

G4 Igneous Petrology and Geochemistry Option Assessed Exercise.

Chemical and Isotope Evolution of the Mantle-Crust System.

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Abstract:

The evolution of the crust mantle system can be modelled utilising a forward-modelling approach whereby hypotheses regarding components of the crust-mantle are made. These proposals are then modelled using equilibrium melting equations and results from phase diagrams, and finally these results are compared with actual rock compositions. These results show that the Earth's mantle has been depleted by the formation of the continental crust, corresponding to 1-2% of melting of between 28-56% of the primitive mantle. Some inherent errors probably have a bearing on the results.

Introduction.

A very major concern of geochemistry since the 1960's has been the study of the composition and evolution of the Earth's mantle. This has come about because of the establishment of the plate tectonic geological tenet, which implies that the process is driven by solid-state convection in the mantle. A result of this is that the internal differentiation history of the mantle can be ascertained from studies of the chemical signal brought to the surface in melts. The first important point is that the two most common types of volcanism, mid-ocean-ridge type and ocean-island type show a distinct geochemical difference in their basalts. The geological settings together with the geochemical character of these two forms of basalt suggest that there is a chemical layering within the mantle. This may reflect the extraction of the continental crust at some point in the Earth's history, as is believed to be the case. The wide variety of geochemical compositions seen in ocean-island basalts (OIB) when compared with the much more homogeneous mid-ocean-ridge basalts (MORB) suggests that the upper layer of the mantle is well mixed compared with the lower layer. The standard composition of MORB, together with the difficulty in modelling the composition of the continental crust, due to the re-inclusion of material through sedimentary and metamorphic effects, means that the best way to reveal the evolution of the crust-mantle system is to model the composition of normal MORB (N-MORB) over a range of possible conditions. Because the composition and the degree and depth of melting of the mantle source control the composition of a basalt at the surface, the latter

factor should reveal the former properties. However the deduction of this is not a simple single-stage process, instead requiring a trial-and-error modelling approach. This is done by hypothesising about the controlling parameters, calculating the effects of this, and then comparing the results with actual observations.

The rare-earth-elements (REE) are extremely useful for modelling the depth and degree of melting of a mantle source. This is the result of a combination of factors: their chemical properties vary according to their atomic number, and their charge and size make them strongly incompatible to moderately compatible in mantle phases; in garnet, the light REE's are incompatible and the heavy REE's compatible, so that the presence or absence of a particular set of REE's can reflect the presence or absence of garnet, giving an indication of depth, and the relative concentration can divulge the degree of melting. Other mantle phases have their characteristic REE signature and so knowledge of these, as with garnet, can inform us about the source domain. The most widely used REE's are Sm and Nd as they are parent and daughter in the radioactive decay $^{147}\text{Sm} \rightarrow ^{143}\text{Nd}$ with a half life of 1.06×10^{11} yr. Sm is more compatible than Nd (Hofmann, 1997) so that the relative concentrations of radiogenic $^{143}\text{Nd}/^{144}\text{Nd}$ may be used to test models of the long-term evolution of the crust-mantle. This is because Neodymium's relative incompatibility means that the Earth's initial budget of the stable 144 isotope goes preferentially into a melt, along with a small amount of decayed Sm. At the same time Sm remains in the residue of melting, so that the relative ratio of decayed product to stable isotope is a higher value than the same ratio in the melt.

Calculation of REE Abundances in mantle melt and residues.

