

ISOTOPIC GEOCHEMISTRY OF SUBDUCTION ZONE MAGMAS

GEOCHEMISTRY OF TWO-COMPONENT MIXTURES

Subduction-related magmatism is probably the principle way in which new material is added to the continental crust at present. Such magmas are, however, often mixtures of mantle-derived and crust-derived components. Thus before exploring their isotope geochemistry, we need to consider the effects of mixing on isotope ratios.

When two components contribute material to magmas, we might expect that the proportion contributed by each might vary. If we plot the concentration of any two elements in different samples of this mixture against each other, they must lie on a straight line between the two end members. However, if we plot ratios of elements, or isotope ratios, they need not lie on a straight line. Indeed, in the general case they do not; rather they will define a curve whose equation is:

$$Ax + Bxy + Cy + D = 0 \quad 22.1$$

where x and y are the variables of the abscissa and ordinate respectively. If end members are designated 1 and 2 and have ratios x_1 and y_1 , and x_2 and y_2 respectively, then

$$A = a_2b_1y_2 - a_1b_2y_1 \quad 22.2$$

$$B = a_1b_2 - a_2b_1 \quad 22.3$$

$$C = a_2b_2x_1 - a_1b_2x_2 \quad 22.4$$

$$D = a_1b_2x_2y_2 - a_2b_1x_1y_1 \quad 22.5$$

where a_i is the denominator of y_i and b_i is the denominator of x_i . The curvature of the mixing line will depend on the ratio r :

$$r = a_1b_2/a_2b_1 \quad 22.6$$

The greater the value of r , the greater the curvature. Only in the special case where $r=1$ is the line straight. This is illustrated in Figure 22.1. This result is completely general and applies to mixing of river water and seawater, etc. as well as mixing of magmas.

Taking a concrete example, if our plot is $^{143}\text{Nd}/^{144}\text{Nd}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$, then the curvature depends on the ratio of $(^{144}\text{Nd}_1/^{86}\text{Sr}_2)/(^{144}\text{Nd}_2/^{86}\text{Sr}_1)$. Since to a very good approximation the amount of ^{144}Nd and ^{86}Sr is proportional to total Nd and Sr respectively, r is approximated by $\text{Nd}_1\text{Sr}_2/\text{Nd}_2\text{Sr}_1$. If we express this ratio as $r = (\text{Nd}/\text{Sr})_1/(\text{Nd}/\text{Sr})_2$ we see that the curvature depends on the ratio of the Nd/Sr ratio in the two end members. In mantle-derived rocks Sr/Nd does not deviate greatly from 10, so mixing curves will be close to straight lines. In crustal rocks and sediments, deviations from $r = 1$ are more likely and curved mixing lines therefore more common. Note that on a $^{207}\text{Pb}/^{204}\text{Pb}$ — $^{206}\text{Pb}/^{204}\text{Pb}$ plot, mixing curves will always be straight lines because the denominators are the same (i.e., $a = b = ^{204}\text{Pb}$).

Two component mixtures will also form straight lines on isochron plots, which are ratio-ratio plots, e.g., $^{87}\text{Sr}/^{86}\text{Sr}$ — $^{87}\text{Rb}/^{86}\text{Sr}$, because the denominators are the same. Thus mixing lines can be mistaken for isochrons and visa versa. One way to distinguish the two is a ratio-element plot. A ratio-element plot, for example $^{87}\text{Sr}/^{86}\text{Sr}$ vs. Sr, will also in general be a curved line described by equa-

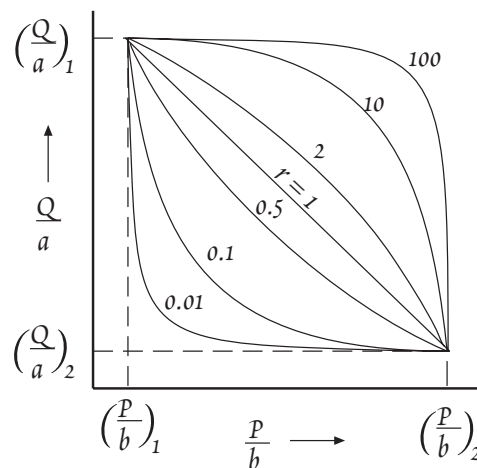


Figure 22.1. Plots of ratios of elements or isotopes, Q/a versus P/b for mixing of end members 1 and 2. The numbers along the curves are the values for r .

