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Isotope and trace element models of crustal evolution

BY R. K. O'NIONS AND P. J. HAMILTON

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Some of the isotopic constraints on the development of continental crust from about 3.8 Ga ago are reviewed. Particularly it is noted that Archaean granitic (*sensu lato*) rocks have initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios close to predicted values for the bulk Earth at the time before emplacement, whereas those Phanerozoic granites investigated so far diverge considerably from the bulk Earth and betray the existence of later continental crust in their provenance.

Geochemical evidence for recycling of some continent-derived elements into the mantle is examined and the important distinction between selected element recycling and bulk return of continental material is emphasized. Various transport models that have been proposed to model the development of continental crust are examined and some of their differences and similarities, particularly with respect to implications for continental recycling, are highlighted.

INTRODUCTION

Although the continental crust constitutes only 0.3% of the Earth's total mass, it contains a large proportion of the global inventories of the trace elements of large ionic radius, including the heat-producing elements K, U and Th. The appreciation that the continental crust is a reservoir for such elements, complementary to a mantle reservoir supplying them, has spawned various attempts to model the time-dependent interactions between the two reservoirs (Armstrong 1968; Armstrong & Hein 1973; Russel & Birnie 1974; O'Nions *et al.* 1979; Jacobsen & Wasserburg, 1979*a*; Doe & Zartman 1979). All such models utilize estimates of the chemical compositions of mantle and crustal reservoirs and aim to be consistent with the deduced age distribution pattern within the continental crust and to reproduce the isotopic compositions of one or all of Sr, Nd and Pb in mantle-derived materials.

The growth of continental crust and concomitant differentiation of the mantle are problems not readily separable from the thermal history of the entire Earth. For example, the apparent absence of continental crust greater than 3.8 Ga in age may be considered to be a reflection of either higher or lower mean temperature for the Earth before this time. An initially cool Earth would not undergo early differentiation and the onset of continental growth would be delayed until the temperature of the Earth increased through radioactive decay to the required level. If the Earth was substantially hotter before 3.8 Ga ago than during subsequent times, then vigorous convection may have prevented the stabilization of continental crust. At present there are few direct constraints on the early thermal history of the Earth (see Smith, this symposium) and it can only be inferred by extrapolation of the deduced present thermal state of the Earth back in time, and from analogies made with the early thermal histories of other planetary objects. Models of mantle differentiation must involve assumptions, either implicitly or explicitly, about the nature of transport processes before 3.8 Ga ago and thus about the Earth's initial thermal state. Whereas a paucity of knowledge concerning the early history of

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the Earth is a limitation, geochemical modelling has been of great value in identifying the characteristics of the geochemical reservoirs constituting the continental crust and mantle.

The purpose of the present article is to evaluate some of the constraints that lead to the formulation of models of continental growth and mantle differentiation and to review the contribution that such geochemical modelling has made to date.

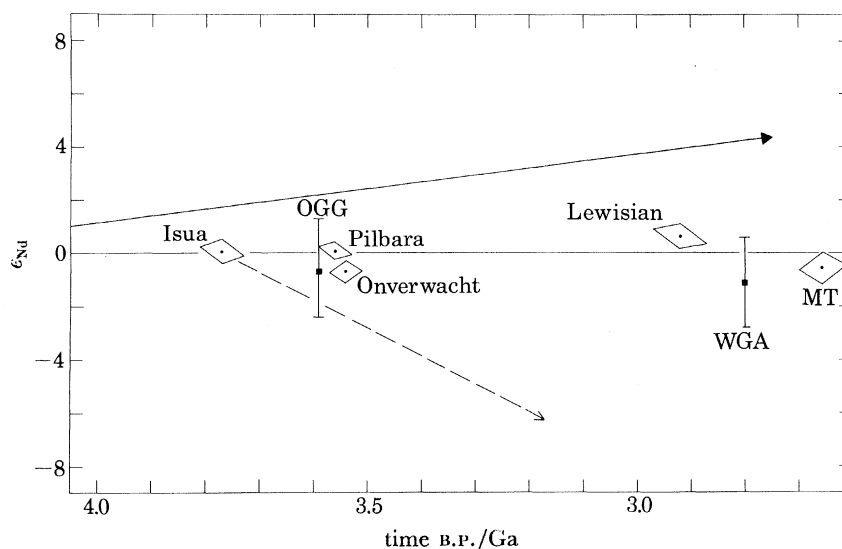


FIGURE 1. A plot of $\epsilon_{Nd}(t)$ against time for the Archaean (igneous and metaigneous); ϵ_{Nd} is equal to 10^4 times the deviation of the initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratio and the $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of a reservoir with chondritic Sm/Nd ratio at the appropriate time (DePaolo & Wasserburg 1976*a*). Results from whole-rock isochron determinations are indicated by 95% confidence limit polygons (Hamilton *et al.* 1978, 1979*a, b*, 1980; Zindler *et al.* 1978). Other data points are shown for a single whole-rock analyses by DePaolo & Wasserburg (1976*a, b*) for Amitsoq gneiss (OGG) and Fiskenaasset anorthosite (WGA). The dashed line indicates the evolution of continental crust formed 3.77 Ga ago with a typical crustal Sm/Nd ratio that deviates by -40% from the chondritic ratio ($f = -0.4$). Note that the samples all plot close to the line $\epsilon_{Nd}(t) = 0$. Results from the Stillwater intrusion (2.70 Ga old), giving $\epsilon_{Nd}(t) = 2.8 \pm 0.2$, have not been plotted, as these appear to be contaminated with continental crust. Extension of solid line indicates position of m.o.r.b. at present day.

ISOTOPIC CONSTRAINTS ON CONTINENTAL EVOLUTION

In addition to estimates of the chemical composition of the mantle and the continental crust the abundances of radiogenic isotopes in these reservoirs are the major constraints on continental evolution.

