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R. K. O'Nions

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Isotopic abundances relevant to the identification of magma sources

By R. K. O'Nions, F.R.S.

Department of Earth Sciences, University of Cambridge,
Downing Street, Cambridge CB2 3EQ, U.K.

The behaviour of natural radiogenic isotope tracers in the Earth that have lithophile and atmophile geochemical affinity is reviewed. The isotope tracer signature of oceanic and continental crust may in favourable circumstances be sufficiently distinct from that of the mantle to render a contribution from these sources resolvable within the isotopic composition of the magma. Components derived from the sedimentary and altered basaltic portion of oceanic crust are recognized in some island arc magmas from their Sr, Nd and Pb isotopic signatures. The rare-gas isotope tracers (He, Ar, Xe in particular) are not readily recycled into the mantle and thus provide the basis of an approach that is complementary to that based on the lithophile tracers. In particular, a small mantle-derived helium component may be readily recognized in the presence of a predominant radiogenic component generated in the continents. The importance of assessing the mass balance of these interactions rather than merely a qualitative recognition is emphasized.

The question of the relative contribution of continental–oceanic crust and mantle to magma sources is an essential part of the problem of generation and evolution of continental crust. An approach to this problem through consideration of the isotopic composition of sediments is briefly discussed.

Introduction

Naturally occurring radiogenic and non-radiogenic isotope tracers offer a valuable approach to the problem of evaluating the relative contributions of mantle, oceanic crust and continental crust to the sources of magmas. The principal aim of the present contribution is to review some background to the use of these tracers in the light of their general geochemical behaviour. Only those tracers that involve the radiogenic daughter products of comparatively long-lived (half-life $\geqslant 10^9$ a) parent nuclides will be considered here, and the reader is referred to accompanying articles in this volume for discussions involving non-radiogenic tracers. In classical geochemical terms these include isotope tracers with atmophile (He, Ne, Ar, Xe), lithophile (Ca, Sr, Nd, Hf, Pb), chalcophile (Pb) affinity, and parent isotopes involved in the production of the radiogenic components that are exclusively lithophile in character (^{40}K, ^{87}Rb, ^{147}Sm, ^{176}Lu, ^{232}Th and $^{235,\,238}$U). The large scale chemical differentiation of the Earth into continental crust, atmosphere–hydrosphere, mantle and core has been accompanied by a major fractionation of these trace elements such that the reservoirs possess characteristic isotope tracer compositions. Under favourable circumstances, contributions to magma sources from those portions of the Earth under consideration here may be recognizable from the measured abundance of one or more of these radiogenic tracers.

The application of the natural radiogenic isotope tracers to the identification of magma source regions in general has become progressively more sophisticated. On the one hand a purely qualitative approach may be adopted whereby an attempt is made to resolve the isotope tracer pattern characteristic of a particular component, such as altered oceanic crust or pelagic clay, within the overall tracer pattern of an erupted magma. The development of analytical techniques for the measurement of the isotope tracer abundances and the establishment of criteria for recognizing the patterns of particular components has been a major preoccupation of geochemists to date. However, the ultimate goal is to discover the mass balance associated with the contributions of various components to a magma, because this is an inherent part of the geochemical cycling of the elements and the formation of the major geochemical reservoirs within the Earth. In this contribution attention will be directed to those areas where some progress has been possible in this regard.

ISOTOPE TRACERS AND EARTH DIFFERENTIATION

It is generally accepted that subsequent to its formation, the Earth chemically differentiated into mantle, crust and atmosphere–hydrosphere. The continental crust has strongly concentrated the Earth's major heat-producing elements K, U and Th and other lithophile trace elements with large ionic radii. This group of elements includes a number of those parent and daughter isotopes that are currently exploited as radiogenic tracers (e.g. ^{40}Ca, ^{87}Sr, ^{143}Nd, ^{176}Hf, $^{208,\,207,\,206}$Pb). The element fractionation that accompanies continent generation (e.g. K/Ca, Rb/Sr, Sm/Nd, Lu/Hf) leads to different and distinguishable radiogenic tracer abundances in the continent and mantle after a period of time which depends upon the half-life of the parent isotope, the magnitude of parent–daughter fractionation, and the analytical precision associated with the measurement of the tracer abundance (figure 1).

At this juncture it should be recalled that a new segment of continental crust formed by differentiation of the mantle should have a radiogenic isotope tracer signature identical to the mantle from which it was derived. Consequently any contribution that it may make to a new magma would be indistinguishable from a contemporary mantle contribution unless sufficient time has elapsed for the new continental segment to develop distinctive isotope tracer characteristics. The simple fact that a mantle contribution may not be distinguishable from a contribution from new continental crust which has had a short residence time in the continents may in some instances severely limit the possibility of making unequivocal statements about magma provenance.

The isotope tracers of the rare gases He, Ne, Ar and Xe have radiogenic components related to the decay of the lithophile elements K, U and Th, and largely reside in the atmosphere after reaching the surface of the Earth. With the exception of He which escapes from the outer atmosphere, the rare gases are conserved. Considerations of the isotopic compositions of Ar (see, for example, Ozima 1975) and Xe (Staudacher & Allègre 1982) suggest that a substantial portion of the terrestrial rare-gas inventory was released into the atmosphere early in the history of the Earth, more than 4 Ga ago.

The transport of rare-gases in the Earth is essentially unidirectional (figure 2) and in this respect the rare-gas behaviour differs fundamentally from the lithophile radiogenic tracers. Thus whereas a lithophile tracer derived from a continental source may be recycled into the mantle and subsequently recognized as a component of a mantle-derived melt, there is little likelihood of a resolvable amount of rare gas from the atmosphere being recycled in this way. Xenon, which is strongly absorbed on to sedimentary material (Podosek *et al.* 1980) is one possible exception to this generalization, which is in need of further evaluation.

