Nature of Mantle Heterogeneity in the North Atlantic: Evidence from Deep Sea Drilling

J. Tarney, D. A. Wood, A. D. Saunders, J. R. Cann and J. Varet

Phil. Trans. R. Soc. Lond. A 1980 **297**, 179-202
doi: 10.1098/rsta.1980.0209

Phil. Trans. R. Soc. Lond. A **297**, 179–202 (1980)
Printed in Great Britain

Nature of mantle heterogeneity in the North Atlantic: evidence from deep sea drilling

By J. Tarney,† D. A. Wood,† A. D. Saunders,†
J. R. Cann‡ and J. Varet§
† *Department of Geological Sciences, The University, Birmingham B15 2TT, U.K.*
‡ *Department of Geology, The University, Newcastle upon Tyne NE1 7RU, U.K.*
§ *Bureau de Recherches Géologiques et Minières, Orléans, France*

Studies of dredged and drilled samples from the North Atlantic ocean have revealed that basalts with a wide range of major and trace element compositions have been generated at the Mid-Atlantic Ridge (M.A.R.). Many of the basalts erupted between latitudes 30° and 70° N do not have the geochemical characteristics of normal mid-ocean ridge basalts (m.o.r.b.) depleted in the more-hygromagmatophile (hyg.) elements. Drilling along mantle flow lines transverse to the ridge has shown that different segments of the M.A.R. have produced basalts with a distinct compositional range for tens of millions of years. As more data have become available, the nature and scale of this variation have been established and tighter constraints can now be placed on the petrogenetic processes involved.

The rare earth elements are used to test quantitatively the effects of open and closed system fractional crystallization, equilibrium partial melting (including continuous melting), zone refining and mantle mixing processes on basalt chemistry. When evaluated in terms of the more-hyg. elements, the results show that major heterogeneities must exist in the mantle sources feeding the M.A.R. Ratios of many of the more-hyg. elements remain consistent in space and time in basalts erupted at a particular ridge segment, but vary widely between different ridge segments. These ratios are not significantly modified by the processes of basalt generation. The hyg. element relations provide a major constraint on the nature of heterogeneity in the Earth's mantle and the processes producing it. The mantle sources of anomalous ridge segments can be best explained in terms of variable veining of a hyg. element depleted host by a hyg. element enriched liquid or fluid generated by very small degrees of partial melting. Such incipient melting, as well as subduction zone processes, may be viable mechanisms for changing hyg. element ratios in the mantle source regions on the scale observed. These processes can be integrated into a model for mantle evolution which involves (1) upward migration of incipient melts to provide a hyg. element enriched source for alkali basalts and a hyg. element depleted source for normal m.o.r.b., and (2) extraction of continental crust and recycling of the depleted residue into the mantle at subduction zones. Also, some recycling of continental material into the mantle may be required to explain Pb isotope patterns.

INTRODUCTION

The question of the nature of chemical heterogeneity in the Earth's mantle can be approached from several directions and on several scales, among which the record provided by erupted mantle-derived silicate melts is potentially the most complete in a spatial and temporal sense. Eruption of magma at oceanic spreading centres provides an abundant supply of basalt samples accessible by dredging, the geochemistry of which may reflect variations in mantle composition along the spreading axis for many hundreds of kilometres, assuming that the effects due to partial melting, fractional crystallization, magma mixing and contamination can be allowed for. Deep sea drilling has also permitted the recovery of basalts erupted at the ridge axis many tens of millions of years earlier, in several cases the sites being located along mantle flow lines transverse to the ridge. Thus basalt compositions can be monitored in time and provide an indication of the degree of uniformity of the mantle source feeding a particular ridge segment for many tens of millions of years.

Previous studies indicate that the Mid-Atlantic Ridge (M.A.R.) consists of segments erupting mid-ocean ridge basalts (m.o.r.b.) of two main types:

(1) Normal ridge segments (e.g. 20–30° N, 50–60° N) erupting tholeiitic basalts with low absolute abundances of the more-hygromagmatophile (hyg.) elements, i.e. those elements having bulk-mantle–basaltic-liquid distribution coefficients (D) significantly less than unity (this term is used in preference to 'incompatible' and may be qualified by less-hyg. for elements with D near to 0.1 and more-hyg. for elements with D near to or less than 0.01 (see Wood *et al.* 1979*a*)). These basalts are depleted in the more-hyg. elements relative to chondrites, for example Th/Hf is less than 0.1 and Rb/Sr is less than 0.01 (Schilling 1971; Frey *et al.* 1974; Wood *et al.* 1979*b*). They have low $^{87}Sr/^{86}Sr$ ratios (*ca.* 0.7023–0.7027; Hart 1971), low radiogenic to non-radiogenic Pb isotope ratios (e.g. $^{206}Pb/^{207}Pb$ ranges from 17.5 to 18.5; Tatsumoto 1978) and high $^{143}Nd/^{144}Nd$ ratios (0.5131–0.5133; DePaolo & Wasserburg 1976; O'Nions *et al.* 1977).

(2) Ridge segments with positive residual gravity, depth and heat flow anomalies, which erupt basalts enriched in the more-hyg. elements. The type consists predominantly of tholeiitic basalts but shows much greater variation in hyg. element concentrations and ratios and in radiogenic isotope ratios than basalts erupted at normal ridge segments (Wood *et al.* 1979*a*; Tarney *et al.* 1979). Ratios of more-hyg. to less-hyg. elements are high; for example, Th/Hf is about 0.2 and Rb/Sr is about 0.04 (Hart *et al.* 1973; Wood *et al.* 1979*b*). These basalts have high $^{87}Sr/^{86}Sr$ ratios (> 0.7027; White *et al.* 1976), higher radiogenic to non-radiogenic Pb isotope ratios (e.g. $^{206}Pb/^{207}Pb = 18.0–19.5$; Tatsumoto 1978) and lower $^{143}Nd/^{144}Nd$ ratios (less than 0.5131; O'Nions *et al.* 1977). Nevertheless, these isotopic ratios are much lower (higher for Nd) than calculated bulk Earth values, suggesting that these basalts, as well as those from normal ridge segments are derived from mantle sources that have suffered previous depletion (Gast 1968; O'Nions *et al.* 1978).

In some areas (e.g. the Reykjanes Ridge), where anomalous ridge segments grade into normal ridge segments, the erupted basalts have lower hyg. element abundances and progressively approach the composition of normal m.o.r.b. Nevertheless they can still be distinguished from normal m.o.r.b. by their higher Sr and Pb isotope ratios (White & Schilling 1978; Sun *et al.* 1975) and by element ratios such as La/Ta (Wood *et al.* 1979*a*; Tarney *et al.* 1979). We shall refer to the two main types of basalt (normal and enriched) as N-type m.o.r.b. and E-type m.o.r.b. respectively, but emphasize that there is a gradation between them, with transitional (T-type m.o.r.b.) compositions erupted at some ridge segments.

The nature of the compositional variation between basalt types in the North Atlantic has generally been discussed on the basis of analytical data for a few elements and/or isotope ratios on a limited number of samples dredged from near the ridge axis. Recent Atlantic drilling by Legs 37, 38, 45, 46, 49, 51, 52 and 53 of the Deep Sea Drilling Project has provided a large number of samples from several latitudes (figure 1). These samples have added two further dimensions to the array of data already available from dredged samples: (*a*) variations with time along mantle flow-lines and (*b*) variations with depth in the oceanic crust. High precision analyses of up to 40 major and trace elements, by X-ray fluorescence and neutron activation techniques, are now available for many of these samples. Several publications have discussed the geochemical and petrological variations observed in basalts recovered by individual drilling legs (see, for example, Blanchard *et al.* 1976; Joron *et al.* 1978; Tarney *et al.* 1978; Wood *et al.* 1978). This comprehensive body of data, together with data on dredged samples and on ocean island basalts, will be used as the basis for a discussion of the petrogenesis of the different types of m.o.r.b. erupted at the Mid-Atlantic Ridge, for the implications this has for the nature and scale of mantle heterogeneity in the North Atlantic, and ultimately for the processes involved in the evolution of the sub-oceanic upper mantle.

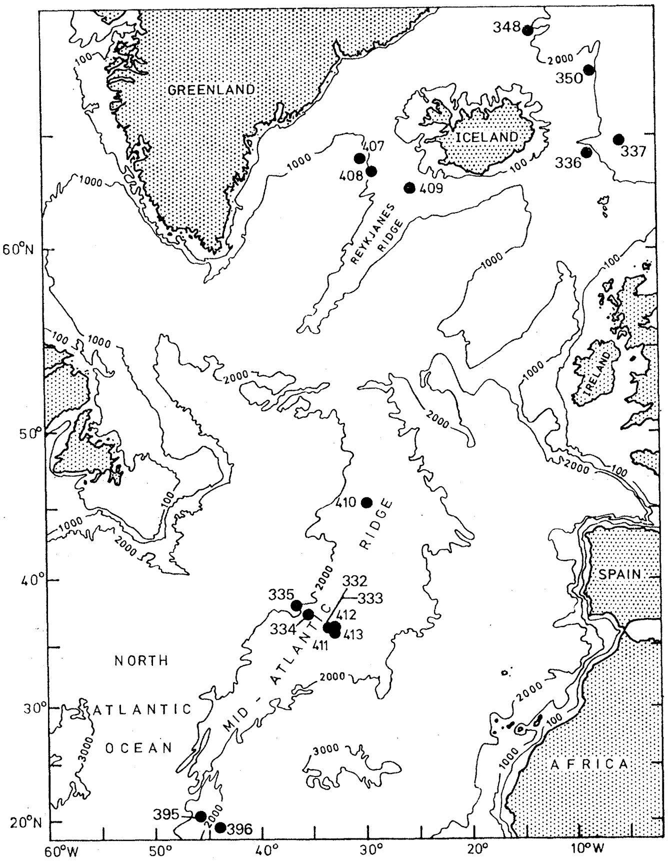

FIGURE 1. Map of the North Atlantic ocean showing some of the recent D.S.D.P. sites drilled.

PROCESSES INFLUENCING THE COMPOSITION OF BASALTIC LIQUIDS

The crustal and upper mantle processes that are involved in basalt genesis, and the contribution that each makes to the chemical diversity observed in erupted basalts, are controversial. This is apparent from the large number of conflicting models that have been proposed to explain trace element and isotope variation between m.o.r.b. types. Much of this controversy has involved the geochemical gradient from Iceland along Reykjanes Ridge (Schilling 1973; Sun *et al.* 1975; Sigvaldason 1974; O'Nions *et al.* 1976; Flower *et al.* 1975; O'Hara 1975, 1977). The debate has been concerned mainly with evaluating the model of binary mixing of the deep mantle plume (E-type m.o.r.b.) and low-velocity zone (N-type m.o.r.b.) sources to produce T-type m.o.r.b. (Schilling 1973) and various alternative models. With additional data it has recently become clear that the binary source mixing model cannot satisfactorily explain *all* the trace element and isotope variations observed in the Iceland–Reykjanes Ridge segment of the M.A.R., nor indeed the trace element and isotopic variations observed in basaltic rocks globally (Langmuir *et al.* 1978; Tarney *et al.* 1979; Wood *et al.* 1979*a*, *b*; Sun *et al.* 1979; Sun, this symposium). If mixing of sources is responsible for the compositional variation then more than two end member sources have been involved.