Progress to date has centred upon the radiogenic daughter products of ^{40}K ($T_{1/2} = 1.25$ Ga), ^{87}Rb ($T_{1/2} = 48.8$ Ga), ^{147}Sm ($T_{1/2} = 106$ Ga), ^{232}Th ($T_{1/2} = 14.0$ Ga), ^{235}U ($T_{1/2} = 0.7$ Ga) and ^{238}U ($T_{1/2} = 4.47$ Ga), which are ^{40}Ar , ^{87}Sr , ^{144}Nd , ^{208}Pb , ^{207}Pb and ^{206}Pb respectively. These long half-life parent isotopes and their daughter products are of great value for dating events that have taken place during the development of the Earth's crust and for tracing differentiation processes occurring on the 1 Ga time scale. However, the long half-life systems provide little information about events occurring on the 100 Ma time scale in the earliest history of the Earth. Events on such a time scale may eventually be traceable by means of the daughter products of a short half-life parent isotope such as ^{129}I (^{129}Xe ; $T_{1/2} = 16$ Ma).

The so-called 'age distribution pattern' in the continental crust has been progressively defined from K-Ar, Rb-Sr, U-Pb and, more recently, Sm-Nd geochronological studies. The latter

three parent–daughter systems, however, have proved to be the most valuable for specifying the times of separation of crustal segments from a mantle reservoir and therefore the timing of continental growth. Consideration of the ages and initial isotopic ratios obtained from whole-rock isochron studies of Archaean terrains have led to the concept of successive additions of crustal material from 3.8 to 2.5 Ga, with minimal reworking. This evidence for progressive growth of ancient crust vitiates its formation during a single episode. The arguments on which this concept is based are well established in the literature and the reader is referred to recent reviews of Rb–Sr and U–Pb data by Moorbath (1975) and O’Nions & Pankhurst (1978).

The results obtained from Sm–Nd isotope studies of Archaean terrains have revealed an impression of early continental crust formation consistent with that deduced from Rb–Sr and U–Pb studies. Some of these results are summarized in figure 1, where the ages (as deduced from Sm–Nd systematics in most instances) are compared with initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios expressed as 10^4 times the deviation ($\epsilon_{\text{Nd}}(t)$) from the model chondritic bulk-Earth value at the appropriate times. The main points to note from figure 1 are the consistency of the $\epsilon_{\text{Nd}}(t)$ values of crustal components, formed between 3.77 Ga and 2.45 Ga ago, with derivation from a reservoir that has evolved with a chondritic Sm/Nd ratio ($\epsilon_{\text{Nd}}(t) = 0$ corresponds to a Sm/Nd ratio of 0.308). The broken line in figure 1 ($f = [(\text{Sm}/\text{Nd})_{\text{crust}}/0.308] - 1.0 = -0.4$) depicts the evolution of a crustal segment formed 3.77 Ga ago and possessing a typical crustal Sm/Nd ratio. Comparing the Nd isotope parameters obtained from the Lewisian gneisses for example with those predicted for typical 3.8 Ga old crust at 2.9 Ga indicates that the Lewisian could not have been produced by reworking of such material. If the parameters used for the bulk Earth in figure 1 are accepted, then the uncertainties in T and $\epsilon_{\text{Nd}}(t)$ associated with each point in figure 1 indicate that the Amîtsoq, Lewisian and other gneisses could not have had crustal prehistories characterized by $f = -0.4$ exceeding *ca.* 100–200 Ma. This conclusion is entirely consistent with previous statements made on the basis of Rb–Sr data (Moorbath 1975; O’Nions & Pankhurst 1978). Because continental crust is produced with a larger fractionation of Rb/Sr than Sm/Nd compared with that of the bulk Earth (typically $f(\text{Rb}/\text{Sr}) = +3.2$), the Rb–Sr isotope system is more sensitive to crustal prehistory than the Sm–Nd system, but unfortunately this potential is generally offset by the perturbation of Rb–Sr systematics by metamorphic effects and consequently the poor precision associated with the determination of initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. However, for the 3.35 Ga old Mont d’Or granite in Zimbabwe (Moorbath *et al.* 1976), the measured initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.711 ± 0.002 allows a crustal prehistory of *ca.* 200–400 Ma to be resolved.

The clear view that emerges from Rb–Sr, U–Pb and Sm–Nd systematics of a quasi-continuous development of Archaean continental crust from a reservoir sufficiently large to maintain bulk-Earth characteristics (see also McCulloch & Wasserburg 1978) contrasts with the more complex impressions of crustal evolution that arise from similar investigations of Phanerozoic crust. An example of this complexity is illustrated in figure 2, where the initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios calculated for Caledonian and Tertiary granitic rocks are compared in terms of the $\epsilon_{\text{Nd}}(t)$ parameter with the bulk Earth, the present-day range of mid-ocean-ridge basalts (m.o.r.b.) and the 505 Ma old Bay of Islands ophiolite. The m.o.r.b. have positive $\epsilon_{\text{Nd}}(t)$ values, indicating evolution in a mantle source region with a Sm/Nd ratio greater than that of the bulk Earth. This feature has been attributed to the extraction of continental crust with a Sm/Nd ratio less than the bulk Earth. Similarly, the Bay of Islands ophiolite also possesses a positive $\epsilon_{\text{Nd}}(t)$ value demonstrating derivation from a source with a similar Nd-isotope evolution

to that of m.o.r.b. (Jacobsen & Wasserburg 1979*b*). Many models of crustal growth appeal to the accretion of material generated at destructive plate margins. Nd-isotope investigations of island-arc tholeiites (figure 3) formed in such environments indicate that an important component is derived from a source indistinguishable from that of m.o.r.b. (Hawkesworth *et al.* 1977, 1979; DePaolo & Wasserburg 1977). However, Caledonian granites (figure 2), Hercynian granites from France and the Sierra Nevada batholith (Allègre *et al.* 1979) do not have positive $\epsilon_{Nd}(t)$ values typical of depleted mantle. On the contrary they have generally negative $\epsilon_{Nd}(t)$ values in the range 0 to -24 , closer to typical values for old continental crust. Hamilton *et al.* (1980) have shown that reasonable estimates of provenance age can be made for Caledonian granites that are comparable to estimates made from inherited zircons in the same granites. For those Caledonian and Tertiary granitic rocks shown in figure 2, it is impossible to specify precisely the $\epsilon_{Nd}(t)$ value of any mantle-derived component at the time of their emplacement.