The calculations presented here assume equilibrium melting, ignoring the effects of fractional melting. In order to calculate REE abundances in an amount of melt the following formula (equation 1) is used:

$$C_L/C_0 = 1/(D + F - PF)$$

Where C_L is the concentration in the magma, C_0 is the concentration in the source (primitive mantle in this case), D is the bulk distribution coefficient (solid/liquid concentration) for any mantle chemical element (calculated by the sum of the products of distribution coefficient and proportion by mass, for each mineral phase), P is the distribution coefficient weighted according to contribution to the melt (calculated by the sum of the products of distribution coefficients and proportion of phase introduced, for each mineral phase), and F is the melt fraction. Figure 1 shows the calculated concentrations (based on Appendix: Table 3) of REE's with atomic numbers 57 to 71 for deep mantle melt fractions of 0.5%, 1%, 5%, and 10% relative to values obtained from chondritic meteorites (assumed to correspond to the bulk Earth), to be the upper four trends. These show that the calculated melt fraction concentration of lighter REE's is substantially higher than the value for the bulk Earth, with the concentration decreasing roughly linearly with increasing atomic number. Higher melt fractions are still enriched but less so, decreasing with increasing fraction, and display the same linear trend. This reflects the fact that lighter incompatible REE's would be expected to go into the melt first, with the heavier incompatibles becoming involved as more of the mantle becomes involved, to take the place of earlier-removed light REE's. The lower four trends in figure 1 show the calculated concentrations of REE's in the residual mantle after extraction of each melt fraction, again relative to chondritic concentrations (Appendix: Table 5).

These values were calculated using the following (equation 2):

$$C_0 = FC_L + (1-F)C_R$$

Where C_R is the concentration in the residue, and the other terms are the same as for the previous equation.

Although it might be expected that the most enriched melt fraction would result in the most depleted residue, this is not the case. In fact the opposite trend is produced, with the lowest melt

fraction residue showing least depletion and the highest fraction showing most. This is because the lower trends reflect the absolute depletion of the residues, so that the smallest melt fraction,

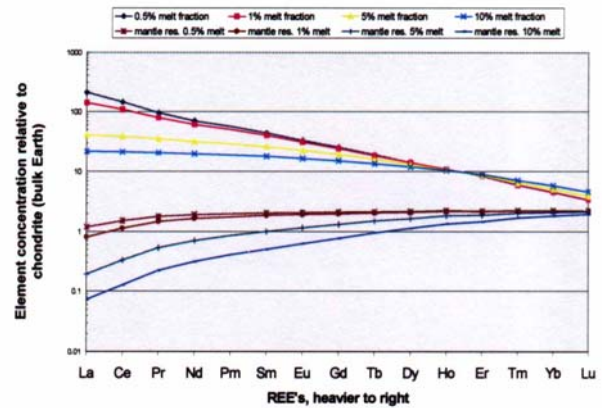


Figure 1. Concentrations of REE's relative to chondritic values (\approx bulk Earth) for 0.5%, 1%, 5%, and 10% deep mantle melt fractions, and the corresponding residual mantle concentrations.

although relatively enriched in light REE's, has only removed a quantitatively small amount of light REE's, where a 10% melt fraction has removed a relatively low, but quantitatively high amount.

Calculating MORB REE Abundances.

The model to be tested assumes that MORB is generated by partial melting of mantle depleted by extraction of the crust. Thus the next stage is to calculate REE concentrations in melts generated from the mantle residues left after the initial stage of melting. It is believed that MORB's are the result of shallow mantle melting (spinel lherzolite), so melting of spinel lherzolite was modelled. To produce the necessary 7 Km of ocean crust from adiabatic decompression of normal temperature mantle requires about 12% melt (McKenzie & Bickle, 1988), followed by 20% fractional crystallisation of olivine, before eruption. The 12% melt was modelled using equation 2 again with the non-normalised first-stage residual mantle values. The concentration of REE remaining in the fractionated melt was then evaluated using the following (equation 3):

$$C_f/C_p = F^{D-1}$$

Where F is the fraction of melt remaining after crystallisation, C_f is the concentration in the fractionated melt, C_p is the concentration in the primary magma, and D is the bulk distribution coefficient of the crystallising phase(s) (olivine in this case). Figure 2 shows the results of the four modelled 3-stage evolved MORB's, relative to average MORB (N-MORB) (Appendix: Table 8). It shows that compared to N-MORB

(corresponding to 1 on the y-axis), a modelled initial melt fraction of 1% corresponds most closely to N-MORB, although visual estimation suggests that a value closer to 2% is closer to the actual composition, these values corresponding to extraction of the oceanic crust.