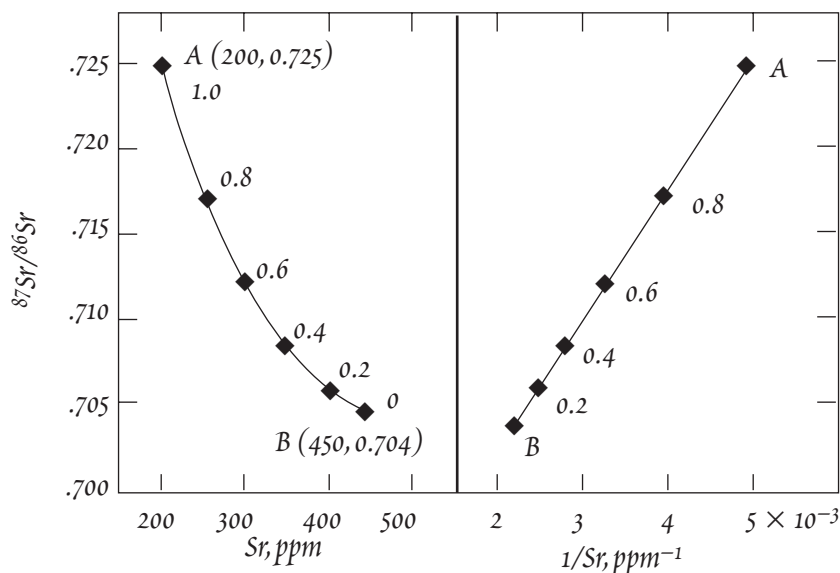


Figure 22.2. Mixing hyperbola formed by components A and B. After Faure (1986).

tion 22.1, but a ratio plotted against the inverse of the denominator, for example $^{87}\text{Sr}/^{86}\text{Sr} - 1/\text{Sr}$, will be a straight line. Such a plot can be a useful discriminator between isochrons and mixing lines because only in the latter case will $^{87}\text{Sr}/^{86}\text{Sr} - 1/\text{Sr}$ necessarily define a straight line (Figure 22.2). Again, this result is completely general, and while the general principals have been illustrated with isotope ratios, they apply equally well to elemental ratios.

When the compositions of a magma or series of magmas appear to reflect mixing, we are often faced with having to decide whether (1) two mantle-derived magmas are mixing, (2) two distinct mantle sources are mixing, or (3) a mantle-derived magma is mixing with assimilated crust. In case (2), plots involving an elemental concentration will not fall on mixing lines because partial melting and fractional crystallization will change element concentrations. Isotope ratios will not be changed by magma genesis so a plot of two isotope ratios will describe a mixing line in case (2) as well as cases (1) and (3). Recognizing crustal assimilation in subduction zones magmas can be particularly difficult because many of geochemical effects characteristic of crustal assimilation can also result from the presence of subducted sediment component in such magmas. As we see later in the course, stable isotopes are particularly useful in recognizing assimilation. This is so because fractionation of stable isotope ratios in the mantle materials have comparatively uniform stable isotope ratios, whereas crustal rocks very often have stable isotope ratios that are different from mantle values.

ISOTOPIC COMPOSITIONS OF SUBDUCTION-RELATED MAGMAS

As we noted, subduction zone magmatism is probably the principal mechanism by which new crust has been created in the Phanerozoic, and perhaps throughout geologic time. In addition, subduction zones are the region in which oceanic crust and its veneer of sediment are recycled into the mantle. Given the obvious importance of subduction zones in the evolution of the Earth, it is worth briefly considering the isotope geochemistry of subduction-related magmas.