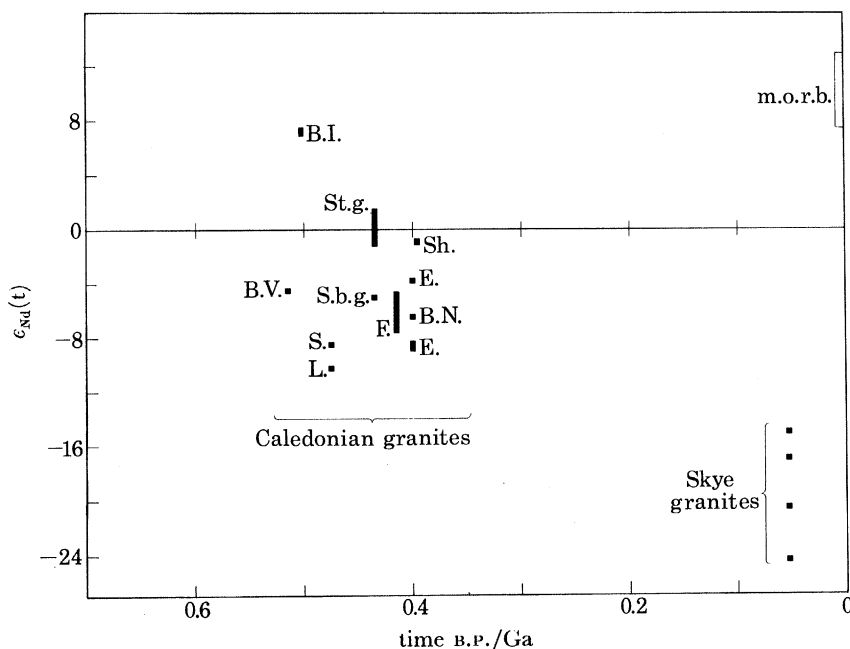


FIGURE 2. Values of $\epsilon_{Nd}(t)$ for some Phanerozoic granitic rocks. Caledonian granites (*s.l.*) from N England and Scotland, and Tertiary granites from Skye, Scotland (see figure 1 for definition of $\epsilon_{Nd}(t)$). Most of the granites have $\epsilon_{Nd} \leq 0$ in marked contrast to Lower Palaeozoic oceanic crust as represented by the 505 Ma old Bay of Islands (B.I.) ophiolite (Jacobsen & Wasserburg 1979*b*) and modern mid-ocean-ridge basalt (m.o.r.b.). Abbreviations used are: St.g., Strontian tonalites and granodiorites; S.b.g., Strontian biotite granite; Sh., Shap; E., Etive; B.V., Ben Vuirich; B.N., Ben Nevis; F., Foyers; S., Strichen; L., Longmanhill.

The continental crust evolves with mean $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios that are respectively lower and higher than for contemporary mantle, a feature that renders Sr and Nd of continental derivation potentially distinguishable from that of mantle derivation. This distinction is of value in identifying recycled crustal components in mantle-derived materials. For example the ranges of $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of m.o.r.b. are compared in figure 3 with the same parameters in island-arc tholeiites from the South Sandwich Islands and Marianas and calc-alkali volcanics from the Lesser Antilles. For a given $^{143}\text{Nd}/^{144}\text{Nd}$ ratio most of these samples possess higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios than do fresh ocean-floor basalts, which

indicates the involvement of a component with higher $^{87}\text{Sr}/^{86}\text{Sr}$ than has m.o.r.b. O'Nions *et al.* (1977, 1978) have shown that the submarine alteration of ocean-floor basalts produces an increase of their $^{87}\text{Sr}/^{86}\text{Sr}$ ratio but no change in $^{143}\text{Nd}/^{144}\text{Nd}$ ratio. Both Hawkesworth *et al.* (1977) and DePaolo & Wasserburg (1977) have attributed the Nd and Sr isotope characteristics of island-arc tholeiites to the involvement of Sr in their source of continental provenance, most probably from alteration of ocean-floor basalt, but possibly (Hawkesworth *et al.* 1979) from pelagic sediment also (figure 3). In either situation a clear case can be made for the recycling of continental Sr into the mantle.

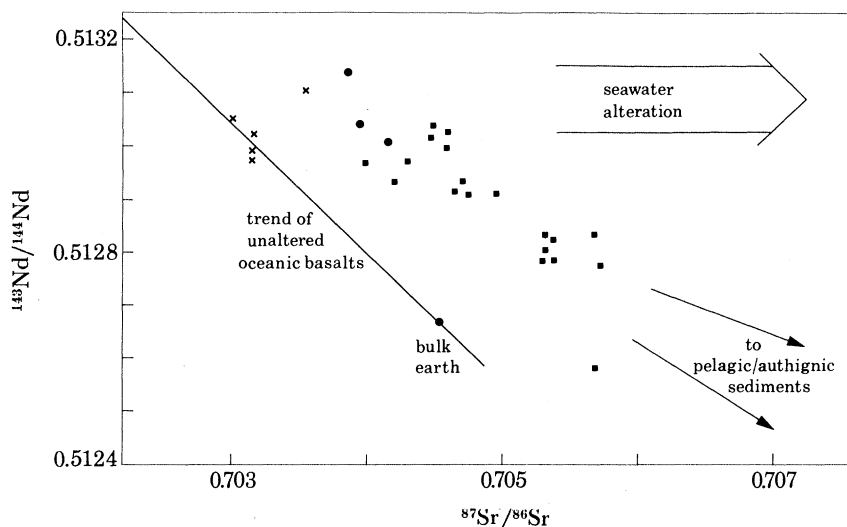


FIGURE 3. Comparison of $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in Recent and unaltered oceanic basalts (DePaolo & Wasserburg 1976 *a, b*; Richard *et al.* 1976; O'Nions *et al.* 1977) with island-arc basalts from the South Sandwich Islands (●), Marianas (×) and Grenada (■) (Hawkesworth *et al.* 1977, 1979; DePaolo & Wasserburg 1977). Note that most samples are displaced to the right of the trend for unaltered oceanic basalts in the sense anticipated for seawater alteration of ocean-floor basalt or possibly admixture of authigenic sediments.

