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

# Melting of the Mantle Past and Present: Isotope and Trace Element Evidence [and Discussion]

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# Melting of the mantle past and present: isotope and trace element evidence†

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Estimates are made of the abundances of some lithophile trace elements, particularly heat-producing elements, in the bulk Earth. The applicability of abundance estimates based on extra-terrestrial analogues, and terrestrial heat flow data are discussed.

Sr, Nd and Pb isotope data are briefly reviewed and used to identify basalt source regions in the mantle which have been depleted or enriched in these and other lithophile trace elements. An assessment is made of the rôle of silicate liquid transfer in the production of depleted mantle. The timing of the transfer event(s) can be constrained using Rb-Sr, Sm-Nd and U-Pb isotope data and cover the period of Earth history during which granitic crust has been stabilized.

Calculations of the heat production in the source regions of mid-ocean ridge and other basalts suggest that the convective processes involved in the generation of oceanic lithosphere are driven mainly by heating from beneath, as the internal heat generation is comparatively small.

Trace element data from Archaean to Recent volcanics are used to estimate maximum limits on the amount of mantle melting which has occurred in the last 3.5 Ga.

## INTRODUCTION

The Earth's crust preserves a record of mantle-derived silicate melts produced over the last 3.8 Ga of Earth history. This continuing irreversible differentiation of the Earth is also closely linked to the evolution of the atmosphere, which, like the crust, is generally thought to be of secondary origin. While gravitational energy released in accretion and core formation was undoubtedly a significant (and largely unknown) energy source in the primitive Earth, the dominant factor in producing melting and consequent differentiation through most of Earth history has been heat production by the radioactive isotopes of K, U and Th. This heat production has declined significantly over the age of the Earth, and may have been augmented in the earliest stages by extinct radioactivities whose record is now preserved only in the meteorites. Differentiation has also resulted in the removal of significant proportions of heat-producing and other large ion lithophile elements from the mantle and their transfer to the crust and atmosphere. Material transport is probably also a dominant factor in the removal of the heat itself from the Earth's interior, as a result of convection and of cooling of emplaced lithosphere. Thus the transport of heat, of heat-producing elements and of the major elements forming the bulk of the crust and atmosphere are complexly linked in an evolutionary process.

Models of crustal origin have been largely based on consideration of Sr and Pb isotopes, and involve inferences concerning fractionation of Rb/Sr, U/Pb and Th/U during crustal formation. Differential impoverishment of the mantle in lithophile trace elements can be clearly

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† L.-D.G.O. Contribution No. 2610.

demonstrated from the isotope geochemistry of mantle-derived melts. On the other hand, boundary conditions on the amount of residual primordial gas in the atmosphere and the rate of supply of volatiles from the mantle are provided by both abundances and isotopic compositions of atmospheric rare gases.

In the present article, estimates are made of the abundances of heat-producing elements in the whole Earth and in those parts of the mantle from which melts are now derived. These results are compared with the amounts of mantle melting which appears to have taken place throughout Earth history.

## Abundances of heat-producing elements in the Earth

Throughout most of Earth history, $^{40}$K, $^{238}$U, $^{235}$U and $^{232}$Th have been the significant heat-producing elements. However, very early in Earth history, $^{26}$Al, and to a lesser extent $^{244}$Pu, could have been significant contributors. Estimates of the abundances of heat-producing and other large ion lithophile elements in the Earth have been made on the basis of both their abundances in meteorites and terrestrial samples. In addition, mean global heat flow data can be used to constrain abundances of heat-producing elements if certain assumptions are made about the dominant mechanisms of heat transport in the mantle.

It has been apparent since the work of Gast (1960) that the terrestrial abundances of the

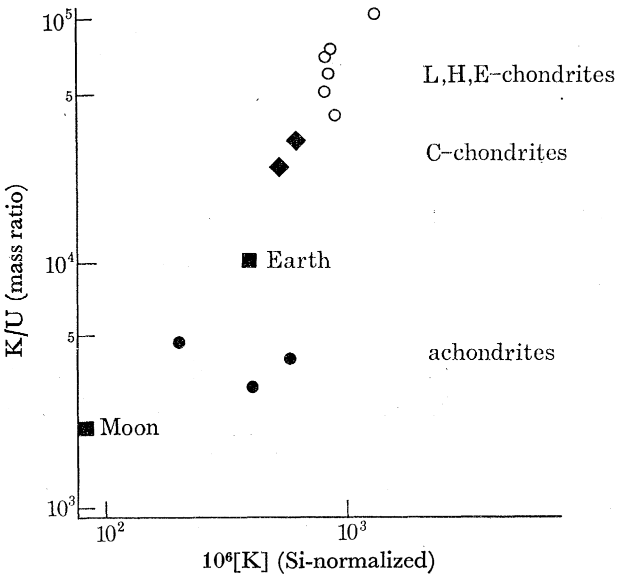

Figure 1

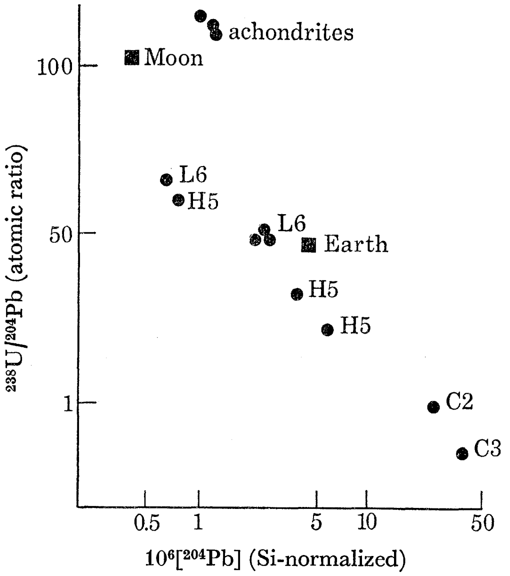

Figure 2

Figure 1. Plot of Si-normalized K concentration against K/U (mass ratio) in the Earth, Moon and meteorites. The meteorite data are from the compilations of Morgan (1971) and Goles (1971). The K/U ratio of the Earth is taken as $10^4$ (table 1) and the K content is a whole Earth value based on the U content of the Earth estimated from heat flow data (table 2). The K/U ratio of the Moon is based on many published analyses of lunar rocks and the U content is based on lunar heat flow measurements (Langseth *et al.* 1976). K (plotted) = [K(observed) × 14.5]/Si (observed).