Island-arc and continental margins volcanics (IAV) are distinctive in many of their geochemical features. Isotopic studies have now demonstrated the reason for this: their sources contain a component of subducted oceanic crust and sediment. The first evidence to this effect was a study of Pb isotope ratios in the Lesser Antilles by Armstrong in 1971. Figure 22.3 compares Pb isotope ratios in a number of arcs to those of MORB and sediments. The similarity between the arc magmas and the sediments is striking and certainly not coincidental. The sediment, or rather a small part of it, is being subducted to depths of 100 km beneath the arc where it enters the magma source region. In terms of their Sr-Nd systematics, however, island arcs overlap the MORB and OIB fields considerably (Figure 22.4), although they have some tendency to plot to the high $^{87}\text{Sr}/^{86}\text{Sr}$ side. This may be because the basalts of the subducted oceanic crust may also be an important source of Sr and Nd. The Nd of old (< 150 Ma) oceanic crust will not be very different from that of modern MORB. However, hydrothermal activity at mid-ocean ridges results in isotopic exchange between basalt and seawater, shifting the

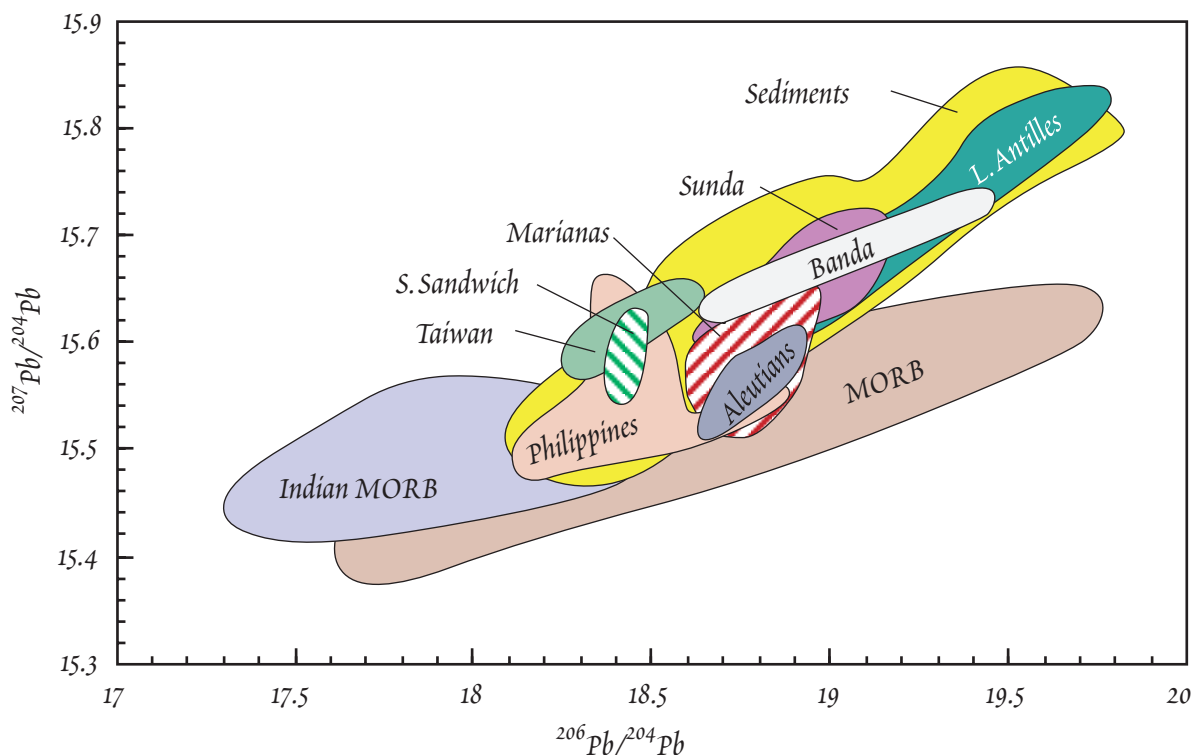


Figure 22.3. $^{206}\text{Pb}/^{204}\text{Pb}$ — $^{207}\text{Pb}/^{204}\text{Pb}$ for 3 arcs and the sediments available for subduction beneath them. In each case, the arcs define an array between MORB and the associated sediment.

$^{87}\text{Sr}/^{86}\text{Sr}$ of the oceanic crust to higher values (mean value of altered oceanic crust is probably in the range of 0.703–0.7035). One can also see by comparing Figure 22.4 with 20.1, that Sr and Nd in island arc volcanics can qualitatively be described as a mixture of altered oceanic crust, depleted mantle, and sediment. In some cases, however, anomalous mantle, similar to that of mantle plumes, may also be involved.

