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A GENERAL MIXING EQUATION WITH APPLICATIONS TO ICELANDIC BASALTS

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The mixing equation applied by Vollmer [1] to Pb and Sr isotope ratios is shown to be a general equation applicable to consideration of element and isotope ratios. The mixing equation is hyperbolic and has the form:

$$Ax + Bxy + Cy + D = 0$$

where the coefficients are dependent on the type of plot considered: i.e. ratio-ratio, ratio-element, or element-element. Careful use of this equation permits testing whether mixing is a viable process, places constraints on end member compositions, allows distinction between mixing of sources and mixing of magmas, and should allow distinction between recent mixing and long-term evolution of sources.

The available chemical data for postglacial basalts from Iceland and along the Reykjanes Ridge are not consistent with either mixing of magmas or simple mixing of an enriched ocean island source with a depleted ocean ridge source. If the available analyses for basalts are representative of the source regions, the data are consistent with at least two models neither of which can be properly tested with the available data.

(1) There are two separate mixing trends: one beneath Iceland with the alkali basalt source and a depleted Iceland source as end members; the second along the Reykjanes Ridge with a heterogeneous ocean ridge basalt source and a source similar to that for intermediate basalts on Iceland as end members. The depleted Iceland source and the depleted ocean ridge source are not the same.

(2) The chemistry of the basalts is not determined by mixing. Instead the basalts are derived from a multiplicity of sources with a similar history which have been isolated for hundreds of millions of years.

1. Introduction

With the increased precision and facility of new analytical methods, geochemists are becoming increasingly concerned with evaluating the role of mixing in the petrogenesis of suites of igneous rocks. Mathematical equations describing the mixing process have been developed by numerous authors [1–5]. In most cases, these equations are not of a general nature and are best suited to specific applications.

While there is no problem depicting mixing in element versus element plots, some confusion exists concerning what constitutes a mixing curve when a ratio is plotted against an element or another ratio. This paper presents the mixing equations for three possible plots in a two-component system, i.e. ratio-ratio, ratio-element, and element-element, and ways to test for mixing and to place limits on the composition of end members. Only the mixing of two components will be considered here for illustrative purposes. The

n dimensions necessary to evaluate n end members requires consideration of hyperbolic surfaces, volumes, etc., of mixing.

2. The general mixing equation and its modifications

Vollmer [1, p. 295] developed a mixing equation for considering variations in the $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ ratios found in alkali basalts from southern Italy. This equation is generally applicable to plots of both isotopic and elemental ratios. It is a general mixing equation for two components and is a hyperbola of the form:

$$Ax + Bxy + Cy + D = 0 \qquad (1)$$

Symbols used are: x, y = general variables along the abscissa and ordinate, respectively; x_i, y_i = coordinates of data point i; a_i = denominator of y_i ($a_i = 1$ if y is an element); b_i = denominator of x_i ($b_i = 1$ if x is an element); A, B, C, D = coefficients of the general variables x and y; and r = a ratio related to coefficient B which reflects the extent of hyperbolic curvature of a mixing curve.

The coefficients A, B, C and D of equation (1) are a function of the type of plot. A mixing curve for each type of plot may be calculated through any two typical data points which are well separated. End member compositions are not necessary for calculating mixing curves. Indeed, constraints on the end member compositions can be obtained from the data.

2.1. Ratio-ratio plots

When using ratio-ratio plots (e.g. K/Rb-Ba/Sr or $^{87}Sr/^{86}Sr$-$^{206}Pb/^{204}Pb$) the coefficients of equation (1) are from Vollmer [1].

$$\begin{aligned} A &= a_2b_1y_2 - a_1b_2y_1 \\ B &= a_1b_2 - a_2b_1 \qquad\qquad r = a_1b_2/a_2b_1 \qquad (2) \\ C &= a_2b_1x_1 - a_1b_2x_2 \\ D &= a_1b_2x_2y_1 - a_2b_1x_1y_2 \end{aligned}$$

The mixing curve resulting from this equation is a hyperbola whose curvature is controlled by the B coefficient. The numerical value of r is a function of the extent of the curvature between two points and of the overall curvature of the hyperbolic curve. If $r = 1$, then the mixing curve is a straight line. If $r \neq 1$, the sense of the hyperbolic curvature (concave up or concave down) is dependent on the relative concentrations of a and b in the end members. Two possible examples are given in Fig. 1. As r becomes progressively greater than or less than 1, the hyperbolic form of the function becomes more pronounced. To estimate the curvature of a given set of data the value of

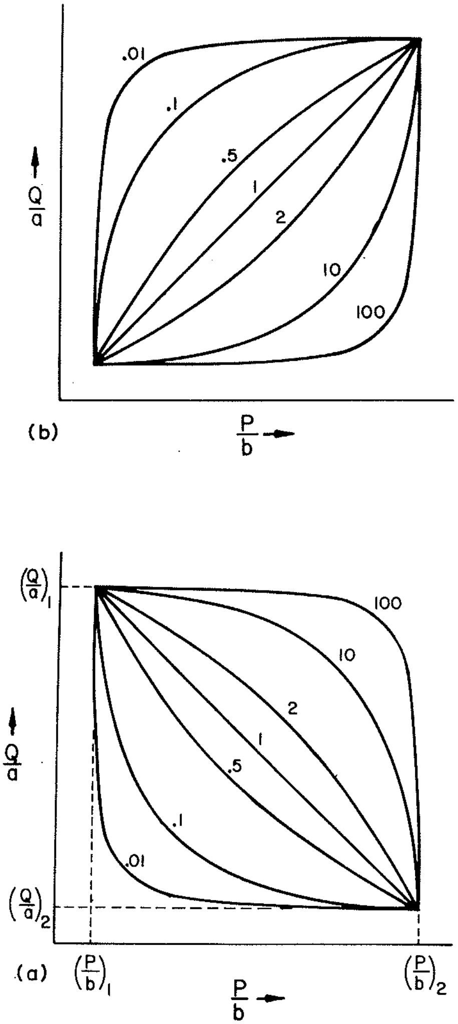

Fig. 1. Plots of ratios of elements or isotopes, Q/a versus P/b, for the mixing of end members 1 and 2. The numbers along the curves are the values for r (see equation 2). Fig. 1a and 1b show two different possible positions for end members 1 and 2.

r should be determined for samples as widely separated as possible.

