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Cooling and contamination of mafic and ultramafic magmas during ascent through continental crust

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When magma ascends turbulently through continental crust, heat transfer can be rapid and the wall rocks of the conduit can melt and be assimilated into the magma. Calculations are presented for cooling, crystallization and contamination during the turbulent ascent of a komatiite, a picritic basalt and a tholeiitic basalt. Primitive magmas, like komatiite and picritic basalt, are predicted to erupt with moderate to large amounts of olivine phenocrysts except at very high flow rates. Little crystallization takes place in a basalt on ascent, and any phenocrysts are likely to be inherited from the magma chamber. The erosion rate of the conduit walls and amount of contamination are greatest in primitive magmas and least for cool, fractionated magmas. Contamination is also affected by flow rate. For low flow rates, where the Reynolds number is significantly less than 2000, movement is laminar and the magma is likely to solidify against the dyke walls and so the amount of contamination is negligible. Maximum contamination will occur for flow rates at Reynolds number around 2000 and the total amount of contamination will decrease as the Reynolds number increases above this value. This kind of contamination can produce trends on geochemical diagrams which are opposite to those produced by assimilation and fractional crystallization processes in magma chambers. Indices of crustal contamination such as ^{87}Sr, REE, K_2O and other incompatible elements can be greatest in magmas with high values of Mg/(Mg + Fe) and low SiO_2. Both highly incompatible and highly compatible trace elements can show positive correlation with one another (for example, Ni and K_2O). These features are shown by the Plateau lavas of Skye, Scotland, and some lava groups of the Deccan Traps. Curved trends produced in this way on many types of geochemical diagrams are not mixing hyperbolas and do not necessarily point towards contaminant compositions.

Thermal erosion rates are proportional to the difference between the magma temperature and the fusion temperature of the wall rocks. Contamination will thus tend to be selective towards rocks of low fusion temperature. Because of their high temperatures, komatiites are relatively indiscriminate in what they assimilate, while basalts are highly selective. The calculations show that komatiites are highly susceptible to contamination by both continental and oceanic crustal components. Under suitable flow conditions they can be contaminated with up to 30% of crustal material. Contamination could result in spurious conclusions about their age and mantle-source characteristics. The geochemical differences between komatiites and closely associated basaltic komatiites can often not be attributed to fractionation of olivine. These basaltic komatiites may represent highly contaminated komatiite rather than an unrelated magma type derived from a different mantle source.

1. Introduction

An important problem in petrology concerns the degree to which mantle-derived magmas are contaminated as they pass through continental crust, or derive their characteristics from ancient or enriched sub-continental mantle. Contamination may explain the striking differences between many continental basalts and mid-ocean ridge basalts. The former are typically enriched in silica, incompatible trace elements and radiogenic strontium [1], and can have values of neodymium, lead and oxygen isotope ratios characteristic of continental crust [2–4]. In some examples, such as the Hebridean plateau lavas of the British Tertiary [2,4,5], the geochemical arguments for crustal contamination seem conclusive. The question of crustal contamination during the Archean also arises when interpreting the geochemistry of komatiites, since it is plausible that some of these exceptionally high temperature magmas had to ascend through continental crust [6].

There are several mechanisms for the interaction of mantle-derived magmas with crustal

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material. Magmas from crustal and mantle sources can mix in either chambers or conduits [7,8]. The walls, floor and roof of magma chambers can melt and in fluid dynamically favourable circumstances can contaminate the resident magma. Blocks of country rock can also be stoped into the chamber. Assimilation in magma chambers is likely to be commonly associated with fractional crystallization [8,9]. Hydrous fluids derived from dehydration reactions of crustal rocks surrounding mafic magma could also be absorbed, resulting in selective contamination by elements which are enriched in the fluid phase [2,10].

Watson [11] has shown that selective contamination of some elements, such as potassium, can occur during dissolution of minerals or rocks into basaltic magma. Selectivity is caused because alkali elements have chemical diffusivities which are orders of magnitude greater than silica, and thus can attain transient chemical equilibrium with the host magma long before dissolution and homogenisation is complete.