Figure 2. Plot of Si-normalized $^{204}$Pb concentrations against $^{238}$U/$^{204}$Pb (atomic ratio) in the Earth, Moon and meteorites. The $^{238}$U/$^{204}$Pb ratios of the meteorites have been calculated from the published Pb isotope compositions (Tatsumoto *et al.* 1972; Gale *et al.* 1972). The $^{238}$U/$^{204}$Pb ratios for the Earth and Moon are the conventionally estimated values from the Pb isotope compositions of terrestrial and lunar rocks, and the U contents are the same as those used in figure 1. $^{204}$Pb (plotted) = [$^{204}$Pb (observed) × 14.5]/Si (observed).

more volatile lithophile elements such as K and Rb are probably lower than in chondrites, and that the volatile to refractory element ratios such as K/U and Pb/U are lower in the Earth. The great variability of these ratios in the Earth, Moon and meteorites is illustrated in figures 1 and 2, where Si-normalized Pb and K contents of various planetary materials are plotted versus $^{238}U/^{204}Pb$ and K/U ratios respectively. These diagrams show approximately two orders of magnitude variation in K/U and $^{238}U/^{204}Pb$ between the Earth, Moon and meteorites, indicating that each planet will have its own unique values for volatile/refractory element ratios and that there is no reason to expect a particular class of meteorites to be an adequate chemical analogue of the Earth, or of the Moon. It is significant that the slopes of the lines in figures 1 and 2 are approximately 1:1, indicating that the Si/U ratios are essentially constant in these materials, consistent with the fact that U is present at about 0.010–0.012 c.a.u. in all types of chondrites (see, for example, Morgan 1971). Not only does this suggest that the ratios of other refractory elements may be essentially constant within planetary objects, but it also indicates that a fairly reliable estimate of the U content of the Earth can be made on the basis of meteorite abundances. If it is assumed that the Earth's core is free of U then the mantle plus crust U abundance is between 0.030 and 0.035 part/$10^6$ (cf. Wasserburg, MacDonald, Hoyle & Fowler 1964). Previous estimates of the K/U ratio of the Earth (Wasserburg *et al.* 1964; Gast 1972) have been based mainly upon ratios in the continental crust, and were very close to $10^4$. Subsequent to these attempts good quality K and U data have become available on basalts. These more recent data, summarized in table 1, suggest that the earlier estimates of K/U at $10^4$ are not in need of revision and can now be considered well established. The lower estimate of K/U made by Fisher (1975) on the basis of $^4$He and $^{40}$Ar abundances in basaltic glasses probably reflect different diffusion rates of these gases in the mantle.

TABLE 1. K/U RATIOS FOR TERRESTRIAL ROCKS

| | $10^6$ [K] | $10^9$ [U] | $10^{-4}$ K/U |
|---|---|---|---|
| oceanic basalts† | | | |
| Reykjanes Ridge (6)[1] | 1438 | 108 | 1.3 |
| S Atlantic: D.S.D.P. Leg 3 (9)[2] | 507 | 24 | 2.1 |
| Gorda Ridge (5)[3] | 1390 | 142 | 1.0 |
| Juan de Fuca Ridge (3)[3] | 1286 | 176 | 0.7 |
| Famous: Atlantic (4)[4] | 150 | 15 | 1.0 |
| continental crust | | | |
| average shield[5] | 15000 | 700 | 2.0 |
| SW Australian shield[6] | 26000 | 300 | 0.9 |

† All data for oceanic basalts are for basaltic glasses or rocks considered to be particularly fresh. The number in parentheses is the number of samples on which the average has been computed.

1, Sun *et al.* (1975); 2, Frey *et al.* (1974); 3, Church & Tatsumoto (1975); 4, Langmuir *et al.* (1977); 5, Heier (1973); 6, Lambert & Heier (1968).

In the light of the above estimates the mean global heat flow data can be used to estimate the U content of the Earth. Using a mean global heat flow value of 60 mW m$^{-2}$ (e.g. Chapman & Pollack 1975) and assuming that the heat loss per unit time at the surface equals the heat generated in the Earth, then the mean U content of the crust plus mantle is calculated at 0.035 part/$10^6$ (Tera, Papanastassiou & Wasserburg 1974). However, if we use the estimate of 80 mW m$^{-2}$ by Williams & Von Herzen (1975), which includes revised values for oceanic heat flow, then the U content is estimated at 0.046 part/$10^6$ (O'Nions & Pankhurst 1977). The difference in these estimates of U-abundance suggests either that there is a time constant for heat loss from the interior of the Earth in the range $10^8$–$10^9$ a or that the Si/U ratio of the Earth departs by a small amount from chondrites. These alternatives cannot be easily evaluated at this stage.

On the assumption that the ratios of refractory elements in the Earth, such as Sr/U, Sm/U and Sm/Nd, are equal to those in chondrites, then abundances of other lithophile elements in the Earth can be calculated (table 2).

