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Nonlinear Nature of the Unavoidable Long-Lived Isotopic, Trace and Major Element Contamination of a Developing Magma Chamber [and Discussion]

M. J. O'Hara, D. K. Bailey, J. V. Smith and R. J. Pankhurst

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Nonlinear nature of the unavoidable long-lived isotopic, trace and major element contamination of a developing magma chamber

By M. J. O'Hara
Geology Department, University College of Wales, Aberystwyth, Dyfed SY23 3DB, U.K.

Contamination of magmas by crustal materials is a possible alternative explanation of many of the trace element and isotopic features of basalts which have been advanced as evidence of mantle heterogeneity. The space problems associated with the emplacement of large masses of plutonic cumulates in most central volcanoes, and with the formation of the gabbro–dunite portion of the oceanic crust, indicates that at least some digestion of pre-existing crustal rocks has occurred. Contamination is therefore unavoidable. In the ocean basins, contamination is not due directly to incorporation of sea water, but to the digestion of previously erupted basalts which may have been hydrothermally altered by circulating sea water, plus some sediment.

In a magma chamber that is periodically replenished with parental magma and periodically tapped to provide lava flows during fractional crystallization, contamination produces changes in the composition of the erupted product which are not, in general, linear between the initial and final states of the system. Moreover, the change in composition produced need not lead towards the composition of the contaminant. Provided that the periodic additions and subtractions of magma are small relative to the size of the magma chamber, the effects of short-term variations in the amount of contamination are smoothed out, while the effects on incompatible element concentrations are persistent long after active contamination has ceased. The effects on major components that enter the crystallizing phases are constrained by the need for the remaining liquid to conform to the relevant low-pressure phase equilibria.

INTRODUCTION

No currently plausible model of the evolution of the mantle permits it to be chemically homogeneous. Our most widespread and most readily available probes into the chemistry of the upper mantle are the basalts that emerge from it. Currently, interpretations of the differences in isotope and trace element chemistry between basalts from different sources provide the principal characterizations of alleged chemical differences between different mantle source regions.

Unfortunately, the interpretations of the isotope and trace element chemistry tend to ignore extensive field, major element and experimental data that indicate that the erupted lavas are not primary magmas.

Even when the reality of extensive near-surface fractionation of the erupted lavas is conceded, there has been a tendency to assume that the isotopic ratios, and the ratios of highly incompatible elements, will have remained unmodified during the fractionation process. The validity of this latter assumption needs to be tested if the ascending magmas have been contaminated by pre-existing crustal materials during the evolution of the near-surface chambers. Even cursory inspection of the space problems indicates that contamination of the magma chambers is a probable event. The gabbro–peridotite cumulates and intrusives, which form the cores of all dissected central volcanoes, have replaced crustal rocks and previously erupted basalts

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whose substance could have been available to contaminate the magma chamber. Subsidence of the replaced crustal material into the magma is unlikely on density grounds, is unsupported by gravity data, and would in any case lead to extensive melting and assimilation of the subsided plug. Lateral displacement of the replaced material is not generally in evidence (but there are exceptions), and upward displacement is not supported by field evidence from active basaltic volcanoes. The missing crustal material must have been redistributed through the plutonic and extrusive pile in a form that prevents its immediate physical recognition, i.e. as contamination whose effects are seen partly in the cumulates and partly in the lavas. One must also ask, does the gabbro layer of the ophiolites terminate sharply upwards in a chilled roof onto which the lowest basalts were erupted, or has it advanced upwards through previously erupted basalt during the growth of the ocean floor section?

Qualitatively, contamination of the most 'primitive' m.o.r.b. (mid-ocean ridge basalt) magma by the types of material likely to be present in the average oceanic or continental crust will obviously lead towards enrichment of $^{87}Sr/^{86}Sr$, $^{144}Nd/^{143}Nd$ and $^{207,206}Pb/^{204}Pb$ ratios in the magma. It will also lead towards general enrichment in all of the less compatible elements such as the rare earth elements (r.e.e.), Fe, Ti, K etc., and to modifications of their ratios. It should be easy to prove that these effects cannot result solely from simple closed system fractional crystallization, or even of fractionation in more sophisticated magmatic plumbing systems. This is the sense in which the chemistry of basalts from oceanic islands and continental environments differs from that of m.o.r.b. magmas.

I have urged that the effects due to contamination, and all other effects occurring during the fractionation process, must be quantified and removed from the data before any conclusions are reached about the chemistry of the mantle source regions on the basis of the chemical variations in the erupted basalts (O'Hara 1973, 1975, 1977). Perhaps more effort should go into characterizing the geochemical differences between mantle fragments in kimberlite, in order to establish how inferred mantle heterogeneity compares with observed heterogeneities in selected parts of the mantle.

The debate would be simplified if it could be demonstrated that contamination is not a significant factor. Two principal arguments in favour of minimal contamination have been advanced in personal, chiefly verbal, communications to the author:

(1) geochemical differences between basalts are nonlinear, and composition changes are not directed towards the likely contaminants;

(2) geochemical differences between basalts from different sources are too uniform in the short term, and too persistent in the long term, to have resulted from a random process such as contamination.

