.3%. For ridges, we used an analytic solution for corner flow, which depends on two parameters, α, the angle of the lower plate boundary to the vertical, and v_x, the spreading rate. Because the activity ratios are governed by the small melt fractions present at the onset of melting, the main factor controlling their value should be the mean initial melting rate. This argument gives values of the activity ratios that agree well with those from the full two dimensional calculations at high melting rates, and is not far from the truth at low melting rates. We have shown that the initial melting rate is constrained by $(^{230}Th/^{238}U)$ to be less than 8×10^{-8} yr^{-1}. The $(^{226}Ra/^{230}Th)$ data constrain the transport time of the melt to the surface to be short compared to the half-life of ^{226}Ra, or 1600 years.

Conclusions

The $(^{230}Th/^{238}U)$ data require at least the first few percent of melt to be generated in the garnet stability field. We have shown that the observed $(^{230}Th/^{238}U)$ and $(^{226}Ra/^{230}Th)$ ratios in Hawaiian magmas can be produced by a simple model with a melting parameterisation that is consistent with laboratory experiments. The melt fraction at which the melt separates from the matrix is around 0.1%. Melt with the highest activity ratios is expected to come from the edge of the plume, where melting is slowest. These melts mix with the main volume of melt, and affect the overall activity ratio. The main factor determining the activity ratio for mid-ocean ridges is the mean initial melting rate Γ. A melting rate of $0 < \Gamma < 8 \times 10^{-8}$ yr^{-1} is required to generate the observed ratios of $(^{230}Th/^{238}U)$ of 1.1–1.2 in MORB. The observed values of $(^{226}Ra/^{230}Th)$ require that the principal means of melt transport to the surface is by flow in channels much larger than the pore size, rather than by percolation.

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