TABLE 2. BULK EARTH ELEMENT CONCENTRATIONS (CRUST PLUS MANTLE)

| | $10^6$ × concentration | | $10^6$ × concentration |
|---|---|---|---|
| K | 462 | Rb/Sr | 0.03 |
| Rb | 1.31 | K/U | $10^4$ |
| Sr | 41 | K/Rb | 350 |
| U | 0.046 (0.035) | $^{238}$U/$^{204}$Pb | 9.0 |
| Th | 0.18 | Sm/Nd | 0.32 |
| $^{204}$Pb | 0.005 | $^{143}$Nd/$^{144}$Nd | 0.5126 |
| Sm | 0.30 | $^{87}$Sr/$^{86}$Sr | 0.705 |
| Nd | 0.95 | | |

Values given are calculated for K/U from table 1, and mean global heat flow of 80 mW m$^{-2}$ assuming that the heat lost per unit time from the Earth's surface equals the amount generated. It is assumed that the terrestrial Sr/U, Sr/Nd, and Sm/Nd ratios are chondritic (cf. Tera *et al.* 1964). The Rb/Sr ratio and bulk Earth $^{87}$Sr/$^{86}$Sr ratio were calculated from the covariation of $^{87}$Sr/$^{86}$Sr and $^{143}$Nd/$^{144}$Nd ratios in oceanic basalts (O'Nions *et al.* 1977). N.B. Isotope ratios are atomic ratios, others are mass ratios.

The U value in parenthesis is the maximum estimated U content of the bulk Earth assuming that the Earth has a chondritic Si/U ratio. All other concentrations will be approximately 30% lower if the Earth's U content is overestimated from heat flow data (see text).

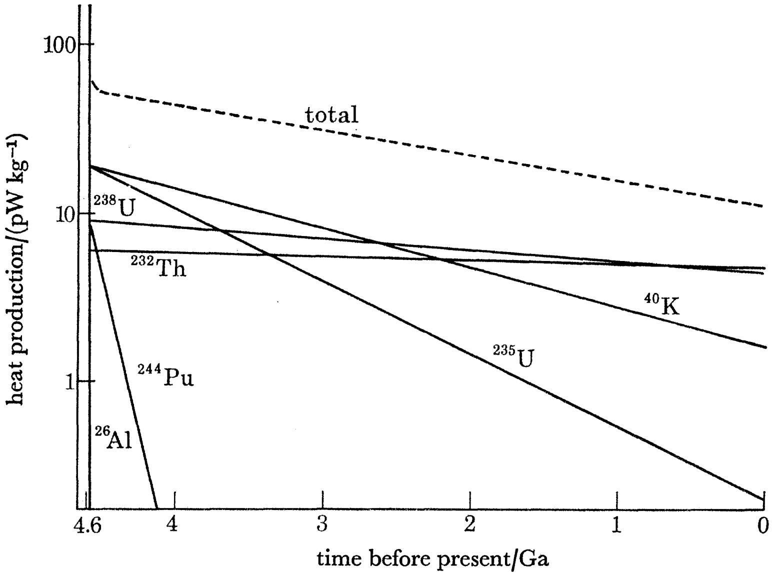

FIGURE 3. Heat production of various radioactive elements as a function of time. Heat production for U, Th and K is averaged over a bulk Earth (crust plus mantle) having the present-day abundances given in table 2, extrapolated backwards over the last 4.6 Ga. For $^{26}$Al and $^{244}$Pu, heat production is extrapolated forward from 4.6 Ga ago, assuming abundances of these nuclides at that time as inferred from measurements of the meteorite Allende; i.e. $^{26}$Al/$^{27}$Al = 5 × 10$^{-5}$ (Lee *et al.* 1976), $^{27}$Al of bulk Earth = 1.1% (Mason 1966); $^{244}$Pu/$^{238}$U = 0.016 (Drozd *et al.* 1976). Heat production by $^{26}$Al at the time of Allende formation lies far above the plot, at 1.7 × 10$^5$ pW kg$^{-1}$, falling to 10$^{-2}$ pW kg$^{-1}$ about 8 Ma later. Heat production in the early Earth is critically dependent upon the time of Earth accretion relative to Allende formation.

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Using the estimates of heat-producing elements in the Earth's crust plus mantle (hereafter referred to as bulk Earth values) from table 2, the heat production per kilogram of the bulk Earth has been calculated (figure 3), as a function of time. The present heat production in the bulk Earth is approximately 11 pW kg$^{-1}$ which compares with 53 pW kg$^{-1}$ 4.5 Ga ago if only K, U and Th are considered. However, $^{26}$Al and $^{224}$Pu could have contributed very early in Earth history, and if the Earth had started to accrete 4.6 Ga ago the heating from the decay of $^{26}$Al would have caused melting throughout the whole Earth. This radioactive heating plus additional heating from the energy liberated during accretion (the exact amount being dependent on the accretion rate) would probably be sufficient to ensure a very early formation of the core, probably within the first 100 or 200 Ma of Earth history.