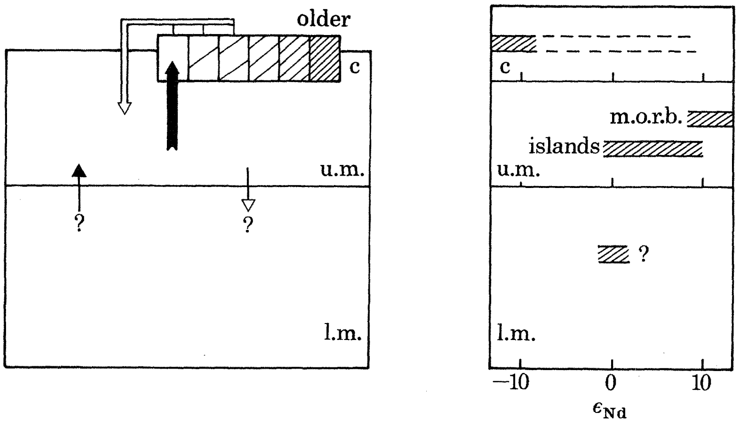

FIGURE 1. Schematic illustration of the behaviour of lithophile natural radiogenic tracers in the Earth such as ^{87}Sr and ^{143}Nd, respectively the daughter products of ^{87}Rb and ^{147}Sm. The mantle is represented on the left-hand side as two chemical reservoirs (upper and lower), and the continental crust as a series of units with different ages. The continental crust has developed through the extraction of material principally from the upper mantle, and the solid arrow represents transport to the most recently accreted portion. The open arrow represents the possible return of continental material to the mantle. An example of the use of the ^{143}Nd radiogenic tracer is illustrated in terms of the ϵ_{Nd} notation. (Deviation of ^{143}Nd/^{144}Nd of sample from a standard chondrite-derived value in parts per 10^4.) Upper mantle materials have generally positive ϵ_{Nd} values with mid-ocean ridge basalts (m.o.r.b.) having the highest values. New continental crust accreted from this source will have ϵ_{Nd} values indistinguishable from the mantle source. The tracer can readily distinguish older continental crust which has evolved to negative values of ϵ_{Nd} from upper mantle material, and the resolution that can be achieved increases with increasing age of the crust. Continental crust with a recycled older continental component in addition to a contemporary mantle component, will be recognizable in circumstances where the tracer composition of the two components are distinct and the mass balance is favourable. Conversely continental crust recycled into the mantle may also impose a recognizable isotopic signature.

HYDROTHERMAL ALTERATION OF THE OCEANIC CRUST

The apparent deficit in conducted heat flow at the mid-ocean ridges has been attributed to the removal of heat convectively by hydrothermal processes (Wolery & Sleep 1976). The estimated flux of seawater required to remove this heat depends upon the maximum temperatures attained by the hydrothermal systems. Estimates made by Wolery & Sleep and Edmond (1981) on the basis of observations made on hydrothermal vents in the E Pacific are very similar at approximately 10^{14} kg a^{-1} H_2O. The abundances of heavy metals such as Nd and Pb in seawater and the mass fluxes of the metals into the ridges are so low that there is a near negligible overall effect on the isotopic composition of the oceanic crust (figure 3). For example, O'Nions *et al.* (1977, 1978) and McCulloch *et al.* (1980) failed to find significant shifts in the ^{143}Nd/^{144}Nd of altered ocean basalts attributable to hydrothermal alteration. In contrast, the concentration of strontium in seawater is approximately 6 orders of magnitude larger than Nd at approximately 8 mg l^{-1} and the estimated mass flux of Sr into the ridges is 10^9 kg a^{-1} (figure 3). Observations of the ^{87}Sr/^{86}Sr ratios in the high-temperature hydrothermal fluids emanating at the East Pacific Rise suggest that seawater Sr entering the ridges with ^{87}Sr/^{86}Sr = 0.7091 has extensively exchanged with the Sr in the oceanic crust. Given that new ocean floor is generated at a rate of 3 km^2 a^{-1}, the mean ^{87}Sr/^{86}Sr ratio of the oceanic crust after high temperature hydrothermal alteration has been estimated to be *ca.* 0.704 (Albarède *et al.* 1981). As a result of these hydrothermal interactions the oceanic crust has a well defined and characteristic isotopic tracer signature (figure 4), which renders contributions it makes to magma sources recognizable if the mass balance is favourable.

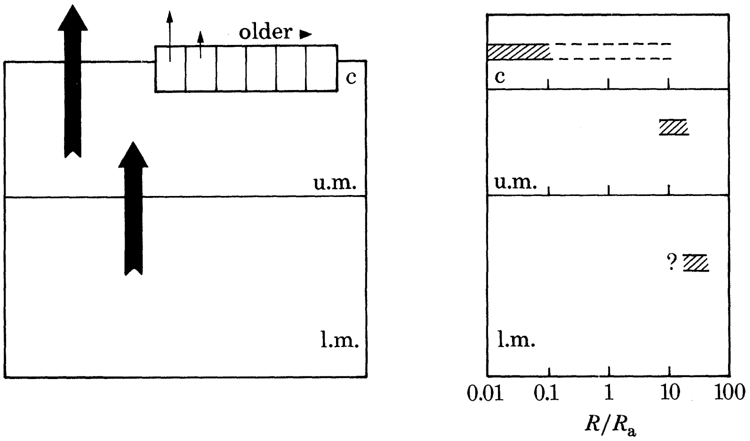

FIGURE 2. Schematic illustration of the behaviour of He as an atmophile rare gas isotope tracer. Helium 3 escaping from the Earth is almost entirely primordial and has *ca.* 10^{-5} of the abundance of ^{4}He which is mainly radiogenic in origin. The transport of helium contrasts with that of the lithophile tracers (figure 1) in that it is unidirectional. The major portion of ^{3}He leaves the mantle through the oceans and only a minor portion leaves through the continents. The ^{3}He/^{4}He ratio in terrestrial materials, R, is compared with the same ratio in the atmosphere R_a. The helium associated with mantle samples is relatively enriched in ^{3}He ($R/R_a \approx 8$–30) and that associated with old continental crust depleted in ^{3}He ($R/R_a \approx 0.01$–0.1). These large differences render small contributions of mantle-derived helium to magmas within the continents readily recognizable.

