Differentiation and Evolution of the Mantle [and Discussion]

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Differentiation and evolution of the mantle†

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Evidence for isotopic heterogeneity (particularly with respect to Nd and Sr isotopes) in sub-oceanic and sub-continental mantle is reviewed. The ranges of isotopic heterogeneity in both sub-ocean and sub-continental mantle, as deduced from basalts and ultramafic nodules, are comparable.

The isotope data are compared with the results obtained from simple two-reservoir models with time-dependent transport between the reservoirs. The deduced isotopic characteristics of the upper mantle are readily reproduced if only 50% of the mantle is involved in the production of the continental crust.

> Thus the concentric structure of the Earth is augmented . . . elements are slowly accumulating in the outer Earth shells. These are the marks of age imparted upon the Earth; the world ages.
>
> T. F. W. Barth (1962)

INTRODUCTION

Chemical heterogeneity can be recognized in the Earth on scales that range over many orders of magnitude. The distinctive chemical compositions of the continental crust, mantle and core represent heterogeneity on the largest scale, whereas on smaller scales chemical heterogeneity may exist within each of these major subdivisions of the Earth. The continental crust is readily accessible in part and an evaluation of the nature and origin of the heterogeneity within it comprises a basic goal of geological research. In contrast, the mantle is far less accessible and the scale and degree of chemical heterogeneity must be inferred either indirectly from seismic velocity structure, or more directly from the chemistry of mantle melt products and xenoliths erupted at the surface. The former, indirect, approach is limited by its insensitivity to small changes in chemical composition and the latter, more direct, approach requires that details of the melting processes can be reconstructed and inferences can be made concerning the original locale of the materials in the mantle. Despite the inherent difficulties involved, an increasing amount of attention is being paid to the possible nature, extent and location of heterogeneities in the mantle, for the simple reason that potentially they may retain records of the rate of crustal extraction, crust mantle mixing events and the efficiency of convective motions in mixing the mantle together with their time-dependent behaviour. This potential exists because the continental crust is a secondary geological feature which has developed by a quasi-continuous extraction of material from the mantle. Continental crust appears to have been first stabilized some 3800 Ma ago, which requires that heterogeneities must have been produced in

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the mantle from at least that time: their survival to the present day will depend upon the precise nature of convective motions in the mantle. The history of those differentiation events that cumulatively have produced the continents is most readily decipherable from the abundances of daughter products of parent isotopes having half-lives with a similar order of magnitude to the age of the Earth. At the present stage in the development of isotope geochemistry, these daughter products include the isotopes of Ar, Sr, Nd and Pb, and whereas more will be added to this list in the future, the present list includes elements of sufficiently diverse geochemical behaviour to provide valuable constraints.

The extent of chemical heterogeneity in any part of the mantle at the present day reflects the sum total of material transport from that portion of the mantle to the outer part of the Earth, additions to that portion by virtue of crustal recycling and partial or complete eradication of resulting heterogeneity by mixing associated with convective motions in the mantle. In this paper the isotopic evidence for mantle heterogeneity will be briefly reviewed and the results obtained from the investigation of simple models of the Earth with time-varying rates of transport of material between component parts will be presented. Other papers in this volume also review isotopic data pertaining to chemical heterogeneity in the mantle and the reader is referred to these for additional discussion.

Heterogeneity in the upper mantle

The mean oceanic heat flow is approximately 90 mW m^{-2}, which is substantially higher than the *ca.* 30 mW m^{-2} heat input into the base of the continental crust (Pollack & Chapman 1977), and is indicative of higher average temperatures beneath the ocean basins than the continents (see, for example, Bullard 1952). Of considerable current interest is the extent to which this large-scale inequality of heat loss from the mantle reflects a chemical heterogeneity on a similar scale. In addition to the lower geothermal gradients existing beneath continental areas compared with the ocean, and the lateral thermal gradients which must therefore exist at a given depth between them, travel time residuals of shear waves also are indicative of different mantle structures (Sipkin & Jordan 1976). The seismic data suggest that these differences may extend to *ca.* 400 km depth beneath some cratons but may be much shallower, around 100 km, in more recently tectonically active areas. Although complete agreement does not exist about the physical state of the upper mantle beneath the continents and oceans, it is clear that sub-continental mantle is in some way stabilized against convection; it is difficult to envisage how this can be achieved without the existence of a fundamental and large-scale chemical heterogeneity, in the upper mantle. Both Oxburgh & Parmentier (1978) and Jordan (1978) suggest that average sub-continental mantle has been depleted in basaltic components and consequently heat-producing elements resulting in a reduced mean atomic number which compensates for its lower average temperature.

More direct examinations of chemical heterogeneity in the upper mantle must involve either the study of xenoliths or basaltic partial melt products of the mantle. Such an approach immediately raises questions concerning the precise locations in the mantle from which the materials were extracted and how representative they are of the upper mantle. Whereas those physical properties of the mantle, as reflected by seismic velocities and heat flow, sample a large volume of mantle, xenolithic material in kimberlites and other volcanics are minuscule samples of the mantle. Because the occurrence of a kimberlite is a rare geological phenomenon in space and time, can a kimberlite be expected to transport to the surface xenoliths which are truly representative of the sub-continental mantle? Basalts reach the surface in relatively larger volumes; however, in many instances there is little direct constraint on the depth of the melting event that produced them. Despite these inherent limitations these are the most direct probes of the upper mantle available to us and they do provide much important information.

SUB-OCEANIC MANTLE

Volcanic rocks erupted along the mid-ocean ridge crests account for the largest proportion of volcanic rocks erupted on Earth, and as such are volumetrically the largest samples of mantle-derived material accessible to us. In addition to mid-ocean ridge volcanics, volcanics are erupted in back-arc, island arc and intra-plate situations and collectively with mid-ocean ridge volcanics compose the most important probes of sub-oceanic mantle chemistry.