The asymptotic nature of a curve can be used to determine either a minimum or maximum value for one of the ratios in each end member. No more than two of the four end member ratios may be asymptotically constrained in any one plot. If a ratio is used in more than one plot, however, it may be possible to obtain both minimum and maximum values for that ratio. The constraints on the actual values of the end members depend on the extent of the hyperbolic curvature: the greater the curvature, the more rigorous the constraints. Of course, the intercept of any curve as one ratio goes to zero places a minimum or maximum value on the other ratio.

2.2. Ratio-element plots

When plotting an element along the ordinate and a ratio along the abscissa (e.g. K/Rb vs. Sr), $b = 1$ and the coefficients for equation (1) become:

$$\begin{aligned} A &= a_2y_2 - a_1y_1 & & \\ B &= a_1 - a_2 & b &= 1 \\ C &= a_2x_1 - a_1x_2 & r &= a_1/a_2 \\ D &= a_1x_2y_1 - a_2x_1y_2 & & \end{aligned} \qquad (3)$$

This equation is also a hyperbolic function controlled by the B coefficient. As in the ratio-ratio plots, a straight line results if $r = 1$. Applying the same reasoning developed earlier, minimum or maximum values for the elemental concentrations or ratios of end members may be specified by consideration of asymptotes and intercepts on various plots.

2.3. Element-element plots

Mixing produces straight lines on element-element plots. The coefficients for equation (1) are:

$$\begin{aligned} A &= y_2 - y_1 & & \\ B &= 0 & a &= b = 1 \\ C &= x_1 - x_2 & r &= 1 \\ D &= x_2y_1 - x_1y_2 & & \end{aligned} \qquad (4)$$

3. Guidelines for the use of mixing equations in igneous petrogenesis

For a suite of samples, the evaluation of mixing as a geologic process may be complicated. In addition to simple mechanical mixing, it may be necessary to consider processes such as partial melting of mixed sources, differentiation, contamination, or alteration. All of these may obscure or destroy simple mixing relations. As an aid to the rigorous application of a mixing model, guidelines are given below outlining some of the areas requiring special attention. In general, to adequately test for mixing, a broad spectrum of high-quality isotopic and elemental data on the same samples must be available. Averages of data or analyses combined from different samples are not appropriate.

3.1. Appearance of data when plotted

On a ratio-ratio and ratio-element plot, data consistent with mixing will lie along a hyperbolic curve for both isotopic and elemental ratios. A linear relation occurs when the ratios of the concentrations of the two denominators are the same for all data points, i.e. $r = 1$, or if the data lie along an asymptote. In the latter case r may be significantly greater or less than one. For ^{87}Sr/^{86}Sr-^{87}Rb/^{86}Sr and ^{207}Pb/^{204}Pb-^{206}Pb/^{204}Pb, and ^{87}Sr/^{86}Sr-1/^{86}Sr plots, the denominators (^{86}Sr or ^{204}Pb) for both ratios are identical and thus mixing produces straight lines.

3.2. Tests for mixing

If the data appear to be consistent with some mixing model, mixing curves should be calculated for the appropriate plots. A mixing curve can be calculated using any two data points which are representative and well separated.

All of the elemental and isotopic data for a suite of samples must be consistent to substantiate mixing, so all plots of appropriate elements and isotopes should conform to mixing curves. Furthermore, the individual samples should maintain the same relative relationship to one another on all plots, because the order of the data points is a function of the extent of mixing which is the same regardless of the plot used.

Even if the data lie near a mixing curve, the agreement may be fortuitous and apply solely to the two points chosen to calculate the curve. Since the overall curvature of a mixing curve is dependent on the ratios of the denominators of each end member, all intermediate points should have the ratios of their denominators proportionately intermediate to the two end member values. To test the consistency of the denominator ratios, a companion plot may be constructed by plotting one of the original ratios versus the ratio of the denominators of the two original ratios. For example, plots of P/a versus b/a, or Q/b versus a/b are companion plots for the ratio-ratio plot P/a versus Q/b. If the mixing curve on the original plot applies to all the data, the data will plot as a straight line on the companion plot. Then the mixing curves calculated from one pair of data points on the original ratio-ratio or ratio-element plot will be the same as the mixing curves from all other pairs of data points. In many cases, companion plots (i.e. both axes have the same denominator) may be the best plots to use to test for mixing, because on companion plots mixing results in linear trends.

3.3. Constraints on end members

Once the validity of a mixing curve is established, the best mixing hyperbola may be calculated by using a least squares fit of the linear data on the companion plot. While the shape of the mixing curve is optimized by this procedure, its placement on the original plot is not unique and must be fitted to the data. The asymptotes and intercepts on the hyperbolic plots or the intercepts on companion plots may then be used to constrain end members.

3.4. Mixing of magmas versus mixing of sources

When mixing is involved, the difference in behavior between slightly compatible and incompatible elements may allow a determination of whether mixing occurred in the source before separation of magma (mixing of sources) or between magmas after their separation from their sources (mixing of magmas). This distinction is possible because partial melting and differentiation do not affect the ratios of incompatible elements. Therefore, ratio-ratio plots involving exclusively incompatible elements should show mixing relations for both mixing of magmas and mixing of sources. Partial melting and differentiation will offset the ratio of a slightly compatible element to an incompatible element. Thus, if a ratio-ratio plot of isotopes or incompatible elements shows a mixing trend while one with a slightly compatible/incompatible ratio does not, mixing of sources rather than mixing of magmas is suggested.

In a similar way, incompatible element-incompatible element plots will show linear arrays for mixing of magmas but not for mixing of sources because of the effects of different degrees of partial melting and differentiation. To test a ratio for mixing of sources each of the elements should be normalized to a third incompatible element. For examples, K/Ba-Rb/Ba is a normalized ratio plot for K/Rb. Normalized ratio plots should show linear data arrays both for mixing of magmas and mixing of sources.