CHEMICAL RESERVOIRS

The mantle, continental crust, oceans and atmosphere constitute major reservoirs within the Earth for groups of elements with particular chemical properties. Material has been exchanged between these reservoirs, and the evaluation of the time-dependent nature of this exchange encompasses fundamental questions of Earth differentiation.

The time-dependent behaviour of elements in the oceans, lakes and rivers is an area of active study that has developed with use of the concept of residence time or period of passage introduced by Barth (1961). In a situation where the input flux of a component i into the oceans J_i^I is exactly balanced by the removal of flux J_i^R , the total amount of i resident in the oceans M_i is related according to

$$\tau_i = M_i/J_i^I, \quad (1)$$

where τ_i is the residence time.

Concepts related to these will be used here in a discussion of those chemical reservoirs comprise the mantle and continental crust. At the outset, however, it should be recalled that the mass of the continental crust has changed with time and that the mantle has undergone a commensurate depletion; therefore the amounts of i in the continents and the mantle

M_i^M , M_i^C are functions of time. Transport of a component from a mantle reservoir to the continental crust has commonly been described by a rate constant $k_i(t)$ whereby the flux from the mantle J_i^M is related to $M_i^M(t)$ according to

$$J_i^M(t) = k_i^M(t) M_i^M(t). \quad (2)$$

The inverse of the rate constant k_i has been termed the process time (O'Nions *et al.* 1980) for those situations where J_i^M is not equal to J_i^C , and M_i^C , for example, changes according to

$$dM_i^C/dt = J_i^M - J_i^C. \quad (3)$$

If the fluxes to and from the crust or mantle are equal, however, $J_i^C = J_i^M$, and there is no net change of M_i in either reservoir ($dM_i/dt = 0$), then, from (1) and (2),

$$M_i^M/\tau_i^M = k_i^M M_i^M, \quad (4)$$

and the residence time τ_i is equal to the inverse of the removal rate constant k_i (see also Li 1977).

Some authors (for example, Garrels *et al.* 1973), have used the term residence time in situations where input and removal fluxes are not equal ($dM_i/dt \neq 0$) by defining an instantaneous residence time with respect to either the input or output flux. A residence time specified in this manner is formally identical to the inverse of the input or removal rate constant termed process time above. However, a distinction will be made here between these two situations: residence time will be reserved for situations where $dM_i/dt = 0$ and process time will be used where $dM_i/dt \neq 0$.

The distribution of radiometric ages in the continental crust may potentially be related to the process or residence times of crustal components. The way in which a particular removal flux operates on the reservoir will exert a strong influence on the material that can survive from a particular point in time. If the flux operates uniformly on the reservoir, or the reservoir is thoroughly well mixed, then after one residence time has elapsed 50% of the original inventory of an element will remain. The residence time, τ_i , can be considered as a half life for that element in a well mixed reservoir such that the present surviving mass of i after a time t has elapsed (M_t) is related to the initial mass M_0 by

$$M_t = M_0 e^{-ct}, \quad (5)$$

where c is a constant equal to $(\ln 2)/\tau$. When t is equal to 6τ , then M_t is reduced to 1.6% of M_0 , and can be considered to have been exhausted.

For the mantle and continents, however, there is no justification for assuming that the reservoirs, particularly the continents, are well mixed and operated on uniformly, and so the expectation that 6τ will essentially exhaust the reservoir will not be fulfilled and material may survive for shorter or longer periods. Such a situation requires that a smaller subset of reservoirs would have to be defined for a more accurate description of the real behaviour.

UNIDIRECTIONAL OR BIDIRECTIONAL TRANSPORT

Whereas it is generally accepted that the continents are secondary in origin and post-date the formation of the Earth, views concerning the nature and rate of their development are widely divergent. The most fundamental differences centre upon the role (if any) of crustal recycling in the evolution of continental crust. The strongest advocacy for crustal recycling

is implied in the models of crustal evolution proposed by Armstrong (1968, and this symposium) and Armstrong & Hein (1973). In these models it is envisaged that continental crust is fully developed about 4.0 Ga ago and recycled through the mantle without any net change of crustal mass. Such models require that low density crust is recycled into the mantle, intimately mixed with mantle material, and then returned to the continents through mantle differentiation processes. Armstrong (1968) and Armstrong & Hein (1973) have shown that the initial Sr and