## Nature of material transport from the mantle

Basically there are two lines of reasoning which lead to the conclusion that the Earth has irreversibly differentiated and that material has been transported from the mantle to reservoirs in the crust and the ocean/atmosphere system. The first line of evidence is derived from investigations of crustal rocks formed at different times throughout Earth history and details of the composition of the atmosphere. Numerous radiometric dating studies in West Greenland (e.g. Moorbath, O'Nions, Pankhurst & McGregor 1972; Moorbath, O'Nions & Pankhurst 1973, 1975), Rhodesia (Hawkesworth, Moorbath, Wilson & O'Nions 1975; Hickman 1975), Labrador (Hurst, Bridgwater, Collerson & Wetherill 1975; Barton 1975), Minnesota (e.g. Goldich & Hedge 1975), Norway (Taylor 1975), and South Africa (Allsop, Roberts, Schreiner & Hunter 1962; Hurley, Pinson, Nagy & Teska 1972; Jahn & Shih 1974), have conclusively demonstrated the existence of considerable amounts of acid crust before 3000 Ma. Both Sr and Pb isotope studies of Archaean rocks have been taken to indicate that very little granitic crust could have been stabilized before *ca.* 4000 Ma ago, and that the crust was progressively added to in its early history by material with isotopic characteristics similar to those inferred for the mantle at that time (see reviews by Moorbath (1975) and O'Nions & Pankhurst (1977) for more detailed discussions). These conclusions are in concert with, and based on, very similar reasoning to the classical study of Hurley *et al.* (1962). It has been recognized since the work of Brown (1952) on the abundances of rare gases in the atmosphere that very little of the atmosphere could be residual from the time of Earth formation. Rather the observed fractionation pattern of rare gases in the atmosphere, and the inferred fractionation patterns of those in the mantle (Ozima & Alexander 1976) suggest that the bulk of the Earth's atmosphere has been derived by outgassing of the mantle. Similar conclusions have been arrived at on the basis of the $^{40}$Ar inventory of the Earth (Turekian 1959) and the $^{40}$Ar/$^{36}$Ar ratios in the atmosphere and gases from mantle-derived basalts (Ozima 1975). Some workers, notably Ozima (1975) and Fanale (1972), have argued for an early catastrophic degassing of the Earth, whereas in contrast the crust appears to have grown more continuously. The timing and rates of supply of materials to the crust and atmosphere are problems which are still surrounded by considerable uncertainty and speculation.

The second line of evidence comes from studies of mantle-derived basalts and their derivatives. It has been recognized for more than a decade that some basalts generated at mid-ocean ridges (m.o.r.b.) do not possess sufficient $^{87}$Rb to support their $^{87}$Sr contents (Tatsumoto, Hedge & Engel 1965). Within the context of a model Earth, with meteoritic initial $^{87}$Sr/$^{86}$Sr ratio, and an age of *ca.* 4.5 Ga, taken with the assumption that the Rb/Sr of m.o.r.b. liquids are not less than their source regions, this observation has been interpreted as the result of an earlier depletion in the particular source region of Rb relative to Sr (Tatsumoto *et al.* 1965; Gast 1968).

It has been subsequently demonstrated that not all basalts formed at spreading centres show this characteristic (see, for example, Hart, Schilling & Powell 1973; O'Nions & Pankhurst 1974) and that evidence for the event(s) alluded to can also be found from a consideration of other parent-daughter systems such as the Sm–Nd system. A number of Nd isotope data on oceanic volcanics have now been published (Richard, Shimizu & Allègre 1976; DePaolo & Wasserburg 1976; O'Nions, Hamilton & Evensen 1977), and overall there is a very clear covariation between $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ ratios (O'Nions *et al.* 1977) demonstrating that Rb/Sr and Sm/Nd have fractionated coherently in the sub-oceanic mantle throughout Earth history. These data permit a new estimate of the bulk Earth Rb/Sr ratio to be made if the reasonable assumption is made that Sm/Nd of the bulk Earth is chondritic. The present day $^{143}Nd/^{144}Nd$ for a chondritic Earth is 0.51264 which corresponds to a bulk Earth $^{87}Sr/^{86}Sr$ and Rb/Sr ratios of *ca.* 0.705 and 0.032 respectively (O'Nions *et al.* 1977). This estimate is in good agreement with an independent estimate of DePaolo & Wasserburg (1976). It can now be inferred that all recent basalts which have $^{87}Sr/^{86}Sr$ ratios less than *ca.* 0.705 have been generated from source regions which are depleted relative to the bulk Earth. This point is further made in figure 4 where the parameters ΔNd and ΔSr are compared. These parameters are defined as:

$$\Delta\mathrm{Sr} = 10^3 \left\{ \frac{(^{87}\mathrm{Rb}/^{86}\mathrm{Sr})_{\mathrm{ss}} - (^{87}\mathrm{Rb}/^{86}\mathrm{Sr})_{\mathrm{B.E.}}}{(^{87}\mathrm{Rb}/^{86}\mathrm{Sr})_{\mathrm{B.E.}}} \right\}$$

and

$$\Delta\mathrm{Nd} = 10^3 \left\{ \frac{(^{147}\mathrm{Sm}/^{144}\mathrm{Nd})_{\mathrm{ss}} - (^{147}\mathrm{Sm}/^{144}\mathrm{Nd})_{\mathrm{B.E.}}}{(^{147}\mathrm{Sm}/^{144}\mathrm{Nd})_{\mathrm{B.E.}}} \right\},$$

where ss refers to a single stage model value, and B.E. the bulk Earth model values (see caption to figure 4). The origin of figure 4 (ΔNd = 0.0; ΔSr = 0.0) thus corresponds to a basalt derived from pristine unmodified mantle. The Nd and Sr isotope data of O'Nions *et al.* (1977) are shown in figure 4, and mostly plot in the −ΔSr, +ΔNd quadrant. This demonstrates that virtually all basalts erupted in the ocean basins including those in Iceland and Hawaii are derived from source regions which have been depleted to variable extents in Rb and light r.e.e. Basalts such as those from Tristan da Cunha, which have isotopic compositions similar to bulk Earth values, are volumetrically trivial in the ocean basins.