It must be stressed that a close correlation of calculated mixing curves with data are permissive arguments for geologic mixing. In themselves, these equations cannot prove the existence of mixing; they can only verify or refute it as a possible process.

3.5. Mantle evolution versus recent mixing: applications of the mixing equation to isotope systematics

A problem with the interpretation of isotopic data has been the impossibility of distinguishing between mixing and evolution lines on conventional isochron plots. Straight lines on isochron plots are produced both by recent mixing of two sources and by evolution through time of many sources which had initially the same isotope ratio and different parent/daughter ratios (closed system evolution). This section presents a method for discriminating between these two possibilities. The basis of the method is that the shape of a data array on an isotope ratio-isotope ratio plot with different denominators on each axis depends on different element ratios for closed system evolution and for mixing. Using the Nd and Sr systems as an example, on a $^{87}Sr/^{86}Sr$-$^{143}Nd/^{144}Nd$ plot the shape of a data array derived from closed system evolution depends on the Sm/Nd and Rb/Sr ratios, while the shape of a data array caused by mixing depends on the Nd/Sr ratio, because this ratio controls the B coefficient of the mixing equation.

The first step is to examine the data on an isotope ratio-isotope ratio plot (e.g. $^{87}Sr/^{86}Sr$-$^{143}Nd/^{144}Nd$). Excessive scatter suggests that the systems developed independently in heterogeneous sources. A tight fit about a curve would suggest that the two systems evolved together controlled by similar events or processes. Two simple possibilities are: recent mixing of two sources, and evolution through time of a multiplicity of sources which were originally homogeneous in their isotope ratios.

If there is a definite trend of the data on an isotope ratio-isotope ratio plot, the parent/daughter ratios for the isotope systems should be plotted against one another (e.g. Rb/Sr-Sm/Nd). Excessive scatter on this plot shows that recent processes probably have controlled the trace element distributions. If the data have little scatter, they should be checked to see if they, through time, could have given rise to the isotope ratios, assuming an initially homogeneous source. For example, a linear array on a $^{87}Sr/^{86}Sr$-$^{143}Nd/^{144}Nd$ plot requires a linear array of fixed slope (but not fixed location) on a Sm/Nd-Rb/Sr plot irrespective of the time involved. This is true if the ancient source was initially homogeneous in its isotope ratios and if recent processes have not seriously affected the parent/daughter ratio. Curved data arrays are more complicated to treat quantitatively, but the sense of curvature can be qualitatively checked for agreement.

If the parent/daugher plot is consistent with the isotopes, conventional isochron plots for each radiometric system should yield similar ages. Even if the ages agree, the next step should be to calculate mixing curves for both the isotope and parent/daughter plots, and to make companion plots (e.g. Nd/Sr-$^{87}Sr/^{86}Sr$, Nd/Sr-Rb/Sr) to check the mixing curves, since ancient mixing would yield data arrays consistent with both the models of evolution of a multiplicity of sources and recent mixing of two sources.

In these ways, the data are checked for consistency with closed system evolution and mixing models. If the data are consistent only with mixing then the mixing end members have had independent histories through two or more fractionation events. If the data are consistent with both mixing and evolution, mixing may be ancient or recent. If the data are consistent with evolution but not with mixing, then the ancient formation of heterogeneous sources from a former homogeneous source by a non-mixing process is suggested.

4. Iceland and the Reykjanes Ridge

Mixing models have been proposed for basalt petrogenesis along the ocean ridges around ocean islands to account for the observed chemical variations [6]. Iceland and the Reykjanes Ridge have been the site of the most intensive study [5–11]. At least two sources are involved: a depleted source along the ridge far from Iceland, and a relatively enriched source beneath and near Iceland. The question is what processes at what time(s) have controlled the chemistry of the intermediate samples. Schilling's model [6] is recent mixing of an enriched ocean island source with a depleted ocean ridge source. O'Nions et al. [8] suggest a multiple-source model with no mixing where the heterogeneities in the basalts occurred during fractionation events in the mantle greater than 200 m.y. ago. Hart and Schilling [9], O'Nions et al. [8], and Schilling [12], have evaluated mixing of magmas and conclude that it is too simple a model to explain all the data.

Data from three different sets of samples from postglacial basalts from Iceland and the Reykjanes Ridge will be used to test the various models. Schilling [6], Hart et al. [7] Sun et al. [5] and S.R. Hart (unpublished data) have analyzed samples from the Reykjanes Ridge and its extension onto Iceland for Sr and Pb isotope ratios, K, Rb, Ba, Sr, Cs and rare earth elements (REE). O'Nions et al. [8,11,19] have analyzed other samples primarily from Iceland for Sr and Nd isotope ratios, REE and Sr. Sun and Jahn [10] have analyzed still other samples from Iceland for Pb and Sr isotope ratios. Interlaboratory comparison of $^{87}Sr/^{86}Sr$ data [7,10,13] shows the data of O'Nions et al. [8,11] to be approximately 0.00011 higher on the same samples. For comparison purposes the data of O'Nions et al. have been lowered by 0.00011. We will consider first the data of O'Nions et al. [8,11,19], then the other data [5–7,10].

4.1. $^{87}Sr/^{86}Sr$-Ce/Yb: evidence against magma mixing on Iceland

The $^{87}Sr/^{86}Sr$ and Ce/Yb data were plotted by O'Nions et al. [8, p. 326] and are replotted here with a mixing curve added (Fig. 2a). Although the tholeiitic data appear to lie on a mixing curve, the companion plot (Fig. 2b) shows enough scatter to suggest the mixing curve is not valid. This plot demonstrates that mixing of magmas is probably not an important process for the Iceland-Reykjanes Ridge tholeiites, and particularly for the alkali basalts since they plot off the mixing curve. This agrees with the conclusion of O'Nions et al. [8] who suggested that the alkali basalts could not be involved in magma mixing. But, while the ^{87}Sr/^{86}Sr-Ce/Yb plot refutes magma mixing, it does not refute mixing of mantle sources prior to final melting, because Yb is a slightly compatible element if any garnet, clinopyroxene or orthopyroxene remain in the residue.