TABLE 1. MINERAL–LIQUID PARTITION COEFFICIENTS OF Ce AND Yb IN BASALTIC SYSTEMS

	set 1			set 2	
	Ce	Yb		Ce	Yb
olivine	0.0010	0.0015	olivine	0.0069	0.014
orthopyroxene	0.003	0.049	orthopyroxene	0.024	0.34
diopside	0.098	0.28	augite	0.15	0.62
garnet	0.021	4.00	plagioclase	0.12	0.067

Set 1 represent high-pressure values compiled from experimental studies (Hanson 1977).
Set 2 represent low-pressure values compiled from phenocryst-matrix studies of basaltic lavas (Arth & Hanson 1975).

Notwithstanding the importance of source inhomogeneities in controlling the compositions of m.o.r.b., their chemistry has clearly been subsequently modified by the processes involved in magma genesis, notably partial melting and crystal fractionation. Most of these processes involve crystal–liquid equilibria, and their effect on those elements that obey Henry's law can be expressed as a function of D. Using published equilibrium equations for these processes, we have modelled their effect on the rare earth element (r.e.e.) concentrations in basaltic liquids and compared them with the variations observed in m.o.r.b. We have selected the r.e.e. for two reasons. First, the systematic variation in their atomic properties causes considerable systematic variation in D, with the smaller ions of the heavy r.e.e. (e.g. Yb) being more readily substituted into the crystal lattices of the major mantle mineral phases than the larger light r.e.e. (e.g. Ce). Thus, both the more-hyg. and the less-hyg. elements can be modelled with this group. Secondly, the mineral–liquid partition coefficients (K_ds) for the r.e.e. have been studied experimentally for most of the major mantle minerals. The K_ds used in the models are given in table 1.

We present these models in figure 2 on a log–log plot of $(\mathrm{Ce/Yb})_N$ against $(\mathrm{Ce})_N$. Data for the different m.o.r.b. types and some Mg-rich undersaturated continental lavas have been plotted in figure 2. These data show that m.o.r.b. form a *continuous* series from N-type m.o.r.b. ($(\mathrm{Ce/Yb})_N < 1$) through T-type m.o.r.b. ($(\mathrm{Ce/Yb})_N \approx 1$) to E-type m.o.r.b. ($(\mathrm{Ce/Yb})_N \approx$ 2–10). Moreover, the intra-continental, undersaturated (nephelinite–basanite–alkali basalt) lavas from Ross Island, Antarctica (Sun & Hanson 1975*b*) and southeast Australia (Frey *et al.* 1978) lie on the continuation of this trend ($(\mathrm{Ce/Yb})_N \approx$ 10–25). The r.e.e. correlation of this wide range of basalt types could imply that a genetic relation exists between them. This may be a consequence of their present upper mantle sources being ultimately derived from a common primary source (i.e. the primordial mantle). However, the isotope and more-hyg. element data for these basalts precludes their derivation directly from a homogeneous mantle by a single-stage process. Thus, it appears that the chemistry of any erupted basalt represents the net effect of several processes which have acted upon it, and its immediate source, during their multi-stage evolution from the primordial mantle source.

We shall consider briefly the implications of the numerical modelling and attempt to evaluate the significance of each process in the petrogenesis of m.o.r.b.

1. *Closed system crystal fractionation*

The low Mg numbers of most m.o.r.b., regardless of type, suggest that they do not represent primary liquids generated in the mantle, but have undergone some crystal fractionation in their journey to the Earth's surface. Major and trace element variations in m.o.r.b. suggest that the evolved basalts belong to a series of low-pressure crystal fractionation trends (ol. ± pl. initially and pl. + cpx. + ol. ± Fe oxide subsequently) related to the range of primary liquids (Wood *et al.* 1979*a*). Crystal fractionation is particularly extensive in basalt series erupted on ocean islands and commonly leads to silicic differentiates (Wood 1978; Weaver *et al.* 1979).

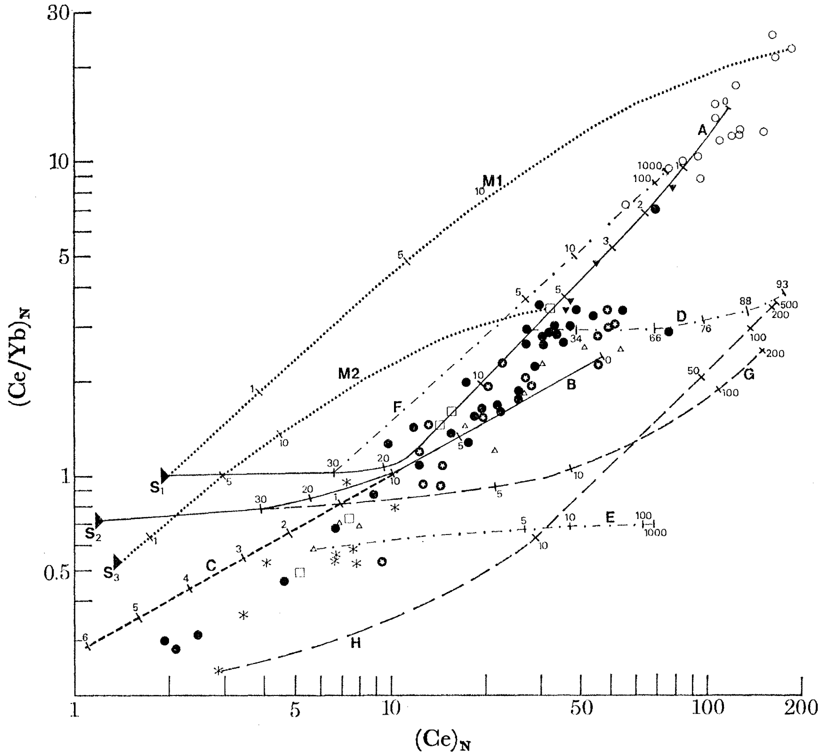

Figure 2. A chondrite-normalized log–log plot of Ce/Yb against Ce for m.o.r.b. and some continental undersaturated lavas. Closed circles, Iceland (O'Nions *et al.* 1976; Wood 1978); open triangles, M.A.R. 63° N; closed inverted triangles, M.A.R. 45° N; open squares, M.A.R. 36° N; asterisks, D.S.D.P. leg 38 samples M.A.R. 65–76° N (Schilling 1975; Wood *et al.* 1979*b*); crosses, N-type m.o.r.b. from the Atlantic (Frey *et al.* 1974) and Pacific (Hart 1976); open circles, undersaturated basalts from ocean islands and melilitites, nephelinites and alkali basalts from continental lava series (Sun & Hanson 1975*b*; Frey *et al.* 1978). The lines and curves represent numerical models for batch partial melting (solid lines), continuous melting (short dashed lines), crystal fractionation (dot–dashed lines), zone refining (broken lines) and mixing of lherzolite with undersaturated liquids (dotted lines). See text for details of the models and explanation of letters and numbers.

The behaviour of trace elements during closed system crystal fractionation may be modelled by the Rayleigh equation (Neumann *et al.* 1954). Curve D (figure 2) represents the closed system crystal fractionation model for the high-Ce/Yb basalt–rhyolite series of Eastern Iceland (Wood 1978) with the use of set 2 partition coefficients in table 1. This model clearly shows that the Ce/Yb ratio is unaffected in the basaltic range of low pressure crystal fractionation (in this case up to 70% crystal fractionation). The numbers on curve D represent percentage crystal fractionation.

Different fractionation series have been frequently found interdigitated in a single drill hole into ocean crust (e.g. Site 407 at 63° N; Tarney *et al.* 1979) and in lava sequences on Iceland (Wood *et al.* 1979*b*). This suggests that crystal fractionation at the M.A.R. is occurring in discrete magma reservoirs which are discontinuous in space and time. The large cumulate sequences observed in ophiolite complexes emphasize that crystal fractionation processes make a major contribution to the compositional variation observed in m.o.r.b. (Elthon 1979). However, much of this low pressure fractionation may not occur in a closed system.

2. *Open system crystal fractionation*

This involves the continual replenishment of a magma chamber with primitive basaltic liquid and only partial extraction of the fractionated liquid. O'Hara (1977) has shown that the trace element composition of the liquid in a magma chamber plumbed in this way rapidly converges to a steady state. We have used his equation to model the r.e.e. composition of the steady-state liquid by varying the fraction of liquid erupted from the magma chamber (Y) for a constant fraction of crystallization (X) of a low-pressure and a high-pressure fractionating phase assemblage, curves E and F, respectively (figure 2). It is the X/Y ratio that controls to what extent the light and heavy r.e.es can be fractionated: significant fractionations only occur for very low values of Y, i.e. less than 0.01 (Pankhurst 1977). For curve E a low-pressure phase assemblage (50% pl., 27.5% ol., 22.5% cpx.), an X value of 0.01, a T-type m.o.r.b. initial liquid and set 2 partition coefficients (table 1) were used. The numbers marked on the curve represent X/Y ratios. This process produces only a slight increase in $(\mathrm{Ce/Yb})_{\mathrm{N}}$ for large increases in $(\mathrm{Ce})_{\mathrm{N}}$. The trend is similar to the closed-system model (curve D) and suggests that the observed low-pressure crystal fractionation trends in m.o.r.b. could be due to either the open or the closed-system process.

Acknowledging the evolved nature of most terrestrial basalts, O'Hara (1975) proposed that they had undergone substantial high pressure eclogite crystal fractionation. Moreover, he suggested that subsequent re-equilibration and crystal fractionation at low pressures had removed any evidence of the high pressure event. Curve F shows a model for fractionation of an eclogite phase assemblage (86% cpx., 14% gt) with the use of the open-system equation, set 1 partition coefficients (table 1), the same X/Y conditions as curve E and a 30% partial melt of a garnet lherzolite chondritic mantle as the initial liquid. The high $(K_{\mathrm{d}})^{\mathrm{gt/liq.}}_{\mathrm{Yb}}$ results in significant fractionation of the Ce/Yb ratio and could explain most of the variation observed in the basalts if extreme X/Y values and higher garnet/clinopyroxene ratios in the fractionating assemblage are invoked. Whether such conditions could be attained in the upper mantle is questionable.