Thus arc magmas are themselves mixtures of mantle and crustal material, and continental margin volcanism, or accretion of intra-oceanic arcs, involves both additions of new material from the mantle and recycling of older crust. The proportion of sediment in arc magma sources can be estimated from mixing models (e.g., Figure 22.5) and is generally quite small, typically a percent or two. Nevertheless, because sediment has much higher concentrations of Pb, Sr and Nd than mantle, significant proportions of these elements, and sometimes most of the Pb, are derived from the sediment. Continental margin magmas generally assimilate some of the crust through which they ascend, which results in

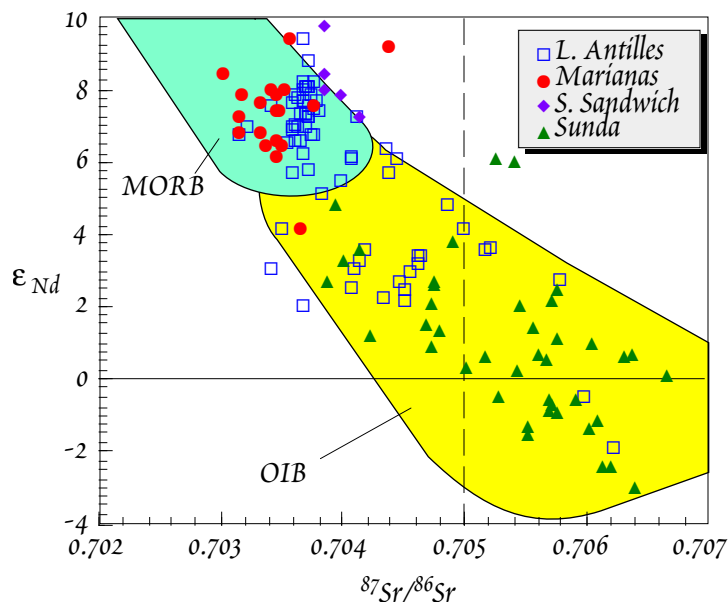


Figure 22.4. Sr and Nd isotope ratios for 4 intra-oceanic island arcs for which there is reasonably extensive data.

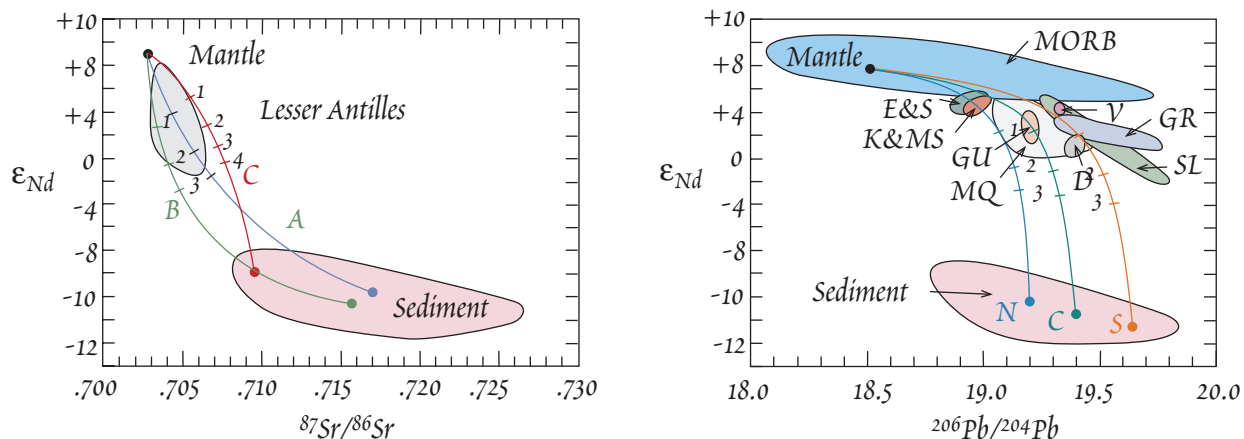


Figure 22.5. a. (left) Models of mixing between depleted mantle (labeled mantle) and 3 different sediment end-members (A, B, and C) for the Lesser Antilles. Tick marks indicate the percent sediment in the mixture. As we pointed out earlier in the course, mixing lines are generally curved. The nature of the curvature largely depends on the amount of the carbonate, which is Sr-rich, in the sediment. b. (right) This figure shows mixing lines between mantle and sediment from the northern (N), central (C), and southern (S) part of the arc. Mixing lines involving Pb are highly curved because the Pb/Nd ratio of sediment is much greater than that of mantle. Addition of less than 3 or 4 percent sediment is required to explain the isotopic variations in the Lesser Antilles. Fields for individual islands are shown (GR: Grenada, V: St. Vincent, SL: St. Lucia, MQ: Martinique, D: Dominica, GU: Guadeloupe, K&MS: St. Kitts and Monserrat, E&S St. Eustis and Saba). From White and Dupré (1986).

further reworking, or high-level recycling, of continental crust.