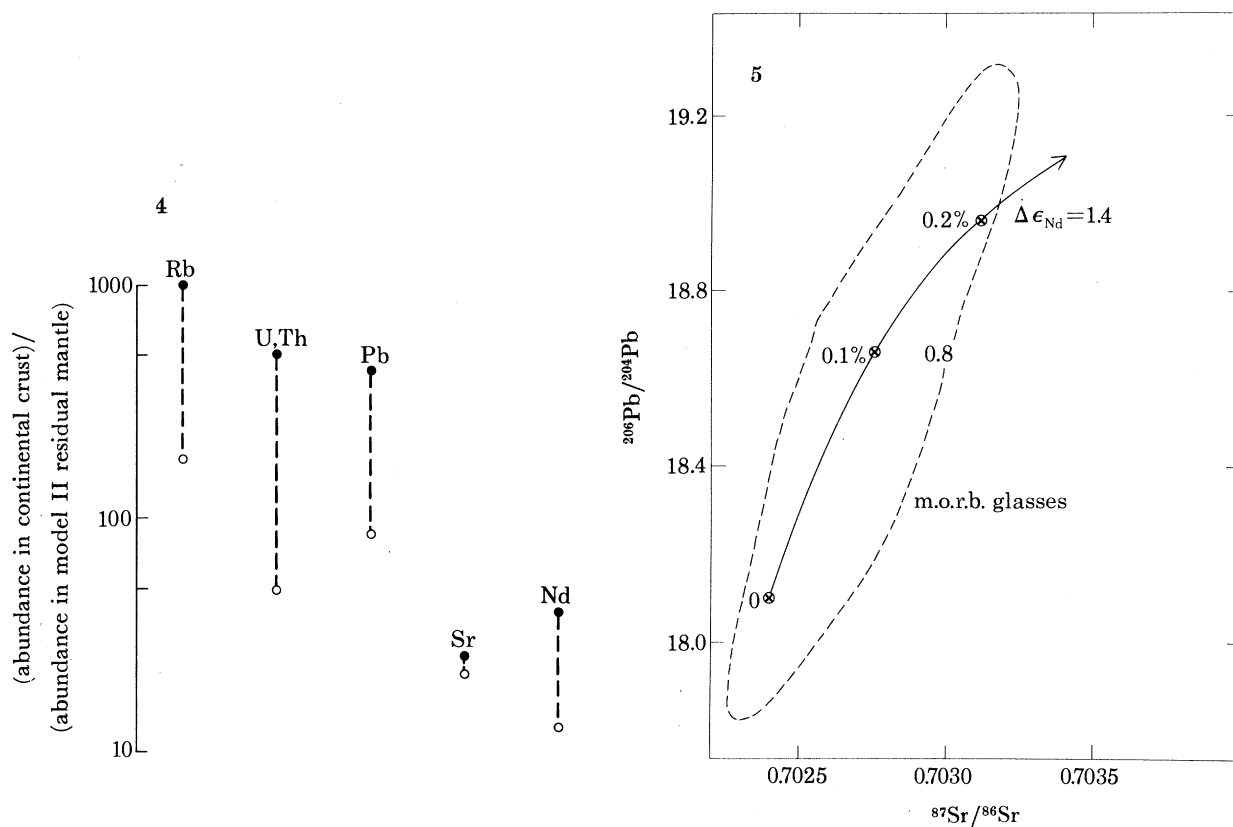


FIGURE 4. Comparison of abundances of Rb, Sr, Nd, U, Th and Pb in the upper (●) and lower (○) continental crust (after Taylor 1979) with those in the residual mantle (model II of O'Nions *et al.* (1979)).

FIGURE 5. Plot of $^{206}\text{Pb}/^{204}\text{Pb}$ against $^{87}\text{Sr}/^{86}\text{Sr}$ ratio showing predicted effect of mixing upper continental crust (Taylor 1979) with residual mantle (model II of O'Nions *et al.* (1979)). Residual mantle without admixed continent is labelled 0, and the $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for 0.1 and 0.2% (by mass) of added crust are indicated. The $\Delta\epsilon_{\text{Nd}}$ values are equal to the change in ϵ_{Nd} effected by the mixing. The mixing vector (solid, arrowed, line) is compared with the range of $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in some m.o.r.b. (Cohen *et al.* 1980), but this is only for comparative purposes and it is not proposed as a unique interpretation of the m.o.r.b. data.

Pb isotope ratios of continental crustal rocks or mantle-derived materials are compatible with such a model. The difficulties arise in these models more in the physical problems of subducting and recycling most of the continental mass during the first few hundred million years of its existence. An alternative view of continental growth is that new crust once cratonized cannot be returned to the mantle and the differentiation process is therefore irreversible. The models of mantle differentiation explored by Jacobsen & Wasserburg (1979*a*), for example, do not involve any recycling of material.

The problem of assessing the importance of continental recycling is one of finding criteria by which the absence of a previously existing segment of continental crust can be demonstrated, or its return to the mantle can be recognized in the chemistry of mantle-derived materials. To pursue the last possibility further, it seems that the most useful chemical criteria must be centred upon elements showing a strong relative concentration in the continental crust. For example table 1 shows the estimated proportions (O'Nions *et al.* 1979) of some lithophile elements (K, U, Th, Rb, Sr, Sm and Nd) that have been released from the mantle to the continental crust. The proportions of Sr, Sm and Nd released are small compared with those of K and Rb, and, in comparison, the release of Si, for example, is entirely negligible. The abundances of these particular elements in the upper and lower continental crust are compared

TABLE 1. COMPARISON OF RELEASE FACTORS†

	global‡	O.H.E. model II§	J.W. model II
K	0.28	0.75 (0.38)	—
Rb	0.36	0.83 (0.42)	0.93 (0.31)
Sr	—	0.22 (0.11)	0.31 (0.11)
Nd	—	0.19 (0.10)	0.41 (0.14)
Sm	—	0.16 (0.08)	0.29 (0.10)
Pb°	0.22	0.75 (0.38)	—
Th	—	0.75 (0.38)	—
U	—	0.75 (0.38)	—

† Release factor is the fraction of original inventory released from mantle reservoir to the crust.

‡ Global (whole Earth) release factors after Anders & Owen (1977).

§ Release factors for model II (O'Nions *et al.* 1979), which only involves release from half of the mantle by mass. Numbers in parentheses correspond to global release.

|| Release factors for model II (Jacobsen & Wasserburg 1979*a*), which involves release from one-third of the mantle. Numbers in parentheses correspond to global release.

with those in residual mantle in figure 4. The abundance levels of K and Rb in the mantle should be far more sensitive to recycling than are those of Sr or Nd, and furthermore they will be considerably more sensitive to recycling of the upper continental crust than to that of the lower. The recognition of trace-element abundance heterogeneities imposed on the mantle by recycling of continental material from the chemical variability of mantle-derived materials is not straightforward, however. Such trace-element abundance variations must be distinguished from those imposed by differential extraction of crustal constituents from the mantle and those imposed by melting and crystallization processes in the case of observations on mantle-derived magmas.