Magmas could also assimilate wall rock while flowing through dykes. It is this latter process which is considered in this paper. We adapt our previous work on the flow of hot komatiites over the ground [12,13] to the ascent of mafic and ultramafic magmas through the crust. The central idea of the previous and present work is that turbulent flow causes thermal erosion of the dyke wall rocks or ground and leads to contamination of the magmas.

Our investigation is based on a quantitative study of the turbulent flow of magma through fractures and a calculation of the rate of melting of the wall rocks. We evaluate the amount of contamination and the eruption temperature, which are influenced by the initial magma temperature, the flow rate, dyke width, temperature, composition and distribution of rock types in the crust and the magma composition. The results suggest new interpretations of the petrological and geochemical features of some basalts. We also assess under what conditions komatiites can ascend through continental crust and how contamination might affect their chemistry. Our main geological conclusions are outlined in the final section.

2. Fluid dynamical principles and assumptions

Shaw and Swanson [14] were among the first to analyse quantitatively the ascent of basaltic magma through the crust using the principles of fluid dynamics. They concluded that the large volume and great horizontal extent of the Columbia River flood basalts required that the flows were turbulent with Reynolds numbers greatly exceeding 10^3. Calculations by subsequent workers [13,15] have confirmed that basaltic magmas can ascend under turbulent conditions if the flow rate is sufficiently high.

Since no turbulent flows of basaltic lava have been reported, most volcanologists have concluded that basaltic magma flows in dykes are laminar. However, observations of historic lava eruptions may be misleading for a number of reasons. No historic lavas with the volume, extent and estimated discharge rate of flood and plateau basalts have been documented [14,16]. In addition, basaltic lava flows usually exsolve gas and cool at the surface by fire-fountaining, an effect that substantially increases the viscosity and yield strength of the magma [17]. Thus the flow behaviour of lava is not necessarily a reliable guide to the magma's behaviour during ascent. Our calculations presented below suggest that turbulent conditions during ascent should not be regarded as exceptional, even in basaltic magmas.

Hulme [18] proposed that lunar lava flows melted the ground to form the sinuous rilles found in the Mare regions of the Moon. He suggested that the lunar basalt lavas were turbulent, because of their relatively high discharge rate and low viscosity. Huppert et al. [12] and Huppert and Sparks [13] developed a model for thermal erosion in turbulent komatiite lavas and calculated typical erosion rates of several metres/day in the lava channels. They concluded that komatiites could become contaminated by up to 10% of the underlying ground.

The present treatment combines these ideas and adopts the thermal erosion model of Huppert and Sparks [13] to magma ascent through the crust. The basic theory of thermal erosion can be found in Hulme [19] and Huppert and Sparks [13]. Aside from the forces driving the flows, the main differences between flow along the ground and up a fracture are that the vertical flow is bounded by two rather than one solid surface and the wall rocks will differ in composition, temperature and melting temperature as the magma moves from the base of the crust to the surface. Pressure-induced variations on the magma liquidus temperature, crystallinity and cooling will also influence the temperature history of the magma in the conduit.

The main results of Huppert and Sparks [13] are now summarised in a form modified for magma ascent. The magma rises in the conduit driven by the excess hydrostatic pressure gradient $g\Delta\rho$ which is a result of the different density $\Delta\rho$ between the magma of density ρ and the mean density of the column of rock overlying the magma source. This turbulent flow is resisted by frictional forces at the wall. The balance of these two effects leads to the following relationship between the flow rate, Q, and the dyke width, D:

$$Q = (g\Delta\rho/f\rho)^{1/2} D^{3/2} \tag{1}$$

where f is a friction factor. The value of f could range between about 0.01 and 0.06, depending on the roughness of the conduit and the magnitude of the Reynolds number. For convenience we shall assume a constant value of 0.03 throughout this paper.