Interestingly, the Lesser Antilles may be something of a present-day analogy to the isotopic pattern in the southwest US that we discussed in the Lecture 20 (Figure 20.4). The arc is built perpendicular to the continental margin (an unusual situation). Archean crust occurs in the Guiana highland, which is drained by the Orinoco River, which has deposited a considerable volume of sediment in front of the arc. Because of the age of the drainage basin, the sediment of the Orinoco contains Pb, Sr and Nd that is somewhat unusual. Isotopic compositions in the sediment grade northward (Figure 22.6). This northward variation is mirrored by in the isotopic composition of arc lavas, and reflects a decreasing continental contribution with distance from the continent.

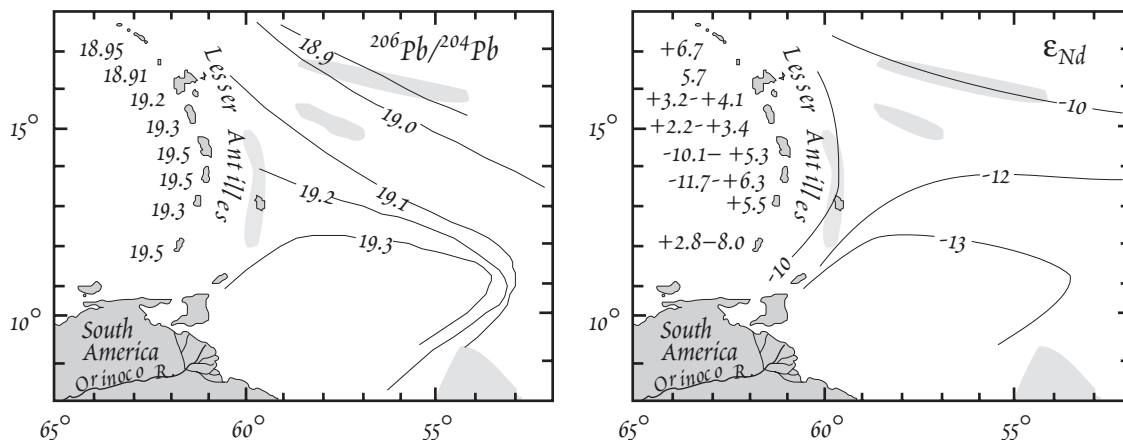


Figure 22.6. Contours of $^{206}\text{Pb}/^{204}\text{Pb}$ and ϵ_{Nd} in sediment in front of the Lesser Antilles island arc. Range or mean of these parameters in Lesser Antilles arc volcanics is written adjacent to each island (White and Dupré, 1986).

^{10}Be in Arc Lavas

If further evidence of the presence of subducted sediment in arc magmas is needed, it is provided by yet another isotopic system: ^{10}Be . We have discussed how ^{10}Be is created by spallation in the atmosphere. Because of its half-life is only 1.6 Ma, and cosmic rays penetrate solid matter so poorly, cosmogenic Be should not be present in the interior of the Earth. Yet it is present in IAV (Figure 22.7). It is possible that some neutron reactions might create ^{10}Be in the Earth's interior, however. In addition, cosmogenic ^{10}Be in rain is known to be rapidly absorbed on clays, and even very young basalts might also absorb ^{10}Be . For these reasons, it way important control experiments by measuring ^{10}Be in non-arc lavas. As Figure 22.7 shows, ^{10}Be is not present in non-arc lavas. Thus the only reasonable interpretation of ^{10}Be in arc magmas is that it is derived from subducted sediment.