These difficulties can potentially be overcome by resorting to isotopic rather than trace-element abundance considerations. The most promising situations utilizing an isotopic approach are those involving the isotopes of elements with high mantle release factors (figure 4; table 1), where one of the isotopes is the radiogenic daughter of a parent isotope that also has a high release factor. Thus Pb isotopes should be useful (particularly Pb derived from the upper continental crust) as should ^{87}Sr because of the large release factor ^{87}Rb . Although Nd and Sr have comparatively small but similar release factors, the small factor for ^{147}Sm renders ^{143}Nd less useful than ^{87}Sr . This is evident from figure 5, where the effect of a hypothetical recent addition of 0.1 and 0.2% (by mass) of upper continental crust on the Sr, Nd and Pb isotope compositions of a residual upper mantle is illustrated. The addition of 0.1% (by mass) of continental crust to the whole upper mantle would in fact correspond to the

instantaneous recycling of approximately 5% (by mass) of continental crust. The purpose of the calculations presented in figure 5 is to predict the effects of such recycling rather than to propose that recycling of such magnitude has indeed taken place. The addition of 0.2% of continental crust can be expected to have a pronounced effect on mantle Sr and Pb isotope compositions, but a very small and barely resolvable effect on $^{143}\text{Nd}/^{144}\text{Nd}$. The Pb and Sr isotopic variations in m.o.r.b. could be attributed to recycling of continental crust, but other explanations are also possible (Cohen *et al.* 1980). Clear evidence for the recycling of Sr of continental provenance is only identifiable from the Nd and Sr isotopic relations of island-arc basalts summarized in figure 3. Many, but not all, island-arc basalts are displaced to the right of the main trend defined by unaltered oceanic basalts, a feature attributed to seawater alteration of ocean-floor basalt (Hawkesworth *et al.* 1977, 1979; DePaolo & Wasserburg 1977; O'Nions *et al.* 1977, 1978). It is less certain at present whether or not ocean-floor pelagic or authigenic sediment is involved. Sr of continental provenance is recycled into the mantle and by inference so are some other elements, such as K, for which ocean-floor basalts appear to be a sink. Scarfe & Smith (1977) have estimated that approximately 10^{10} kg of K per year are removed by alteration of ocean-floor basalt. However, it is by no means clear that bulk recycling of continental crust occurs (cf. Molnar & Gray 1979). Recycling is an identifiable part of continental evolution, and bidirectional transport models are required for an adequate description of the processes.

Because elements can be decoupled during the process of continental erosion and transport, it will be necessary to consider the return fluxes of individual species and assess their residence times in the continental crust independently. It must be emphasized again, however, that the identification of a particular recycled component (e.g. Sr) does not in itself prove the bulk return of continental crust into the mantle.

STATUS OF GEOCHEMICAL MODELS

A number of models describing the chemical evolution of the mantle and continental crust have been published, the salient features of which are summarized in table 2. All of the models are box models of the type illustrated in figure 6, in which the continental crust or a crustal layer is represented by one box and the mantle, or a portion thereof, is represented by a second. The models of Armstrong (1968), Armstrong & Hein (1973) and Richter & Ribe (1979) differ from the others in that they involve further subdivision of these boxes in an attempt to simulate the isotopic heterogeneity therein. Transport of material occurs from the mantle box into the crustal box (see figure 6 for example) and, with the exception of the Jacobsen & Wasserburg (1979*a*) treatment, there is a return transport from the crust to the mantle. Some other important differences between these models, such as the time of onset of chemical differentiation and the amount of continental crust produced as a function of time, are indicated in table 2.

It should be noted that in the approach used by O'Nions *et al.* (1979) the crustal box (figure 6) includes both oceanic and continental crust, which allows transport before the formation of the earliest surviving crust (*ca.* 3.8 Ga B.P.) to be accommodated. In the time interval *ca.* 4.5 to *ca.* 3.8 Ga ago the model implies that the crust behaved essentially as oceanic crust and that with the exception of volatiles the residence time for material in the outer layer of the Earth was short. This approach suffers, however, in that the recycling of material

TABLE 2. COMPARISON OF TRANSPORT MODELS

model	reference	start time B.P./Ga	fraction of mantle	uni/bi- directional	crustal growth rate	elements modelled	comments
A.	1, 2	4.0	1.0	bi-	nonlinear	Rb, Sr, U, Pb	constant crustal mass from 4.0 Ga to present day
R.B.	3	3.1 ± 0.3	1.0	bi-	nonlinear	U, Pb	models seek solution from 4.5 Ga; result given is best solution
D.Z.	4	4.0	1.0	bi-	nonlinear	U, Pb	additions to continents linear, recycling decreases with time; upper crust recycled preferentially
O.H.E. I	5	4.5	1.0	bi-	nonlinear	Rb, Sr, U, Pb, Sm, Nd, K, Ar	} model II preferred; ocean and continental crust not distinguished
O.H.E. II	5	4.5	0.5	bi-	nonlinear	K, Ar, Rb, Sr, Sm, Nd, U, Pb	
J.W. I	6	3.6	0.33	uni-	nonlinear†	Rb, Sr, Sm, Nd	three-layer mantle: undepleted, depleted and differentiating
J.W. II	6	3.6	0.33	uni-	nonlinear†	Rb, Sr, Sm, Nd	two-layer mantle: depleted and undepleted
R.R.	7	4.5	1.0	bi-	nonlinear	Rb, Sr, Sm, Nd	essentially same as Armstrong models (1, 2)

References: 1, Armstrong (1969); 2, Armstrong & Hein (1973); 3, Russel & Birnie (1974); 4, Doe & Zartman (1979); 5, O'Nions *et al.* (1979); 6, Jacobsen & Wasserburg (1979); 7, Richter & Ribe (1979).

† Concluded from calculations, not imposed as a condition.

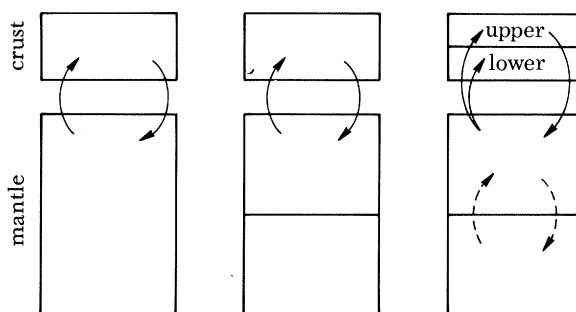


FIGURE 6. Illustration of box models of the type used to describe transport between chemical reservoirs in the Earth such as those in table 2. The left diagram depicts the whole mantle as a box that can chemically interact with crust, illustrated by a second box. The crustal box may be either the continental crust, or the whole crustal layer of the Earth. The middle diagram depicts a situation where only part of the mantle interacts with the crust (see O.H.E. and J.W. models in table 2). The diagram on the right is a more complex situation, where the crustal box is divided into upper and lower continental crust, and material is selectively returned from the upper continental crust to the mantle (see D.Z. model, table 2). Allowance is also made for a limited interaction between the subdivided mantle boxes. Only the J.W. model I described in table 2 has included this possibility.

from oceanic- and continental-type crust cannot be dealt with separately, and such a distinction will clearly be desirable in future models. Some classes of model (table 2) maintain the present continental mass from early in Earth history (4.0 Ga ago for Armstrong's models). Existing isotopic data from the continental crust and depleted mantle require that such a large continental mass must be almost quantitatively recycled through the mantle, which appears to be geologically indistinguishable from the assumption that continental crust never existed at all at this time!