After initiation of turbulent flow, the heat transfer, H, at one wall is related to θ, the magma temperature, and T_m, the melting temperature of the wall rock through a heat transfer coefficient, h_T, defined by:

$$H = h_T(\theta - T_m) \tag{2}$$

The heat transfer coefficient is related to the flow variables by:

$$h_T = 0.02 \frac{k}{D} Pr^{0.4} Re^{0.8} \tag{3}$$

where k is the thermal conductivity of the magma, Pr is its Prandtl number and Re is the Reynolds number based on the dyke width.

Under turbulent flow conditions, and when $\theta > T_m$ heat flow through the walls causes them to melt at a rate given by:

$$U = \frac{h_T(\theta - T_m)}{\rho_\infty[c_\infty(T_m - T_\infty) + L_\infty]} \tag{4}$$

where ρ_∞, c_∞ and L_∞ are the density, specific heat and latent heat of fusion of the wall rock, and T_∞ is the far-field temperature of the wall rock. In the wall rock there is a conductive temperature profile, which also moves with constant velocity U ahead of the melting interface.

Balancing the heat flux through the dyke walls under steady conditions, we obtain the following differential equation for the temperature of the magma as a function of the vertical co-ordinate z:

$$\begin{aligned}
&[1 + c^{-1}L_x f'(T_L - \theta)] \frac{d\theta}{dz} \\
&\quad = -2(h_T/\rho c Q)(\theta - T_m) \\
&\qquad -(h_T/\rho_\infty Q)[c_\infty(T_m - T_\infty) + L_\infty]^{-1} \\
&\qquad \times (\theta - T_m)^2 + c^{-1}L_x f'(T_L - \theta)\frac{dT_L}{dz} - G
\end{aligned} \tag{5}$$

where c is the specific heat of the magma, L_x is its latent heat, T_L is the liquidus temperature (which is a function of z), Q is the flow rate per unit horizontal length of the dyke, G is the liquid adiabat of the magma, $f(T_L - \theta)$ is the fractional crystal content of the magma, which is a non-linear empirical function of the difference between the liquidus and ambient temperature and $f'(T_L - \theta)$ is the derivative of this function.

Calculations were carried out using three different magma compositions (Table 1). Composition (1) is a komatiite, composition (2) is a picritic basalt, and composition (3) is a tholeiitic basalt. Their estimated one atmosphere liquidus temperatures are listed in Table 1. Compositions (1) and (2) have olivine as the liquidus phase under all crustal pressures. Composition (3) is close to a multiply-saturated liquid at crustal pressures.

Additional relationships are required to take account of the variations in properties of wall rock and magma with depth. The geothermal gradient, which determines the value of T_∞ at a given depth, was assumed to be that given by Oxburgh [20] for the average continental anorogenic geotherm. An empirical function was fitted to this geotherm and the geothermal gradient could be changed by a simple multiplicative factor. The liquidus temperature gradient with depth was taken as 2.7°C/km, which is an adequate approximation of experimental data [21,22] for anhydrous systems. The adiabatic gradient was assumed to be 0.3°C/km. Empirical functions relating crystal content to temperature were derived from experimental data on each of the magma types for which calculations were made (Table 2). We assumed that the crystal

TABLE 1

Compositions of the three magma types used in the calculations: 1 = komatiite, 2 = picritic basalt, 3 = tholeiitic basalt. These compositions were principally used to derive empirical relationships between viscosity, crystal content and temperature for each magma type. The 1 atm liquidus temperature used for each magma is also listed. Compositions are simplified from analyses of lavas given in the literature

	1	2	3
SiO_2	46.9	47.8	50.3
TiO_2	0.2	0.6	1.8
Al_2O_3	3.7	12.0	16.1
FeO	10.2	9.0	11.1
MgO	33.0	17.8	6.9
CaO	5.3	11.2	9.7
Na_2O	0.5	1.3	3.0
K_2O	0.2	0.3	1.1
T (°C)	1650	1370	1200

content at a particular depth was dependent only on the difference between the magma temperature and the liquidus temperature at that depth. This is a simplification of the complicated relationships documented in experiments on natural compositions at different pressures. However, the calculations are not sensitive to detailed changes in phase relationships. Additional empirical functions, as listed in Table 2, were employed to relate the crystal content to the MgO content of the liquid and the viscosity of the magma. Values of the other physical parameters used are listed in Table 3.