4.2. ^{87}Sr/^{87}Sr-La/Ce: evidence for source mixing on Iceland

The ^{87}Sr/^{86}Sr-La/Ce plot (Fig. 3a), using data from O'Nions et al. [8], should test mixing of sources because both La and Ce are incompatible. It shows a

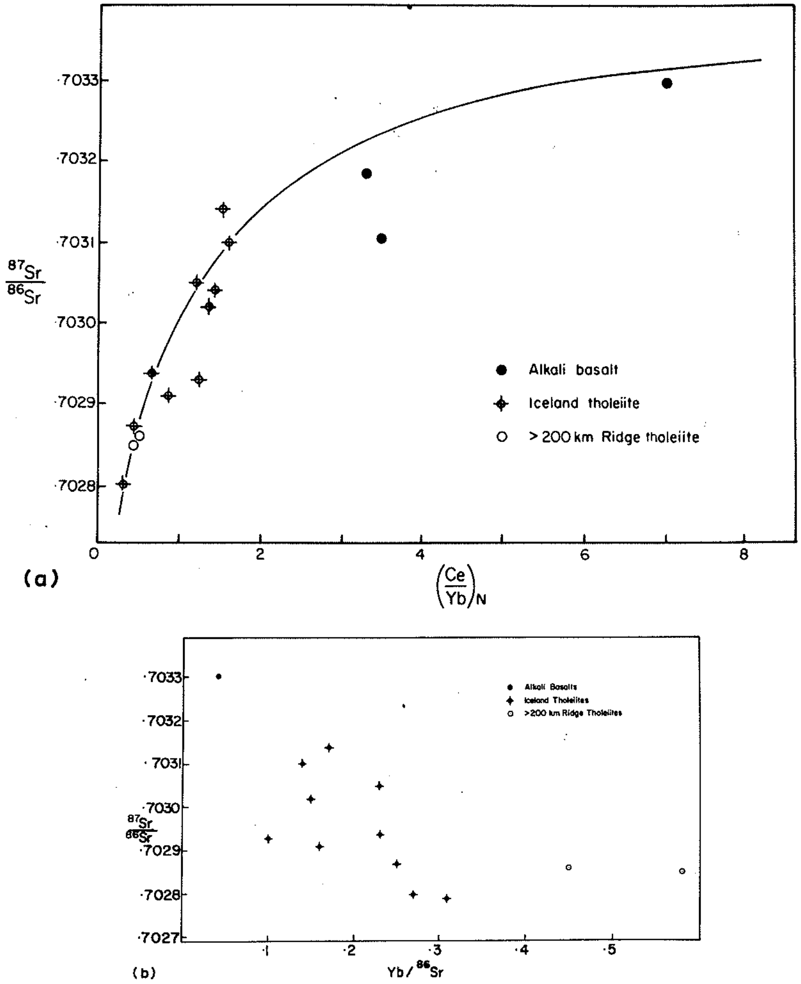

Fig. 2. (a) Plot of ^{87}Sr/^{86}Sr versus the chondrite-normalized Ce/Yb ratio for basalts from Iceland and along the Reykjanes Ridge within and greater than 200 km from Iceland and a mixing curve. (b) Companion plot of ^{87}Sr/^{86}Sr versus weight Yb/^{86}Sr ratio. Data from O'Nions et al. [8,11]. The analytical uncertainty in ^{87}Sr/^{86}Sr at two sigma is reported to be about 0.00006 and in the element ratios it is probably about 5%. On the companion plot, ^{87}Sr/^{86}Sr-Yb/^{86}Sr, the scatter of the data is much greater than the analytical uncertainty.