The measured Rb/Sr and Sm/Nd ratios in the erupted basalts relative to those of the source region are a function of the melting processes. The compatibility of the measured Rb/Sr and Sm/Nd ratios with simple partial melting models can be examined by computing the parameters $\delta'_{\mathrm{Nd}}$ and $\delta'_{\mathrm{Sr}}$ defined as follows:

$$\delta'_{\mathrm{Nd}} = 10^3 \left\{ \frac{(^{147}\mathrm{Sm}/^{144}\mathrm{Nd})_{\mathrm{m}} - (^{147}\mathrm{Sm}/^{144}\mathrm{Nd})_{\mathrm{B.E.}}}{(^{147}\mathrm{Sm}/^{144}\mathrm{Nd})_{\mathrm{B.E.}}} \right\}$$

and

$$\delta'_{\mathrm{Sr}} = 10^3 \left\{ \frac{(^{87}\mathrm{Rb}/^{86}\mathrm{Sr})_{\mathrm{m}} - (^{87}\mathrm{Rb}/^{86}\mathrm{Sr})_{\mathrm{B.E.}}}{(^{87}\mathrm{Rb}/^{86}\mathrm{Sr})_{\mathrm{B.E.}}} \right\},$$

where m refers to the measured ratio in the sample.

The data from figure 4 are compared in figure 5 with computed equilibrium partial melting trajectories, and the $\delta'_{\mathrm{Nd}}$ and $\delta'_{\mathrm{Sr}}$ values computed for each sample. It is clear that many

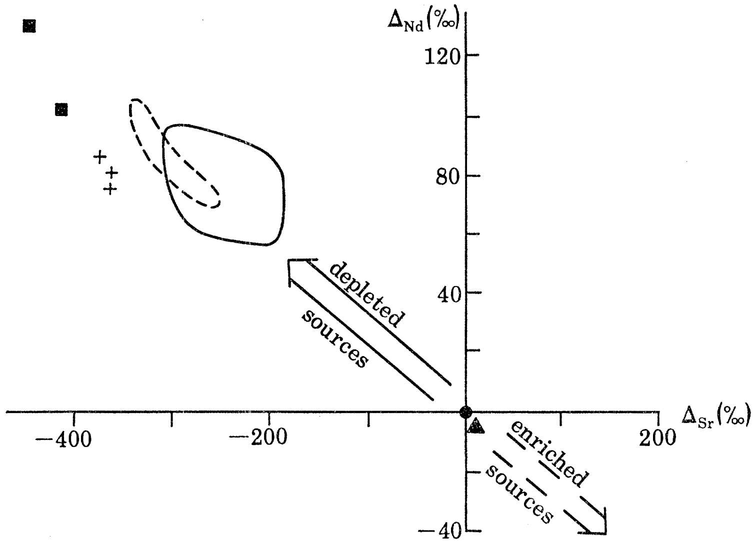

FIGURE 4. ΔNd and ΔSr values (see text for definitions) for oceanic basalts, where the values are the difference (per mille) between the computed single-stage parent–daughter ratios and those of the bulk Earth composition (table 2). Note that most of the oceanic basalt data, including those from the islands of Hawaii (solid line) and Iceland and Reykjanes ridge (broken line), fall in the −ΔSr and +ΔNd quadrant: ■, mid-Atlantic ridge; +, Ascension Island. This indicates their derivation from source regions which have been significantly depleted relative to the model bulk Earth composition. Oceanic basalt source regions which have been significantly enriched with respect to the model bulk Earth composition (●) have not yet been found, but note Tristan da Cunha (▲). Data taken from O'Nions *et al.* (1977).

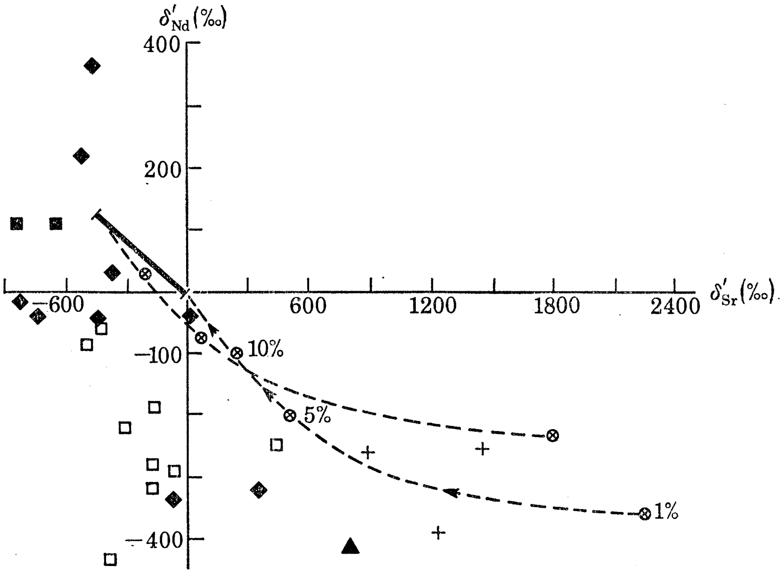

FIGURE 5. Plot of $\delta'_{Nd}$ and $\delta'_{Sr}$ values (see text for definitions) for oceanic basalts, where $\delta'_{Nd}$ is the difference (per mille) between the measured $^{147}Sm/^{144}Nd$ and that inferred for the bulk Earth, and $\delta'_{Sr}$ is the analogous value for $^{87}Rb/^{86}Sr$. The range of oceanic basalt source regions (solid line) is defined by the differences between the computed single stage parent–daughter ratios and the model bulk Earth values (expressed as ΔNd and ΔSr in figure 4). Equilibrium partial melting trajectories are shown for melting of a source of model bulk Earth composition ($\delta'_{Nd} = \delta'_{Sr} = 0$) and for melting of the most depleted oceanic basalt source region so far found. A source composition of 55 % olivine, 25 % orthopyroxene, 15 % clinopyroxene and 5 % garnet, and melting proportions of 1:5:10:10 respectively, have been assumed. Many of the oceanic basalt data do not plot near the melting trajectories suggesting that the actual melting processes are often more complex than the simple model shown. Hawaiian islands, □; Iceland and Reykjanes ridge, ◆; other symbols as figure 4.

oceanic basalts, such as those from Hawaii, fall well away from the computed melting trajectories and it seems very unlikely that these magmas could have been generated by such simple melting processes.