Despite their apparent commonsense force, both arguments are invalid as will be demonstrated in this paper. They reveal, however, very widespread misunderstanding of the characteristics of the probable contamination processes. The purpose of this paper is to rectify these misunderstandings.

NATURE OF THE CONTAMINANT IN THE OCEANIC ENVIRONMENT

Much additional misunderstanding exists here: the contaminant need *not* be sea water itself, although some may be involved, but is the whole section of intercalated sediments and previously erupted basalts, dolerites and gabbros, parts of which have been hydrothermally

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altered in contact with sea water, other parts of which have been altered (weathered) at low temperatures. This average section requires careful geochemical and isotopic characterization with particular regard to the isotopic composition of lead in any sulphide minerals present.

Geochemical effects of contamination

Figure 1 shows in stylized form the forsterite-rich corner of a hypothetical ternary diagram forsterite–A–B (cf. O'Hara 1977, fig. 4). The effects of contamination of the magma chamber will be treated with the aid of this figure for the simplest possible case, in which only one crystalline phase is separating throughout the evolutionary history, whether or not contamination occurs. (The general principles remain the same if two or more crystallizing phases are involved in the evolutionary paths, but the behaviour becomes much more complex if contamination results in crystallization of an extra phase that would not otherwise have appeared during the evolutionary history, or results in a change of the character of the second phase that would have appeared.)

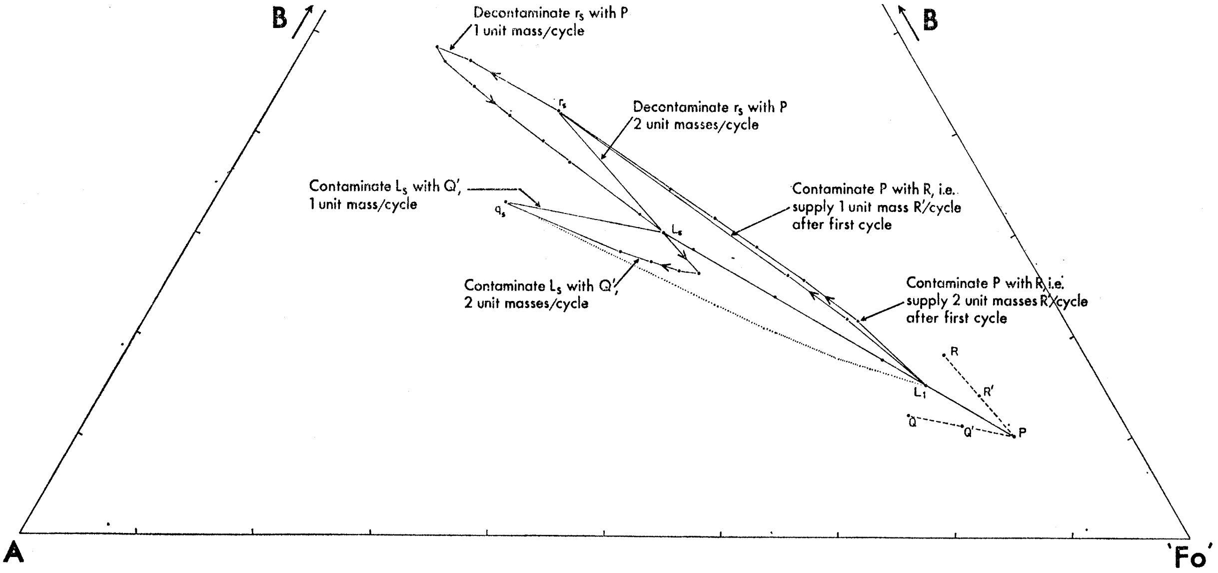

FIGURE 1. Part of ternary system forsterite–silica–anorthite (stylized), or compatible – incompatible A – incompatible B, or compatible – isotope A – isotope B, to illustrate effects of contamination in a periodically replenished, fractionated and partly drained magma chamber.

During the crystallization histories to be considered with the aid of figure 1, 'forsterite' behaves as a compatible component, A and B as perfectly incompatible components. In the labelling of this figure, 'forsterite' can be replaced by 'compatible element'; A and B by 'silica' and 'anorthite' or any other major components (provided no second phase cystallizes); 'incompatible element A', 'incompatible element B'; or by 'isotope A', 'isotope B', without altering the force of the conclusions to be reached.

Consider a magma chamber being fed with batches of a primary magma of composition P. Let each cycle comprise (i) fractional crystallization of a fraction $X = 0.33$ of the original mass of magma at the start of the cycle, followed by, (ii) escape of a fraction $Y = 0.17$ of the original mass of magma at the start of the cycle (*ca.* 0.25 of the residual liquid) as a lava flow, followed by (iii) replenishment of the chamber with a new batch of primary magma, of unit

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mass, which mixes with the residual magma before repeating (i), etc. (Note: these values of X and Y are probably several orders of magnitude too high to describe the real behaviour of the magma chamber, but their choice illustrates the general principles and shortens the calculations.) If there is no contamination, the successive lava flows have compositions advancing from L_1 to L_S, the steady state in these circumstances (see O'Hara 1977).