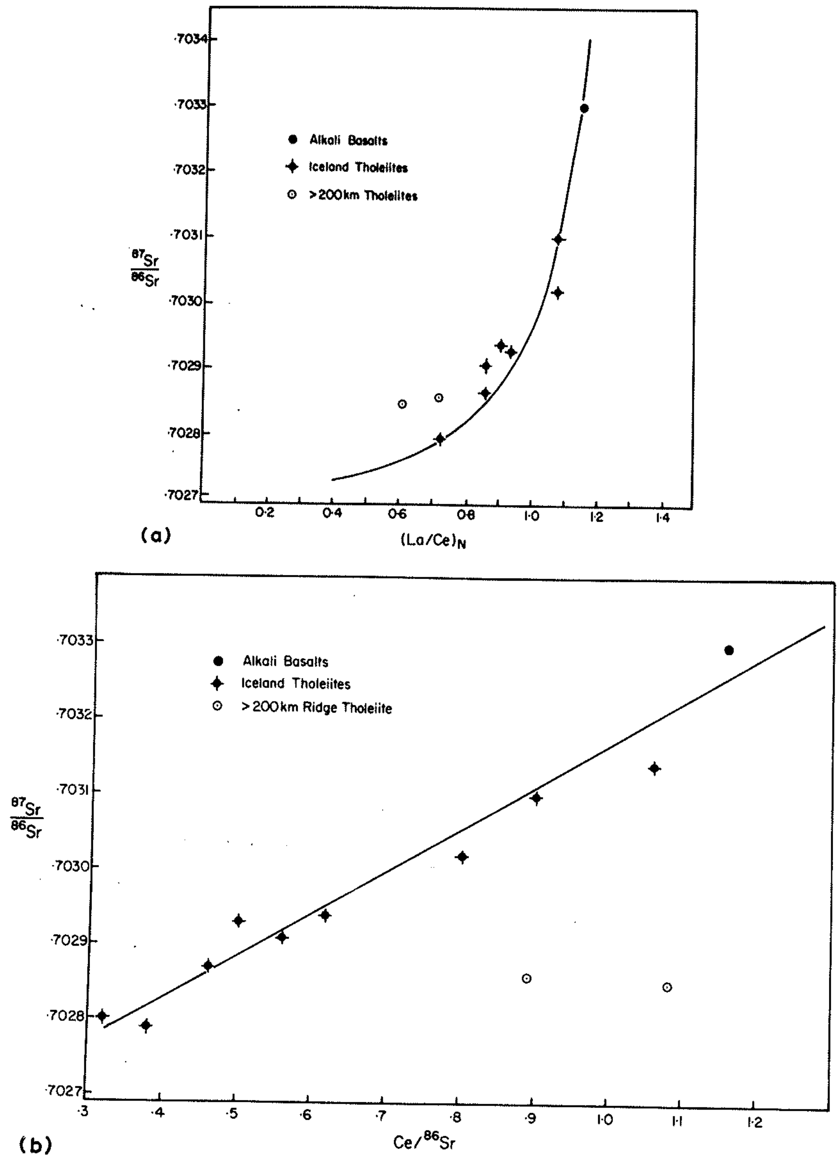

Fig. 3. (a) Plot of $^{87}Sr/^{86}Sr$ versus La/Ce for basalts from Iceland and along the Reykjanes Ridge with a mixing curve. (b) Companion plot of $^{87}Sr/^{86}Sr$ versus $Ce/^{86}Sr$. Data are from O'Nions et al. [8]. The analytical uncertainties are the same as those reported in Fig. 2. The Iceland data on the companion plot lie within the analytical uncertainty of the mixing lines. The two samples from greater than two hundred kilometers from Iceland along the Reykjanes Ridge plot well off the line.

fairly good fit of the data to the mixing curve. The companion plot (Fig. 3b) shows a good linear correlation with the exception of the two samples from greater than 200 km south along the Reykjanes Ridge. The asymptotes and intercepts of the mixing curves give a minimum $^{87}Sr/^{86}Sr$ ratio of 0.70270 for the more depleted source and a maximum (La/Ce) ratio of 1.28 for the enriched source. The basalts further south along the Reykjanes Ridge have $^{87}Sr/^{86}Sr$ ratios as low or lower than 0.70263 [7,14] which is lower than the y intercept on the $^{87}Sr/^{86}Sr$-La/Ce plot. These plots suggest that if mixing of sources is important for the Iceland basalts, the Reykjanes Ridge basalt source greater than 200 km from Iceland is not the depleted source component.

4.3. Evaluation of mixing along the Reykjanes Ridge

Although the O'Nions et al. data [8,11] suggest that the source represented by the Reykjanes Ridge samples greater than 200 km from Iceland probably is not involved in the mixing taking place beneath Iceland itself, the Reykjanes Ridge samples collected by Schilling do show trends on relevant plots which are compatible with mixing of a depleted ocean ridge source with a source similar to an *intermediate* source on Iceland represented by basalts on the extension of the Reykjanes Ridge onto the Reykjanes peninsula.

Rb-Rb/K (Fig. 4a,b). This plot should show a perfect mixing relation only for mixing of magmas. Although mixing of magmas is ruled out by element-element plots (see Hart and Schilling [9] and Schilling [12] all samples lie fairly close to a mixing curve on both the Rb-Rb/K plot and its companion plot (1/K-Rb/K). Melting and differentiation processes appear to be causing a variation of about a factor of two in Rb abundance for a given Rb/K ratio.

The generally good fit of the mixing curve could be accounted for in at least two ways:

(1) If the tholeiites are generated by similar extents of partial melting within a factor of two, then a plot of the sources on a Rb-Rb/K plot would have the same shape as the plot of the basalt data. This would be consistent with two-component mixing of an alkali basalt-like source with a depleted ocean ridge basalt source.

(2) The extent of partial melting could be inversely correlated with the extent of source enrichment, i.e. the least amount of melting is associated with the most enriched, alkali basalt source, while the most melting occurs in the most depleted source.

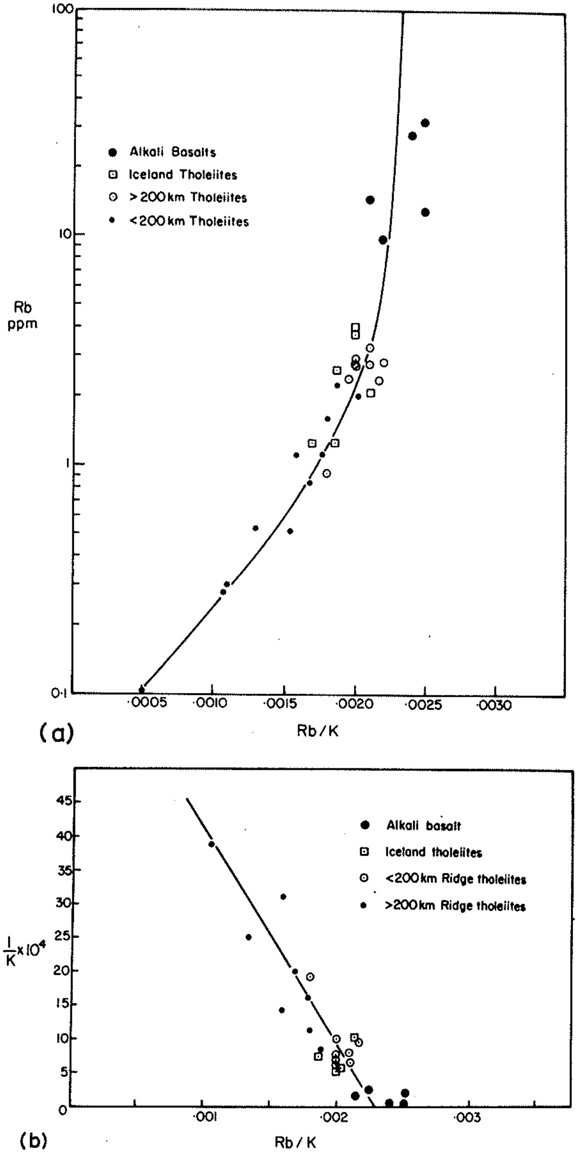

Fig. 4. (a) Plot of Rb/K versus Rb for samples from the Reykjanes Ridge and its extension onto Iceland and for alkali basalts from Iceland with a mixing curve. Note that the plot is semilogarithmic. (b) Companion plot of Rb/K versus 1/K. Analytical uncertainties are ±3%. All data are from S.R. Hart (unpublished).

$^{206}Pb/^{204}Pb$-Rb/K (Fig. 5). Although the mixing line in Fig. 5 follows the trend of the data, there is enough scatter to suggest heterogeneity in the source regions in addition to mixing. Unfortunately, companion plots cannot be made because Pb abundance data is lacking except for a few of the samples. In general, plots of Pb isotopes versus the available trace element data seem compatible with two-component source mixing for the Reykjanes Ridge samples.