3. *Equilibrium partial melting*

We have used the equations for batch melting (Shaw 1970; Consolmagno & Drake 1976) and continuous melting, i.e. multi-stage melting of a source with a small fraction of liquid retained in the residue throughout melting (Langmuir *et al.* 1977), to model this process. Curve A (figure 2) is a batch melting model for a garnet lherzolite source (55% ol., 25% opx., 15% cpx., 5% gt, with a melting mode of 10%:20%:40%:30% respectively) with the use of set 1 partition coefficients (table 1) and a two times chondrite source composition (S_1) – suggested by the least refractory lherzolite nodules as the primitive mantle composition (Frey & Green 1974). (The initial source compositions used in the models presented here are for reference only: the log–log nature of the plot means that the curves can be moved freely relative to the axes without changing their shape.) The percentage of partial melting is marked on the curve. The curve is very steep and closely approximates the trend of the basalts until 16.67 % melting, when garnet is consumed. For degrees of melting greater than 16.67 %, the melting mode for the remaining phases was recalculated to 100 %. Liquids formed by less than 1 % melting have Ce/Yb ratios identical to the nephelinite and basanite lavas. Curve B (figure 2) is a batch melting model for a three-phase lherzolite (50 % ol., 25 % opx., 25 % cpx., with a melting mode of 15 %:35 %:50 %: respectively) with the use of set 1 partition coefficients (table 1) and a light r.e.e. depleted initial source (S_2), which is suggested by the r.e.e. patterns and Nd isotope data for many N-type and T-type m.o.r.b. This model shows that partial melting of a garnet-free source is less effective in fractionating Ce and Yb than a garnet-bearing source. It is clear from curves A and B that liquids formed by more than about 15 % batch melting have almost the same Ce/Yb ratios as their source.

Line C (figure 2) represents a continuous melting model for the mantle residue left after 10 % batch melting in model B with 2 % melt retained in this residue. Points 1–6 on this line represent successive 2 % melting increments with 2 % melt always retained in the residue. Continuous melting is thus capable of generating basalts that have lower $(Ce/Yb)_N$ ratios than the initial source (Langmuir *et al.* 1977). The batch melting model B and the continuous melting model C taken together represent the dynamic melting model suggested by Wood (1979) to explain the origin of the comagmatic picritic basalts ($(Ce/Yb) \leqslant 1$) and olivine tholeiites of the Quaternary volcanic zones of Iceland from a similar mantle source. Dynamic melting can generate liquids spanning the whole range of basalt Ce/Yb ratios in figure 2.

4. *Zone refining*

In this process a fraction of melt forms and passes through solid mantle of a similar composition to the initial source of the melt with which it repeatedly equilibrates. We have used the equation derived by Harris (1974) to model the enrichment of the r.e.e. in the liquid caused by this process. This is governed by D and the number of equivalent volumes of mantle through which the melt has passed (n). The maximum enrichment of an element by zone refining equals $1/D$. Curve G (figure 2) represent a zone refining model for a 30 % batch melt of model B ascending through the corresponding initial source composition. Curve H represents the zone refining of an N-type m.o.r.b. liquid through a garnet lherzolite (initial source of model A). Set 1 partition coefficients were used in both models and the numbers on the curves are values of n. The models show that zone refining can significantly change the $(Ce/Yb)_N$ ratio of a liquid, especially if garnet is involved. However, it increases $(Ce)_N$ much more rapidly than $(Ce/Yb)_N$ compared with the trend observed in m.o.r.b. No basalt series appear to follow the curved trends produced by zone refining. It therefore seems unlikely that this process plays a direct role in m.o.r.b. genesis.

5. *Mixing in the mantle source regions*

Frey & Green (1974) and Hanson (1977) have pointed out that there is geochemical and textural evidence in ultramafic nodules and from tectonically emplaced ultramafic bodies to suggest that the mantle is variably veined on a small scale. The veins are commonly rich in clinopyroxene and minor hydrous phases. The composition of the veins is variable, but they are commonly enriched in more-hyg. elements and in some cases they are similar to liquids produced by very small degrees of partial melting of a mantle source with two or three times chondritic trace element abundances. Two contrasted types of veining may be considered. (1) The veins represent a liquid formed by equilibrium partial melting of the host mantle, in which case the two components will be in isotopic equilibrium and have similar more-hyg. element ratios. Some of the clinopyroxenite and gabbro veins found in peridotite complexes have been intepreted in this way (Menzies & Allen 1974; Dick 1977). (2) The veins are derived from distant, geochemically different, sources, in which case hyg. element and isotopic ratios of the bulk source (veins + host) will lie on binary mixing curves between the two components. Many of the ultramafic nodules found in continental volcanics have been intepreted in this way (Frey & Green 1974; Frey & Prinz 1978).

We have used the general binary mixing equation (Langmuir *et al.* 1978) to model the second type of veining. Curve M_1 (figure 2) mixes the highly undersaturated olivine melilitite liquid (sample 2927 of Frey *et al.* 1978) with a two times chondritic source (S_1). Curve M_2 mixes an alkalic ocean floor basalt (Site 413, 36° N; Wood *et al.* 1979*a*) with a light r.e.e. depleted source (S_3). The numbers on the curves refer to the percentage of veins. These curves show how a whole spectrum of *mantle source* compositions may be generated by this type of veining. Moreover, curve M_2 shows how a depleted source may be re-enriched in hyg. elements relative to chondrites. The calculated light r.e.e. enriched source of the nephelinites of SE Australia preferred by Frey *et al.* (1978) falls between the mixing curves in figure 2. Thus, from the r.e.e. data at least, component A (Frey *et al.* 1978) of the proposed veined mantle source could be a partial melt. Lloyd & Bailey (1975) have also suggested that the sub-continental mantle may be veined by metasomatic fluids rich in CO_2, H_2O (and probably Cl and F) and the hyg. elements. Because of the high solubility and possible complexing of hyg. elements with Cl-rich and F-rich fluids, the hyg. elements may be more enriched in this way than by partial melting.

6. *Contamination*

O'Hara (1977 and this symposium) has suggested that much of the observed trace element and isotope variation in m.o.r.b. could be the result of assimilation of significant proportions of hydrothermally altered basaltic crust (in which the abundances of the mobile elements Cs, U, K, Rb, Sr, Ba, Pb, and to a smaller extent the light r.e.e. and Th, have been modified, and the $^{87}Sr/^{86}Sr$ ratio has moved towards that of sea water) into open system magma chambers. One of the strongest arguments against this suggestion is the systematic *regional* nature in the chemical variation of m.o.r.b. (figures 3–5) and the strong correlation between isotopic ratios and those of the more-hyg. elements (both mobile and immobile). Bearing in mind the highly irregular nature of alteration and elemental mobility in ocean crust layer 2 (see, for example, Pritchard *et al.* 1978; Floyd & Tarney 1978), the process of contaminating a magma chamber with such material would undoubtedly lead to a range of contaminated liquids showing equal chemical irregularity. This is not observed.

Conclusions drawn from the numerical models for the r.e.e.

1. The trend defined by m.o.r.b. in figure 2 can only be generated from a mantle with chondritic r.e.e. distributions if processes involving garnet–liquid equilibration have been involved at some stage.

2. To generate nephelinite–basanite series by small degrees of partial melting the source must be either chondritic or, more probably, light r.e.e. enriched (Sun & Hanson 1975*b*; Frey *et al.* 1978).

3. Multi-stage partial melting processes have been involved in producing at least some of the very light r.e.e. depleted N-type and T-type m.o.r.b., e.g. some picritic basalts from Iceland (Wood 1979).

4. The 15–30% partial melting suggested by experimental evidence and major element variations to produce m.o.r.b. from a peridotite source (Green & Ringwood 1967) does not significantly fractionate the light and heavy r.e.e. Thus the r.e.e. ratios observed in m.o.r.b. reflect pre-existing inhomogeneities in their upper mantle sources if such degrees of melting have been involved.

5. A light r.e.e. depleted mantle veined with light r.e.e. material derived through very small degrees of partial melting of garnet lherzolite (or perhaps introduced as metasomatic fluids) could adequately explain the range of r.e.e. distributions observed in m.o.r.b. (Tarney *et al.* 1979).

It is clear from figure 2 that if data for only a limited number of elements is considered, then several of the processes discussed above could explain the observed geochemical variations in m.o.r.b., for example, eclogite fractionation of an N-type m.o.r.b. primary magma or dynamic melting of a chondritic garnet lherzolite. However, when data for other hyg. elements and radiogenic isotopes are considered, many of these models become untenable. Thus below we shall summarize the observed variations in more-hyg. element abundances and ratios in North Atlantic basalts and discuss their implications for mantle processes and mantle evolution.

Hygromagmatophile element variations in North Atlantic basalts

Several recent papers have discussed the patterns of hyg. element (Cs, Rb, K, Th, U, Ta, Nb, Ba, Sr, Hf, Zr, P, Ti, Y and the r.e.e.) variation in North Atlantic drilled basalts (see, for example, Tarney *et al.* 1978, 1979; Wood *et al.* 1978, 1979*a*, *b*; Cann *et al.* 1978; Joron & Treuil 1977; Joron *et al.* 1978; Bougault *et al.* 1979; Bougault *et al.*, this symposium). The main features can, however, be illustrated and summarized by means of a few diagrams (figures 3–5; see also Bougault *et al.*, this symposium).

Figure 3 shows plots of Th against Hf and Nb against Zr for drilled basalts recovered from several latitudes of the M.A.R. It is apparent that different, but consistent, ratios of these element pairs characterize basalts from different regional segments of the ridge. Thus ratios in basalts at 63° N (Reykjanes Ridge), and also on Iceland, differ from those at 45° N and 36° N (Famous area) and again from those in N-type basalts at 22° N. Moreover, these characteristic element ratios are maintained in basalts erupted over periods of at least 15 Ma at 36° N, 36 Ma at 63° N and 110 Ma at 22° N (Tarney *et al.* 1979; Wood *et al.* 1979*a*). Many other more-hyg. element pairs could be chosen to illustrate the same feature; in each case the ratios remain consistent in basalts erupted at a particular ridge segment for long periods of time.

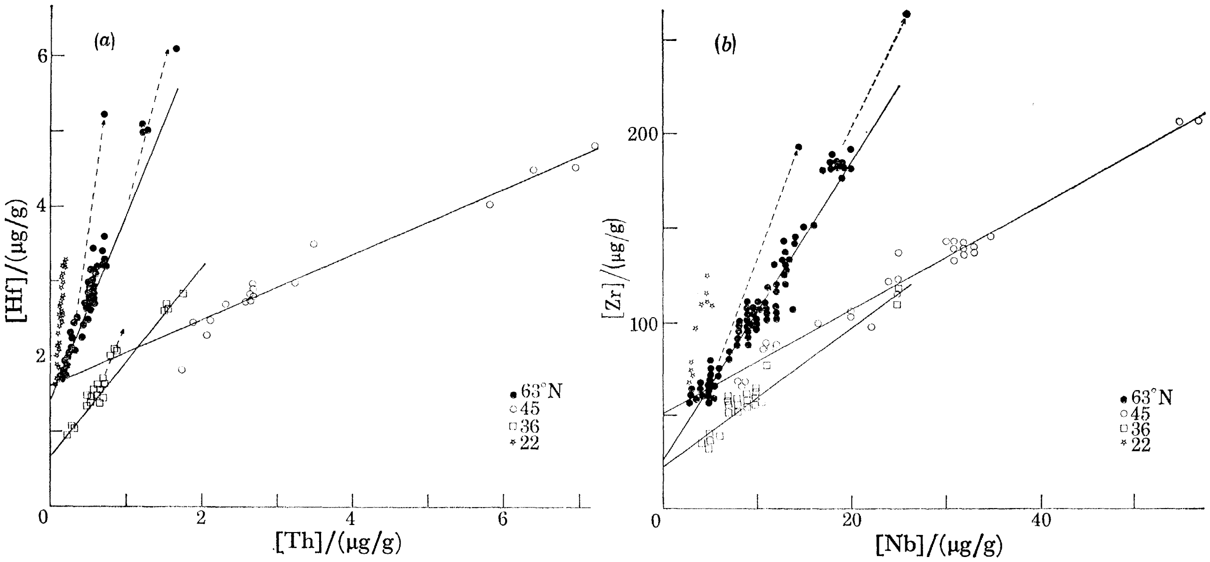

FIGURE 3. Hf–Th and Zr–Nb diagrams for drilled basalts from latitudes 63° N, 45° N, 36° N and 22° N along the M.A.R. Broken lines represent crystal fractionation vectors.