There are a number of well documented examples where Sr of continental derivation is recognized in oceanic basalts generated at destructive plate margins (see, for example, Hawkesworth *et al.* 1977; DePaolo & Wasserburg 1977). One of these situations is illustrated in figure 5, where significant shifts in ^{87}Sr/^{86}Sr in both back-arc and island arc basalts can be resolved.

Some portion of the marine Sr entering the oceanic crust contributes to island arc volcanics and the remainder will be recycled into the mantle. If it is assumed, for example, that *all* of the Sr in the basalt part of the oceanic crust is recycled into the upper mantle, then the average ^{87}Sr/^{86}Sr ratio of the upper mantle would be increased by only about 2×10^{-5} after 10^8 a.

ROLE OF PELAGIC CLAY

Pelagic clay accumulates at approximately 1.1×10^{12} kg a^{-1} (Li 1972). The Sr-, Nd- and Pb-isotope compositions of pelagic clay are distinct from pristine mantle-derived basalt with lower ^{143}Nd/^{144}Nd ratios and higher ^{87}Sr/^{86}Sr and ^{207}Pb/^{204}Pb for a given ^{206}Pb/^{204}Pb (figure 6). Although the accumulation rate is small, it would take only 10^9 a to accumulate an amount equal to the entire existing sedimentary mass. The paucity of pelagic clays in the geological record has been noted previously (see, for example, Armstrong 1981), which requires that either accumulation rates were lower in the past, or pelagic clay has been recycled into the mantle, or alternatively occluded into the continental crust in a hitherto unrecognized form.

The introduction of pelagic sediment into the source region of island arc tholeiites is well documented. Kay *et al.* (1978) demonstrated that Aleutian islands basalts have ^{207}Pb/^{204}Pb and ^{206}Pb/^{204}Pb ratios consistent with a component of pelagic sediment and Cohen & O'Nions (1982*b*) have more recently demonstrated that the South Sandwich Island arc tholeiites show a similar shift away from the typical m.o.r.b. composition towards those of pelagic clay (figure 5). The fraction of the global budget of pelagic clay recycled through the island arc system is

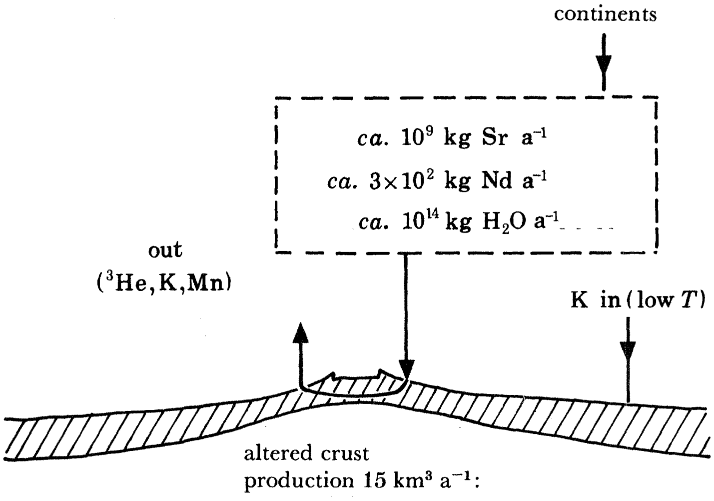

FIGURE 3. Modification of oceanic crust by hydrothermal alteration of oceanic ridges. The integrated heat flow deficit of ridges suggests that seawater is cycled through oceanic crust at *ca.* 10^{14} kg a^{-1} (Wolery & Sleep 1976). The average $^{87}Sr/^{86}Sr$ ratio of altered oceanic crust is estimated at 0.7038 (Albarède *et al.* 1981). Note that although K is stripped out of ocean floor basalts at the ridges, some K is returned to the ocean floor at low temperatures.

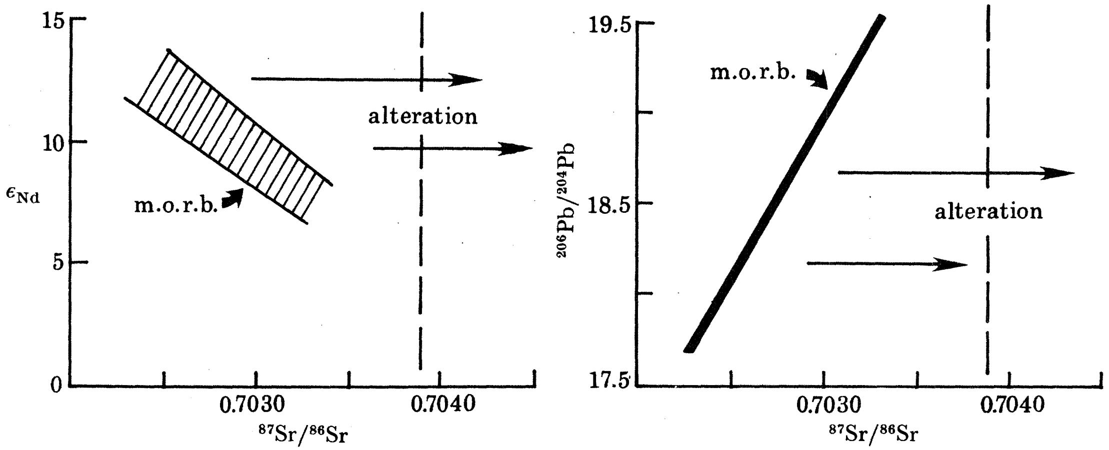

FIGURE 4. The effects of hydrothermal alteration, as depicted in figure 3, on the Sr, Nd and Pb isotope composition of mid-ocean ridge basalts.