Now consider contamination of the magma chamber from the first replenishment by materials Q, R, both of which are richer than P in both of the incompatible components (or isotopes) A and B. Q contains a higher A/B ratio than P; R contains a lower A/B ratio than P.

For the sake of argument it is assumed that with each addition of primary magma, the magma chamber is enlarged by assimilation of an appropriate volume of rock from the roof and walls, offset to some extent by subsidence of underlying cumulates towards the mantle (whose volume has been depleted by that of the primary magma batch). Ignoring all complications due to differing densities of the primary magma, the solid and the molten contaminant, two extreme cases of contamination will be treated here: first assuming the magma chamber were receiving regular additions of new magma equivalent to two unit masses of a 1:1 mixture of P with either Q or R (Q′, R′ respectively) from the outset; and second, assuming steady state L_S is reached before contamination commenced.

The evolution of the successive lava flows towards new steady states in these cases is shown in figure 1 by the trends L_1–q_s and L_1–r_s respectively (for construction method see O'Hara (1977), fig. 4: a calculation based on one unit mass of the effective addition of R′ per cycle is also shown in figure 1).

In all calculations shown in figure 1, it has been assumed that X and Y remain unchanged. If, however, the X/Y ratio changes as a result of the contamination, as seems likely, then q_s, r_s will be located either nearer or further away from Q′, R′ dependent upon whether the amount of fractionation decreases or increases with respect to the amount of lava escape in each cycle (q_s and r_s must, of course, fall on extrapolations Fo–Q′ and Fo–R′).

Also shown in figure 1 are the paths of change that would be followed if the magma chamber had reached steady state L_s *before* contamination began, and then underwent contamination to reach the new steady state q_s. Note that the path followed may be markedly nonlinear, dependent upon the effective mass of contaminated magma added in each cycle.

Figure 1 also shows the effect of decontaminating the steady state r_s by feeding the magma chamber solely with primary magma P. Again the mass added per cycle is critical in determining the path followed, which may again be markedly nonlinear.

Two further points must be noted before passing to the conclusions based upon figures 1 and 2. First, the constructions have assumed that the composition P remains constant. This may be reasonable for continuous process environments, such as the mid-ocean ridge situation, but in static source volcanoes a progressive depletion of incompatible elements might be expected to affect the composition of P with time. Secondly, the individual steps taken by the magma composition in figure 1 in each cycle are relatively large, because X and Y have been chosen to be very large. When X and Y are very small, the individual steps also become very small. A simple calculation indicates the possible size of X and Y for the mid-ocean ridge situation. If the mantle is upwelling at 3 cm/year and undergoing 10% partial melting, *ca.* 0.3 cm^3 (cm^{-2}/year) of magma are available. If this is added into a permanent magma chamber 300 m thick at the ridge crest, then $X \approx 10^{-5}$ if the magma is fed in once a year, but smaller still if there is a more frequent draining of the mantle. From the constraints of the

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ratio of lava to cumulate in the final section, Y must be of the same order of size, unless eruptions are very infrequent.

Figure 2 extracts from figure 1 the composition vectors of the real contamination PQ′, PR′, and the composition vectors of the contamination *apparent* in the steady state lavas that would be erupted (L_q, L_r) for a variety of possible changes of the X/Y ratio as a result of the contamination.