All the above relationships assume that the flow is fully turbulent and thus that the Reynolds number is in excess of approximately 2000. They also assume that the flow has come to a steady state. They are not relevant to the initial stages of the flow, when the magma is beginning to force its way through the crust.

We assumed that the crust had a thickness of 40 km and divided it into a lower half with a melting temperature of 1200°C and an upper half with a melting temperature of 1000°C. This allowed us to investigate the relative contributions of lower and upper crust to the contaminant. While the real crust is much more complex and variable, we used an oversimplified crust in order to reveal the essential features of the model. The effects of further complexities are assessed in section 4.

The calculations required numerical solution of

TABLE 2

The formulae used for: fractional crystal content, X; magnesium oxide content expressed as a weight percentage, MgO; liquid viscosity in Pa s, μ_L; and bulk viscosity in Pa s, μ_B; where θ is the temperature in degrees Kelvin and T_L is the liquidus temperature

$$X = f(T_L - \theta)$$
$$= a\Delta\theta^3 + b\Delta\theta^2 + c\Delta\theta \qquad (\Delta\theta \equiv T_L - \theta)$$
$$\mathrm{MgO} = \alpha X^2 + \beta X + \gamma$$
$$\mu_L = A \exp(B/\theta)$$
$$\mu_B = \mu_L(1 - 1.67X)^{-2.5}$$

Komatiite

$a = 5.3809\times10^{-9}\ \mathrm{K}^{-3}$ $\quad \alpha = -47.707$
$b = -5.676\times10^{-6}\ \mathrm{K}^{-2}$ $\quad \beta = -10.404$
$c = 2.810\times10^{-3}\ \mathrm{K}^{-1}$ $\quad \gamma = 33$

$A = 3.64189\times10^{-7}\ \mathrm{MgO} + 1.1682\times10^{-6}$
$B = 25921.884 - 294.659\ \mathrm{MgO}$

Picritic basalt

$a = 7.3260\times10^{-8}\ \mathrm{K}^{-3}$ $\quad \alpha = -44$
$b = -1.575\times10^{-5}\ \mathrm{K}^{-2}$ $\quad \beta = -30.7$
$c = 2.347\times10^{-3}\ \mathrm{K}^{-1}$ $\quad \gamma = 17.78$

$A = 1.914\times10^{-7}\ \mathrm{MgO} + 4.745\times10^{-6}$
$B = 24668 - 256.845\ \mathrm{MgO}$

Tholeiitic basalt

$a = 0$ $\quad \alpha = -44$
$b = 0$ $\quad \beta = -30.7$
$c = 0.005\ \mathrm{K}^{-1}$ $\quad \gamma = 17.78$

$A = 6.636\times10^{-6}$
$B = 2.213\times10^{4}$

TABLE 3

The values of the physical parameters used in this study (z is the depth in km)

$c = c_\infty = 730$ J/kg °C
$k = 1$ W/m °C
$L_x = 8\times10^5$ J/kg
$\rho = 2800$ kg/m^3
$\rho_\infty = 2700$ kg/m^3
$T_\infty = 8.211\times10^{-3} z^3 - 0.8z^2 + 30.875z$

$$\left.\begin{array}{l} T_m = 1000°\mathrm{C} \\ L_\infty = 3\times10^5\ \mathrm{J/kg} \end{array}\right\} (z < 20\ \mathrm{km})$$

$$\left.\begin{array}{l} T_m = 1200°\mathrm{C} \\ L_\infty = 4\times10^5\ \mathrm{J/kg} \end{array}\right\} (z > 20\ \mathrm{km})$$

(5) since many of the parameters are depth dependent and the viscosity will increase as the ascending magma cools and crystallizes. Two kinds of calculation were carried out. The majority of calculations involved specifying the flow rate and the initial magma temperature at the base of the crust. We then determined the variation of temperature, crystal content, melting rate, Reynolds number and amount of contamination with height. In the second kind of calculation, we determined the flow rate that allowed the magma to erupt at its one atmosphere liquidus temperature.