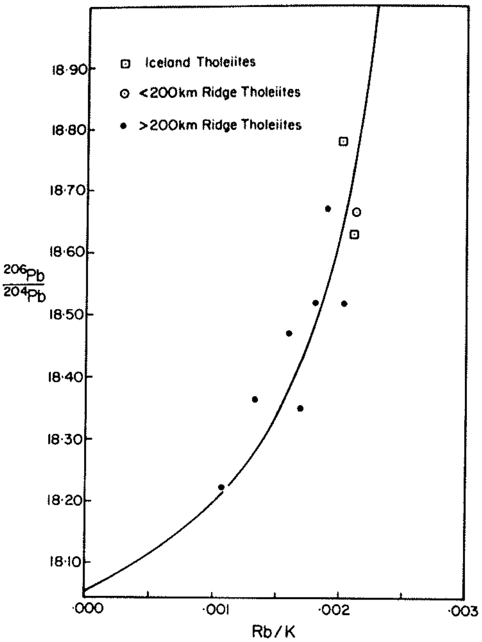

Fig. 5. Plot of $^{206}Pb/^{204}Pb$ versus Rb/K with a mixing curve for samples from the Reykjanes Ridge and its extension onto Iceland. $^{206}Pb/^{204}Pb$ data have an analytical uncertainty of ±0.1%. Data from Sun et al. [5] and S.R. Hart (unpublished).

$^{87}Sr/^{86}Sr$-Rb/K (Fig. 6). As pointed out by Hart and Schilling [9] and Hart et al. [7], the $^{87}Sr/^{86}Sr$ data do not follow a smooth trend down the Reykjanes Ridge. Instead, they seem to be divided into two groups with an irregular boundary between them about 200–250 km down the ridge. Those beyond 200 km have $^{87}Sr/^{86}Sr$ ratios of 0.7026–0.7028, while those within 200 km have ratios of 0.7029–0.7031. While the samples with higher $^{87}Sr/^{86}Sr$ ratios form a tight group, the samples with lower $^{87}Sr/^{86}Sr$ ratios show more scatter, with a variation of almost a factor of two in La/Sm, Rb/K, and Ba/K for a given $^{87}Sr/^{86}Sr$ ratio. For a given trace element ratio, $^{87}Sr/^{86}Sr$ varies from about 0.7027 to 0.7030.

Although the Sr isotope data appear less compatible with mixing than the Pb isotopes, this may be due in part to the small range in $^{87}Sr/^{86}Sr$ observed in the samples. The Pb and Sr isotopes and the trace element data suggest that if mixing is occurring, the ocean ridge end member, where most of the scatter is observed, is heterogeneous, particularly in the Pb and Sr isotopes.

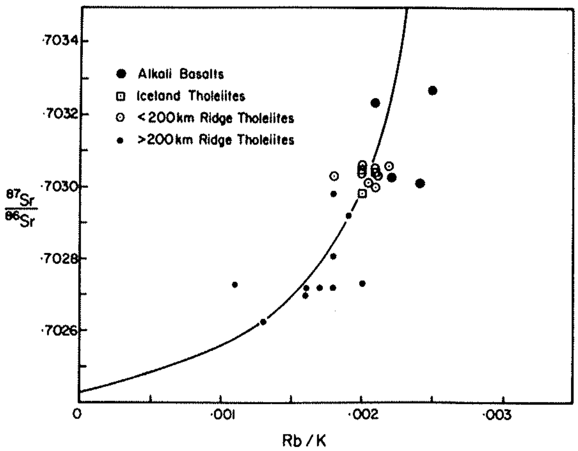

Fig. 6. Plot of $^{87}Sr/^{86}Sr$ versus Rb/K for samples from the Reykjanes Ridge and its extension onto Iceland and for alkali basalts. The mixing curve was calculated using K/Sr = 4 for the lowest $^{87}Sr/^{86}Sr$ samples and K/Sr = 8 for samples with $^{87}Sr/^{86}Sr$ = 0.70305. Data from Hart et al. [7] and S.R. Hart (unpublished).

Could Reykjanes Ridge mixing include the most enriched source on Iceland? On most plots, the data from alkali basalts from Iceland are near the mixing trends of the Reykjanes Ridge basalts. Exceptions are plots of $^{87}Sr/^{86}Sr$ versus the Pb isotope ratios and Pb isotope ratios versus 1/Pb. On the $^{87}Sr/^{86}Sr$-$^{206}Pb/^{204}Pb$ plot (Fig. 7), the mixing curve curves away from the alkali basalts. The sense of curvature, however, depends on the Sr/Pb ratio of one sample from far down the Reykjanes Ridge, and more Sr and Pb data are needed.

On the $^{206}Pb/^{204}Pb$-1/Pb plot (Fig. 8) the alkali basalts have too high a $^{206}Pb/^{204}Pb$ ratio to fall on the mixing curve for the Reykjanes Ridge and Reykjanes peninsula basalts. We can conclude that if Pb and Sr are nearly incompatible during melting, the alkali basalt source on Iceland does not contribute significantly to mixing along the Reykjanes Ridge, except insofar as it may contribute to the chemistry of the Reykjanes peninsula end member.