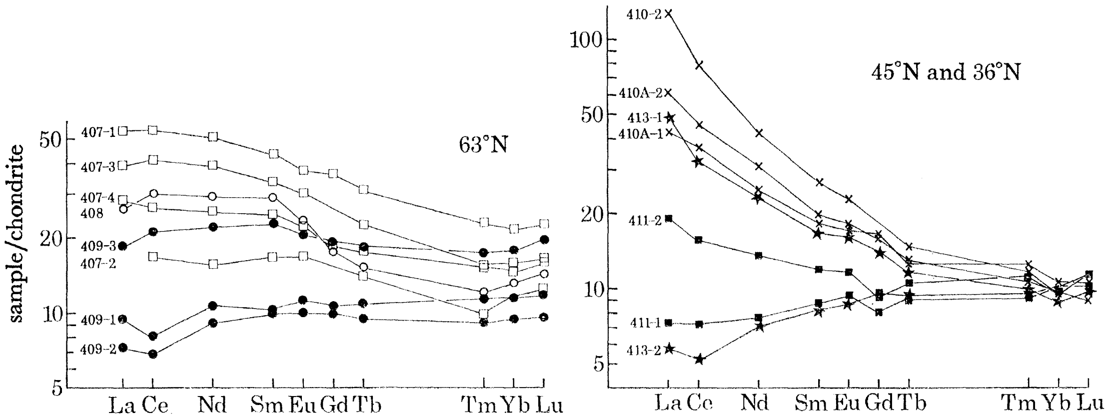

FIGURE 4. Chondrite-normalized r.e.e. patterns for basalts from 63° N, (Sites 407, 408 and 409), 45° N (Site 410) and 36° N (Sites 411 and 413) along the M.A.R.

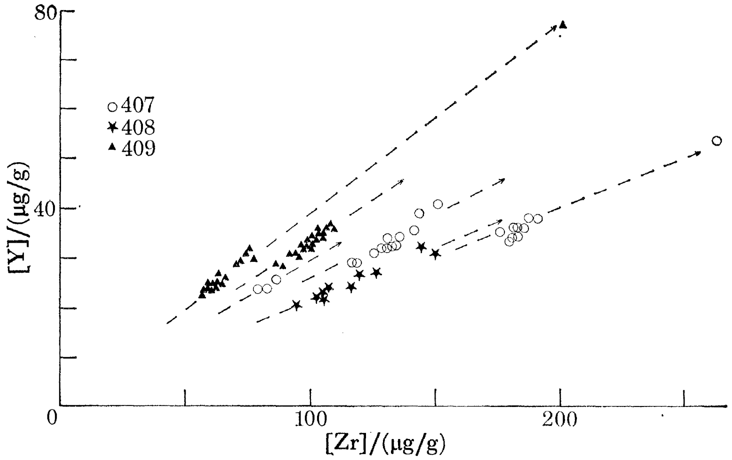

FIGURE 5. Y plotted against Zr for basalts drilled at D.S.D.P. sites 407, 408 and 409 at 63° N (Reykjanes Ridge). Broken lines represent crystal fractionation vectors.

Regional differences are also seen in the *shapes* of the chondrite normalized r.e.e. patterns (figure 4). Those from 36° N and 45° N tend to be concave upwards, with high La/Ce ratios (see also Langmuir *et al.* 1977) and limited variation in heavy r.e.e.; however, those from 63° N are convex upwards with lower La/Ce ratios. Similar patterns occur in Icelandic basalts (O'Nions *et al.* 1976) and in basalts from several drilled sites to the north of Iceland (Schilling 1975). Although modified, the differences are still apparent, irrespective of whether the patterns are light r.e.e. enriched or light r.e.e. depleted.

Several conclusions may be drawn from these data.

1. Inter-regional differences in hyg. element ratios are maintained over a wide range of trace element concentrations. Although the fractionating processes associated with basalt generation may have contributed to the range of hyg. element abundances, they have clearly not significantly modified the *ratios* of the more-hyg. elements, which must therefore be characteristic of the mantle source.

2. Because consistent ratios are observed in space and time within a particular region, it implies that the volumes of mantle with these characteristic hyg. element ratios must be large.

3. The mantle source heterogeneities observed in the North Atlantic as a whole cannot be reconciled with *two*-component mantle source mixing models. There are at least three distinct sources.

Biaxial element plots that include a less-hyg. element such as Y (or heavy r.e.e.) on one axis, for example Zr against Y (figure 5), show much larger variations in ratio for basalts erupted at each latitudinal ridge segment than plots which involve only more-hyg. elements. Clearly the variations in these plots include those produced by magmatic processes as well as those resulting from mantle source heterogeneities, since Y and the heavy r.e.e. have the highest D values among the hyg. elements. Magmatic processes may also have contributed to the dispersion exhibited by the Nb versus Zr plot (figure 3*b*), but this has not obscured the marked regional differences in Zr/Nb ratio.

Biaxial plots of hyg. elements with closely similar chemical properties produce an array of points for each region with zero intercept. However, where there is a small but significant difference in the chemical properties of the two elements the correlation line intercepts the axis of the less-hyg. element (e.g. figure 3), at least for basalts from anomalous ridge segments. In figure 3*b*, for instance, Zr/Nb ratios increase slowly but systematically for each region with decreasing concentrations of the two elements. It is possible to interpret this feature in terms of a variably veined mantle having two components: a depleted host having low Nb and Zr contents and high Zr/Nb ratios similar to N-type m.o.r.b., and a vein component having high Nb and Zr contents and low Zr/Nb ratios (Tarney *et al.* 1979).

M.A.R. basalts show a rather restricted range of less-hyg. element (e.g. Y and the heavy r.e.e.) concentrations, which suggests that the different mantle sources are relatively homogeneous in these elements, but markedly heterogeneous in their more-hyg. element concentrations. This observation together with the approximately chondritic values of ratios of hyg. elements with similar ionic character, for example Nb/Ta, Hf/Zr and Y/Tb (Joron *et al.* 1978; Bougault *et al.*, this symposium), indicates that the heterogeneous mantle sources have ultimately been derived from a homogeneous chondritic precursor mantle (referred to here as the primordial mantle).

We believe that hyg. element relations in North Atlantic basalts may provide important constraints on the processes which have produced chemical heterogeneities in the Earth's mantle. It is therefore necessary to consider the hyg. element geochemistry of basalts in more detail.

The hyg. element composition of the primordial mantle

Ringwood (1966) and Ganapathy & Anders (1974) have shown that the relative abundances of refractory elements in the Earth are similar to those of carbonaceous chondrites. Most of these element ratios are also close to chondritic in E-type m.o.r.b. (Wood *et al.* 1979*b*). The moderately volatile hyg. elements (Cs, Rb, K and P) have been depleted in the Earth relative to the refractory elements (Gast 1960). Sun & Nesbitt (1976) have calculated values for those elements in the Archaean upper mantle using data from Archaean basalts and komatiites. Thus reasonable estimates can be made for the abundances of the hyg. elements in the primordial mantle relative to each other.

Plots of the hyg.-element abundances of the various m.o.r.b. types normalized to estimated primordial mantle values, with the elements arranged in order of increasing D (Sun *et al.* 1979; Wood *et al.* 1979*a*) help to illustrate the interrelations of these elements (figure 6). We use chondritic values for the refractory elements (Nb value based on a Zr/Nb ratio of 16 in chondrites (Graham & Mason 1972); Hf based on Zr/Hf of 31.3 (Ganapathy *et al.* 1976)) and values for Cs, Rb, K and P from Sun *et al.* (1979). The order of elements (their relative D values) has been established from the enrichment factors between the different m.o.r.b. types. However, it must be borne in mind that if minor mineral phases such as phlogopite, ilmenite and apatite remain refractory during small degrees or different conditions of partial melting, certain elements (e.g. K, Ti, P) may depart from this order.

Variations of the more-hyg. elements in m.o.r.b.

In figure 6*a* we have plotted an 'average' N-type m.o.r.b. composition (Sun *et al.* 1979; Wood *et al.* 1979*b*) together with undersaturated basalts of E-type m.o.r.b. and continental series. N-type m.o.r.b. shows a progressive decrease in the relative abundance of the more-hyg. elements from Ce to Cs. In contrast, the undersaturated basalts show a general progressive increase from Y to Ta with higher La/Ce and Ta/La ratios relative to the primordial mantle (Hanson 1977, figure 6; Wood *et al.* 1979*b*), followed by a decrease to Rb and especially Cs. The absolute abundances of the more-hyg. elements (Ce–Cs) in the undersaturated basalts are, however, nearly an order of magnitude higher than in average N-type m.o.r.b. The two components of the E-type m.o.r.b. pattern on this diagram (i.e. the increase between Y and Ta and the relative decrease between Ta and Cs) are unlikely to have been produced by a single-stage process. The relative decrease between Ta and Cs may record an earlier depletion event corresponding perhaps to that indicated by the Nd isotope compositions of these basalts (O'Nions *et al.* 1978), whereas the increase between Y and Ta corresponds to the light r.e.e. enriched nature of the sources of undersaturated basalts (Frey *et al.* 1978). The negative K, Ti, Zr, Hf, Ba and Rb anomalies in the olivine melilitite could perhaps be attributed to minor mantle phases such as phlogopite, ilmenite and zircon remaining refractory during the small degrees of partial melting involved in its genesis.