The dissolved Pb and Nd contents of seawater and their fluxes into the ridge system (figure 3) are too low to modify $^{143}Nd/^{144}Nd$ (ϵ^0_{Nd}) and $^{206}Pb/^{204}Pb$ values of the basalts to a measurable extent. The flux of marine Sr into the ridges with $^{87}Sr/^{86}Sr = 0.7091$ is expected to result in a modification of the isotope compositions of the basalts as indicated. The approximate ranges of Sr-, Nd- and Pb-isotope compositions of unaltered m.o.r.b. glasses are indicated (Cohen *et al.* 1980; Cohen & O'Nions 1982*a*, *b*; Dupré & Allègre 1980).

very poorly known. The crude estimate of 10^{11} kg a^{-1} shown in figure 6 is derived from estimates made by Kay (1980). It seems possible therefore that significant amounts of pelagic sediment may have been recycled into the mantle and could thereby have exerted an important control on the isotopic evolution of the upper mantle.

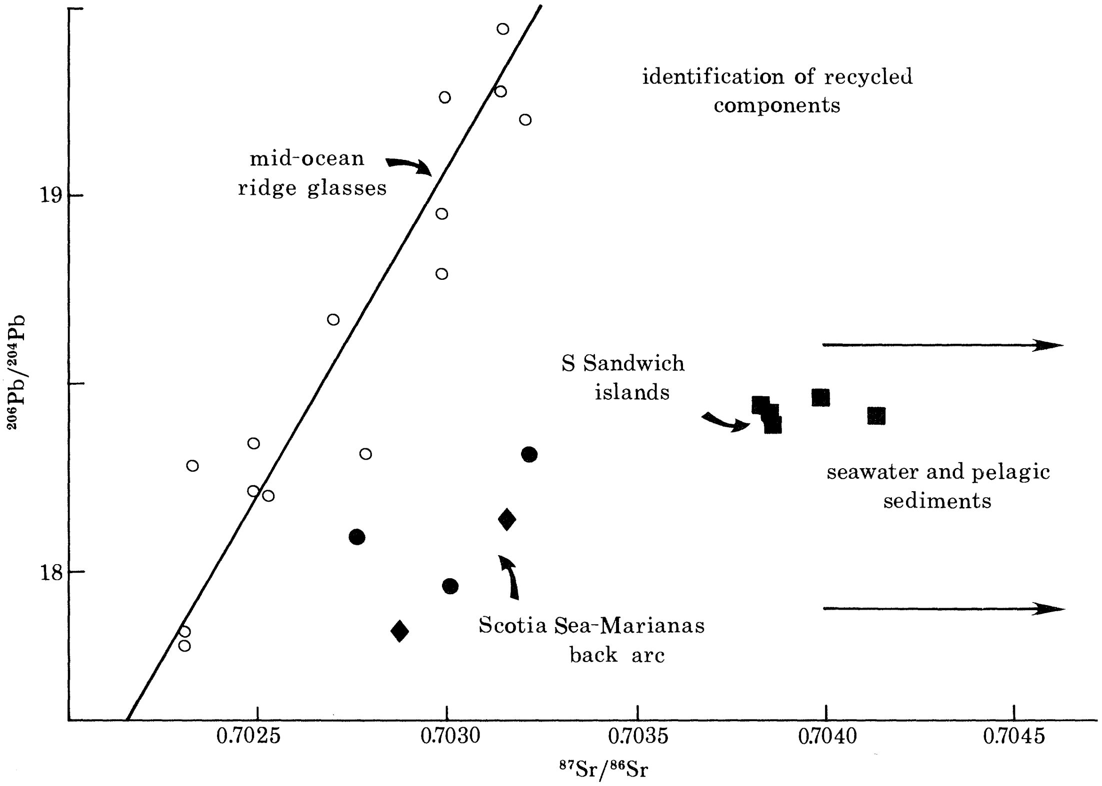

FIGURE 5. Comparison of $^{206}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ ratios in unaltered mid-ocean ridge basalt glasses and back-arc (Scotia Sea, Parece Vela and Philippine Basins) glasses (after Cohen & O'Nions 1982*b*).

The shift in $^{87}Sr/^{86}Sr$ ratio of island-arc and back arc, samples is thought to reflect the addition of continent derived Sr into the basalt source. The Sr may have been introduced as altered ocean floor basalt (see figure 4) or pelagic clay. Their alternatives may be evaluated further if $^{207}Pb/^{204}Pb$ is considered (see figure 6).

ATMOPHILE–LITHOPHILE TRACER RELATIONS

The large number of observations on the Sr, Nd and Pb-isotope compositions for ocean floor and ocean island volcanics have been complemented in recent years by measurements of the isotopic abundances of rare-gas in similar materials. For example, $^{3}He/^{4}He$ ratios are available for a number of samples for which $^{87}Sr/^{86}Sr$ ratios are also available (figure 7). The $^{3}He/^{4}He$ ratio 'R' of mid-ocean ridge basalts when compared with this same ratio in the atmosphere R_a shows a small variation with $7 < R/R_a < 9$. Whereas the $^{87}Sr/^{86}Sr$ ratios of mid-ocean ridge basalts correlate positively with $^{206}Pb/^{204}Pb$ ratios (figure 4), they do not exhibit any systematic relations with $^{3}He/^{4}He$. Nor are there any obvious straightforward or systematic relations between $^{3}He/^{4}He$ and $^{87}Sr/^{86}Sr$ ratios evident for ocean island basalts. For example, Tristan da Cunha basalts have $^{87}Sr/^{86}Sr$ ratios that are among the highest found for oceanic basalts but their R/R_a value is lower than those typical of m.o.r.b. Two other islands associated with hot spots, namely Iceland and Hawaii, show a large range of $^{3}He/^{4}He$ values, with some samples showing considerable enrichments of ^{3}He relative to m.o.r.b. with R/R_a in excess of 20. However, in both Iceland and Hawaii no correlation of R/R_a with $^{87}Sr/^{86}Sr$ is evident. The lack of correlation between helium and strontium isotopes both within individual oceanic islands and in general throughout the ocean basins indicates a fundamental decoupling between these two systems. Condomines *et al.* (1983) have suggested that at least