Of interest now is the mechanism by which the source regions of virtually all oceanic basalts have been depleted. However, before asking specific questions about the medium in which K, Rb, and other large ion elements are transported through the mantle, it is pertinent to summarize the current understanding of the mechanism(s) of irreversible differentiation of the Earth. At present, mantle material beneath a spreading centre undergoes a phase change to a solid and liquid phase. Some of the liquid phase (relatively enriched in large ion elements), separates to form the oceanic crust leaving a depleted residue. The oceanic crust interacts to some extent with seawater and its chemistry is modified. Modifications are known to involve the alkali and alkaline earth elements (Hart 1971) and Sr isotope compositions (Hart 1971; Hart, Erlank & Kable 1974; Dasch, Hedge & Dymond 1973; O'Nions & Pankhurst 1976). Measurements carried out in this laboratory (O'Nions *et al.* 1977; and unpublished data) have so far failed to reveal any modification of $^{143}Nd/^{144}Nd$ ratios of submarine basalts, even though the $^{87}Sr/^{86}Sr$ ratios may be very considerably modified. When finally subducted, the ocean crust may have a significantly different $^{87}Sr/^{86}Sr$ ratio and alkali element content, but is expected to have essentially unmodified $^{143}Nd/^{144}Nd$ ratios. Both tholeiitic and calc-alkaline volcanism occurs at subductive plate margins and this has long been recognized as a route via which mantle material finally reaches the crust (Taylor 1967).

Isotope studies of South Sandwich Island arc tholeiites (Hawkesworth *et al.* 1977) partly confirm this idea. The $^{143}Nd/^{144}Nd$ ratios of the tholeiites are characteristic of m.o.r.b. but the $^{87}Sr/^{86}Sr$ ratios of *ca.* 0.7040 are higher and consistent with derivation from ocean crust contaminated by seawater. Thus island-arc volcanism may well provide a route whereby mantle material is transferred to the crustal reservoir, but in detail the process is complex and involves some recycling of seawater Sr which is largely derived from continental run off.

The precise mechanism of material transport from the mantle is complex inasmuch as we are primarily interested in understanding the transport of material out of the system before the 'current' melting event. A boundary condition in this process is that not enough of the major elements (Fe, Al, Ca, etc.) be removed to leave a residue too refractory to melt at temperatures of 1100–1200 °C. Thus the process responsible is most likely to be one involving a small amount of silicate liquid loss or transport of the elements out of the system in a volatile phase. Support can be mustered for both of these viewpoints, and of course they may not be mutually exclusive. However, the availability of both Sr and Nd isotope data on a number of oceanic basalts (O'Nions *et al.* 1977) permits a closer examination of the problem. At the present time we have no evidence of enriched source regions melting to produce basalts in the ocean basins (figure 4), and the problem is only one of reducing $\Delta Sr$ and increasing $\Delta Nd$ sympathetically. The calculations of O'Nions *et al.* (1977) have shown that this can be achieved by melting, but it must be emphasized that other processes, which at the present time we cannot model, may produce indistinguishable results.

The timing of the material transport event(s) from the mantle is a topic of considerable current interest. For example, Sun & Hanson (1975) and Brooks *et al.* (1976) have suggested that Rb-Sr data from oceanic volcanics can be interpreted in terms of a single mantle fractionation event at 1.6–2.0 Ga. The Pb isotope data can also be interpreted in terms of a two stage model, yielding a similar time for the fractionation event (Sun, Tatsumoto & Schilling

1975; Tatsumoto 1966). In general, isotope geochemists have been cautious to point out that such models may be an oversimplification since in detail the data do not exactly fit a two stage model (see Gale & Musset (1973) for a discussion of Pb isotope data). Furthermore, the crust does not appear to preserve evidence of any world wide event in this time period. To illustrate how non-unique the interpretations of the Pb isotope data are, two-stage and continuous fractionation models are compared in figure 6. The total spread in $^{207}$Pb/$^{204}$Pb and $^{206}$Pb/$^{204}$Pb values in oceanic basalts is 20‰ ($\Delta 207$) and 170‰ ($\Delta 206$) respectively. Curves for these values have been plotted in figure 6. The $\Delta 207$ and $\Delta 206$ curves in figure 6 intersect at approximately 1.6 Ga and require up to a 2.2 times increase in $^{238}$U/$^{204}$Pb ratio at the time of fractionation. This model is compared with the other extreme, namely, continuous U/Pb fractionation models which demonstrate that fractionation events occurring throughout a major portion of Earth history can produce the observed range of Pb isotope compositions. Such continuous or quasi-continuous U/Pb fractionation events over a large period of time, rather than a single event, are more compatible with other cited evidence for an essentially continuous transport of material from the mantle to the crust.