Not all arc lavas have ^{10}Be . For example, there is no ^{10}Be in lavas from the Lesser Antilles, where Pb and other isotopes suggest a significant contribution from sediment. The same is true of the Sunda arc. In both these arcs, however, the sediment pile is so thick that most sediment is accreted in a forearc wedge rather than subducted. In the Lesser Antilles, seismic and other studies of the forearc show that only the lower 100 m or so of sediment is carried into the subduction zone and possibly subducted. These are pre-Miocene sediments. Using our rule of thumb that a radioactive isotope will be gone after 10 half-lives, we can predict that sediment older than 16 Ma should have no ^{10}Be . Thus it is no surprise that ^{10}Be is not present in Lesser Antilles sediments.

Th Isotope Geochemistry of Arc Magmas

Another isotope system that has contributed significantly to our knowledge of island arc processes is the ^{230}Th - ^{238}U system. This system has been important in confirming the role of fluids in arc magma genesis. As we discussed before, the equilibrium situation is that the activity of ^{230}Th is equal to the activity of ^{238}U , and hence the ratio ($^{230}\text{Th}/^{232}\text{Th}$) will be equal to the ($^{238}\text{U}/^{232}\text{Th}$) ratio. Equilibrium should characterize the mantle before melting (as well as old sediment). Because Th is more incompatible than U, the ($^{238}\text{U}/^{232}\text{Th}$) ratio in a melt should decrease, but the ($^{230}\text{Th}/^{232}\text{Th}$) ratio of a melt will be the same as that of its source. Thus on a conventional plot of ($^{230}\text{Th}/^{232}\text{Th}$) against ($^{238}\text{U}/^{232}\text{Th}$), the melt should be driven to the left of the equiline. This is what is observed in MORB for example.

As Figure 22.8 shows, though many arc magmas are close to equilibrium, and some do plot to the left of the equiline, at least some arcs have ($^{238}\text{U}/^{232}\text{Th}$)—($^{230}\text{Th}/^{232}\text{Th}$) values that plot to the right of the equiline, i.e., in arcs, U appears to be going in the melt more readily than Th. The explanation of this is that U is enriched in the peridotitic mantle source of arc magmas by hydrous fluid transport from the lithospheric slab (the sediments and basalts of the oceanic crust). U is fairly soluble in water; Th is quite insoluble. Thus hydrous fluids should transport U more readily than Th.

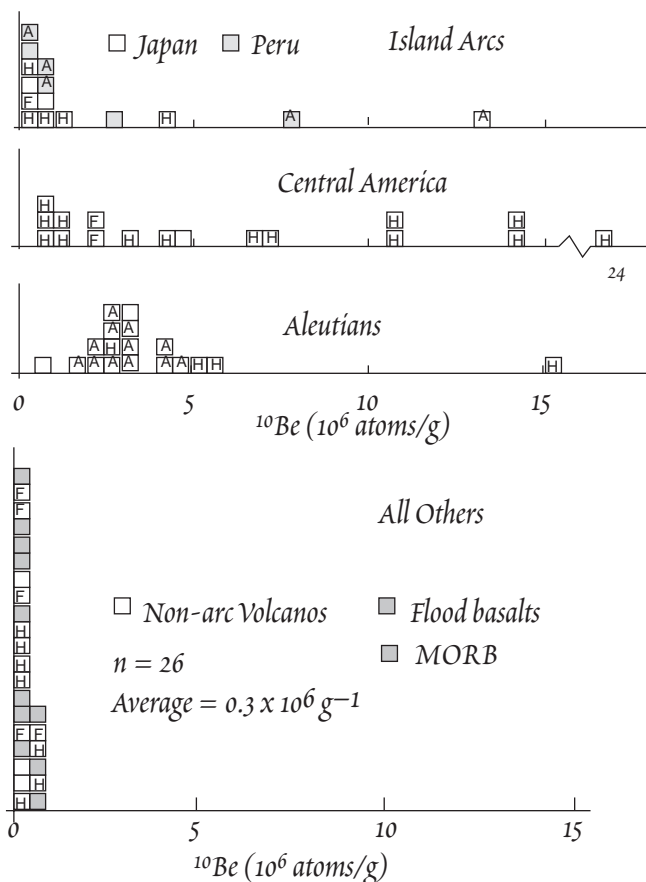


Figure 22.7. Comparison of ^{10}Be contents in arc (left) and non-arc (right) lavas (from Tera et al., 1986). "A" indicates sample from active volcano, "H" a historic eruption, and "F" (fresh) indicates collected during eruption.