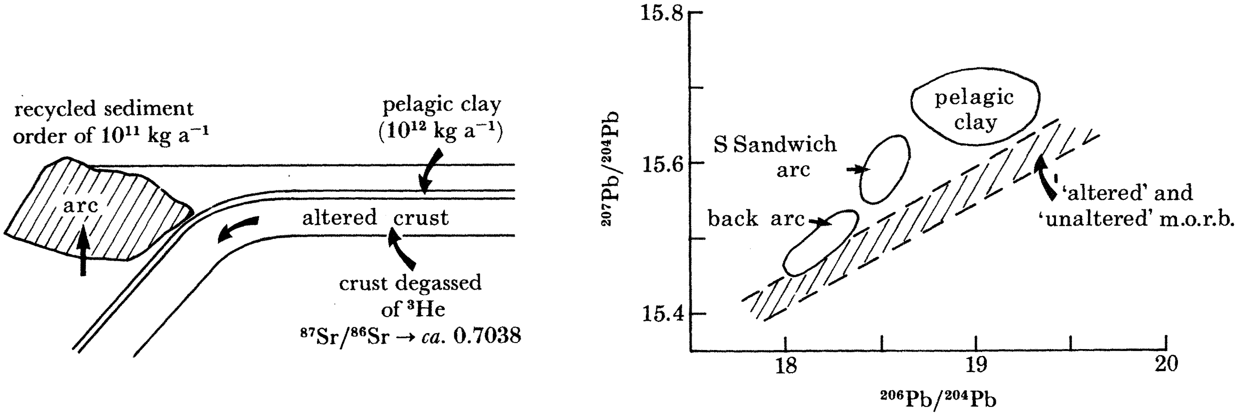

FIGURE 6. Tracing of recycled pelagic sediments into the source region of island arc volcanics. In addition to upper mantle, altered oceanic crust (with a modified ^{87}Sr/^{86}Sr ratio: see figure 4) and pelagic clay are potential sources. The distinctive Pb isotope composition of pelagic clay renders this component recognizable in many island arc basalts such as the South Sandwich Islands. The order of 10^{11} kg a^{-1} of pelagic clay may be recycled through arcs (Kay 1980) and a fraction of the 10^{12} kg a^{-1} deposited in oceans is recycled further into the mantle.

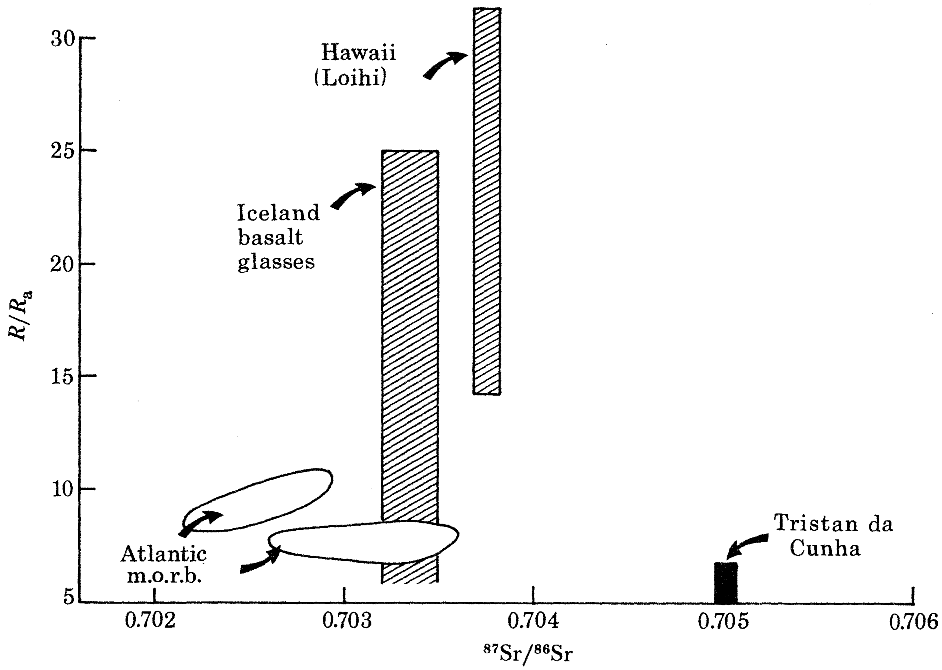

FIGURE 7. An example of the relations between a lithophile (^{87}Sr/^{86}Sr) and an atmophile (^{3}He/^{4}He) tracer in mantle-derived materials. The ^{3}He/^{4}He ratio, R, is expressed relative to the same ratio in the atmosphere ($R_a = 1.4 \times 10^{-6}$). Mid-ocean ridge basalts show a restricted range of ^{3}He/^{4}He ratios and ^{87}Sr/^{86}Sr. In contrast ^{87}Sr/^{86}Sr ratios of ocean island basalts exhibit a wide variation and some samples from Iceland and Hawaii show large enrichments in ^{3}He and $R/R_a > 25$. However, within a particular island such as Iceland the ^{87}Sr/^{86}Sr and ^{3}He/^{4}He (R/R_a) ratios are decoupled. The source of the excess ^{3}He is likely to be located in the deeper parts of the mantle possibly below the convecting upper mantle. Data from Kurz *et al.* (1982); Condomines *et al.* (1983).

in the case of the Icelandic volcanics some of the range in $^3He/^4He$ may arise from variable additions of radiogenic helium that has developed within the Icelandic crust itself. However, it is likely that the source of the primordial ^3He component lies deep within the mantle and probably within the lower mantle (McKenzie & O'Nions 1983; Allègre *et al.* 1983; O'Nions & Oxburgh 1983). The evolution of the atmophile rare gas and lithophile tracers in the lower mantle may have been largely decoupled from that taking place in the upper mantle, and additional local variability may arise from any mass transfer that accompanies jetting from the lower thermal boundary layer of the upper mantle (McKenzie & O'Nions 1983).