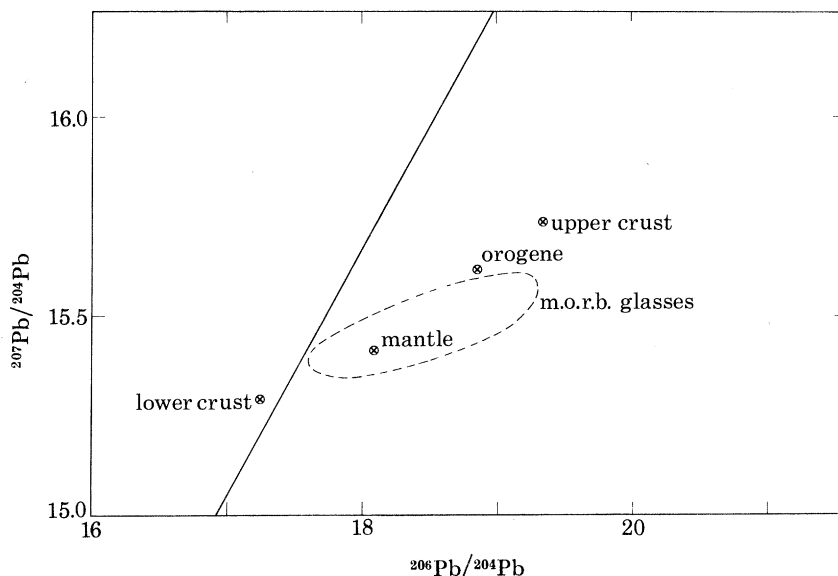


FIGURE 7. Comparison of the field of some m.o.r.b. glasses (Cohen *et al.* 1980) with a 4.55 Ga isochron drawn through initial Pb isotope compositions of Tatsumoto *et al.* (1973) and results of a model investigated by Doe & Zartman (1979). The points (x) for lower and upper continental crust, mantle and orogene are the end results of the D.Z. model (table 2). The model involves a uniform addition of material to the continental crust from 4 Ga B.P. to the present day. Upper crust, with a more radiogenic lead isotope composition than the lower crust, is preferentially recycled into the mantle, at a decreasing rate, which results in the mantle and 'orogene' (a mixture of continent and mantle derived material) plotting to the right of the 4.55 Ga isochron at the present day (solid line). All transport models involving preferential recycling of the upper continental crust will produce present-day Pb isotope compositions displaced in a similar sense to the above.

The models of O'Nions *et al.* (1979) and Jacobsen & Wasserburg (1979a) have attempted to reconcile estimates of the Nd and Sr isotope composition of the continental crust and mantle for specific points in time, and, further, from mass balance considerations, to constrain the mantle fraction that has been involved in the generation of continental crust. Both models concur in concluding that less than the whole mantle has been involved, and they suggest less than one-half and one-third respectively. The difference in these estimates reflect the uncertainties in estimates of the trace-element composition of these reservoirs.

The two-reservoir models discussed above, or in actual fact three-reservoir models when part of the mantle is considered to be undepleted, can successfully accommodate the broad features of the Nd and Sr isotope chemistry of the continental crust and mantle. However, they fail to reproduce the deduced lead isotope composition of the mantle as summarized in figure 7, which appears to require evolution in an environment where the U/Pb ratio has

increased with time (see, for example, Tatsumoto 1978). This could be achieved in a two-reservoir model if the extracted continental crust has a lower U/Pb ratio than has the residual mantle. However, it is difficult to reconcile this with the extreme Pb isotope compositions of some ocean-island volcanics that have Nd and Sr isotope composition closer to the bulk-Earth values than has m.o.r.b., and with the correlation between Pb and Sr isotope compositions in m.o.r.b. (Cohen *et al.* 1980).

The introduction of an additional reservoir with a mean Pb isotope composition less radiogenic than that of the bulk Earth and complementary to that of m.o.r.b. is required. As discussed by O'Nions *et al.* (1979) and Cohen *et al.* (1980) there are two prime candidates for such a reservoir, namely a deep reservoir in the Earth, possibly the core, into which Pb has been selectively concentrated (see, for example, Vollmer 1977), or alternatively the lower continental crust. Internal differentiation of U and Pb in the continental crust has been demonstrated from the Pb isotope composition of crustal rocks (Moorbath *et al.* 1969; Black *et al.* 1971) and by investigations of granulites and amphibolites (Heier & Thoresen 1971). Any preferential recycling of continental crust with high U/Pb ratio would impose a more radiogenic lead isotope composition on the mantle, as indicated in figure 5. The important question, however, is the extent to which such a process may have occurred. Doe & Zartman (1979) have recognized the potential importance of upper crystal recycling, and the results of a model investigated by them are shown in figure 7. However, it remains to be demonstrated whether such a large amount of upper crustal recycling as that envisaged by Doe & Zartman (1979) has occurred, and the possibility of a deeper reservoir of Pb in the Earth cannot be eliminated.

There are several reasons for assuming that the fluxes of material between the mantle and an outer layer of the Earth have changed as a function of time.

(i) Little continental crust older than 3.8 Ga appears to exist, indicating that the characteristic fluxes before 3.8 Ga B.P. cannot be the same as the subsequent ones.

(ii) The mantle reservoir supplying material to the continents has become depleted with time (M_1^M decreased); therefore, even at constant k_1^M , the flux J_1^M must decrease.