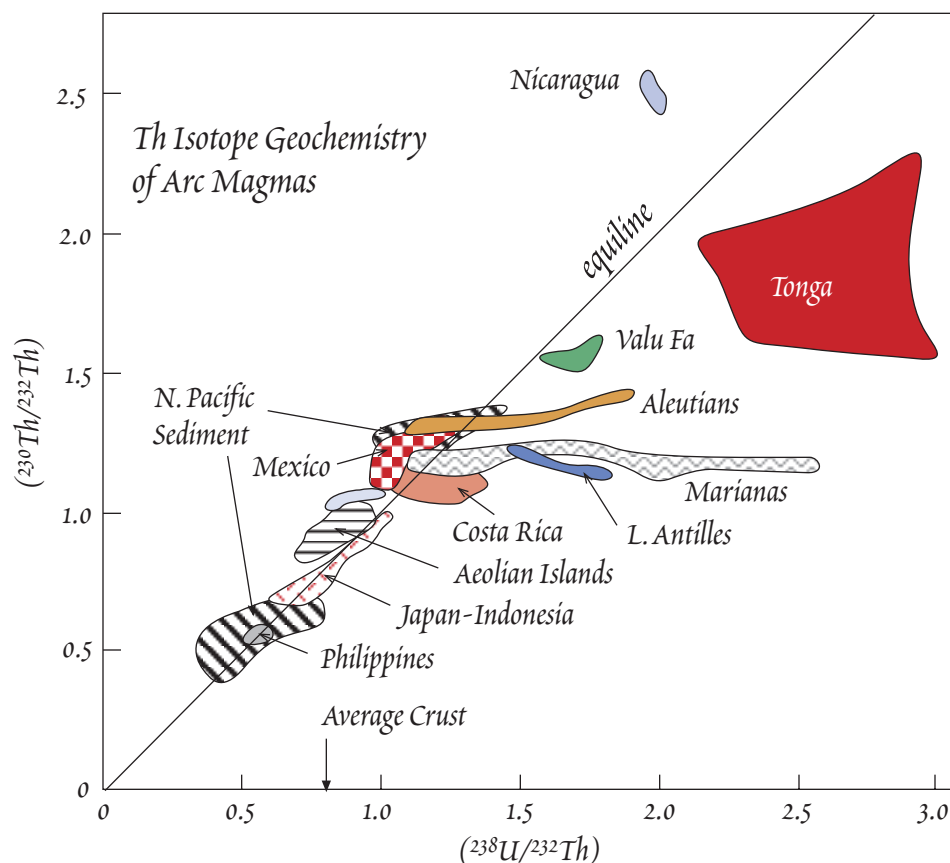


Figure 22.8. $(^{230}\text{Th}/^{232}\text{Th})$ vs. $(^{238}\text{U}/^{232}\text{Th})$ in island arc magmas. From McDermott and Hawkesworth (1991).

The idea that fluids might be important in transporting material from the slab to the magma genesis zone was proposed on other grounds (the abundance of water in these magmas, the enrichment in alkalis and alkaline earth trace elements, which are fairly soluble). The Th isotope studies provide confirming evidence of this idea.

REFERENCES AND SUGGESTIONS FOR FURTHER READING

- Armstrong, R. L., Isotopic and chemical constraints on models of magma genesis in volcanic arcs, *Earth. Planet. Sci. Lett.*, 12, 137-142, 1971.
- Faure, G. 1986. *Principles of Isotope Geology*. New York: Wiley & Sons.
- McDermott, F., and C. Hawkesworth, Th, Pb, and Sr isotope variations in young island arc volcanics and oceanic sediments, *Earth Planet. Sci. Lett.*, 104, 1-15, 1991.
- Tera, F., L. Brown, J. D. Morris, I. S. Sacks, J. Klein, and R. Middleton, Sediment incorporation in island-arc magmas: Inferences from ^{10}Be , *Geochim. Cosmochim. Acta*, 50, 535-550, 1986.
- White, W. M., and B. Dupré, Sediment subduction and magma genesis in the Lesser Antilles: isotopic and trace element constraints, *J. Geophys. Res.*, 91, 5927-5941, 1986.
- White, W. M., Geochemical evidence for crust-to-mantle recycling in subduction zones, in *Crust/Mantle Recycling at Convergence Zones*, vol. edited by S. R. H. a. L. Gulen, 43-58 pp., Kluwer Academic Publishers, Dordrecht, 1989.