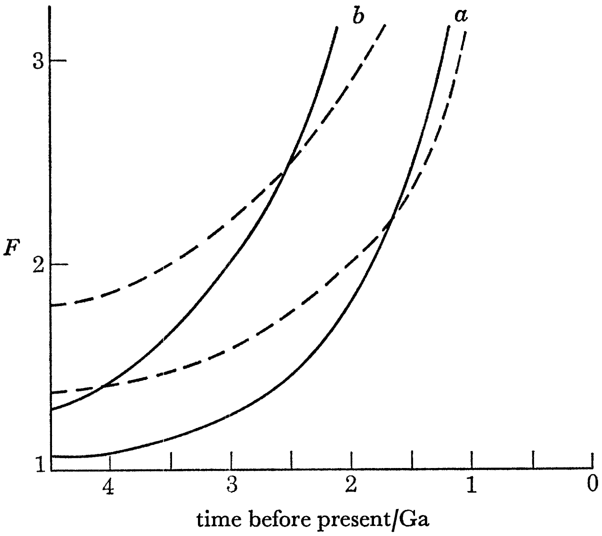

FIGURE 6. Plot of fractionation factor $F$ (which is $^{238}$U/$^{204}$Pb measured today, divided by $^{238}$U/$^{204}$Pb at time $t$ in the past but corrected for decay as if measured today) against time for $\Delta 207$ (solid lines) and $\Delta 206$ (broken lines) equal to 20‰ and 170‰ respectively. These $\Delta 207$ and $\Delta 206$ values are the observed per mille variations in $^{207}$Pb/$^{204}$Pb and $^{206}$Pb/$^{204}$Pb ratios in oceanic volcanics. Two models are compared to illustrate the non-uniqueness of interpretation. The two-stage model interpretation (*a*) requires a U/Pb fractionation event at *ca.* 1.6 Ga. and a maximum change in $^{238}$U/$^{204}$Pb of about 2.2. Continuous ($n$-stage) fractionation models (*b*) can also produce the observed $\Delta 207$ and $\Delta 206$ values. Measurements of $^{238}$U/$^{204}$Pb values in errupted volcanics suggest that $F$ values up to 2.5 are not unreasonable. Decay constants are from Jaffey *et al.* (1971).

## HEAT PRODUCTION IN A DIFFERENTIATED MANTLE

It is of interest to examine the distribution of heat in the differentiated Earth *vis-à-vis* the measured surface heat flow. The mean oceanic heat flow is in excess of the mean global heat flow and greater than 90 mW m$^{-2}$. If all the heat lost by cooling of the oceanic lithosphere were generated in the upper mantle at the present time then the average upper mantle heat production would be 38 pW $kg^{-1}$, approximately three times the estimated bulk Earth heat production (figure 3). By far the most voluminous volcanics erupted at the surface are m.o.r.b. which are derived from l.i.l. depleted source regions and only trivial amounts of basalt are derived from undepleted source regions (figure 4). To date no oceanic basalts have been found which come from source regions substantially enriched over the bulk Earth model, which coupled with an estimated heat production in the source region of m.o.r.b. of 4.5 pW $kg^{-1}$ (compared with 13 pW $kg^{-1}$ for the bulk Earth) suggests that a significant amount of the heat lost by cooling of the oceanic lithosphere is generated in the lower mantle. Consequently the convective processes in the upper mantle which lead to magma generation beneath mid-ocean ridges appear to be driven to a large extent by heating from below. A discussion of the mechanisms of heat transfer from the lower to upper mantle is beyond the scope of this paper. It is worth noting, however, that whatever the mechanism of heat transfer, it does not appear to be accompanied by the transport of the heat-producing elements to a near surface environment.

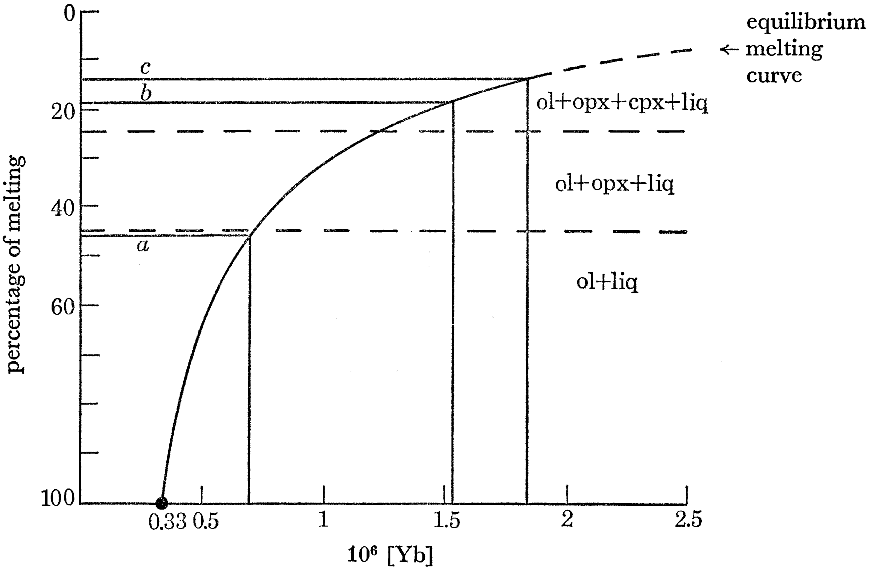

FIGURE 7. Percentage of equilibrium partial melting of a peridotite source with 0.33 part/$10^6$ Yb against Yb contents of liquids produced. The equilibrium melting curve has been calculated from the equations of Shaw (1970) and O'Nions & Clarke (1972), employing $K_D^{Yb}$ values for olivine-, orthopyroxene-, and clinopyroxene-liquid from Schnetzler and Philpotts (1972). The bulk Earth (crust plus mantle) Yb content of 0.33 part/$10^6$ (●) assumes 1.5 × chondritic r.e.e. abundances. The melting ranges of clinopyroxene and orthopyroxene are from Mysen & Kushiro (1976). Neither the position of these boundaries nor the use of an incremental rather than an equilibrium melting model significantly change the position or shape of the melting curve. Its position is much more dependent upon the selected Yb content for the bulk Earth. The Rhodesian komatiite Yb content (*a*) is the average peridotite komatiite from Hawkesworth & O'Nions (1977). Yb contents of the Tertiary Baffin Bay tholeiites (*b*) and D.S.D.P. Legs 2 and 3 glasses (*c*) are from O'Nions & Clarke (1972) and Frey *et al.* (1974) respectively.