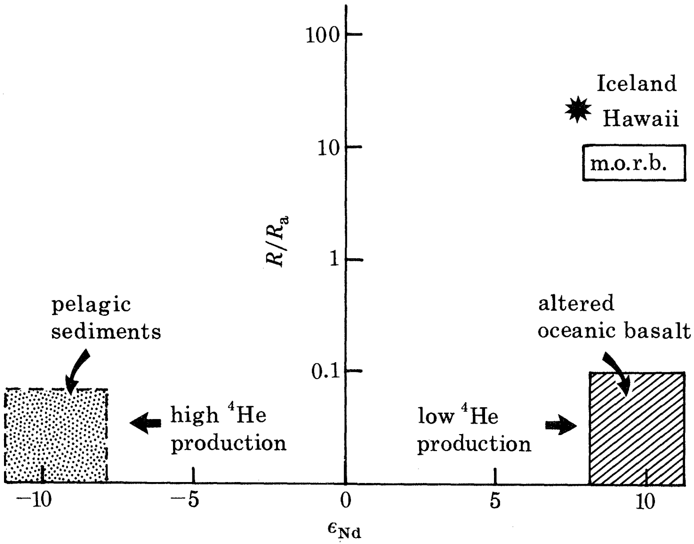

FIGURE 8. Anticipated relations between $^3He/^4He$ (R/R_a) and $^{143}Nd/^{144}Nd$ (ϵ_{Nd}) in mid-ocean ridge basalts, Hawaiian and Icelandic basalts, altered ocean floor basalt and pelagic clay. The initial mantle helium contained in ocean floor basalt will be largely lost after eruption and radiogenic helium will be generated with $R/R_a \approx 0.01$; the ϵ_{Nd} value is not expected to change as a result of hydrothermal alteration. Pelagic clays possess an estimated range of ϵ_{Nd} values as shown (Goldstein & O'Nions 1981; Goldstein *et al.* 1984), and will generate radiogenic He according to their U and Th content. Involvement of pelagic sediment in magma genesis may be reflected in both the ϵ_{Nd} and $^3He/^4He$ values of the erupted basalts.

The use of the rare-gas tracers such as $^3He/^4He$ for evaluating the relative contributions of oceanic crust, continental crust and mantle to magma sources has not progressed very far to date. Kurz *et al.* (1982), for example, have suggested that the low R/R_a value of the Tristan da Cunha basalts may reflect the contribution of oceanic crust or recycled sediment to the magma source. However, whereas this is certainly a possibility, it remains to be demonstrated that processes operative at high levels within the oceanic crust are not responsible for these very low values. Because radiogenic helium is expected to have $R/R_a \approx 0.01$ (Andrews 1984) which compares with $7 < R/R_a < 30$ for oceanic basalts, the potential certainly exists for the recognition of a small component (low percentage) of mantle derived helium in the presence of much larger amounts of helium generated in the continental crust. The anticipated relations between He- and Nd-isotopes in potential source materials are indicated in figure 8. It is noteworthy that both altered oceanic basalt and pelagic sediments are likely to have $R/R_a < 1$, yet quite distinctive Nd-isotope compositions. The involvement of these components in the source of mantle-derived magmas may be recognizable eventually from a comparison of the He- and

Nd-isotope systematics. It should be emphasized that this particular approach is very much in its infancy and these systematics are introduced here to indicate the potential offered by the combined use of these tracers.

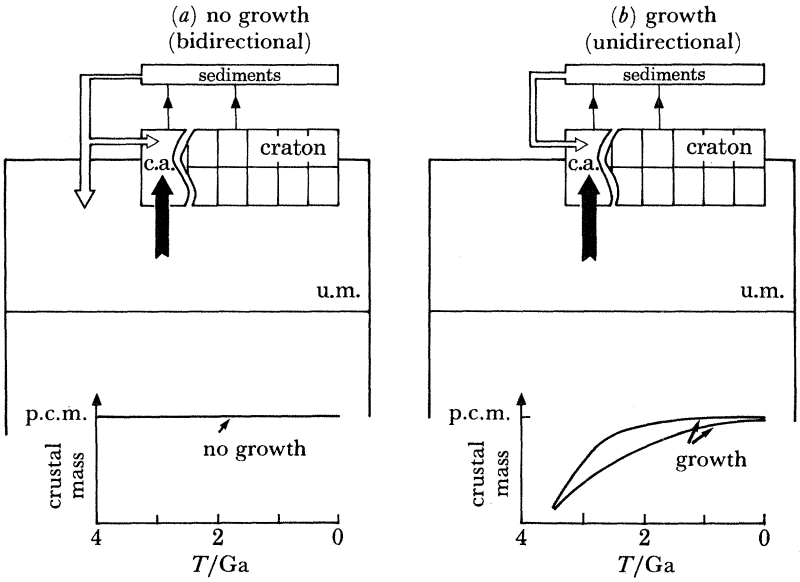

Figure 9. Comparison of a growth (increasing continental mass with time) and a no-growth (constant continental mass through time) model for the evolution of the continental crust.

(*a*) In the no-growth model (such as supported by Armstrong 1981) the present-day continental mass (p.c.m.) is maintained over the last 4 Ga. New additions from the mantle (most probably only upper mantle) are added as new continental accretions (c.a.) which may be a mixture of recycled and pre-existing continental crust. The mass flux from the mantle to the continental crust must be balanced by a return flux at all times. (*b*) The particular growth model illustrated presupposes that continental crust once formed is indestructible (cf. Moorbath 1975) and the return mass flux to the mantle is zero. Newly accreted continent (c.a.) may have identical Sr-, Nd- and Pb-isotope characteristics to those in the no-growth model.