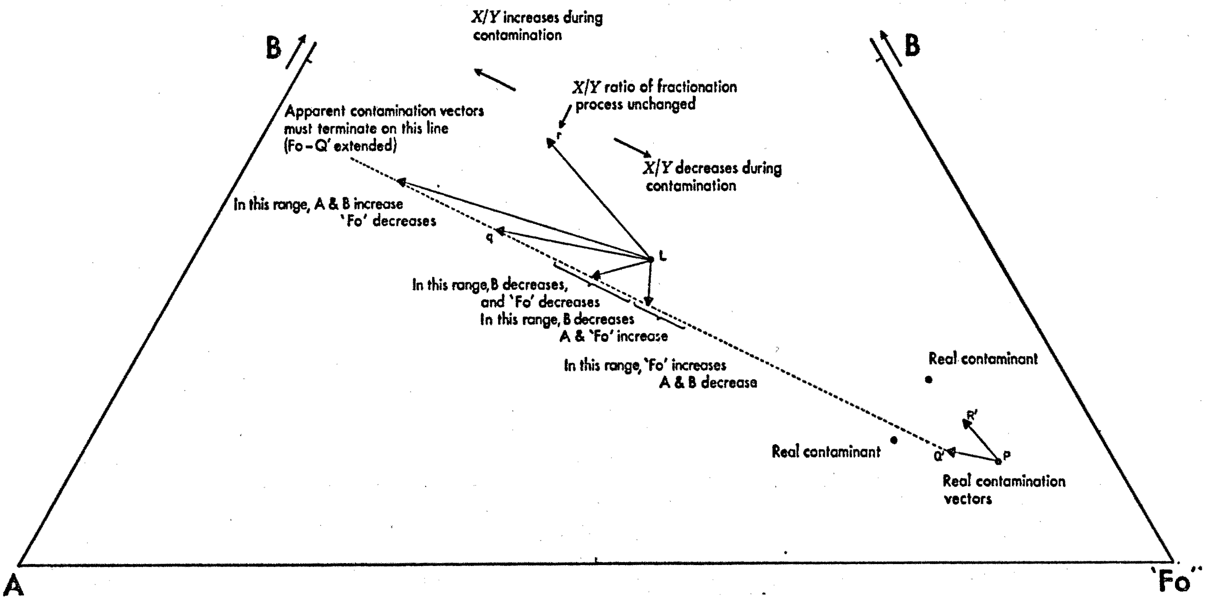

FIGURE 2. As figure 1, but showing the vectors of composition change between steady states before and after contamination.

Observations 1–3. The composition vectors of apparent contamination L_q, L_r which reflect change in the lava composition do not point (1) towards the actual contaminants Q, R, or (2) towards the average composition of the material being added to the system in each cycle (ends of vectors PQ′, PR′); nor (3) do they generally parallel the composition vectors of the actual contamination PQ′, PR′.

Observations 4–6. (4) The A/B ratios of the contaminated steady-state lavas, q_s, r_s, have been modified from that of L_s towards those of the respective contaminants. This is true in all cases where one phase only is crystallizing (but is not necessarily true if a second phase begins to crystallize at some point in each cycle, and contamination is accompanied by a rise in the ratio of the mass fractions of crystallization (X) to magma escape (Y) from the chamber during the contamination process). (5) The absolute concentrations of all three constituents have been modified in the general sense expected from contamination of P by Q or R in the case considered in figure 1. If, however, there were a significant change in the X/Y ratio this observation is not necessarily true (see figure 2). A decrease of the X/Y ratio accompanying contamination, however unlikely this seems, could lead to the absolute content of A in L_q being *less than* that in L_s despite the fact that P is being contaminated by a material richer in A than itself. (6) It is even possible in these circumstances for the compatible component (forsterite) to *increase* in q_s, r_s relative to L_s, despite the fact that the contaminants Q, R are poorer in that component than is the primary magma P.

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Enough has been demonstrated to show that effects due to contamination cannot be ruled out simply because the shift in composition between the steady states does not follow what might be called the intuitively expected trend. The actual results depend upon the form of the phase equilibria and the parameters of the fractionation, draining and refilling of the magma chamber. Any claim to reject a particular contamination process on the grounds just cited implicitly assumes certain forms of the phase equilibria and certain ranges of values for the fractionation, draining and refilling parameters of the magma chamber. These assumptions should be made explicit.

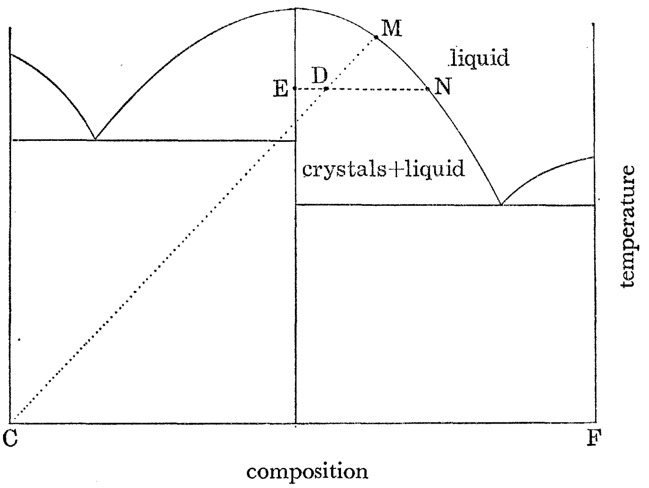

FIGURE 3. Temperature–composition section through a hypothetical thermal divide, to illustrate how contamination of a crystal saturated magma M with material C may produce a change in the liquid composition that is the precise opposite of that expected.

Observation 7. Once contamination has ceased, effects upon erupted lava chemistry are long-lived, particularly if the values of the fractionation parameters X (mass fraction crystallized) and Y (mass fraction escaping in each cycle) are small. Ratios of incompatible components 'remember' the contamination for longer than do the compatible components, and the path of change is not necessarily linear towards the primary magma or the new steady state to be achieved.

Observation 8. When X and Y are small, the mass of the magma chamber is large relative to the new magma batch added in each cycle. The steady-state compositions q_s, r_s are then remarkably insensitive to short-term fluctuations in the absolute amount of P, or the composition of the effective contaminated magma Q′, R′, which is added in each cycle. Near uniformity in the erupted product can accompany extensive short-term random fluctuations in the contamination process.

APPARENT PARADOX IN THE EFFECTS OF CONTAMINATION

The potentially paradoxical effects of contamination in systems that contain crystals and liquid may be further illustrated by reference to the hypothetical phase diagram shown in figure 3.