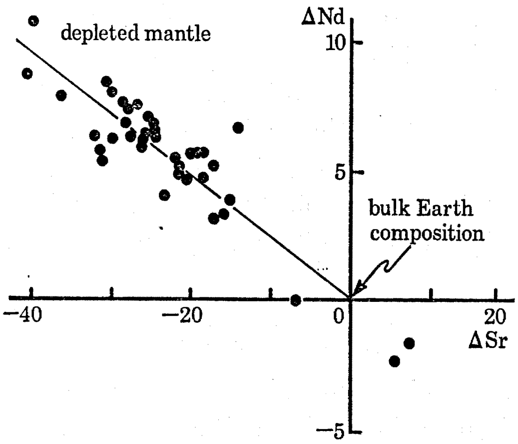

FIGURE 1. ΔNd–ΔSr diagram for unaltered oceanic volcanics. ΔNd = $[({}^{147}\mathrm{Sm}/{}^{144}\mathrm{Nd})_{\mathrm{t.i.}} - ({}^{147}\mathrm{Sm}/{}^{144}\mathrm{Nd})_{\mathrm{b.E.}}]/({}^{147}\mathrm{Sm}/{}^{144}\mathrm{Nd})_{\mathrm{b.E.}}$, where b.E. = bulk Earth and t.i. is the time-integrated value calculated by using the measured ^{143}Nd/^{144}Nd ratio (see O'Nions *et al.* 1978). ΔSr is defined in an analogous manner but with the ratio ^{87}Rb/^{86}Sr. The data plotted include mid-ocean ridge basalts (those with the most negative ΔSr and positive ΔNd values) and ocean island basalts. Data are from Richard *et al.* (1976), DePaolo & Wasserburg (1976*a*, *b*), O'Nions *et al.* (1977), Carter *et al.* (1978) and Zindler & Hart (1978). ΔNd and ΔSr are expressed as percentages.

A considerable amount of Sr, Nd and Pb isotope data now exist for volcanic rocks erupted in the ocean basins, which are pertinent to considerations of heterogeneity in the sub-oceanic mantle. The Nd and Sr isotope data available for oceanic volcanics are summarized in figure 1, in terms of the parameters ΔNd and ΔSr (O'Nions *et al.* 1977, 1978). These parameters are defined in the caption to figure 1, but can simply be thought of respectively as expressions of the deviations of the measured ^{143}Nd/^{144}Nd or ^{87}Sr/^{86}Sr ratios from those predicted for undifferentiated mantle at the time of their formation. Thus the origin (ΔNd = ΔSr = 0) of the plot in figure 1 corresponds to Nd and Sr isotope compositions identical to those predicted for undifferentiated mantle, and positive and negative values indicate evolution of a mantle source region with Sm/Nd and Rb/Sr ratios different to those of the bulk Earth. Positive values for ΔNd correspond to an evolution of Nd isotopes in a source with Sm/Nd greater than the bulk Earth (or light rare earth depleted relative to chondritic abundances), and negative values are indicative of the converse. Similarly, positive and negative ΔSr values indicate Sr isotope evolution in environments with Rb/Sr respectively greater and less than the bulk Earth value of 0.03 (DePaolo & Wasserburg 1976*b*; O'Nions *et al.* 1977). Nearly all of the oceanic basalts plotted in figure 1 have positive ΔNd and negative ΔSr values, indicating that source regions from which they were derived have evolved with time-integrated Sm/Nd and Rb/Sr ratios respectively greater and less than the bulk Earth. Mid-ocean ridge basalts which, in view of their great abundance relative to basalts erupted in other environments, may be expected to provide the best estimate of the isotopic characteristics of the upper mantle, have the most extreme values of ΔNd and ΔSr. ΔNd and ΔSr values of ocean island basalts encompass part of the range of the mid-ocean ridge basalts but extend to values close to those of the bulk Earth, indicating that small amounts of essentially undifferentiated mantle have survived to recent times; however, the upper mantle must have a bulk isotopic composition close to that of mid-ocean ridge basalt. Next to mid-ocean ridges the most voluminous source of basalts are in island-arcs; however, because they may contain Sr of crustal derivation (Hawkesworth *et al.* 1977; DePaolo & Wasserburg 1977; O'Nions *et al.* 1978), they have been omitted from figure 1. Whereas it is probable that Sr from the continental crust has been recycled through the mantle over a substantial portion of Earth history, the comparatively large and recent additions to the source region of island-arc basalts would result in a markedly biased estimate of ΔSr for the upper mantle. Ultramafic nodules found in basalts erupted in intraplate environments such as Hawaii have been analysed for ^{87}Sr/^{86}Sr (Shimizu 1975), but Nd isotope data have not as yet been reported. The Sr isotope data for the spinel lherzolites are within the range of ocean island basalts and it can be expected that the Nd isotope compositions will also be in this range.