(iii) The rate of growth of continental crust appears to have been greater in the Archaean than in the Phanerozoic, indicating that the difference between J_1^M and J_1^C was at a maximum in the Archaean.

O'Nions *et al.* (1979) accommodated these observations by describing transport between the two reservoirs in terms of time-dependent transport coefficients of the form

$$k(t) = k_0(t) e^{-t/\tau}. \quad (5)$$

The time-dependent fluxes of K and Sr in model II of O'Nions *et al.* (1979) are shown in figure 8. The difference between the fluxes from the mantle and the crustal layers ($J_1^M - J_1^C$) reaches a maximum in the interval between 3.5 and 2.5 Ga ago, even though the flux of K from the mantle has decreased from *ca.* 10^{12} kg a^{-1} 4.5 Ga ago to *ca.* 2.6×10^{10} kg a^{-1} at the present day. This is because the time constant describing upward transport is 2 Ga and that describing downward transport is 0.5 Ga. Although the present-day fluxes from the mantle, J_1^M , are not well constrained by this model, it is interesting to compare them with the estimated flux of K through the mid-ocean-ridge system (see appendix 1). The agreement between the model value of 2.6×10^{10} kg a^{-1} and the estimate from appendix 1 of $1.8-1.5 \times 10^{10}$ kg a^{-1} is remarkably good.

The flux of a particular element into the mantle along subduction zones is more difficult to estimate. Alteration of ocean-floor basalt may provide a mechanism for the subduction of some continent-derived elements, and subduction of pelagic sediment another. An assessment of these fluxes is central to a proper understanding of contemporary evolution of the continents.

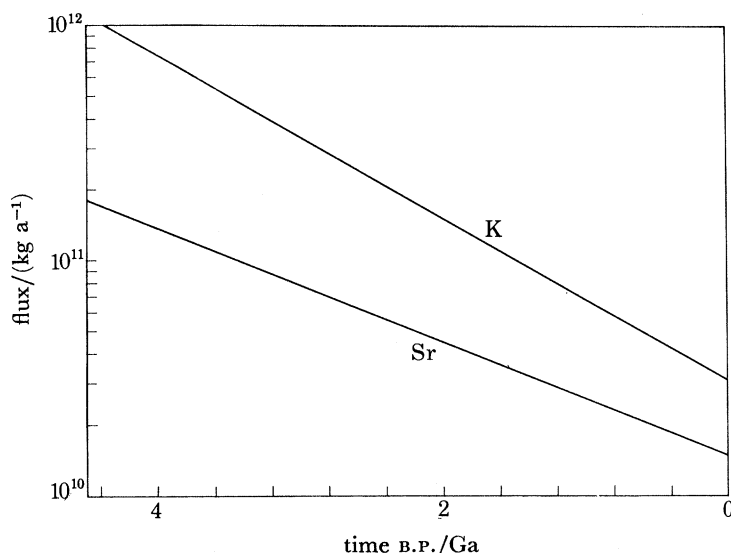


FIGURE 8. Illustration of the time-dependent change of fluxes from the mantle in a situation where the mantle reservoir is progressively depleted with time as a result of continental growth. The results shown are the K flux and the Sr flux (multiplied by 10) from the mantle to the crustal layer for O.H.E. model II (table 2). The K flux exceeds 10^{12} kg a⁻¹ 4.4 Ga ago and is about 3.0×10^{10} kg a⁻¹ at the present day, a 30-fold reduction. The process time changes only by a factor of 9, from 0.42 Ga to 3.8 Ga, during the same time interval.

CONCLUDING REMARKS

Information derived from long half-life parent-daughter systems has provided important constraints on continental evolution, in terms of both specifying the chronology of crust-forming events and tracing the transport between reservoirs through daughter-product abundances. The crustal 'age distribution pattern' is one of the most important constraints that can be applied to transport models of mantle differentiation and crustal growth. However, this is in need of considerable refinement, which is only possible through further geochronology aimed at a more representative sampling of the continents than has been possible hitherto.

Evidence exists for the recycling into the mantle of some continental constituents, such as radiogenic Sr and, by inference, other elements derived from the continents and located in altered oceanic crust. However, these observations should not be construed as evidence for wholesale recycling of continental crust, and they highlight the necessity for considering the reservoir properties of elements residing in the continental crust independently.

The apparent peak in continental growth in the Archaean can be reconciled through transport models whereby the fluxes from both the mantle and a crustal layer both decrease with time, and recycling is implicitly dominated by oceanic-type crust. In contrast models appealing to the existence of the present continental mass from *ca.* 4.0 Ga ago involve the near-quantitative destruction of continental crust during the Archaean, and extremely short residence times for elements in the continents. The feasibility of destroying low-density differentiated crust over a short time interval remains to be demonstrated.

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APPENDIX. ESTIMATES OF PRESENT-DAY MANTLE K FLUX, J_K^M

(a) Ocean crust formation

Ocean crust production rate = $3.25\text{--}2.66 \text{ km}^2 \text{ a}^{-1}$ (Williams & Van Herzen 1974).

Thickness of ocean crust = 7 km (Elthon 1979).

Density of ocean crust = $3.2 \times 10^{12} \text{ kg km}^{-3}$.

Mass of ocean crust produced (m^{oc}) = $7.28\text{--}5.95 \times 10^{13} \text{ kg a}^{-1}$.

Concentration of K in ocean crust (C_K^{oc}) = $2.5 \times 10^{-4} \text{ kg kg}^{-1}$ (Elthon 1979).

$J_K^M = C_K^{oc} m^{oc} = 1.8\text{--}1.5 \times 10^{10} \text{ kg a}^{-1}$.

(b) Geochemical model (O'Nions *et al.* 1979)

Present transport coefficient for K (k_K^M) = $2.6 \times 10^{-10} \text{ a}^{-1}$.

Mass of residual mantle (m^M) = $2.0 \times 10^{24} \text{ kg}$.

Concentration of K in residual mantle (C_K^M) = $5 \times 10^{-5} \text{ kg kg}^{-1}$ (O'Nions *et al.* 1979).

$J_K^M = C_K^M k_K^M m^M = 2.6 \times 10^{10} \text{ kg a}^{-1}$.

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