4.4 Effects of processes other than mixing

The key assumption in these arguments is that we can infer the chemistry of the source region through the chemistry of the basalts. To evaluate this assumption, the effects of plagioclase fractionation, residual

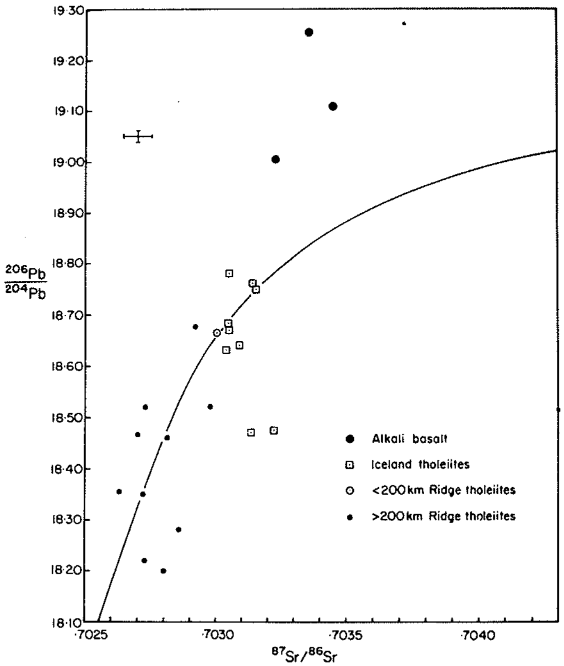

Fig. 7. Plot of $^{87}Sr/^{86}Sr$ versus $^{206}Pb/^{204}Pb$. $^{87}Sr/^{86}Sr$ data are from Hart et al. [7] and Sun and Jahn [10]. $^{206}Pb/^{204}Pb$ data are from Sun et al. [5] and Sun and Jahn [10]. The mixing curve was calculated using Sr data from S.R. Hart (unpublished) and Pb data from Sun et al. [5]. Note that the alkali basalts do not fall on the mixing curve calculated for the tholeiites, all of which are from the Reykjanes Ridge and its extension onto Iceland.

plagioclase and dynamic melting [15] must be considered.

A means of testing for plagioclase fractionation is to compare the La/Sr ratios of samples with their iron contents. As shown by Roeder and Emslie [16], olivine and pyroxene fractionation have but a minor effect on the iron content of the melt, while significantly reducing the MgO contents. Plagioclase fractionation, however, increases the FeO content significantly. Based on FeO contents [17], Schilling's samples from greater than 200 km have experienced less plagioclase fractionation than those from Iceland and near Iceland. The plagioclase fractionation in the less than 200 km samples may cause variations of a factor of two in La/Sr, while that in the greater than 200 km samples should cause less than 50% variation.

Fig. 9 shows La/Sr plotted against $^{87}Sr/^{86}Sr$ for both sets of samples. The spread in the data for La/Sr from samples within 200 km of Iceland is a factor of two to three. This spread probably can be explained by plagioclase fractionation. The samples from greater than 200 km have La/Sr ratios which can be more than four times greater than the mixing curve through the Iceland samples for a given $^{87}Sr/^{86}Sr$ ratio, which is far outside the possible effect of plagioclase fractionation. Plagioclase fractionation, then, does not account for the critical variations among the samples.

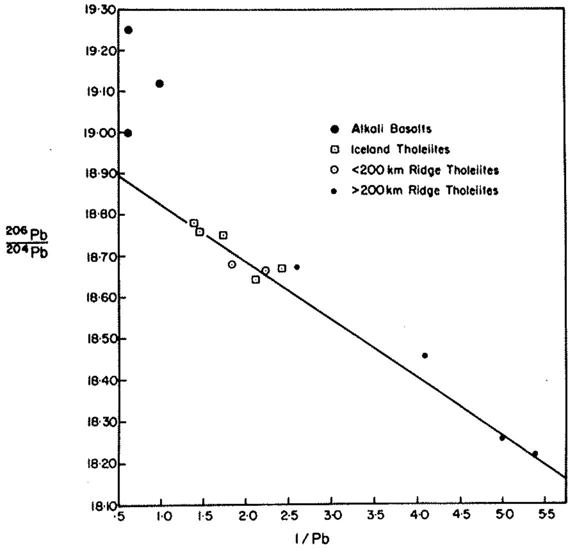

Fig. 8. Plot of $^{206}Pb/^{204}Pb$ versus 1/Pb. Data from Sun et al. [5] and Sun and Jahn [10]. The alkali basalts do not fall on the mixing curve through the Reykjanes Ridge tholeiites.

Variation in the degree of batch partial melting also should not significantly affect the La/Sr ratio, unless plagioclase is an important residual phase. If there were about 15% plagioclase in the residue for the basalts greater than 200 km from Iceland, and no plagioclase in the residue for basalts within 200 km of Iceland, this might explain the difference in La/Sr ratios for the two sets of samples. However, 15% plagioclase is a very large amount for residual mantle compositions.

A third possible explanation could be as follows. If the mantle is heterogeneous on a scale larger than can be homogenized by diffusion, melting may occur in the enriched portions of the mantle first. Then as melting proceeds, more and more depleted portions of the mantle contribute to the melt, producing a

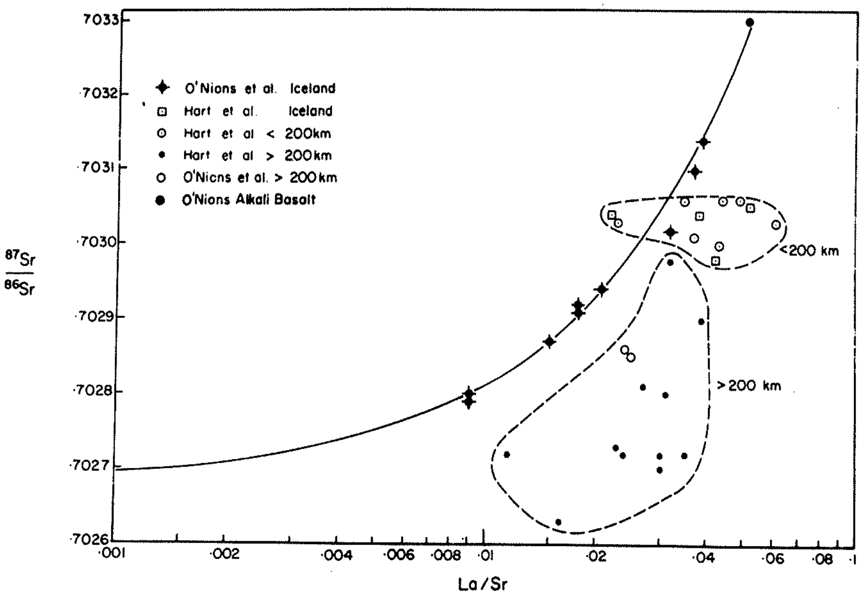

Fig. 9. Plot of La/Sr versus $^{87}Sr/^{86}Sr$ for all samples from Iceland and the Reykjanes Ridge. Samples from greater than 200 km down the ridge do not fall on the mixing curve for the Iceland samples, and fall too far off the curve for the discrepancy to be explained by plagioclase fractionation. Note that the plot is semilogarithmic. Data from Schilling [6], Hart et al. [7], O'Nions et al. [8] and S.R. Hart (unpublished).

correlation between depletion in trace element and isotope ratios [20]. In this model, segments of the mantle are large enough to maintain their heterogeneities through time and during melting.