SUB-CONTINENTAL MANTLE

Relative to the volume of volcanics erupted in the ocean basins, those erupted in continental environments are minor, although in particular instances, such as continental flood basalts, they may achieve impressive proportions. Thus the sub-continental mantle is less well sampled by volcanism than sub-oceanic mantle. An evaluation of the extent of isotopic heterogeneity in sub-continental mantle is hampered, not only by the limited sampling of it by volcanism, but also by the possibility that the volcanics have interacted with continental crust during their passage to the surface, obscuring their original isotopic characteristics. Under favourable circumstances it has been possible to identify continental volcanics that have been contaminated with continental crust. Comprising one notable example are the Tertiary volcanics of NW Scotland, some of which were erupted through 2.9 Ga old Lewisian basement, and differentially contaminated by granulite or amphibolite facies basement (Carter *et al.* 1978). In figure 2 the ΔNd and ΔSr values for Tertiary to Recent continental volcanics are compared, and obviously contaminated samples have been omitted. Thus volcanics from parts of the Tertiary Brito-Arctic province appear uncontaminated and have a similar range of values to oceanic volcanics, but it should be noted that these basalt samples were erupted along the rifted continental margins of the North Atlantic between 50 and 60 Ma ago. In contrast, continental flood basalts have ΔNd and ΔSr values closer to the bulk Earth values, which at first sight indicates possible derivation from an undifferentiated source, but further studies are necessary to demonstrate that this is indeed so with all continental flood basalts. If for the moment it is accepted that the ΔNd and ΔSr values of flood basalts are their primary ones, then it appears that the sub-continental mantle has a similar *range* of values to the sub-oceanic mantle. The problem now arises in establishing the values appropriate to the bulk sub-continental mantle in a situation where volcanism is not considered to provide an adequate sample. The most depleted parts of the mantle will be the most refractory and cannot be expected to furnish basalts (cf. Oxburgh & Parmentier 1978).

Ultramafic nodules furnish additional information about the sub-continental mantle, however, to date comparatively few Nd and Sr isotope analyses have been published for mineral separated from ultramafic nodules. Those data that are available are summarized in figure 2 and it is interesting to note that these have similar values for ΔNd and ΔSr as sub-oceanic mantle.

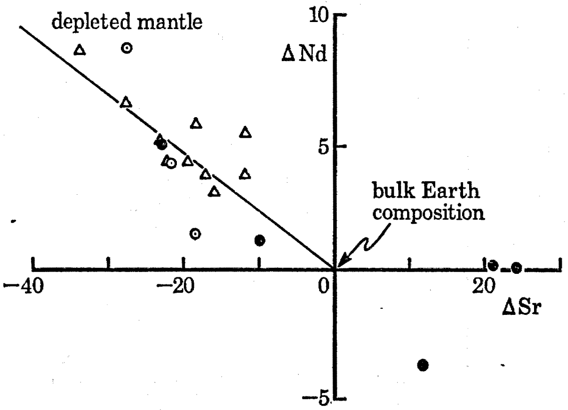

Figure 2. ΔNd–ΔSr diagram for some continental basalts (●, continental flood basalts; △, Tertiary continental basalts) and ultramafic nodules (⊙) from kimberlites. See caption to figure 1 for definitions. Data for continental flood basalts from DePaolo & Wasserburg (1976*b*); uncontaminated Tertiary continental basalts from North Atlantic margin from Carter *et al.* (1978) and garnet lherzolite nodules from Thaba Putsoa and Premier (unpublished data of the authors).

In summary, the range of ΔNd and ΔSr values for materials derived from sub-continental mantle create the impression of a comparable degree of heterogeneity to that inferred for the sub-oceanic mantle. However, whereas it is reasonable to assume that the bulk of the sub-oceanic upper mantle has ΔNd and ΔSr values in the range of mid-ocean ridge basalts, it is far less clear what the bulk of sub-continental upper mantle is. This uncertainty highlights the difficulty of relating the meagre samples of mantle material found at the surface to the bulk source. Intuitively, one would expect the least depleted parts of the mantle to be the most productive in terms of melt products, thus providing a sample biased in favour of the less depleted portion of the mantle. Thus the essentially undepleted character of kimberlite-matrix as deduced from Nd isotope compositions (Basu & Tatsumoto 1978) may be reconciled with the depleted character of the xenoliths that they contain (figure 2). We feel compelled to draw heavily on the geophysical constraints discussed earlier and assume that the sub-continental upper mantle is at least as depleted overall as sub-oceanic mantle, yet contains a comparable degree of heterogeneity.

Mantle heterogeneity through time

A prerequisite to a full understanding of changes in the heterogeneity of the mantle throughout Earth history is a knowledge of the degree and extent of heterogeneity in the Earth immediately after its accretion. Extant models of Earth accretion include both heterogeneous and homogeneous models (e.g. those of Clarke *et al.* 1972; Smith 1977; Ringwood 1975). It is beyond the scope of this paper to enter into a discussion of these opposing viewpoints, and at this stage it is difficult to make unequivocal distinctions between them. The approach taken here is to assume that the Earth's mantle was initially homogeneous in composition, and this assumption will be maintained until such time that the data obtained dictate that initial heterogeneity must be introduced. It must, however, be emphasized that assuming an initial homogeneous rather than heterogeneous Earth is at this stage no more than an expedient.

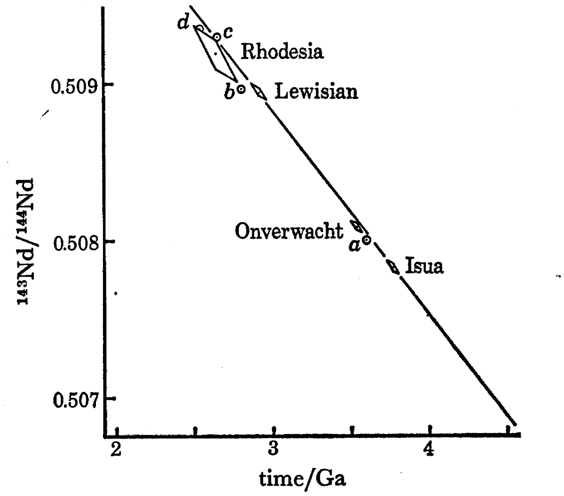

Figure 3. Initial ^{143}Nd/^{144}Nd ratios plotted against age for Archaean rocks and compared with a chondritic reservoir that has a ^{143}Nd/^{144}Nd ratio of 0.50682, 4.55 Ga ago. The single whole rock data (DePaolo & Wasserburg 1976*a*) are (*a*) Great Dyke; (*b*) Preissac-Lacorne granodiorite; (*c*) Fiskenaesset anorthosite; (*d*) Amitsoq gneiss. Whole-rock isochron data for Rhodesian greenstone, Isua metavolcanics, Onverwacht and Lewisian from Hamilton *et al.* (1977, 1978, 1979*a*, *b*). The line drawn corresponds to a Sm/Nd ratio of 0.31 the cosmic abundance ratio (Evensen *et al.* 1978).