The two samples from 63° N and 25° N (figure 6*a*) together with four samples from 45° N, 36° N, Iceland and the Iceland–Faroes Ridge (figure 6*b*) represent the range of m.o.r.b. erupted at the M.A.R. (The significance of the remaining pattern for the Japanese island arc tholeiite will be discussed later.) Clearly many of the basalts erupted at the M.A.R. (other than those from 22–25° N) have very different hyg. element patterns from average N-type m.o.r.b. The most hyg.-enriched sample is a mugearite from Site 410 at 45° N. The sample from 36° N (Site 413) is, however, a very primitive basalt (Mg/(Mg + Fe) = 0.69) but its hyg. element pattern is similar to the 45° N basalt. Both patterns show the same features as the alkali basalt patterns, i.e. a progressive increase between Y and Ta and a relative decrease between Ta and Cs. Thus Ta (and Nb) appear anomalously enriched relative to N-type m.o.r.b. or primordial mantle values, and Ta/La ratios are high. Other basalts recovered from 45° N and 36° N, although having lower hyg. element abundances than the two examples given, also have distinctive high Ta/La ratios. Basalts from 63° N (Reykjanes Ridge) and Iceland similarly have high Ta/La ratios. Even light r.e.e. depleted basalts such as that shown from Site 409, 63° N (figure 6*a*) have notably higher Ta/La and Nb/La ratios than N-type m.o.r.b. We conclude that, irrespective of the degree of light r.e.e. enrichment or depletion in the erupted basalts, the mantle sources beneath Iceland, 45° N and 36° N are significantly different from the N-type m.o.r.b. source. Basalts similar to, or even more depleted than, N-type m.o.r.b. do however occur at 22–25° N segment of the M.A.R. (figure 6*a*) and to the north of Iceland (figure 6*b*).

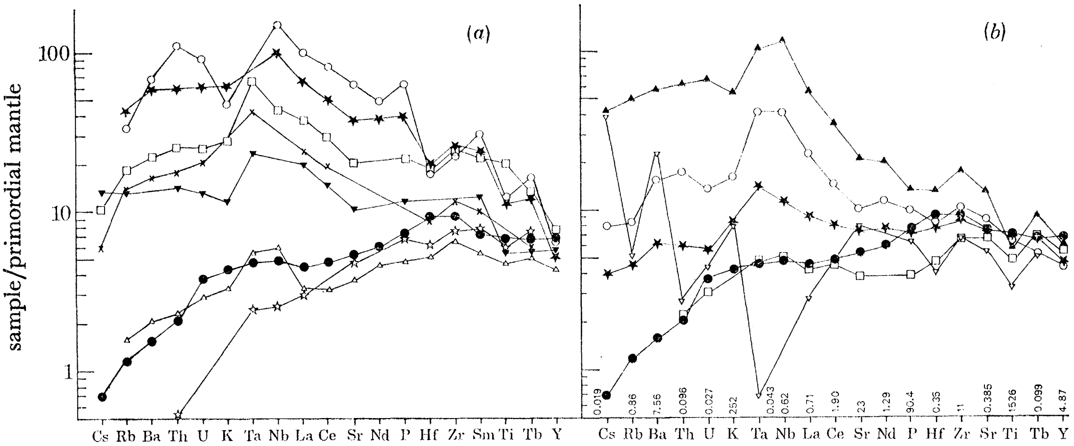

Figure 6. Hyg. element abundances in selected basic lavas normalized to a primordial mantle composition (micrograms per gram) which is given along the abscissa in (*b*). (*a*) Open circles are melilitite 2927 and closed stars are basanite 2679, both from southeastern Australia (Frey *et al.* 1978); open squares, crosses and inverted closed triangles are alkali basalts ISL79, T-2 and Ch50 from Eldgjá (Iceland), Terceira (Azores) and Erta Ale (Afar; Treuil & Joron 1975), respectively; open triangles and stars are representative m.o.r.b. from 63° N and 25° N in the North Atlantic ocean, respectively (Wood *et al.* 1979*a*; Joron *et al.* 1978); closed circles are average N-type m.o.r.b. (*b*) Closed triangles and open circles are E-type m.o.r.b. from 45° N and 36° N M.A.R. respectively; closed stars are tholeiite ISL28 from Askja (Iceland); open squares are N-type m.o.r.b. from the Iceland–Faeroes ridge (Wood *et al.* 1979*b*). Open inverted triangles are island arc tholeiite from Oshima, Japan (Joron & Treuil 1977).

Hyg. element abundance in the N-type m.o.r.b. mantle source

To obtain an estimate for the elemental abundances in the N-type m.o.r.b. mantle source, we assumed that the average N-type m.o.r.b. pattern (figure 6) was generated by 10% batch partial melting (a minimum value) and used *D* values of 0.0003, 0.006, 0.016 and 0.03 for Rb, Ce, Sm and Y respectively for a three-phase (ol.–opx.–cpx.) mantle. We used the batch melting equation to calculate enrichment factors for these elements and thus probably obtained minimum values (because of the small degree of partial melting used) for the source. We then extrapolated the source abundances of the other elements. The calculated abundances are given in table 2 and plotted in figures 2(S_3) and 7. For comparison the calculated abundances of these elements in an E-type m.o.r.b. source from Askja, Iceland (Wood *et al.* 1979*b*) have been included in table 2 and plotted in figure 7. Hanson (1977) has already pointed out that to generate the depleted N-type m.o.r.b. mantle source by a previous melting event of a chondritic, primordial source, only very small degrees of partial melting could have been involved. For high degrees of melting the residue becomes rapidly depleted in the hyg. elements relative to the N-type m.o.r.b. source. Hence if previous extraction of basalt has been involved in generating the present N-type m.o.r.b. mantle source, the residue of this event must have been remixed with less depleted material or the extracted basalts themselves recycled into the mantle.

TABLE 2. CALCULATED HYG. ELEMENT COMPOSITION (micrograms per gram) OF THE MANTLE SOURCES OF AVERAGE N-TYPE M.O.R.B. AND AN E-TYPE M.O.R.B. FROM ICELAND

(See text for the basis and an explanation of the calculations.)

	N-type	E-type		N-type	E-type
Cs	0.0013	0.007	Ce	0.95	1.68
Rb	0.1	0.39	Sr	13.2	17.9
Ba	1.2	4.77	Nd	0.86	1.11
Th	0.02	0.06	P	73.3	61.6
U	0.01	0.015	Hf	0.34	0.26
K	106	216	Zr	11.4	11.3
Ta	0.022	0.062	Sm	0.32	0.42
Nb	0.31	0.72	Ti	1177	1044
La	0.31	0.66	Tb	0.08	0.08
K/Ba	88	45	Y	4.1	2.7
K/Rb	1060	554	Ti/Zr	103	92
La/Th	15	11	Rb/Sr	0.008	0.022
La/Ta	14	11	Zr/Y	2.8	4.2
Th/U	2	4	Zr/Nb	37	15.7

DISCUSSION: NATURE AND CAUSES OF MANTLE HETEROGENEITY IN THE NORTH ATLANTIC

The results from the North Atlantic demonstrate that the processes of basalt generation, while capable of producing considerable fractionation among the r.e.e., do not appreciably modify ratios of the more-hyg. elements in the erupted basalts. Hence consistent hyg. element ratios are observed over a wide range of trace element concentrations. What then causes the ratios to vary on an inter-regional scale? Because trace element patterns are regionally consistent and also temporally persistent in basalts erupted at the same ridge segment, one suspects that the volumes of mantle with this characteristic geochemical imprint are large. Logically, then, the processes fractionating the hyg. elements must be major ones capable of affecting large volumes of mantle. Moreover, they must be processes, or a culmination of processes, that are equivalent to a very small degree of partial melting so that trace elements with closely similar chemical properties can be separated. Of course they must also be processes compatible with all geochemical and isotopic data, and feasible tectonically. We envisage two potential processes capable of explaining the observed trace element patterns: *incipient mantle melting* and *crustal extraction*. Below we consider these processes in some detail and attempt to assess their implications for the geochemical nature and evolution of the upper mantle. A third alternative, that heterogeneities have survived from primary Earth accretion, cannot be entirely discounted, though we feel that it is unlikely in view of: (1) Nd isotopic evidence that the mantle was broadly chondritic with respect to r.e.e. during the Archaean (DePaolo & Wasserburg 1976; Hamilton *et al.* 1979); (2) the relatively constant Y and heavy r.e.e. abundances in primitive M.A.R. basalts; (3) the approximately chondritic ratios of Nb/Ta, Hf/Zr and Y/Tb (Bougault *et al.*, this symposium).

INCIPIENT MANTLE MELTING

The Earth's mantle strives to attain thermal and density equilibrium; modern plate motions attest to the fact that this has yet to be achieved. Gross disequilibria are overcome by convection, with the resultant adiabatic decompression giving rise to moderately high degrees of melting at ocean ridges. Minor thermal (e.g. radiogenic) anomalies or minor tectonic perturbations in a convecting mantle would instead cause temperatures to rise much more slowly towards the mantle solidus. The buffering effect of the latent heat of fusion would moreover prevent temperatures rising much above the mantle solidus, at least on a reasonable time scale, hence the degree of melting would be low. Such *in situ* melts would be enriched in the more incompatible trace elements, but their removal would not seriously deplete the host mantle in basaltic *major elements*. Minor mineral phases might exert a greater control on the trace element concentrations in the melt than is normally possible at higher degrees of mantle melting; there is thus the potential for significant fractionation of elements having low D values. The entry of fluids (CO_2, Cl, F, H_2O, etc.) can also potentially give rise to incipient melting of mantle at its vapour-saturated solidus temperature (Bailey 1970). Incipient melts would be rich in volatiles such as CO_2 and halogens. Their composition might approximate to kimberlitic magmas, invariably highly enriched in Ta, Nb, La, Ce, Rb, Cs, Th and similar hyg. elements, and which are often associated with carbonatites (Bailey 1974).

Removal of such melts would leave a 'depleted' though still fertile mantle residue with a trace element composition similar to the source for N-type m.o.r.b. Upward migration of melts, perhaps with additional zone refining, would continue until the point at which the temperature of the host mantle was significantly below its solidus. Consideration of the entropy changes involved indicate that whereas it is possible to deplete deeper mantle fairly uniformly by melt removal, it is not so easy to disseminate and homogenize such melts in higher level mantle. It is more likely that, in the manner of a continental migmatite terrain, the mantle would be *variably* veined or metasomatised (cf. Lloyd & Bailey 1975). There is now ample evidence of this in upper mantle nodules from kimberlite pipes (see Gurney & Harte, this symposium).

This simple process provides considerable geochemical flexibility in interpreting basalt chemistry. First, there are two components – host and vein – which may have had very different histories. The host may be undepleted or depleted geochemically relative to the primordial mantle; likewise the veins may have been derived from undepleted mantle or from mantle which had suffered some depletion or enrichment in previous melting events. Secondly, given that the ratio of veins to host mantle can vary widely in a particular region, this could give rise to considerable chemical and isotopic diversity in basalts generated during any subsequent melting event. Nevertheless, these variations would be systematic because the more fusible veins would always contribute to the melt. For instance, if the thermal energy for melting is ridge diapirism, and the degree of melting is constrained near a particular value (say 15 %) by the spreading rate and latent heat of fusion, then trace element abundances in the melt will be controlled by those in the veins and will vary directly with the proportion of veins, although the major element composition may be more dependent on the host. This can be illustrated by a simple model of a m.o.r.b.-type source variably veined with material of alkali basalt composition.