Mixing hot, crystal-saturated magma M with cold contaminant C produces mixture D which will re-equilibrate as crystals of E and a new crystal saturated magma N. (Only by

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chance could C–D–M and E–D–N be strictly linear; figure 3 has been plotted in terms of temperature, not thermal energy.) The paradox is that the postulated contamination of M by C has produced a reduced mass of liquid N whose composition has been modified *directly away from that of the contaminant*. This effect occurs at equilibrium, irrespective of any fractionation model chosen. A generalization of more widespread applicability is shown in figure 4. Addition of contaminant or hybridizing material C′ to crystal saturated liquid M′ to produce mixture D′ leads, under isothermal conditions, to crystallization of crystals E′ and development of new magma N′. The composition change M′–N′ is not linear towards the contaminant. Effects are not always as dramatic as this; the example has been chosen to inspire appropriate caution among igneous geochemists who may have to consider contamination as a process.

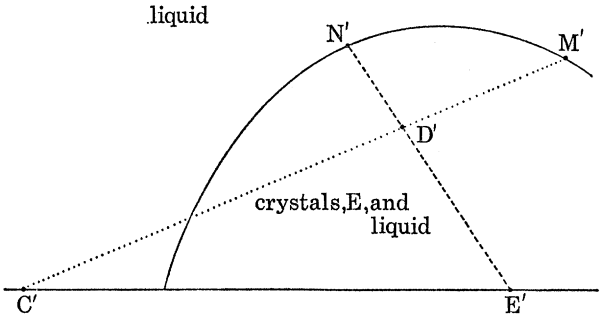

FIGURE 4. Isothermal section of a hypothetical system showing an isotherm on the liquidus field of crystal species, E′. This figure illustrates the general principle of which figure 3 is a specific example.

CONTAMINATION IN COTECTIC SYSTEMS: SEPARATION OF MAJOR AND INCOMPATIBLE COMPONENTS

A general point of potentially great significance arises here. If the magma chamber is fractionating olivine gabbro, then the major element composition of the magma is constrained to remain in equilibrium with olivine, augite and plagioclase feldspar. Contamination with major elements may change the ratios of olivine, augite and plagioclase in the cumulates, but will have no direct effect (except in so far as the temperature of the system is reduced) upon the composition of the liquid. (This proposition is a generalization of the points brought out in connection with figures 3 and 4.) It is therefore quite probable that incompatible elements and isotopic ratios in a basalt province may show fluctuations apparently requiring a high percentage of contamination, while the major elements apparently lend this proposition little support. These are no grounds for rejecting the possible role of contamination in the evolution of such magmas.

CONCLUSION

Contamination and hybridization of liquids in crystal saturated systems is not a simple process susceptible to intuitive argument or intuitive understanding. It can only be understood if the relevant phase equilibria are properly comprehended, and the crystallization and eruption processes correctly modelled. Enough geochemical capacity exists in the scientific community to obtain a solution to this problem and allow us to remove the effects of high-level events from the erupted lavas. Only then can we deduce correctly what chemical

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differences exist between different source regions. Perhaps it may then transpire that the mantle regions feeding the oceanic island volcanoes are actually *more* depleted than those feeding the mid-ocean ridges, substituting another apparent paradox for the physical impossibility of making even a hot but dense fertile mantle plume rise through less dense residual mantle.

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Discussion

D. K. BAILEY (*Department of Geology, University of Reading, U.K.*). On behalf of the organizers, I thank Professor O'Hara for presenting his hypothesis, which offers an alternative explanation for some of the chemical variations seen in lava suites. This will help to sharpen critical appraisal of the volcanic evidence, when this is viewed against the background of chemical heterogeneity in the mantle sources. In the model vertical section shown by the author, the volcano is underlain by a column of mafic cumulates extending right through the crust to the mantle source. In many continental central volcanoes a dilational opening does not seem possible, and the column of cumulates would then be replacing pre-existing lithosphere. Downward removal of continental crust, by stoping and subsidence, would appear to be equally unlikely, so the missing material should now be in the volcanic edifice. Would Professor O'Hara comment on the apparent lack of large volumes of sialic crustal material (assimilated or otherwise) in central basaltic volcanoes in continental interiors?

J. V. SMITH, F.R.S. (*Department of the Geophysical Sciences, University of Chicago, U.S.A.*). Would the author comment on a possible heat budget of a hypothetical magma chamber, and the potential limitation to the extent of contamination?