In interpreting the geological significance of the quantitative results, two aspects of the model should be borne in mind. First, the results are based directly on the heat-transfer formula (3). While this is a good fit to laboratory experiments conducted over a wide range of Prandtl and Reynolds numbers, its application to magmatic conditions requires extrapolation of the Prandtl number. Second, the model does not take into account the variation of viscosity with temperature of the magma close to the melting wall rock. Laboratory experiments suggest that this variation has only a weak influence on the heat-transfer coefficient; but again, the geological range of variation lies outside laboratory conditions.

3. Results

3.1. *Eruption temperatures and crystal contents*

Variations of temperature with depth and flow rate are plotted in Fig. 1 for each of the three magma types. In these calculations the input temperatures were assumed to be the liquidus temperatures at a pressure equivalent to 40 km depth. For all three magma types, the eruption temperature increases with increasing flow rate. The variation of crystal content with depth is shown in Fig. 2. Above some critical flow rate the magma ascent rate is sufficiently large that no crystallization occurs and the lava erupts in a superheated condition.

The flow rate required to erupt at the liquidus temperature increases as the magma becomes more Mg-rich and primitive. The values of Q for this condition are 1950, 170 and 44 m^2/s for the komatiite, picritic basalt and tholeiitic basalt respectively. These rates require fracture widths of 53, 10.6 and 4.3 m. If dyke widths are typically 1–10 m, then komatiites and, to a lesser extent, picritic basalts, will tend to reach the surface with moderate to high olivine phenocryst contents. The calculations suggest that it is difficult for komatiitic liquids with MgO contents of approximately 30% to reach the Earth's surface by passing through thick continental crust. The fact that such liquid compositions have been recognised in the chilled margins of some komatiites [23] suggests that such lavas either have not traversed thick crust or have erupted at exceptionally large flow rates along wide fractures.

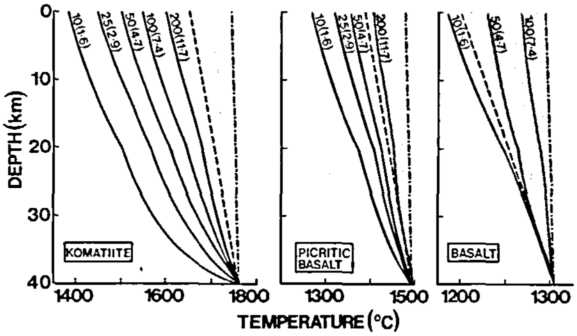

Fig. 1. The variation of magma temperature as a function of depth for the three magma types. Each curve is for a different flow rate in m^2/s. The corresponding dyke width in metres is given in parenthesis. The stippled areas represent regions of superheated magma. The dash-dot line is the liquid adiabat and the dashed line is the liquidus temperature as a function of depth.

The calculations for basaltic magma contrast markedly with those for more Mg-rich magma types. Since basalts have higher viscosities, larger flow rates are required to produce turbulent condi-

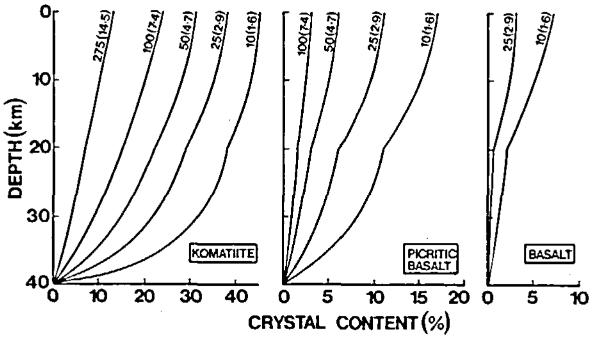

Fig. 2. The variation of crystal content as a function of depth for the three magma types. Each curve is for a different flow rate in m^2/s. The corresponding dyke width is given in parenthesis.