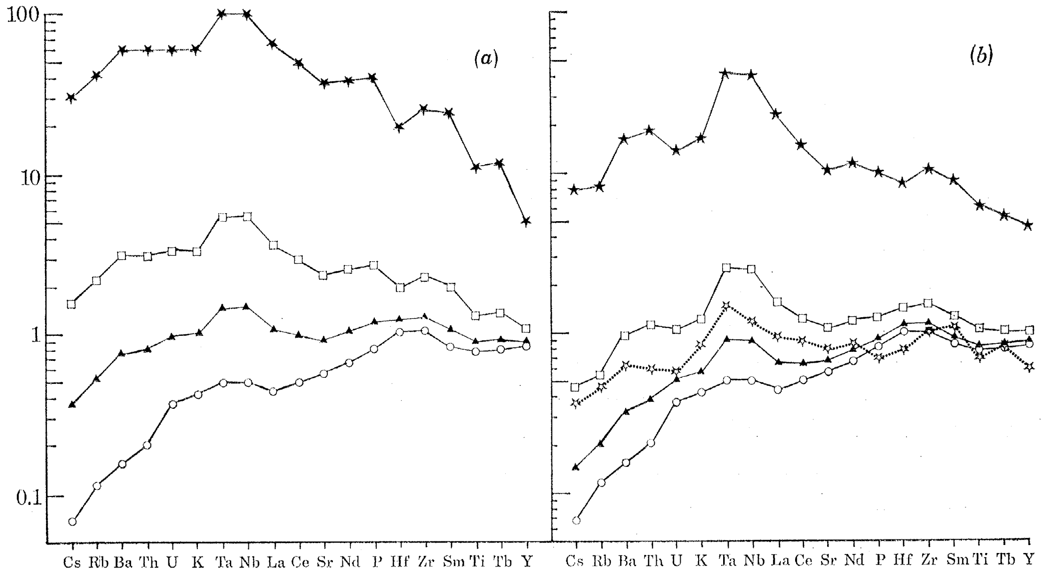

FIGURE 7. Bulk hyg. element composition of N-type m.o.r.b. mantle source (open circles) veined with an undersaturated basic magma (closed stars). Closed triangles and open squares represent the bulk sources with 1 % and 5 % veins respectively. In (*a*), basanite 2679 from southeastern Australia (Frey, Green & Roy 1978) has been used as the vein composition, whereas in (*b*) alkalic basalt 413, 1–2, 110–113 cm from M.A.R. 36° N has been used. The calculated E-type m.o.r.b. source for an Icelandic basalt given in table 2 has been plotted (open stars) in (*b*) for comparison.

We have already shown how veining a mantle with a liquid produced by small degrees of partial melting can produce mantle sources with a wide range of r.e.e. compositions (figure 2). In figure 7*a*, *b* we have extended these models to include a greater range of hyg. elements. In figure 7*a* we have used the calculated N-type m.o.r.b. mantle source as host, and a basanite (sample 2679; Frey *et al.* 1978) as the liquid and then calculated the bulk composition. Even with only 1 % liquid veins the ratios of the more-hyg. elements in the bulk source are intermediate between those of the two end members. The bulk source with 5 % veins is light r.e.e. enriched and similar to the preferred source composition for the basanite (Frey *et al.* 1978, figure 5). Assuming that the N-type m.o.r.b. source had an ^{87}Sr/^{86}Sr ratio of 0.7023 and the basanite liquid a ratio of 0.705 (i.e. bulk Earth value; O'Nions *et al.* 1978) we have calculated the ^{87}Sr/^{86}Sr ratios to be 0.70295 and 0.70355 for the 1 % and 5 % veined sources, respectively. These values are remarkably similar to those observed in E-type m.o.r.b. Figure 7*b* shows a similar model with the use of the alkalic basalt sample 413, 1–2, 110–120 cm (from 36° N) as the liquid. The bulk source with 5 % veins in this model has an r.e.e. pattern very similar to that calculated by Langmuir *et al.* (1977) for the mantle source of m.o.r.b. in the FAMOUS area. These veined sources have the two component characteristics observed in E-type m.o.r.b., i.e.

high La/Ce, low Rb/Sr and higher ^{143}Nd/^{144}Nd ratios than expected from their present day Sm/Nd ratios.

Continental growth and crustal extraction

That the continental crust has grown through time is now convincingly established through isotopic studies (Moorbath 1978; McCulloch & Wasserburg 1978; Hamilton *et al.* 1979). Extraction of crust (by a two-stage or three-stage process) from the mantle system and the whole crust–mantle interrelation has potentially important consequences for the geochemical and isotopic nature of the upper mantle. Of immediate interest is that extraction of crustal material represents, through the integration of these processes, a very small degree of mantle melting. The most significant step in the fractionation of trace elements takes place in subduction zones. Subduction zone magmas, from the most primitive island arc tholeiites to the most enriched high-K calc-alkaline lavas and plutons, have very different ratios of some trace element pairs compared with non-orogenic basalts. In particular, large ion lithophile (l.i.l.) elements (K, Rb, Cs, U, Th, Ba) are enriched relative to rare earth elements and especially with respect to high field strength (h.f.s.) elements (Ta, Nb, Zr, Hf, Ti, P). This feature has been considered by Saunders *et al.* (1980) and Wood *et al.* (1979*b*), and probably results from two factors: (*a*) during subduction, fluids released by dehydration of the oceanic crust transport l.i.l. elements into the zone of melting, and (*b*) minor phases such as ilmenite, rutile, zircon and apatite have enhanced stability in subduction zones and retain h.f.s. elements, or that mineral–melt partition coefficients for h.f.s. elements are significantly higher during hydrous melting. Whatever the reason, ratios between some of the most hygromagmatophile l.i.l. elements (K, Rb, Ba, U, Th) and h.f.s. elements (Nb & Ta) are very high in the continental material extracted and, by implication, very low in the residual material returning for possible recycling in the mantle system. These hyg. element fractionations are evident in the island arc tholeiite plotted in figure 6.

Crustal extraction may be a potential mechanism for changing trace element ratios in recycled mantle material, but the present location of this material is uncertain. For instance, since the abundance of Nb and Ta in crustal material is not very high (relative to other hyg. elements), it follows that the abundance of these two elements in the material returning to the mantle is reduced only slightly. The fact that the source for typical depleted m.o.r.b. has very low abundances of Nb and Ta compared with the sources for E-type m.o.r.b. suggests that recycled material need not contribute significantly to the depleted m.o.r.b. source. (On the other hand it is still feasible that the l.i.l. component of hyg. element enriched material extracted from the depleted m.o.r.b. source by incipient melting can ultimately be removed from the upper mantle during the processes of crustal generation. This would leave a Ta and Nb rich residue in the upper mantle.) Further consideration of the implications of subduction-related processes is necessary to evaluate and at least qualitatively balance the geochemical equations.

Oxburgh & Parmentier (1978) have argued that the depleted refractory harzburgitic lithosphere in the subducting slab is intrinsically less dense than undepleted ('pyrolite') mantle and that, once temperatures of the slab and surrounding mantle are equalized at depth, the refractory lithosphere is actually buoyant enough to rise diapirically. They suggest that this rising material may actually accrete to the subcontinental lithosphere. Presumably any substantial build-up of light refractory material in the oceanic upper mantle would be limited by the opposing effects of convective recycling. Jordan (1978) also maintains, from seismic and heat-flow evidence, that the sub-continental lithosphere is composed of lighter refractory mantle depleted in basaltic constituents, and that this subcontinental tectosphere may vary from less than 100 km thick in young unstable areas to as much as 400 km thick beneath the older cratons. Such a thick, light, subcontinental tectosphere contributes to the stability of continents. The model does, however, apparently conflict with the fact that the majority of basalts erupted on continents have 'enriched' rather than 'depleted' geochemical characteristics. How then can this paradox be resolved?

We suggest that the subcontinental tectosphere is a receptor for the enriched fluids or liquids produced by incipient melting at greater depths. Thus the subcontinental upper mantle may be composed of two contrasted components, a 'depleted' refractory host and more fusible 'enriched' veins of a basic undersaturated composition, but the proportion of veins is too small to affect the geophysical properties of the sub-continental tectosphere. Mild thermal events would be able to mobilize the vein material but not the refractory host. This could explain why mantle nodules appear almost exclusively in erupted alkali basalts. At the higher degrees of melting (resulting from adiabatic decompression or diapirism) necessary to produce tholeiitic magmas, the host would be less refractory and contribute to the melt, thus promoting differing physical conditions of melt segregation which would be unlikely to favour preservation of nodules.

The question then arises as to whether the concept of a veined subcontinental tectosphere has any relevance to the sub-oceanic North Atlantic mantle. Bearing in mind the high proportion of transitional and enriched basalts in the region, it is worth stressing that the mantle source regions were indeed subcontinental before the opening of the Atlantic. One might even speculate that because several earlier orogenic belts (Grenville, Caledonian, Hercynian) ran transverse to the present Atlantic, this might account for some of the variability in the mantle source regions along the present M.A.R. However, there is no reason to believe that veining cannot take place in the sub-oceanic upper mantle (Lloyd & Bailey 1975); it is merely that the subcontinental tectosphere provides a better long-term receptor (as exemplified by the generally more radiogenic character of continental basalts). Melting processes are, however, different at a spreading ridge than in a sub-continental environment in that the main cause of melting is adiabatic decompression resulting from mantle diapirism. A consequence is that the degree of melting is higher, and hence both veins and host mantle contribute to the melt. Because of the buffering effect of the latent heat of fusion, the degree of melting should not vary significantly as the proportion of veins changes; however, the trace element content of the generated liquids will, as we have shown, vary with the proportion of veins.

It is apparent from our own data, and from the data of White & Schilling (1978) that both the geochemical and isotopic dispersions in erupted basalts are much higher in regions near Iceland and the Azores (or 45° N) than in normal m.o.r.b. areas such as 22° N or at the East Pacific Rise. Thus on Iceland and in the FAMOUS area, basalts with l.r.e.e. *depleted* patterns quite commonly occur with basalts having l.r.e.e. *enriched* patterns. Rather than attributing this to some sort of oscillating influence of an enriched plume source with a depleted source, Langmuir *et al.* (1977) and Wood (1979*a*) have accounted for this feature by dynamic continuous melting processes. Continuous melting of a veined mantle could also reproduce these geochemical features. However, it is also apparent that a variably veined mantle could duplicate this feature without the need for continuous melting if the variability in veining was on a scale comparable with that of the volume of mantle involved in a single melting event. If so, some small isotopic differences between associated depleted and enriched erupted basalts might be expected. With a veined mantle model, the geochemical differences between enriched ocean island basalt sources and transitional basalt ridge sources might to a large extent be thermally dependent. Thus the E-type m.o.r.b. erupted in the Iceland, Azores and 45° N regions could be regarded as ocean island sources being sampled at the ridge axis by relatively high degrees of melting. Away from the axis, with much less thermal energy available for melting, the enriched veins would supply most of the liquid and the erupted products would have alkali basalt characteristics.