[A recent study of the element correlations for pyroxene and garnet megacrysts in the Malaita alnoite, Solomon Islands, shows that extensive fractionation of Fe/Mg, Na, Ti and Cr occurred in the manner expected for continuous crystal separation from a single magma chamber that was not periodically refilled. An account of this work by J. Delaney, J. V. Smith & P. H. Nixon is in preparation; it extends an earlier study by P. H. Nixon & F. R. Boyd to be published in *Proc. Second Kimberlite Conf.*]

R. J. PANKHURST (*British Antarctic Survey, c/o I.G.S., 64 Gray's Inn Road, London, U.K.*). Professor O'Hara is to be congratulated on his persistence in chasing the theoretical consequences of his open-system magma chamber model. However, in practical terms it is misleading for him to claim that it has disposed of the criticism that crystal fractionation cannot explain the variability of incompatible trace element ratios frequently observed in volcanic rock suites. Although predicting greater variation in such ratios than in a closed system model, as I have shown (*Nature, Lond.* (1977) **268**, 36–38), Professor O'Hara's equations would require a much greater concomitant range in the absolute abundances of such elements (and also in europium anomalies) than actually occurs, for example, in Icelandic volcanics. The present paper is chiefly concerned with modelling the effects of contamination and provides another useful mechanism for 'decoupling' the behaviour of major and trace elements. At first sight, though, it seems to me that linear mixing trends should still be expected if one incompatible

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trace element (or ratio) is plotted against another. This is now the standard geochemical test for assessing contamination (e.g. Langmuir, Vocke & Hanson (1978), *Earth planet. Sci. Lett.* **37**, 380–392). Would Professor O'Hara comment on this?

M. J. O'Hara. Professor Bailey has identified one critical feature of the evaluation of the possible role of contamination. Partial melting and magma consolidation (at higher crustal levels) is necessarily a dilational process because the residuum is less dense than the source mantle; so is the liquid produced, and its eventual shallow level crystallization products are less dense than the garnet–clinopyroxene or spinel–clinopyroxene assemblage which has been eliminated from the mantle in the partial melting process.

The absence, in most cases, of evident radial dilation, and the improbability of downward removal of continental crust in the case of continental central volcanoes indeed leaves no alternative – the missing material must be in the volcanic edifice *or* in the cumulate column but, obviously, in a form which is not readily recognizable.

In the model presented in my paper, material assimilated by the advancing magma chamber suffers two ultimate fates. Part of it is precipitated as cumulates, part is erupted in the lavas. The specific, very simplified, case of contamination of an olivine tholeiite magma by pelitic material may be considered. Let us suppose that the magma in the chamber is saturated with olivine, plagioclase and augite, and is precipitating olivine gabbro cumulates, when the advancing magma chamber encounters the pelitic horizon. Assimilation of the pelitic material will require thermal energy, and will promote the excessive crystallization of plagioclase and a calcium-poor pyroxene component which may be explicit as orthopyroxene or pigeonite, or occult in a less calcic augite than would otherwise have precipitated. The essential reaction may be written in simplified form as

$$\underset{\text{in magma}}{\mathrm{CaMgSi_2O_6}} + \underset{\text{from pelites}}{\mathrm{Al_2SiO_5}} \rightarrow \underset{\text{in cumulates}}{\mathrm{CaAl_2Si_2O_8 + MgSiO_3}}$$

Part of the contaminant appears, therefore, as a bias in the proportion of precipitating phases, away from that expected from simple fractionation of a cotectic magma and in such a direction as to accommodate part of the added material. Such variations in the ratios of precipitating phases should be detectable and should be correlated to some extent with the nature of the sialic rocks being digested at the top of the magma chamber. This is a testable prediction, which should, moreover, lead to an estimate of the actual depth of the open magma chamber, because the cumulates will show first signs of a bias of mineral proportions at that depth below the intersection with a characteristic sialic horizon.

The remainder of the contaminant, for example the potassium and rubidium content of the pelite, stays in the remaining liquid, whose major element composition shows little evidence of contamination because it is constrained to remain in equilibrium with the precipitating crystals (see my comments on the paper by Morrison *et al.*, this symposium). Lava flow by lava flow this 'incompatible' portion of the contaminant is evacuated from the chamber and appears as an incompatible element enrichment in the lava pile relative to what might otherwise have been expected. For a *very* simple volcano one might write

> volume of crust assimilated ≈ volume of apparently igneous rocks, plutonic and extrusive, minus the volume of parental magma crossing the Moho. (All volumes expressed in some standard state, e.g. non-vesicular crystalline lava.)

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The essential point to grasp is that there may be *no* direct evidence of sialic contamination in the form of partly assimilated xenoliths, and little direct evidence of contamination in the major element composition of the lavas. The evidence resides in the major element composition of the cumulates and the incompatible element concentrations of the lavas.

What has been said above leads to the prediction that volcanoes deriving from chemically identical mantle source regions will yield systematically different lava compositions, cumulate sequences and isotopic differences according to the nature of the crust that they penetrate.

Professor Smith has identified the other critical feature involved in evaluating the possible role of contamination, and one that I have addressed elsewhere (M. J. O'Hara (1978), *Phil. Trans. R. Soc. Lond.* A **288**, 627–629). The thermal budget is complex, but the ultimate source of most of the thermal energy involved is the parental liquid being regularly fed into the advancing magma chamber. This liquid may be much hotter than the evolved magma in the chamber, and the additional heat is available for assimilation of country rocks, metamorphic reactions, losses by conduction, etc., but with a substantial positive contribution from the energy released by cumulate crystallization.