Crust-mantle interactions and evolution of the continents

An assessment of the relative contributions of continental and oceanic crust and the mantle to a particular magma is an intrinsic part of the more fundamental problem of the generation and evolution of the continental crust itself. At one extreme point of view continental crust is thought to develop through a new addition of material from a mantle source without any recycling of pre-existing continental crust. At the other extreme the continents have been considered to evolve with a constant mass whereby additions from the mantle are balanced by a return flux from the continents. The two situations are illustrated schematically in figure 9. Unequivocal tests of the two limiting cases illustrated have not been forthcoming, although it is clear from the foregoing that some unknown quantity of continental material is certainly recycled into the mantle. The difficulty in assessing these different possibilities is that both models are compatible with the known radiometric age distribution pattern in the continents, and general constraints available from the deduced isotopic evolution of the upper mantle (see Armstrong 1981).

The no-growth case (figure 9) requires that the fluxes of various species from the mantle into the continental crust and vice versa are equal for all times. Furthermore, in order that the distribution of radiometric ages in the continents are reproduced, recycling rates must decrease substantially from the early Archaean to the present day.

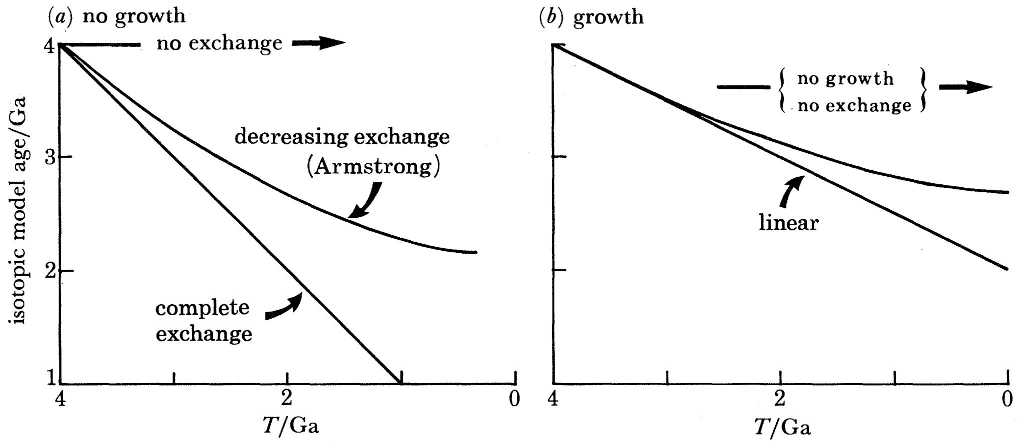

Figure 10. Comparisons of the anticipated isotopic model age such as might be calculated for the ^{147}Sm–^{143}Nd system for the entire continental crust as a function of time for contrasting models of continent generation and evolution.

(*a*) In the no-growth model where the continental crust undergoes no further interaction with the mantle the isotopic model age is the same at all times. The model age is reduced according to the amount of exchange that occurs. (*b*) Growth models (increasing mass) can produce a range of model ages according to growth rates. Once growth stops, the isotopic model age will remain the same. The sedimentary part of the continental crust may be a useful monitor of the state of evolution of at least the upper part of the continental crust (see figure 11).

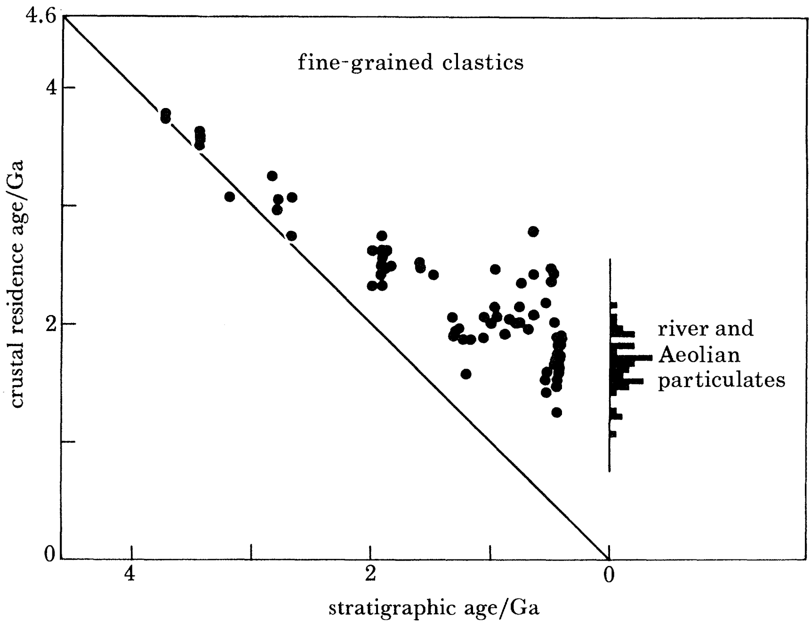

Figure 11. Crustal residence ages of sediments and recent fluvial particulates calculated from Sm–Nd isotopic analyses compared with their stratigraphic ages. The crustal residence ages are calculated relative to a depleted mantle model whereby $\epsilon_{Nd}^{4.6} = 0$ and $\epsilon_{Nd}^{0} = 10$. New additions to the continents according to this model will plot close to the straight line shown. Sediments younger than about 2 Ga are all dominated by older crustal components and recycling of continental material dominates the evolution of the sedimentary mass. Data from O'Nions *et al.* (1984), Goldstein *et al.* (1984), Miller & O'Nions (1983).

The relevance of this basic problem of continent generation and evolution to questions of mantle and crustal contributions to magmas becomes more evident when the problem is resolved into the following component questions:

(i) how does the amount of continental accretion vary with time?

(ii) what amounts of continent or continental components are recycled into the mantle as a function of time?

(iii) what is the contribution of mantle-derived material *vis à vis* recycled continental material to areas of newly accreted continental crust?