Isotopic considerations

Any mantle model must be consistent with Sr, Nd and Pb isotopic data on erupted basalts. The plume model invokes a deeper, enriched and more radiogenic 'ocean island' source mixing with a higher level depleted and less radiogenic m.o.r.b. source. Langmuir *et al.* (1977) have argued, however, that isotopic and other geochemical data on Iceland–Reykjanes Ridge basalts are difficult to reconcile with simple mixing of two contrasted components, an argument supported by our own data (figure 3). A further difficulty is that whereas there is a reasonably good correlation between Sr and Nd isotope ratios among oceanic basalts (O'Nions *et al.* 1977), Pb isotope data correlate less well (Sun & Hanson 1975*a*; Sun, this symposium). In particular, Pb isotope compositions of ocean island basalts are considerably more variable than those for m.o.r.b., which presents difficulties in regarding ocean island sources as representative of pristine undepleted mantle. Indeed, as emphasized by Sun (this symposium), all ocean island sources appear to have had their U/Pb ratios increased (by either Pb removal in a sulphide phase, or by U addition) at some earlier stage in their history since they yield future ages on a single stage growth model. Alternatively, ocean island source regions may have been contaminated to a variable degree by more radiogenic lead; but if so, the source regions for m.o.r.b. appear to be much less contaminated since Pb isotope ratios of m.o.r.b. lie closer to the zero age isochron.

A veined mantle model provides rather more flexibility in interpreting isotopic data. The observed isotopic ratios in basalts derived from a veined mantle will depend upon (*a*) the initial isotopic ratios of the host and in the source of the vein material, (*b*) the parent–daughter ratios in the vein and host and the time-lapse since the veining event, (*c*) the proportion of veins and the degree of isotopic homogenization between vein and host, and (*d*) the degree of partial melting. The host mantle would have Sr and Nd isotopic ratios similar to m.o.r.b., or if more refractory, perhaps even less radiogenic than m.o.r.b. The veins, if derived from an undepleted or slightly depleted source would have isotopic ratios equal to or less radiogenic than bulk Earth. However, assuming some isotopic equilibrium, unless there was significant time lapse between veining and magma generation, erupted basalts would have Sr and Nd isotopic ratios still less-radiogenic and more-radiogenic respectively than bulk Earth values. This appears to comply with the available Sr and Nd isotopic evidence that the source regions of most oceanic basalts have suffered time integrated depletion in Rb/Sr and Nd/Sm (O'Nions *et al.* 1977; DePaolo & Wasserburg 1976). Moreover, because of the dominance of the vein component during melting, Rb/Sr and Nd/Sm ratios would be much higher than those needed to support their observed Sr and Nd isotopic ratios – a feature noted by O'Nions *et al.* (1978), but one more difficult to account for by melting of a homogenous source. The reverse is of course true with depleted m.o.r.b. (i.e. their Rb/Sr ratios are too low to support their ^{87}Sr/^{86}Sr ratios), which would be compatible with the N-type m.o.r.b. source being considered the residue from which incipient melts had been extracted.

An increase in the proportion of veins in the mantle source at a constant degree of melting (assuming more radiogenic vein material or a significant time lapse since the veining event) would yield basalts with higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ ratios. At the same time more-hyg./less-hyg. element ratios would show a corresponding increase. Any resulting Rb/Sr–$^{87}Sr/^{86}Sr$ correlation might simulate a mantle isochron, but need not necessarily have any time significance. Ratios between pairs of more-hyg. elements should not, however, change appreciably because their abundances are dominated by the veins, even if the proportion of veins is small. These are the features observed in basalts from any particular region of the North Atlantic.

Lead isotope relations can be accommodated by a veined mantle model to some extent if the vein material carries the Pb isotope characteristic of its initial source. Variable veining would give rise to a mixing trend between the ratios in the vein and that in the host (i.e. depleted m.o.r.b.), a pattern which can be recognized in most Pb isotope plots (Sun & Hanson 1975*a*; Sun, this symposium). However, this in itself does not provide a solution to the diverse Pb isotope ratios in ocean island basalt sources, with the implied necessity of keeping mantle sources separated for perhaps 2000 Ma. An alternative explanation, if the enriched ocean island source is relatively shallow (as we have implied) rather than deep (as implied by the plume model), is that the upper mantle may be contaminated by continental lead. The possibility of isotopic interchange between crust and mantle was recognized over a decade ago by Armstrong (1968), and has recently been considered for Sr and Nd isotopes by DePaolo & Wasserburg (1979). Molnar & Gray (1969) have suggested that subduction of minor amounts of continental crust is physically possible in some circumstances. More convincing is that recent deep sea drilling in the Mariana Trench has failed to confirm any accretionary wedge of scraped-off sea floor sediment, implying that such sediments may indeed be subducted in considerable amounts. If the suggestion of Oxburgh & Parmentier (1978), that the refractory depleted harzburgite in the subducted slab is intrinsically buoyant and may eventually rise diapirically to underplate the subcontinental lithosphere, is correct, then it is equally feasible that low-density subducted sediment may also be carried upwards into the upper mantle. This has important implications for the Pb isotopic composition of the upper mantle because the Pb concentration in abyssal clays is high (30–75 µg/g; Tatsumoto 1969; Tarney & Donnellan 1977) whereas the estimated Pb content of the upper mantle is very low (less than 2 µg/g). More important, because Pb resides in the clay fraction and its solubility in sea water is low, it directly reflects the Pb isotopic composition of the local continental sediment source. This is particularly relevant with regard to early Precambrian crustal rocks because significant migration of K, Rb, Cs, Th and especially U from the lower crust to the upper crust took place during the Precambrian (Tarney & Windley 1977) leaving the lower crust uranium-poor and now markedly non-radiogenic in Pb isotopes (Moorbath & Welke 1969) and by implication the upper crust U-rich and radiogenic. The latter, transported from the extensively eroded upper crust into the mantle as sediment, may have significantly changed the bulk Pb isotope composition of the upper mantle adjacent to (?Precambrian) subduction zones.

The effects of Sr and Nd contamination from sediment would be smaller and more uniform because (*a*) the Sr content of abyssal clays is lower, relative to mantle values, than Pb, and the isotopic composition of Sr is buffered by seawater Sr (relatively non-radiogenic during the Precambrian) and (*b*) the rare-earth characteristics of sediments change only slightly with time (Nance & Taylor 1976). By contrast, the isotopic composition of sedimentary Pb would strongly reflect the local provenance of the sediments. Thus, if some of the isotopic variation in mantle-derived basalts is indeed attributable to continent–mantle mixing, we suggest that this may explain the poor correlation of Pb isotopes with Sr and Nd isotopes. Because the volume of erupted alkali basalt is low in global terms, the amount of sediment contamination required is not excessive, particularly if the source regions of ocean island basalts are located in the upper mantle (less than 400 km).

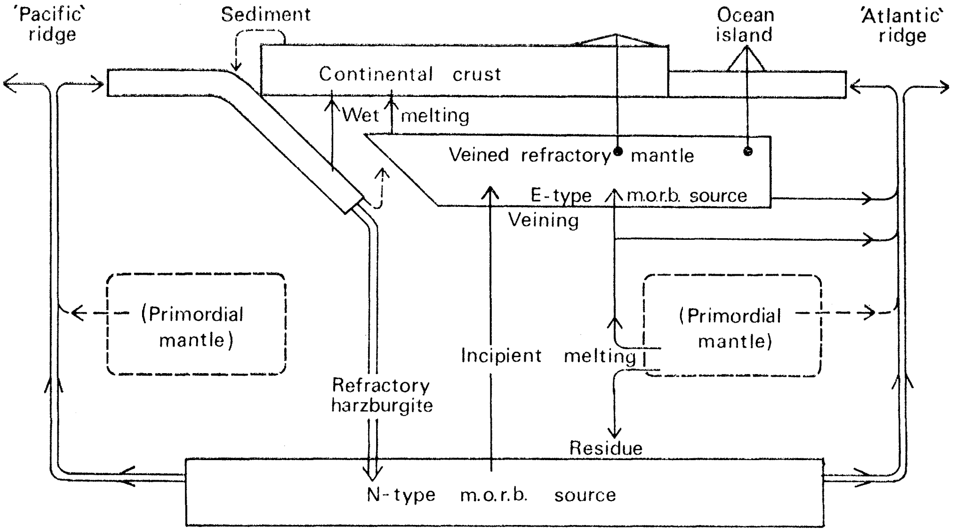

FIGURE 8. Conceptual diagram of mantle evolution illustrating the main paths for element transfer and the relations between different mantle sources. No absolute depth relations are implied. See text for details.

SUMMARY: A MODEL FOR MANTLE EVOLUTION

Our favoured model for the development of inhomogeneities in an evolving mantle, based largely on the hyg. element relations in oceanic basalts, would incorporate the following features (figure 8).

1. A primordial mantle which was homogeneous and included the constituents of the continental crust.

2. Two main processes have been responsible for element transfer:

(*a*) Incipient melting of the (initially) primordial mantle, producing hyg. element enriched undersaturated melts which migrate upwards and vein the upper mantle, and leaving a residue equivalent to the N-type m.o.r.b. mantle source. Hydrous partial melts extracted from this veined mantle source contribute to crustal growth. Thus the continental crust complements, to a first approximation, the hyg. element depletion in N-type m.o.r.b. relative to the primordial mantle.

(*b*) Basalt generation at oceanic spreading centres, followed by partial melting and dehydration of oceanic crust in subduction zones to form continental crust (i.e. the Ringwood cycle).

The high p_{O_2} and p_{H_2O} under which sialic crustal material is generated leads to fractionation of the h.f.s. elements (especially Ta and Nb) relative to the l.i.l. elements. The crustal material generated in these processes is depleted in h.f.s. elements. The residues, which may be located in the upper mantle in (*a*) or recycled into the mantle or partly underplate continents in (*b*) are relatively enriched in h.f.s. elements. The refractory upper mantle residues of continental crust extraction therefore form an important sink for the h.f.s. elements. The involvement of a component of these residues in the veined mantle sources of alkali basalts may account for the relative enrichment of h.f.s. elements in many alkaline rocks.

3. Migration of incipient melts into the upper mantle through time provides a renewable enriched veined source for alkali basalts. This source may be continually dissipated by convective plate motions, by crustal extraction or basalt eruption, but may be preserved for a significant time in certain (e.g. sub-continental) tectonic environments, allowing more radiogenic isotope characteristics to develop. This source may have variable geochemical characteristics depending on the geochemical nature of the mantle component from which the incipient melts had been derived.

4. Higher degrees of melting of this variably veined mantle source during mid-ocean ridge diapirism provides an explanation for E-type and T-type m.o.r.b. Such basalts may be erupted when this veined source is being dissipated, as in the present North Atlantic.

5. Contamination of the uppermost mantle with earlier (Precambrian) subducted continental sediments may account for some of the Pb isotopic characteristics of 'ocean island' basalt sources. The radiogenic Pb complements the unradiogenic Pb of the lower continental crust. This source, as we have noted, is also enriched in Ta and Nb as a result of subduction processes.