Order of size calculations indicate that the excess heat flow over mid-ocean ridges due to the consolidation of the dunite–gabbro layer should be 5–40 times greater than is observed. While much of this excess heat may be carried away by localized hydrothermal convection, there is obviously plenty of energy available for redigestion of the basaltic roof of the magma chamber. Indeed, this is a most efficient way of cooling the magma chamber, crudely analogous to dropping crushed ice into boiling water to cool it, rather than putting the whole kettle into the refrigerator.

In more general terms, an excess heat flow of 10^{-6} cal cm^{-2} s^{-1} (4.2 μW cm^{-1}) will permit the crystallization of *ca.* 0.3 g of cumulate in the underlying magma chamber per annum. This will provide a growth of cumulate thickness of *ca.* 1.1 mm a^{-1}. The growth of substantial cumulate columns 15–25 km deep beneath central volcanoes in periods of megayears would require excess heat flows of the order of 20 h.f.u. if upward conduction were the only mechanism of heat loss. Even after making due allowances for radial heat losses, hydrothermal circulation and longer life of the volcano, it is evident that plenty of thermal energy could be available for redigestion of crust or previously erupted basalt.

The need for very careful field, petrographic, geochemical and mineralogical study of the roofs of exposed magma chambers, particularly in the ophiolites, is clear. If actual thermal gradients close to the chamber can be established then the actual rate of conductive heat transfer from the chamber can be established. Any discrepancy between this rate of loss and that required to produce solidification of the cumulate sequence within an acceptable time may be assigned to the heat used in 'melting' the roof rocks (the process is more complex but the thermal budget is similar), or to hydrothermal circulation.

I note with interest what Professor Smith has to say about the Malaita alnoite. I can envisage a wide spectrum of possibilities between fractionation in a closed system and in systems that are open to different extents. These possibilities are under evaluation by computer modelling at the present time.

Dr Pankhurst's congratulations are particularly welcome, and in the circumstances very generous. I only regret that such persistence should have been necessary in the effort to bring about an interpretation of the trace element and isotope geochemistry of basalts which can be

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reconciled with the facts of petrogenetic life displayed for at least the last 15 years by the field, petrographic, geophysical, experimental and major element evidence.

I am saddened to learn that a search for linear mixing trends in plots of one incompatible trace element (or ratio) against another has become the standard geochemical test for assessing contamination, and still more to see that Dr Pankhurst apparently subscribes to this test.

It is well known, or at least easily verified, that plots of a ratio of two quantities against a third, or of two ratios against each other, will generally lead to true linear arrays in multicomponent space being represented by curves in a rectilinear coordinate plot. Consider, for example, the linear composition array (table 1), which yields the rectilinear plots shown in figure 5. Such plots are uniquely unsuited to the problem under discussion.

Table 1

	P	$3P{:}1Q$	$1P{:}1Q$	$1P{:}3Q$	Q
element					
z	90	70	50	30	10
z'	0	5	10	15	20
z''	20	60	100	140	180
z'''	80	65	50	35	20
ratio					
z/z'	∞	14	5	2	0.5
z''/z'''	0.25	0.92	2	4	9

Simple rectilinear plots of one incompatible trace element against another at least have the merit of representing a linear mixing trend in multicomponent space as a straight line in the plot. This, however, is no protection from the consequences of materials behaviour, as shown in figure 4 of my paper. Consider compositions P, Q shown in figure 6; the bulk systems, such as R, produced by simple contamination of P (primary magma) by Q (contaminant) lie along the straight line PQ, but these compositions are in general subject to variable degrees of crystallization, leading to the production of liquid L and a cumulate, C, whose composition falls at the origin if the two trace elements plotted are totally incompatible. The locus PL will not in

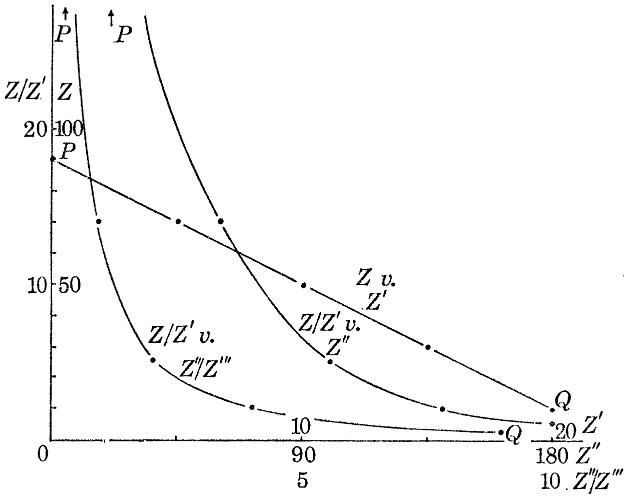

Figure 5

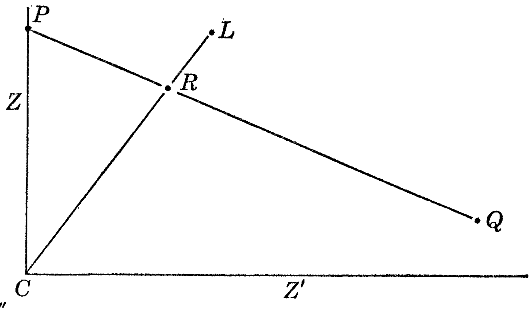

Figure 6

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general be a straight line. (If the open system fractionation envisaged in figures 1 and 2 of my paper is in force, figure 6 becomes yet more complicated.)