Solutions to (i) and (iii) would lead to a specification of the time-dependent changes in mantle-derived additions to the continents which when compared with (ii) would potentially allow a distinction between the growth and no-growth models. Although the present discussion is primarily concerned with question (iii) recent data relevant to this problem will be considered within the framework of the problem as a whole.

The Sm–Nd isotopic composition of fine-grained clastic sedimentary rocks has proved to be an extremely effective monitor of crustal development (McCulloch & Wasserburg 1978; O'Nions *et al.* 1983; Goldstein *et al.* 1984). This important attribute derives from the observation that the Sm/Nd ratios of such materials of *all* ages show remarkably little variation and faithfully reflect the average Sm/Nd ratios of their crustal precursors. These features, coupled with the fact that the sedimentary mass is efficiently recycled with a half-life of *ca.* 0.5 Ga, renders sedimentary rocks effective monitors of mantle additions to the continents. Usually the Sm/Nd isotopic data are used to calculate a single-stage model age relative to some model of mantle evolution (see figure 10 legend); this model age has been termed the crustal residence age (O'Nions *et al.* 1983). Crustal residence age estimates of particulates from modern rivers together with those for ancient sediments are compared with stratigraphic ages in figures 10 and 11. The following principal features evident from these diagrams should be noted.

(i) The erosion products carried by the World's major river systems show a small spread in crustal residence ages and average 1.7 Ga.

(ii) Only Archaean and early Proterozoic sediments have crustal residence ages that are close to their stratigraphic ages. The crustal residence ages of younger sediments show a progressive diversion from their stratigraphic ages.

(iii) The crustal residence ages of Phanerozoic and late Proterozoic sediments are indistinguishable within the present ranges.

New mantle additions to the sedimentary mass must have been comparatively minor during the last 1.0 Ga, because the average crustal residence ages of sediments deposited in this interval are very similar, and any contemporary mantle addition would have a model age equal to the stratigraphic age. Clearly mantle-derived additions to the sedimentary mass and almost certainly to the continents themselves have been considerably less important during late Proterozoic and Phanerozoic times than during the Archaean and earlier Proterozoic. Orogenic belts produced during this former interval, such as the Alps–Himalayas, Caledonides, and Hercynides are dominated by recycling of pre-existing crust. This conclusion is emphasized by the similarity of the crustal residence ages of sediments carried by rivers draining very different terrains (Goldstein *et al.* 1984). The continental crust cannot be growing at anything like its mean rate at the present day.

Lastly mention should be made of a recent attempt by Allègre *et al.* (1983) to assess the possibility that a steady state situation may exist in the global carbon cycle. Although a full assessment of the uncertainties involved in the estimates is difficult to make at present, the estimated flux of carbon from the mantle suggests that the residence time of carbon at the surface is short (figure 12) and an approximate steady state may exist. This would seem to require that a substantial portion of the pelagic sediments in the oceans is returned to the mantle to satisfy the flux.

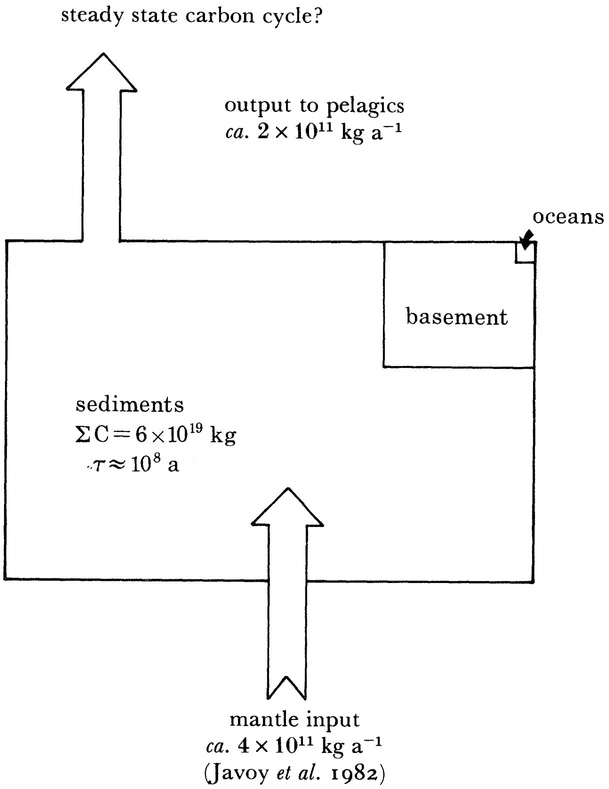

FIGURE 12. The question of changes of mass of continental crust in general and the specific inventory of components of the Earth's surface requires that estimates of fluxes of individual species from the mantle to the continental crust–hydrosphere–atmosphere system and vice versa are made.

An example of recent estimates of the terrestrial carbon budget and fluxes are presented above after Javoy *et al.* (1982). The distribution of carbon between sediments, continental basement and CO_2 dissolved in the oceans is indicated by the relative sizes of the boxes.

CONCLUSIONS

Because of their differential geochemical behaviour during magma genesis and formation of continental crust, the presently exploitable radiogenic isotope tracers taken together provide a very powerful tool for the investigation of the relative contributions of mantle and crustal sources to magmas. In particular a judicious selection of tracers often permits at least qualitative recognition of continental and ocean crust components within the isotope tracer signature of a particular magma. Progress on the elucidation of the mass balance of these interactions both on a global scale and with respect to generation of individual magmas has been slower, although some studies made in selected areas such as those detailed elsewhere in this volume have been very successful in this regard.

The specific topic posed for discussion here is certainly an important one. However, it is an essential part of the more fundamental problem of the generation and development of continental crust. The investigation of the provenance of magmas generated in different tectonic environments throughout time is an established approach to this problem, but there would appear to be considerable scope for exploiting the radiogenic isotope tracer signatures in systems such as the sedimentary mass that generally monitor the exposed continental crust.

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