tions. For example, at $Q = 10$ m^2/s, the Reynolds number varies from 3500 at the base of the crust to only 800 on eruption. The value at the surface is transitional between completely laminar and turbulent conditions. Our calculations would undoubtedly be invalid for lower flow rates, where for $Q = 10$ m^2/s, the phenocryst content is calculated at only 7% and flow rates greater than 44 m^2/s cause superheated lava to erupt (assuming no phenocrysts have been inherited from the magma chamber).

Under laminar flow conditions, heat transfer is much less efficient, so there would be even less heat loss for flow rates less than 10 m^2/s. In laminar flow within a dyke a thermal boundary layer penetrates into the flow by conduction. The distance along the dyke at which the centre of the flow begins to cool significantly is often termed the thermal entry length. This length has been calculated as several hundred kilometres for flows travelling with velocities of order 1 m/s in dykes a few metres wide [19,24]. Although the formation and growth of a chilled margin is likely to reduce the thermal entry length, it is a fundamental requirement of laminar ascent through the crust that the thermal entry length is greater than the crustal thickness. Thus the magma that erupts will have undergone negligible cooling and few crystals could have formed.

The influence of the initial input temperature on the output temperature is surprisingly small. Fig. 3 shows the results for the komatiite magma with $Q = 50$ m^2/s and the assumption that the temperature at the base of the conduit is either 1757°C or 1850°C. The higher temperature represents a strongly superheated liquid. However, the exit temperatures are 1501°C and 1505°C, respectively. The superheated lava cools more rapidly initially since there is no crystallization, and the heat transfer rate is somewhat greater due to the lower viscosity. The same kind of result was found for the other magma types.

The geothermal gradient also has little influence on the temperature profiles calculated (though it will have on the amount of contamination). For a komatiite ascending at $Q = 100$ m^2/s with the average modern continental geotherm, and with twice this average gradient, the eruption temperatures are calculated at 1541 and 1542°C, respectively. This small difference arises because the influence of the geothermal gradient on the temperature profile is only through the second term on the right-hand side of (5), which represents the loss of heat from the magma required to raise the temperature of the melted wall rock, at T_m, to that of the magma, at θ. The value of this term is very much less than that of the first term, which represents the decline of temperature due to heat transfer between the hot magma and the relatively cold wall past which it flows.

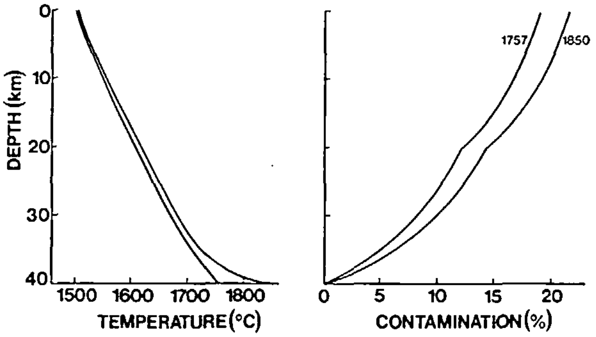

Fig. 3. The variation of temperature and amount of contamination with depth for a komatiite flowing at $Q = 50$ m^2/s. The two curves compare a komatiite which begins ascent on its liquidus at 1757°C and one which is strongly superheated at 1850°C.

3.2. *Contamination*

Fig. 4 shows the variation with depth of the amount of wall rock assimilated for the three magma types for different flow rates. Fig. 5 shows the variation with depth of the contamination and melting rate for $Q = 25$ m^2/s ($D = 2.9$ m) for the three magma types. Fig. 6 shows the final amount

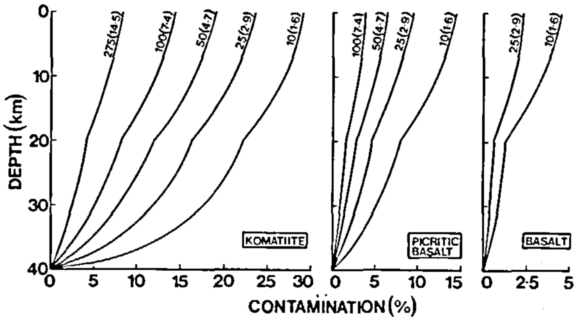

Fig. 4. The variation of the amount of contamination with depth for the three magma types. Each curve is for a different flow rate in m^2/s.

of contamination for each of the three magma types as a function of flow rate.