6. The primordial mantle composition could be reconstituted by compounding (*a*) the N-type m.o.r.b. source, (*b*) the continental crust, (*c*) an upper mantle 'ocean island' source and (*d*) refractory harzburgite.

These studies are supported by the Natural Environment Research Council. D.A.W. and A.D.S. gratefully acknowledge N.E.R.C. postdoctoral fellowships.

REFERENCES (Tarney *et al.*)

Armstrong, R. L. 1968 *Rev. Geophys.* **6**, 175.

Arth, J. G. & Hanson, G. N. 1975 *Geochim. cosmochim. Acta* **39**, 325.

Bailey, D. K. 1970 *Geol. J. spec. Issue*, no. 2, pp. 177–186.

Bailey, D. K. 1974 In *The alkaline rocks* (ed. H. Sorensen), pp. 53–66. London: Wiley.

Blanchard, D. P., Rhodes, J. M., Dungan, M. A., Rodgers, K. V., Donaldson, C. H., Brannon, J. C., Jacobs, J. W. & Gibson, E. K. 1976 *J. geophys. Res.* **81**, 4231–4246.

Bougault, H., Cambon, P., Corre, O., Joron, J. L. & Treuil, H. 1979 *Tectonophysics* **55**, 11–34.

Cann, J. R., Tarney, J., Varet, J. & Wood, D. A. 1978 In *Initial reports of the Deep Sea Drilling Project*, vol. 49, pp. 841–850. Washington, D.C.: U.S. Government Printing Office.

Consolmagno, G. & Drake, M. J. 1976 *Geochim. cosmochim. Acta* **40**, 1421.

DePaolo, D. J. & Wasserburg, G. J. 1976 *Geophys. Res. Lett.* **3**, 249–252.

DePaolo, D. J. & Wasserburg, G. J. 1979 *Geochim. cosmochim. Acta* **43**, 615–627.

Dick, H. 1977 *Am. J. Sci.* **277**, 801.

Elthon, D. 1979 *Nature, Lond.* **278**, 514.

Erlank, A. J. & Kable, E. J. D. 1976 *Contr. Miner. Petr.* **54**, 281–291.

Floyd, P. A. & Tarney, J. 1978 In *Initial reports of the Deep Sea Drilling Project*, vol. 49, pp. 693–708. Washington, D.C.: U.S. Government Printing Office.

Flower, M. F. J., Schmincke, H. U. & Thompson, R. N. 1975 *Nature, Lond.* **254**, 404.

Frey, F. A. & Green, D. H. 1974 *Geochim. cosmochim. Acta* **38**, 1023.

Frey, F. A. & Prinz, M. 1978 *Earth planet. Sci. Lett.* **38**, 129.

Frey, F. A., Bryan, W. R. & Thompson, G. 1974 *J. geophys. Res.* **79**, 5507–5527.

Frey, F. A., Green, D. H. & Roy, S. D. 1978 *J. Petr.* **19**, 463.

Ganapathy, R. & Anders, E. 1974 *Proc. 5th Lunar Sci. Conf.* (*Geochim. cosmochim. Acta Suppl.* **5**), p. 1181.

Ganapathy, R., Papia, G. M. & Grossman, L. 1976 *Earth planet. Sci. Lett.* **29**, 302.

Gast, P. W. 1960 *J. geophys. Res.* **65**, 4.

Gast, P. W. 1968 *Geochim. cosmochim. Acta* **32**, 1057.
Graham, A. L. & Mason, B. 1972 *Geochim. cosmochim. Acta* **36**, 917.
Green, D. H. 1970 *Trans. Leicester lit. phil. Soc.* **44**, 28–54.
Green, D. H. & Ringwood, A. E. 1967 *Contr. Miner. Petr.* **15**, 103.
Hamilton, P. J., Evensen, N. M., O'Nions, R. K. & Tarney, J. 1979 *Nature, Lond.* **277**, 25.
Hanson, G. N. 1977 *J. geol. Soc. Lond.* **134**, 235.
Harris, P. G. 1974 In *The alkaline rocks* (ed. H. Sorensen), p. 427. London: Wiley.
Hart, S. R. 1971 *Phil. Trans. R. Soc. Lond.* A **268**, 573.
Hart, S. R. 1976 In *Initial reports of the Deep Sea Drilling Project*, vol. 34, p. 283. Washington, D.C.: U.S. Government Printing Office.
Hart, S. R., Schilling, J.-G. & Powell, J. L. 1973 *Nature, phys. Sci.* **264**, 104.
Jordan, T. H. 1978 *Nature, Lond.* **274**, 544.
Joron, J.-L., Bougault, H., Wood, D. A. & Treuil, M. 1978 *Bull. Soc. géol. Fr.* **20**, 521.
Joron, J.-L. & Treuil, M. 1977 *Bull. Soc. géol. Fr.* **19**, 1197.
Langmuir, C. H., Bender, J. F., Bence, A. E., Hanson, G. N. & Taylor, S. R. 1977 *Earth planet. Sci. Lett.* **36**, 133–156.
Langmuir, C. H., Vocke, R. D. & Hanson, G. N. 1978 *Earth planet. Sci. Lett.* **38**, 380.
Lloyd, F. E. & Bailey, P. K. 1975 *Phys. Chem. Earth* **9**, 389.
McCulloch, M. T. & Wasserburg, G. J. 1978 *Science, N.Y.* **200**, 1003.
Menzies, M. & Allen, C. 1974 *Contr. Miner. Petr.* **45**, 197.
Molnar, P. & Gray, D. 1979 *Geology* **7**, 58.
Moorbath, S. 1978 *Phil. Trans. R. Soc. Lond.* A **288**, 401–413.
Moorbath, S., Welke, H. & Gale, N. H. 1969 *Earth planet. Sci. Lett.* **6**, 245–256.
Nance, W. B. & Taylor, S. R. 1976 *Geochim. cosmochim. Acta* **40**, 1539.
Neumann, H., Mead, J. & Vitaliano, C. J. 1954 *Geochim. cosmochim. Acta* **6**, 90.
O'Hara, M. J. 1975 *Nature, Lond.* **253**, 708.
O'Hara, M. J. 1977 *Nature, Lond.* **266**, 503–507.
O'Nions, R. K. & Pankhurst, R. J. 1974 *J. Petr.* **15**, 603.
O'Nions, R. K., Evensen, N. M., Hamilton, P. J. & Carter, S. R. 1978 *Phil. Trans. R. Soc. Lond.* A **288**, 547–559.
O'Nions, R. K., Hamilton, P. J. & Evensen, N. M. 1977 *Earth planet. Sci. Lett.* **34**, 13.
O'Nions, R. K., Pankhurst, R. J. & Grönvold, K. 1976 *J. Petr.* **17**, 3.
Oxburgh, E. R. & Parmentier, E. M. 1978 *Phil. Trans. R. Soc. Lond.* A **288**, 415–429.
Pankhurst, R. J. 1977 *Nature, Lond.* **268**, 36.
Pritchard, R. G., Cann, J. R. & Wood, D. A. 1978 In *Initial reports of the Deep Sea Drilling Project*, vol. 49, p. 709. Washington, D.C.: U.S. Government Printing Office.
Ringwood, A. E. 1966 *Geochim. cosmochim. Acta* **30**, 41.
Saunders, A. D., Tarney, J. & Weaver, S. D. 1980 *Earth planet. Sci. Lett.* **46**, 344–360.
Schilling, J.-G. 1971 *Phil. Trans. R. Soc. Lond.* A **268**, 663–706.
Schilling, J.-G. 1973 *Nature, Lond.* **242**, 565.
Schilling, J.-G. 1975 In *Initial reports of the Deep Sea Drilling Project*, vol. 38, p. 741. Washington, D.C.: U.S. Government Printing Office.
Shaw, D. M. 1970 *Geochim. cosmochim. Acta* **34**, 237.
Sigvaldason, G. E. 1974 *J. Petr.* **15**, 497.
Sun, S.-S. & Hanson, G. N. 1975*a* *Geology* **3**, 297.
Sun, S.-S. & Hanson, G. N. 1975*b* *Contr. Miner. Petr.* **52**, 77.
Sun, S.-S. & Nesbitt, R. W. 1976 *Earth planet. Sci. Lett.* **35**, 429.
Sun, S.-S., Nesbitt, R. W. & Sharaskin, A. Y. 1979 *Earth planet. Sci. Lett.* **44**, 119–138.
Sun, S.-S., Tatsumoti, M. & Schilling, J.-G. 1975 *Science, N.Y.* **190**, 143.
Tarney, J. & Donnellan, N. C. B. 1977 In *Initial reports of the Deep Sea Drilling Project*, vol. 36, p. 929. Washington, D.C.: U.S. Government Printing Office.
Tarney, J. & Windley, B. F. 1977 *J. geol. Soc. Lond.* **134**, 153.
Tarney, J., Saunders, A. D., Weaver, S. D., Donnellan, N. C. B. & Hendry, G. L. 1978 In *Initial reports of the Deep Sea Drilling Project*, vol. 49, pp. 657–691. Washington, D.C.: U.S. Government Printing Office.
Tarney, J., Wood, D. A., Varet, J., Saunders, A. D. & Cann, J. R. 1979 In *Implications of deep drilling results in the Atlantic Ocean* (ed. M. Talwani) (Maurice Ewing Series, vol. 2), pp. 285–301. Washington, D.C.: American Geophysical Union.
Tatsumoto, M. 1969 *Earth planet. Sci. Lett.* **6**, 369.
Tatsumoto, M. 1978 *Earth planet. Sci. Lett.* **38**, 63.
Treuil, M. & Joron, J.-L. 1975 *Soc. ital. Miner. Petrol.* **31**, 125–174.
Weaver, S. D., Saunders, A. D., Pankhurst, R. J. & Tarney, J. 1979 *Contr. Miner. Petr.* **68**, 151–169.
White, W. M., Schilling, J.-G. & Hart, S. R. 1976 *Nature, Lond.* **263**, 659–663.
White, W. M. & Schilling, J.-G. 1978 *Geochim. cosmochim. Acta* **42**, 1501.
Wood, D. A. 1978 *J. Petr.* **19**, 393.

Wood, D. A. 1979 *Geochim. cosmochim. Acta* **43**, 1031–1046.

Wood, D. A., Tarney, J., Varet, J., Saunders, A. D., Bougault, H., Joron, J.-L., Treuil, M. & Cann, J. R. 1979*a* *Earth planet. Sci. Lett.* **42**, 77.

Wood, D. A., Joron, J.-L., Treuil, M., Norry, M. J. & Tarney, J. 1979*b* *Contr. Miner. Petr.* **70**, 319–339.

Wood, D. A., Varet, J., Bougault, H., Corre, O., Joron, J. L., Treuil, M., Bizouard, H., Norry, M. J., Hawkesworth, C. J. & Roddick, J. C. 1978 In *Initial reports of the Deep Sea Drilling Project*, vol. 49, pp. 597–655. Washington, D.C.: U.S. Government Printing Office.