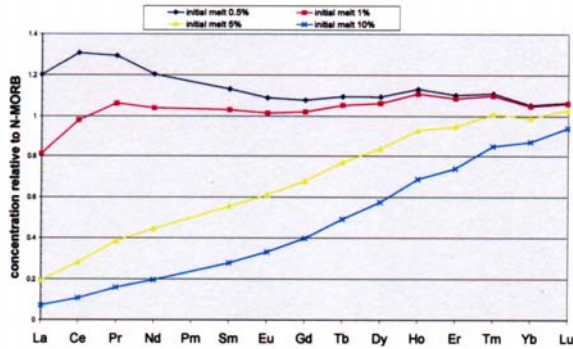


Figure 2. REE concentrations for four modelled MORB's normalised to N-MORB.

These conclusions are dependent on the measured *D* values, which contain higher proportional errors for higher values, and it is therefore wise to use the mid to heavy REE's than on the lightest ones. In the light of this, a case could be made for choosing an initial melt fraction of 5% rather than the lower value chosen here.

Isotopic Implications.

In this section the observation that the average age of mantle differentiation is about 2 billion years (Taylor & McLennan, 1985), is used to test how much melt has been extracted from the mantle to form the continental crust. The initial value and the value at 2 Ga of $^{143}\text{Nd}/^{144}\text{Nd}$ for the bulk Earth was calculated using the following (equation 4):

$$\left(\frac{^{143}\text{Nd}}{^{144}\text{Nd}}\right)_0 = \left(\frac{^{143}\text{Nd}}{^{144}\text{Nd}}\right)_i + \frac{^{147}\text{Sm}}{^{144}\text{Nd}}(e^{\lambda t} - 1)$$

Where $\frac{^{147}\text{Sm}}{^{144}\text{Nd}} = 0.6045 \frac{\text{Sm}}{\text{Nd}}$

$\left(\frac{^{143}\text{Nd}}{^{144}\text{Nd}}\right)_0$ is the ratio measured today ($t=0$), $\left(\frac{^{143}\text{Nd}}{^{144}\text{Nd}}\right)_i$ is the initial ratio at time t , and λ is the decay constant of ^{147}Sm . The present day average of chondritic meteorites was used as a value for the present day bulk Earth. Equation 4 was then used to calculate the $^{143}\text{Nd}/^{144}\text{Nd}$ today of 0.5%, 1%, 5%, and 10% partial melts of primitive mantle generated at 2 Ga, together with their respective residues. Figure 3 shows the results of these calculations (Appendix: Table 9), with $^{143}\text{Nd}/^{144}\text{Nd}$ ratios displayed as a function of time for the bulk Earth and for the melt fractions and residues listed above. The value for MORB measured today is between 0.5130 and 0.5132, and examination of figure 3 shows that the residual mantle values for melts of 1% and 5% are

closest to the present day MORB value. The overall behaviour of the modelled melts and residues can be described with reference to the behaviour of the Sm – Nd system outlined in the introduction. Assuming continental crust formation at 2 Ga, the evolution of Nd ratios in mantle melts shows a high concentration of ^{144}Nd relative to ^{143}Nd so that the gradient of the trend is reduced, the effect increasing with increasing melt fraction. Conversely the evolution of Nd ratios in the residual mantle components shows a lower concentration of ^{144}Nd relative to ^{143}Nd with earlier removal of the stable isotope and retention of the radioisotope parent.