The progress made in dating Archaean volcanics and metavolcanics by using the Sm–Nd method has resulted in the precise determination of a number of initial ^{143}Nd/^{144}Nd ratios which both limit the initial variability of Sm/Nd in at least those portions of the mantle sampled during growth of the continental crust, and further, the subsequent development of heterogeneities in the Sm/Nd ratio of mantle. The available initial ^{143}Nd/^{144}Nd data are summarized in figure 3 and include initial ^{143}Nd/^{144}Nd ratios determined from whole-rock isochrons and calculated from single whole-rock measurements. The most important conclusion to be drawn from these data is that first made by DePaolo & Wasserburg (1976*a*), namely that the Sm/Nd ratio of the bulk Earth is indistinguishable from the cosmic abundance ratio (see, for example, Evensen *et al.* 1978). This conclusion follows from the close fit of *all* of the initial ^{143}Nd/^{144}Nd ratios to the line on the time-initial diagram drawn in figure 3, which corresponds to a Sm/Nd ratio of 0.31. Not only does this observation apparently limit the initial heterogeneity in Sm/Nd in the mantle sampled, but also demonstrates that large variations of Sm/Nd have not survived from early in Earth history, compatible with the failure of differentiation products to survive at the Earth's surface until about 3.8 Ga ago.

It would be desirable to reproduce the above analysis for the Rb/Sr ratio of the mantle by using a time-initial ^{87}Sr/^{86}Sr ratio plot, but unfortunately this is not possible at present because initial ^{87}Sr/^{86}Sr data comparable to the ^{143}Nd/^{144}Nd data do not exist. Alteration and metamorphism readily perturb the Rb–Sr system, precluding the possibility of obtaining reliable initial ^{87}Sr/^{86}Sr ratios.

To our knowledge, the only published precise initial $^{87}Sr/^{86}Sr$ ratios of Archaean volcanics that can be considered reliable are those of the *ca.* 2.7 Ga relict clinopyroxenes from Ontario (Hart & Brooks 1977) and an Onverwacht komatiite (Jahn & Shih 1974). Whereas the ΔSr value of the Onverwacht komatiite† is close to zero, the average ΔSr value for the 2.7 Ga clinopyroxenes is $-120‰$, indicating that Rb/Sr heterogeneity may have survived from before 2.7 Ga, but from not much earlier than 3.5 Ga. This observation is incompatible with the lack of evidence for fractionation of Sm/Nd in the mantle by this time, from measured initial $^{143}Nd/^{144}Nd$ ratios, since it should be recalled that the generation of continental crust from the mantle requires a larger fractionation of Rb/Sr than Sm/Nd and also that the half-life of ^{147}Sm is greater than that of ^{87}Rb.

During the last few years there have been a number of recorded occurrences of positive correlations between Rb/Sr and $^{87}Sr/^{86}Sr$ in suites of continental and oceanic volcanics (see, for example, Brooks *et al.* 1976; Sun & Hanson 1975; Brooks *et al.* 1976; Brooks & Hart 1978), variously referred to as 'mantle isochrons' or 'pseudo-isochrons'. In addition, correlations also exist between $^{143}Nd/^{144}Nd$ and Sm/Nd ratios (see, for example, O'Nions *et al.* 1979), and between $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ (see, for example, Sun & Hanson 1975). Although little consensus exists in the interpretation of the apparent ages that can be extracted from these data, most are agreed that such correlations may under certain favourable circumstances provide information about the timing of a particular mantle fractionation event. However, in some of the Tertiary volcanics from NW Scotland, Carter *et al.* (1978) have demonstrated that crustal contamination can impose isotopic variability within the volcanics which may generate a 'pseudo-isochron' as an artefact of the process. It is imperative that efforts be made to distinguish 'pseudo-isochrons' in continental volcanics resulting from contamination processes from those that reflect genuine mantle heterogeneities.

The possibility of a mantle-wide differentiation event *ca.* 1.6 Ga ago has attracted much attention and debate (Brooks *et al.* 1976; Brooks & Hart 1978). The data used in support of the contention are average Rb/Sr and $^{87}Sr/^{86}Sr$ ratios from continental and oceanic volcanics (Brooks *et al.* 1976), and the Pb isotope compositions of oceanic volcanics (see, for example, Sun & Hanson 1975) and ultramafic nodules from kimberlites (Kramers 1976). The basic question has been whether the *approximation* of the data to a 1.6 Ga age should be used in support of a major event at this time, or alternatively whether such an approximation inevitably arises from a multi-stage evolution of Sr and Pb isotopes in the mantle. Previously we have adhered to the latter point of view (O'Nions *et al.* 1978, 1979*a*, *b*) and noted the compatability of continuous models of mantle differentiation with evidence for a quasi-continuous evolution of the continental crust and the absence for a continent-wide differentiation event *ca.* 1.6 Ga ago. This viewpoint will be maintained herein.

Origin of mantle heterogeneity

Over the last 4.5 Ga, the Earth has evolved into three major chemically distinct reservoirs: core, mantle and crust. Whereas the time of core formation is constrained chiefly by evidence for ancient magnetic fields, crustal history is more directly constrained by radiometric dating. Recent isotopic studies involving Sr, Nd and Pb in Archaean crust (see, for example, Moorbath

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† The Onverwacht lavas have been dated at 3.54 ± 0.03 Ga by the Sm–Nd whole-rock method (Hamilton *et al.* 1979*b*).