## VARIATIONS IN EXTENT OF MANTLE MELTING WITH TIME

The degree to which the mantle has melted throughout Earth history can only be inferred from the incomplete record of basaltic volcanism which has been preserved in the Earth's crust. If the preserved record is at all representative then it suggests that the maximum amount of partial melting of the mantle is less now than it was some 2.5–3.5 Ga ago. This statement is based upon the occurrence of high-Mg ultramafic magmas in the Archaean and their virtual absence by the Phanerozoic. Archaean ultramafic magmas are described elsewhere in this volume and reference is made to those papers for more extensive discussions. Various studies and discussions of Archaean ultramafic lavas (Green 1974; Cawthorne 1975; Bickle *et al.* 1976; Hawkesworth & O'Nions 1977) based upon their major element chemistry and melting relationships have suggested that they are generated by approximately 50 % melting of peridotite, which may be compared with estimates of 20–30 % for mid-ocean ridge basalts. It is unlikely that these estimates can be substantially improved using trace element geochemistry, but some available trace element data are certainly compatible with these estimates. This is demonstrated in figure 7, where the Yb contents of Archaean ultramafic lavas and recent tholeiites are compared with a simple equilibrium melting model. It must be emphasized that the actual melting processes are likely to be more complex than this, but nevertheless the equilibrium melting model does seem to provide a good approximation. The bulk Earth Yb content (table 2) of 0.33 part/$10^6$ is used as a starting point in the calculations. The Rhodesian komatiites analysed by Hawkesworth & O'Nions (1977) could be produced by about 46 % partial melting according to this model. In comparison, the Baffin Bay basalts (O'Nions & Clarke 1972), which are amongst the most Mg-rich tholeiites recorded from the North Atlantic area, could be formed by approximately 18 % partial melting, and the basaltic glasses from D.S.D.P. Legs 2 and 3 (Frey, Bryan & Thompson 1974) by 15 % melting. An approximately two-fold difference in the maximum amount of mantle melting between the Archaean and recent times is thus supported by the trace element data.

The difference in 1 atm† liquidus temperatures between recent ridge tholeiites and Archaean ultramafic liquids is 200 °C or more (see, for example, O'Hara 1968; Green 1974), though the bulk of the Archaean volcanics preserved in the crust have liquidus temperatures more similar to recent magmas. The substantially higher heat production in the Archaean mantle (figure 3) would have resulted in higher temperatures at a given depth in the mantle (Mackenzie & Weiss 1975), and it is to be expected that this would lead to overall higher liquidus temperatures of Archaean, volcanics. However, the actual degree of melting, and liquidus temperatures upon eruption will depend upon the precise position of the geotherm relative to the appropriate peridotite solidus, and the depth of separation of the melt. It is possible that during the Archaean, advanced degrees of melting were only achieved in situations where the thermal gradient was adiabatic to near the surface, and that this condition was not normally achieved in the environment in which many of the Archaean volcanics were preserved.

## CONCLUSIONS

Precise isotope composition data on mantle derived basalts, together with considerations of refractory element ratios in a range of chondrite meteorites, allow the definition of several important lithophile element abundances in the bulk Earth, including Rb, Sr, K, U, Th, Sm and Nd. Relative to an established bulk Earth model it is clear that the vast majority of oceanic basalts are derived from source regions which have been depleted in l.i.l. elements. This includes oceanic island basalts such as Hawaii and Iceland. Furthermore, the calculated heat production in the source region of mid-ocean ridge basalts is much lower than the computed bulk Earth heat production. Consequently it would appear that the convective processes

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† 1 atm ≈ $10^5$ Pa.

responsible for mid-ocean ridge volcanism are largely driven by heat derived from other parts of the mantle (presumably the lower mantle) but material does not appear to be transported from these regions to near the surface.

The higher degrees of partial melting of mantle peridotite in the Archaean, for which there is sporadic evidence, may merely reflect the predictably higher temperatures of the Archaean mantle.

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## *Discussion*

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1. The authors have introduced their talk by discussing the Earth in terms of the chemistry of chondritic meteorites. In chondrites, the K/U ratio is about a factor of 4 greater than the chosen terrestrial value, *ca.* $10^4$; in chondrites, the Rb/Sr ratio is about 0.2 to 0.3, and almost an order of magnitude greater than the value (0.032) derived by the authors for the Earth. For this and other reasons it is clear that a simple chondritic model cannot be applied to the Earth, the early history of which must have been complex.

2. Uranium does not appear to be fractionated relative to other refractory lithophile elements, such as Ca and Al, among the various chemical groups of stony meteorites. The authors' selected U abundance in the bulk mantle plus crust of the Earth, 0.046 part/$10^6$ (by mass) is equivalent to 0.031 part/$10^6$ in the bulk Earth (assuming 32 % by mass of core). This figure (0.031/$10^6$) is 2.8 times the generally accepted mean U abundance in chondrites, 0.011 part/$10^6$. The Al abundance in chondrites is greater than 1 %. A bulk Earth with 0.031 part/$10^6$ U would have at least 2.8 % Al if the Al/U ratio of chondrites is applied. This Al content is equivalent to 7.8 % $Al_2O_3$ in the terrestrial mantle plus crust. Even allowing for the large uncertainties in our data, it appears inescapable that an Earth with 0.046 part/$10^6$ U in mantle plus crust should be much more refractory than is observed. It seems that either the authors' choice of U content is at fault or else the Earth formed from materials, or by processes, different from those involved in the formation of the chondrites.