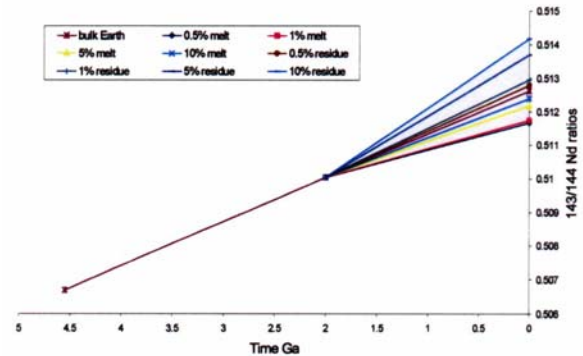


Figure 3. Properties of melt fractions and residues Assuming 2 Ga age of continental crust.

The observation that the continental crust formed at 2 Ga is questioned by some authors (Hofmann, 1997) and for this reason figure 4 has been included to show the effects of varying the age of continental crust formation by 0.5 Ga (Appendix: Table 9).

Only trends for 1% and 5% removed residues at 2.5 Ga, 2 Ga, and 1.5 Ga are displayed as the other residual trends are outwith the values for MORB today. Examination of the trends reveals that based on this type of modelling, a viable argument could be made for choosing a continental crust age within a range of at least 1 billion years, assuming that somewhere between 1% and 5% removed residue corresponds to today's MORB.

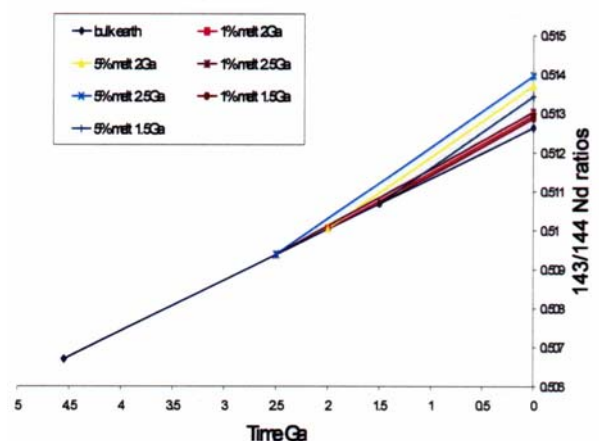


Figure 4. Effects of varying the age of continental crust by +/- 0.5 Ga

Conclusions.

The $^{143}\text{Nd}/^{144}\text{Nd}$ melt fraction trends illustrated in figure 3 reflect the enrichment of the continental crust in incompatible elements. This has occurred at the expense of the mantle (melt-removed residual trends in figure 3). From the modelled MORB and Nd ratio trends, I think 1-2% of the primitive mantle melted to form the continental crust. From the data of Jacobsen & Wasserburg (1979) which estimates the relative masses of different components of the mantle and crust, it is possible to calculate whether the crust was extracted from the whole mantle or part of it. They estimate the mass of the mantle plus crust to be 403.4×10^{25} g. This corresponds to the primitive mantle. They also estimate the mass of the continental crust to be 2.256×10^{25} g. Thus the continental crust is $(2.256 \times 10^{25} / 403.4 \times 10^{25}) \times 100\% = 0.56\%$ of the primitive mantle. This suggests that the modelled figures obtained in the previous sections are too high. Alternatively it could reflect the fact that not all of the mantle has been used in creation of the continental crust. This is best illustrated by considering two cases, a melt fraction of 1% and a melt fraction of 2%. If 1% of the whole mantle melted, this would correspond to a continental crust mass of 4.034×10^{25} g, but as noted above, its mass is 2.256×10^{25} g. This corresponds to 56% of the mass of a 1% melt. For a melt of 2% the figure drop to 28%, so my estimate of between 1-2% melting would require the involvement of 28-56% of the mantle.

Limitations involved in the calculations include the use of equations related to equilibrium melting which do not take any fractional melting into account. Also the calculation of atomic ratio of Sm/Nd from mass ratio used in equation 4 is only an approximation which does not take the variable isotopic composition of Nd into account. As mentioned earlier in the text, bulk distribution coefficients include errors which are largest for the lighter REE's so my conclusions regarding choice of melt percent closer to 1% than 5% could be questioned.

References.

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