1975; Hamilton *et al.* 1978; McCulloch & Wasserburg 1978; O'Nions & Pankhurst 1978) have supported the contention of Hurley *et al.* (1962) that continental crust has grown quasi-continuously through Earth history. This view of crustal formation contrasts with evidence from $^{40}Ar/^{36}Ar$ ratios in the mantle and atmosphere, suggesting that transport of Ar to the atmosphere must have been early and rapid (Fanale 1971; Ozima 1975). Both Earth degassing and the formation of the continental crust are processes of upward transport of material which should be tied to the upward transport of heat in the Earth and thus to its thermal history. Since sources of internal heat, whether residual from the Earth's formation or provided by radioactivity, will diminish with time, thermally driven transport should exhibit a time dependence more similar to the initial peak inferred for Ar transport than to the more gradual and later-peaking process of continental growth.

O'Nions *et al.* (1979*c*) have attempted to reconcile these observations in a model that combines time-dependent upward transport of 'incompatible' elements from the mantle to crust–atmosphere–oceans with a similarly time-dependent return flux from crust to mantle. Models of this general type have also been explored for Pb (Russell & Birnie 1974) or Pb and Sr (Armstrong & Hein 1972) isotopes alone. The model of O'Nions *et al.* (1979*c*) considers the evolution of the K–Ar, Rb–Sr, Sm–Nd and U–Th–Pb parent–daughter systems in two major reservoirs: the mantle and an outer 50 km layer of the Earth that at present contains the continental crust. In each time step, a proportion α_i of the total mantle complement of element i is transported to the outer layer, and a proportion β_i of the crustal complement of i is transported back to the mantle. Individual α_i values may differ for each element considered, but vary synchronously with time in relations of the form

$$\alpha_i = \alpha_i^0 \exp(-t/\tau_\alpha), \tag{1}$$

where α_i^0 is a constant, t is time and τ_α a time constant common to all α. The β_i vary similarly with a different time constant τ_β. Thus if n_i^{M} and n_i^{L} represent the number of moles of i in the mantle and outer layer respectively, we have

$$\frac{\mathrm{d}n_i^{\mathrm{L}}}{\mathrm{d}t} = -\left(\frac{\mathrm{d}n_i^{\mathrm{M}}}{\mathrm{d}t}\right) = \alpha_i(t)\, n_i^{\mathrm{M}} - \beta_i(t)\, n_i^{\mathrm{L}}. \tag{2}$$

This expression has been numerically integrated by using 50 Ma time steps to approximate the continuous case with a 90-stage model.

The composition of the initially undifferentiated mantle was taken from O'Nions *et al.* (1979*a*), which uses the assumption that refractory elements are present in the Earth in the same proportion in which they are in the high-temperature early nebula condensate. It should be noted that the adopted composition differs very little from those of Anders (1978) and Smith (1977), which have been derived in somewhat different ways. Initial isotopic compositions of Sr, Nd and Pb were derived from meteorites and of Ar from nucleosynthetic considerations. Present-day values of these parameters in the mantle and outer 50 km of the Earth can provide other boundary conditions, but are in some ways more difficult to estimate. Taylor's (1978) crustal model was used to estimate the present bulk composition of the outer layer, and a ^{87}Sr ^{86}Sr value of 0.7120 was selected. No attempt was made to estimate present absolute mantle abundances of trace elements, but isotopic compositions of mantle Sr, Nd and Pb were estimated from mid-ocean ridge basalts (m.o.r.b.), volumetrically the most important magmatic product of the mantle. The atmospheric $^{40}Ar/^{36}Ar$ ratio of 295 was used for the outer layer.

Optimal values of the parameters α_i^0, β_i^0, τ_α and τ_β to produce the present chemical and isotopic character of the crust and mantle were determined. In all models investigated, the β^0 for all elements except Ar were equated, corresponding to bulk return of crustal material to the mantle, with a much smaller β^0 for Ar reflecting its escape to the atmosphere and loss from the recycling process. The α_i^0 that produce the best fit to present crust approximate the relative partition coefficients of the corresponding elements between garnet peridotite and a partial melt at equilibrium. Values of the time constants τ_α and τ_β are most closely constrained by present crustal ^{87}Sr/^{86}Sr values. While various combinations of τ_α and τ_β are equally acceptable in this respect (with appropriate adjustment of the α_i^0), only a limited range of time constants yield acceptable crustal growth curves (as represented in the model by the gradual accumulation of K and other lithophile elements in the outer layer). A value of 2.0 Ga for τ_α was found to give an acceptable fit to crustal ^{87}Sr/^{86}Sr and a crustal growth curve peaking at 2.5–3.5 Ga. However, no model in which the crust was extracted from the entire mantle gave both reasonable crustal ^{87}Sr/^{86}Sr values and a mantle ratio as unradiogenic as that observed in m.o.r.b. A model in which only 50% by mass of the mantle contributed to crustal formation is capable of satisfying crust and mantle Sr isotope constraints, as well as the additional boundary conditions described above. Some results of such a model are presented in figures 4 and 5. Figure 4 shows the relative growth of crust with time, as represented by the net rate of transport of K to the outer layer. The growth rate peaks at *ca.* 3 Ga and falls to a present value of about 20% of the peak rate. This model corresponds to τ_α = 2.0 Ga, τ_β = 0.65 Ga. Figure 5 demonstrates the differential evolution of K and Ar in the outer layer, resulting from their widely different coefficients for return transport, β^0, despite very similar upward transport coefficients α^0. 'Catastrophic' outgassing of Ar is thus readily reconcilable with more gradual accumulation of K in the crust, although the two elements are removed from the mantle at similar rates.