When combined with dynamic melting [15], which can lead to basalts having trace element ratios more depleted than their source, such a process could lead to trace element ratios which have been depleted relative to their original values in the source, and isotope values which correlate with the trace elements but which reflect the source. If such processes were occurring beneath parts of Iceland and not beneath the Reykjanes Ridge, this might explain the appearance of two mixing trends.

4.5. Recent mixing versus long-term evolution

We have shown that the data may be compatible with two separate mixing trends, but we have not yet tested the model of O'Nions et al. [8]. They suggest that the chemical variations around Iceland result from multiple, long-term heterogeneities in the mantle, and that there has been no recent mixing.

The smooth trend of the data on isotope-isotope plots is compatible with long term evolution of heterogeneous sources which were initially close to homogeneous. If a line is drawn through the data from the Reykjanes Ridge samples on $^{206}Pb/^{204}Pb$-$^{87}Sr/^{86}Sr$ and $^{208}Pb/^{204}Pb$-$^{87}Sr/^{86}Sr$ plots, the slope of lines on $^{238}U/^{204}Pb$-$^{87}Rb/^{86}Sr$ and $^{232}Th/^{204}Pb$-$^{87}Rb/^{86}Sr$ plots which would give rise to the present-day isotope distribution can be calculated, assuming the ancient source had homogeneous isotope ratios. The actual placement of the line on the parent/daughter plots depends on the time involved. The calculated slope for one of these plots is shown in Fig. 10 along with the data points for the four samples which have been analyzed for all elements. The data are not abundant enough to be certain, but do not rule out a long-term heterogeneous source model.

The next stage in testing for evolution would be to construct mixing curves for the various isotope-isotope and parent-daughter plots. Unfortunately, there are not enough parent and daughter concentration analyses to be definitive, but the mixing curves on the Pb-Sr isotope plots do not appear to include the alkali basalts from Iceland, which could be taken as evidence for a heterogeneous source model.

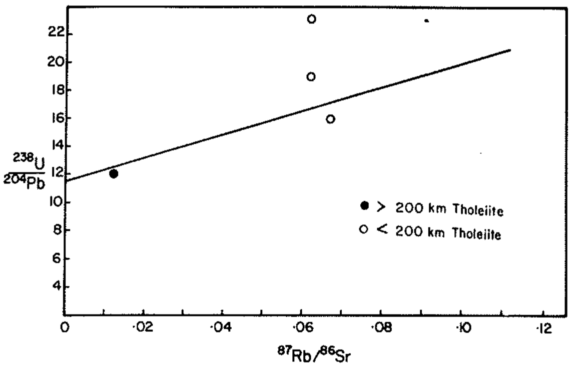

Fig. 10. Plot of $^{238}U/^{204}Pb$ versus $^{87}Rb/^{86}Sr$, which is the parent-daughter plot for the $^{206}Pb/^{204}Pb$-$^{87}Sr/^{86}Sr$ isotope plot. The line is *not* a mixing line; it has the slope which would give rise to the present-day distribution of the data on the isotope plot starting from a homogeneous source. While the slope of the line is fixed, its placement is not and depends on the time since the development of the heterogeneities. Data from Sun et al. [5] and S.R.Hart (unpublished).

Enough data are available, however, to test isochrons for the various isotope systems for the Reykjanes Ridge samples. Because plagioclase fractionation increases the U/Pb, Th/Pb and Rb/Sr ratios, while dynamic melting may increase Sm/Nd, a more accurate isochron may be determined by selecting those samples with minimum parent/daughter element ratios for a given isotope ratio, as suggested by Sun and Hanson [18]. Isochron plots for the three Pb systems and the Nd and Sr system have a lot of scatter but give ages of approximately 500 ± 200 m.y. According to Sun and Jahn [10], the $^{207}Pb/^{206}Pb$ age is 1500 ± 500 m.y., suggesting that the systems may have been isolated some 1500 m.y. ago. The consistently younger isochron ages may reflect a later disturbance of the systems; they may reflect mixing; or they may be fortuitous. The general similarity of ages for the Reykjanes Ridge and Iceland samples is suggestive of mantle heterogeneity established some 500 m.y. ago. Because the alkali basalts fall on some other mixing curves, one might suggest that source heterogeneity is a preferable model. However, if the anomalous alkali basalt data on other plots could be explained in some other way, the isochrons could be interpreted as a result of recent mixing of sources which have evolved separately for hundreds of millions of years.

5. Conclusions

The available data from Iceland and the Reykjanes Ridge are compatible with several possible models:

(1) The variations in the chemistry of the samples result from two mixing series. The chemistry of the Reykjanes Ridge samples reflects mixing between a fairly homogeneous source feeding the Reykjanes peninsula and the Reykjanes Ridge within 200 km of Iceland, and a heterogeneous source represented by normal ocean ridge basalts lying greater than 500 km from Iceland. This mixing is distinct from the mixing on Iceland, which is between an alkali basalt source and a depleted source of different chemistry than that of the ocean ridge basalts to the south of Iceland. The Reykjanes peninsula source is part of the Iceland mixing trend so three component mixing may be possible. The end members of the mixing series must have evolved separately for hundreds of millions of years.

(2) The variations result from one mixing series, which has an enriched source beneath Iceland and a depleted source on the Reykjanes Ridge as end members. In this model, the inconsistency of the Iceland data with the data from the Reykjanes Ridge is due to recent processes in the mantle. For example, dynamic melting of a heterogeneous source or residual plagioclase may cause the appearance of two apparent mixing trends, where there is in fact only one.

(3) The variations do not result from mixing, but result from heterogeneities which were established in the mantle hundreds of millions of years ago. Each individual segment of mantle has evolved separately to contribute to the present day basalts.

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