If we write, in mass fractions, the equation which expresses the contamination and crystallization process, we have

$$(1-a)_P + a_Q \rightarrow b_L + (1-b)_C. \tag{1}$$

Then,

$$Z_L = \{(1-a)\, Z_P + aZ_Q\}/b, \tag{2}$$

where Z_L, Z_P, Z_Q are the concentrations of trace element Z in L, P and Q respectively.

$\mathrm{d}Z_L/\mathrm{d}a$ will not in general be constant because b, the amount of crystallization, is in general a nonlinear function of a, the fraction of contamination (see figure 4b in particular).

If a straight line variation is, by chance, produced in the two-element plot of figure 6, it will not trend from P towards Q. The condition for a straight-line variation is that

$$Z_L - Z_P = m(Z'_L - Z'_P), \tag{3}$$

where m is the slope of the line.

Substituting for Z_L, Z'_L from (2) and rearranging, we have the specific condition for the straight-line variation in figure 6, that

$$b = (1-a) + a\,(mZ'_Q - Z_Q)/(mZ'_P - Z_P), \tag{4}$$

i.e. b would be required to be a linear function of 'a'.

Turning to Dr Pankhurst's statement regarding his 1977 contribution to the problem of Icelandic basalts, I must apologize for my delay in responding, but assure him that his arguments have not been ignored.

Pankhurst (1977) rejected contamination of the Icelandic magma chambers as the origin of the Sr and Nd isotopic characteristics, on the grounds that variations in Sr isotopic ratio are correlated with those of the Nd isotopes (agreed) whereas some altered basalts from D.S.D.P. Leg 37 show contamination of Sr isotopes without contamination of Nd isotopes (agreed). Provided that r.e.e. concentrations are *always* little affected by alteration, this would be a valid argument. Other workers, however, report substantial alterations of the r.e.e. concentrations in submarine basalts, and the point must still be regarded as open to debate.

Disregarding the factor of possible long-lived contamination of the Icelandic magma chambers by digestion of previously erupted and altered basalt, which was ignored by Pankhurst (1977), and overlooking his use of element–ratio plots to represent evolutionary trends (see above), it still emerged from his treatment that an open system fractionation process could be adequate to explain most of the chemical variations within the Icelandic basalts (and even those between Reykjanes Ridge and Icelandic basalts if both are assumed to be derived from a previously depleted source).

Dr Pankhurst (1977, p. 38) gave four reasons for playing down the role of open system fractionation. Of these, the third and fourth lack any force in logic and I hope that on reflection Dr Pankhurst now agrees that the distinction between an open system fractionation process, producing extensive variations in magmas from a common source, and differential partial melting processes producing long-lived variations in the source regions, is scarcely academic, whatever the depth at which fractionation occurs.

Pankhurst's (1977) first point was that he might have used unduly high partition coefficients for the r.e.e. that he had considered, but I believe, on the contrary, that he may have used

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effective bulk partition coefficients that are too low, in that they consider only the crystal–liquid partition, and not the effect of trapped intercumulus liquid, which will affect most strongly the behaviour of those elements whose crystal–liquid partition coefficients differ most from unity.

Pankhurst's (1977) second point was that the proportion of the magma chamber available for eruption as lava would have had to be very small. This is not immediately evident from plotting the data for groups I and II of his table 2 into his figures 1 and 2, where it would appear that values of the X/Y ratio from 1 to 30 might explain the intra-group variations, implying that 3–50% of the magma in the chamber might have escaped as lava, rather than the 0.1% quoted by Pankhurst. These values are, however, strongly dependent upon the partition coefficients used.

Three further points concerned with Dr Pankhurst's (1977) treatment deserve mention here.

The possible role of a spinel which might discriminate successfully between the r.e.e. in both the partial melting process and in subsequent fractionation, was not considered.

Phase equilibria studies have established that orthopyroxene is likely to be in reaction relation with liquid at the beginning of melting at upper mantle pressures. Modelling of the partial melting process should, therefore, cater for the production of liquid and orthopyroxene together, at the expense of other phases, rather than for the production of liquid at the expense of orthopyroxene.

The absence of substantial europium anomalies may imply that there has been insufficient fractionation of gabbro to account *by itself* for the other r.e.e. characteristics. However, the development and size of a europium anomaly is highly dependent upon the oxygen fugacity in the magma chamber during gabbro fractionation. The probability that most of the magmas have undergone at least some gabbro fractionation is indicated by the persistent occurrence of small amounts of phenocrysts of plagioclase, augite and olivine in the lavas.

For the reasons set out above I am unable to agree with Dr Pankhurst that either open system fractional crystallization, or contamination of the magma chamber by previously erupted and altered basalt, can yet be excluded as major factors in the important test case of the evolution of Icelandic basalts.