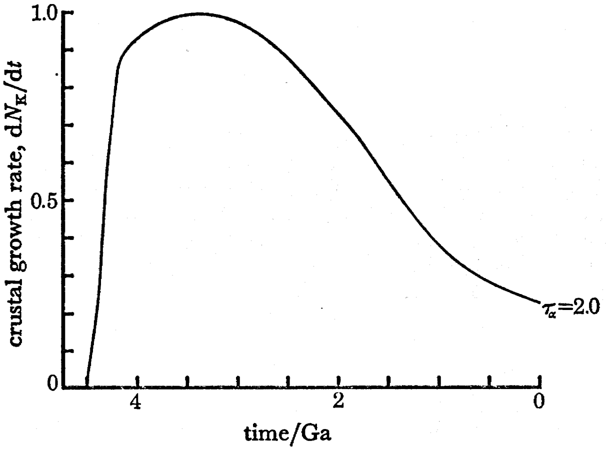

FIGURE 4. Growth rate of K in the continental crust as a function of time. The crustal growth rate is equated here with the time-dependent change in K content of the 50 km layer (dN_K/dt) as calculated from the investigated model (see O'Nions *et al.* 1979*c*). Note that the maximum rate of crustal growth appears to have occurred between 3.5 and 2.5 Ga ago (after O'Nions *et al.* 1979*c*).

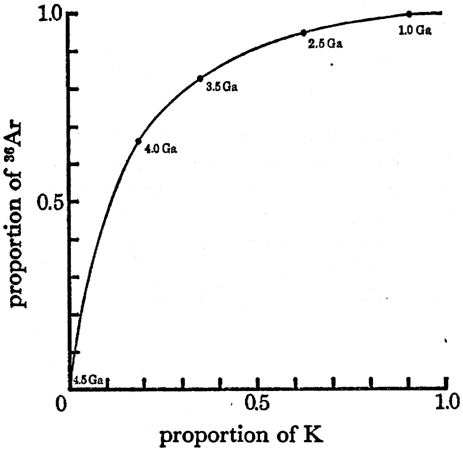

FIGURE 5. Comparative accumulation of ^{36}Ar and K in the 50 km layer as a function of time for 50% mantle model. Note that some 65% of the ^{36}Ar is released from the mantle by 4.0 Ga ago in comparison with only 20% of the K. This reflects the smaller β_0 value used for ^{36}Ar compared with that used for K (after O'Nions *et al.* 1979*c*).

The time taken to 'process' the mantle and the 50 km layer changes as a function of time. This point is conveniently illustrated in figures 7 and 8, by using the reciprocal of the transport

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

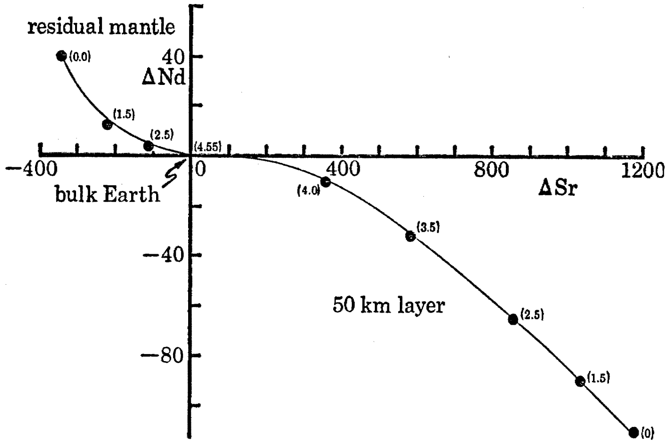

FIGURE 6. ΔNd and ΔSr values (see caption to figure 1 for definition) for the model residual mantle and the outer 50 km layer. The results are for a 50% mantle model. The numbers in parentheses are times in gigayears. Note that at 2.5 Ga the ΔNd value of the residual mantle has only changed by a few per mille whereas ΔSr is about −100‰ and is distinctly different from the bulk Earth value (ΔSr = 0). This is consistent with Archaean metavolcanics having isotopic compositions very close to those of a reservoir with chondritic Sm/Nd, yet with primary clinopyroxenes in 2.7 Ga old volcanics having ^{87}Sr/^{86}Sr ratios less than the inferred bulk Earth for that time and ΔSr values of about −120‰ (after O'Nions *et al.* 1979*c*).

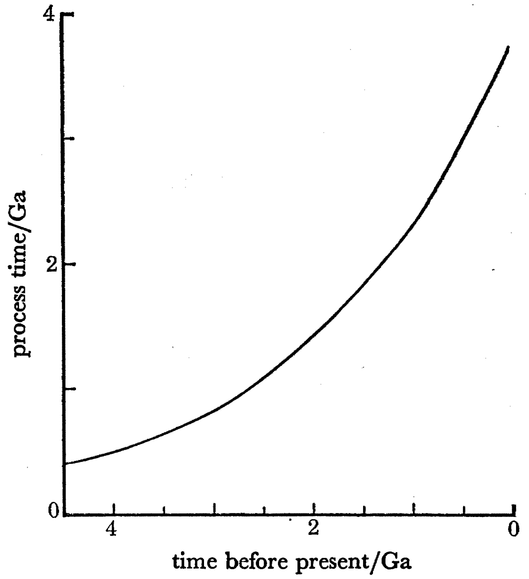

FIGURE 7. Process time for potassium in mantle. The results shown for the 50% mantle model (see text). The process time, which is α^{-1}, increases from about 350 Ma, 4.5 Ga ago to more than 3000 Ma at the present. The process times for other elements such as U, Th, Sm, Nd show a similar time-dependent behaviour.

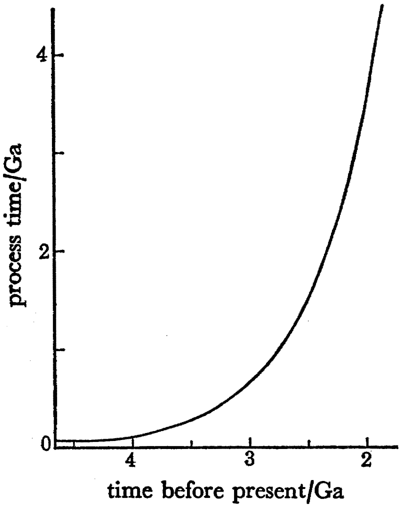

Figure 8. Process time for potassium in the 50 km layer. The results are shown for a 50% mantle model. The process time is β^{-1} and changes from less than 100 Ma, 4.5 Ga ago, to more than 4.0 Ga, 2.0 Ga ago. At the present day the process time exceeds 11 Ga. The potassium content of the 50 km layer is dominated by that in the continental crust and the process times can be considered to be those of the continental crust.

coefficients α and β, for potassium, which are termed process times here. The process time for potassium in the mantle changes from about 300 Ma, 4.5 Ga ago, to more than 3000 Ma at present. In marked contrast, potassium in the outer 50 km layer has a very short process time of about 100 Ma at 4.5 Ga, which reaches 1 Ga about 2.5 Ga ago. After this time the process time increases dramatically to more than 4.0 Ga 2.0 Ga ago and exceeds 11 Ga at present. The very long process time for the 50 km layer is compatible with the often-stated viewpoint that the Earth's continental crust is essentially indestructible. Figure 6 illustrates the evolution of Nd and Sr isotopes in the outer layer and residual mantle, expressed in terms of ΔNd and ΔSr, the per mille deviation from bulk Earth values. Note that the crustal values evolve much more quickly than mantle values in the early stages, and that resolvable crust–mantle differences appear in Sr much earlier than in Nd, reflecting both greater parent–daughter fractionation and shorter half-life for Sr.

While this simple two-reservoir model can satisfactorily reproduce the major features of K–Ar, Rb–Sr and Sm–Nd evolution, together with crustal growth rates consistent with geochronological data, it can only qualitatively reproduce the Pb isotope data. The fact that both continental and oceanic leads are more radiogenic than inferred bulk Earth values (see, Sun this symposium) clearly indicates the necessity for an additional reservoir of relatively unradiogenic Pb. Possible sites of such a reservoir are the core and the lower continental crust. The latter possibility arises from evidence that U may be mobilized from the lower to the upper crust in preference to Pb during granulite facies metamorphism, leaving the lower crust with U/Pb ratios much lower than bulk Earth. Continental sediments preferentially sample the upper crust, containing highly radiogenic Pb, and any recycling of such sediments into the mantle enriches the latter in radiogenic Pb as well, leaving the lower crust and its complement of unradiogenic Pb relatively untouched. Extension of the above model to this three-reservoir model is now under way.

Finally, it should be noted that the requirement imposed by Sr isotopes that half of the mass of the mantle did not contribute to crustal formation and thus remains undepleted has significant implications for heat and mass transport in the mantle. The depleted 50 % of the mantle would have a present-day heat production far too low to account for the inferred mantle flux of *ca.* 70 mW m^{-2}. The remaining heat flow must then arise from some combination of stored internal heat and heat production in the undepleted half of the mantle. In either event, the heat flow must presumably arise from below the convecting, depleted upper mantle, from underlying regions that supply heat but not mass to the Earth's surface.

Relation between simple models and geochemical cycles

The two-reservoir model discussed above has reproduced the broad features of the isotope geochemistry of the Earth's mantle and crust–atmosphere with time-dependent transport coefficients between the two reservoirs. Although it is possible to make geological estimates of the present-day values for those coefficients and thus constrain the models to accomodate them, this has not been carried out since it immediately raises the practical questions of the applicability of present-day values to the geological past.

It is relevant perhaps to compare the simple two-reservoir model with the expected geochemical cycle of potassium, for example (figure 9). In the geologically recent past it is envisaged that potassium may be added to the continental crust through the medium of basalt either directly along paths *a* and *b* or via subduction and remelting of oceanic crust (paths *a*, *c* and *e*). The processes of material addition to the continents are modelled by the transport coefficient α in figure 3. Potassium residing in the continental crust may be recycled into the mantle by subduction of continent-derived sediments, or more indirectly by the subduction of oceanic basalt to which continent-derived K has been added during alteration (paths *d* and *f*). The possibility of direct transport of continental crust into the mantle by tectonic erosion (cf. Molnar & Gray 1979) may have to be seriously considered in the future but is not included here. Thus the transport coefficient β in figure 3, at the present day must emulate paths *d* and *f*. The geochemical complexities included in path *d* plus *f* needs no emphasis,

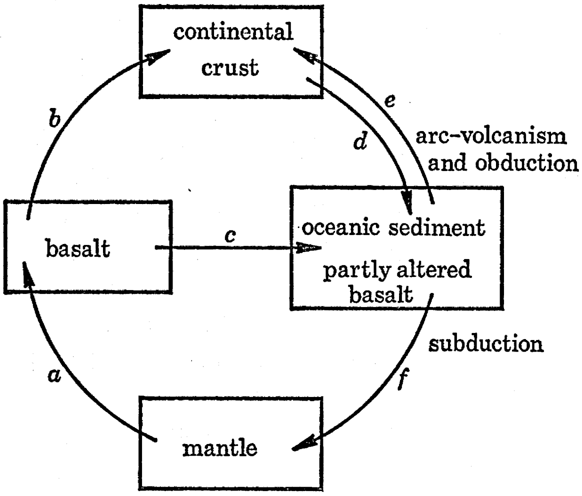

FIGURE 9. The probable geochemical cycle of potassium in the Earth in the geologically recent past. This should be compared with the simplified reservoir model of the Earth used to reproduce the isotopic characteristics of the crust and mantle.

and when considering the difficulty of assessing the ways in which transport rates along these paths may have varied with time, the validity of modelling such processes with the simple transport coefficient β may be questioned. It must be conceded that the model used, in particular for β, may be a poor approximation to reality during the Phanerozoic; however, the important point to bear in mind is that it does seem to accomodate adequately the salient features of crustal growth and the isotopic evolution of the mantle, and is presumably a more realistic description of earlier periods of Earth history when transport rates were greater than those of today, and continental crust developed more rapidly.

CONCLUSIONS

Chemical heterogeneity in the mantle is readily identified from variations in the ratios $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, $^{208}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$; studies of basic volcanics and ultramafic nodules suggest that sub-oceanic and sub-continental mantle exhibit comparable degrees of heterogeneity. Whereas the average isotopic compositions of Sr, Nd and Pb in mid-ocean ridge basalts are considered to provide a good estimate of the values in average sub-oceanic mantle, the much lower productivity of sub-continental mantle in terms of magma render its average Sr, Nd and Pb isotopic composition more difficult to estimate. However, the seismic velocity and thermal structure of sub-continental mantle seem to dictate that it must be more depleted in basaltic constituents than sub-oceanic mantle, implying that continental volcanism preferentially samples the less depleted parts.

Mantle differentiation and crustal growth can be modelled by using a two-reservoir model with time-varying transport of materials between the reservoirs. The evidence for a high rate of transport of ^{36}Ar into the crust-atmosphere very early in Earth history is readily reconciled with the later accumulation of K, U, Th, etc., in the continental crust, if a smaller value of the downward transport coefficient is adopted for Ar compared with non-gaseous elements. The abundances of K, Rb, Sr, Sm, Nd, U, Th and Pb in the continental crust and the estimated Sr and Nd isotopic composition of the crust and mantle can be reproduced by involving transport between the crust and only one half of the mantle.

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Discussion

J. V. Smith, F.R.S. (*Department of the Geophysical Sciences, University of Chicago, U.S.A.*). It is certain that the Earth was bombarded with the same population of bodies as those that formed the lunar maria. Since such bodies must have hit the Earth at higher velocity than the Moon, and since the Earth's exterior should have been hotter than the moon's exterior, catastrophic effects must have occurred at the Earth's surface until at least 3.9 Ga ago. Would such processes require modification of the assumptions of the present model? Secondly, might the convection processes have changed significantly with time, thereby requiring a more complex model? In particular, it is possible that the upper mantle was decoupled chemically from the lower mantle as a result of crystal–liquid differentiation during accretion? Such differentiation might result in essentially all of the radioactive elements migrating to the outer 200 km, such that convection was especially vigorous in the upper mantle (as envisaged by the convection rolls of F. Richter). Is it possible that prolonged cooling was needed before subducting plates could penetrate to great distances (*ca.* 10^3 km), or did the entire mantle convect rapidly since the original accretion of the Earth? Thirdly, should the original spatial distribution be considered? Thus a new heterogeneous accretion model (J. V. Smith 1979, *Mineralog. Mag.* **43**, 1–89) relies on (i) early accretion of hot planetesimals with resultant crystal–liquid differentiation which moves elements like K, Rb, Ba and U to the surface, and (ii) late accretion of cold planetesimals, whose components do not equilibrate completely with the early material. To give an example: based on the cosmochemical model of Ganapathy & Anders and observations of peridotite nodules in kimberlites, it appears that most or all K and Ba are in the outer 200 km, whereas most Na is deeper than 200 km (*Proc. Lunar Sci. Conf.* 8*th*, 333, 1977). Would the isotopic distributions for Pb, Nd and Sr be affected significantly by these three factors, or would the assumption of an exponential time decrease of transport velocity be sufficient to a first approximation?

R. K. O'Nions. I agree with Professor Smith's contention concerning the bombardment of the Earth in its early history and the retarding effect that it will have on accumulation of continental material. This phenomenon would be accommodated by the time-dependent change in β in our model. The τ_β and β_0 values used for K in the 0.5 mantle model result in a highly efficient recycling of this and related elements into the mantle for the first few hundred megayears of Earth history. It may well be that the physical cause of this result is indeed the bombardment that Professor Smith describes.

A priori we have made no assumptions about the scale and nature of convection in the mantle nor possible changes with time. Probably the most significant result in this respect, however, is that no more than half of the mantle appears to have been involved in crustal generation. From this, one might infer that the lower mantle has not been convectively coupled to the upper mantle.

Ultimately it might prove necessary to invoke original spatial chemical heterogeneity in the Earth. In the present model we have assumed initial homogeneity for the sake of convenience and the isotopic data on hand are compatible with this assumption.

D. K. Bailey (*Department of Geology, University of Reading, U.K.*). How would the model be affected by an early episode of pervasive melting and catastrophic degassing of the Earth? Another question concerns the deep continental crust, where the development of granulites indicates an early phase of lithosphere depletion in incompatible elements. What are the envisaged release paths to the surface after this kind of barrier formed?

R. K. O'Nions. The model does in fact involve an efficient and early removal of ^{36}Ar and, by implication, other rare gases from the mantle to the atmosphere which for simplicity has been considered part of the 50 km layer here. However, the critical factor is that other non-gaseous constituents, such as K, are transported into the 50 km layer at the same rate as Ar but are recycled more efficiently, thus retarding their accumulation of the surface.

The internal differentiation of the continental crust to produce granulites has no immediate consequences as far as this simple two-reservoir model is concerned.

The 'release paths' to the surface are envisaged to be via mantle melting and melt transport predominantly into areas where continental crust does not exist.