The results confirm that komatiites are highly susceptible to crustal contamination. For slow ascent rates, the total amount of contamination can reach 25% by mass. These values are substantially higher than the calculations of the contamination of komatiite lavas flowing over the ground [13]. The difference is due to the melting of two solid boundaries in a dyke, whereas in a horizontal flow approximately half the heat is lost to overlying seawater. The difference is also due to the relatively larger temperature contrast between the rising magma and the melting temperature of the surrounding rock. If komatiites ascend through continental crust, it is clear that they can become severely contaminated. The amount of contamination of the erupted lava decreases with increasing flow rate (Fig. 6). Comparison of the calculations for the three magma types illustrates that higher temperature Mg-rich magmas are more susceptible to contamination effects than evolved Mg-poor magmas.

Under laminar flow conditions heat transfer to the walls is by conduction and the transfer rates are very much less than if the flow is turbulent. Further, the temperature of the interface between the magma and the dyke wall is approximately the mean of the centre-line magma temperature and the geothermal temperature at that depth. This is generally less than the solidification temperature of the magma, and so a congealed magma skin grows on the dyke walls which decreases the dyke width and protects the wall from melting.

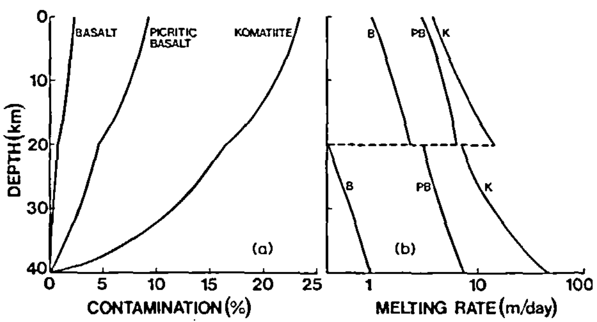

Fig. 5. (a) The variation of contamination with depth for the three magma types for a flow rate of $Q = 25$ m^2/s. (b) Melting rates.

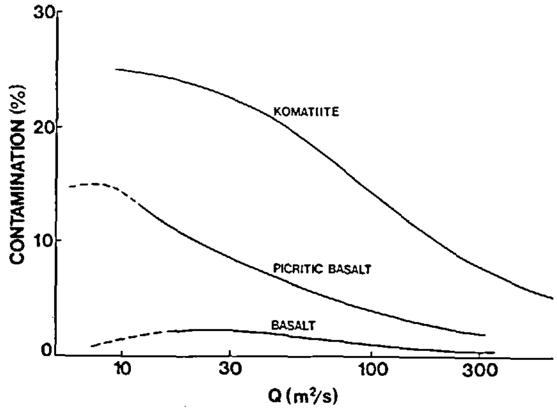

Fig. 6. The total contamination of magma as it erupts onto the earth's surface is shown as a function of flow rate for each of the three magma types. The dashed parts of the curves indicate flow rates where the Reynolds number becomes transitional.

Our calculations show that maximum contamination should be observed in lavas which ascend at Reynolds numbers close to 2000, with a decline in contamination as flow rate and Reynolds number increase (Fig. 6). In a volcanic province discharging lavas at a wide variety of flow rates, little or no contamination should be observed in low flow rate lavas, which would tend to be those of small volume and extent [25]. Lavas erupting just above the critical flow rate would be the most contaminated, whereas those erupting at very high flow rates may again be little contaminated.

In Fig. 4 the melting rates show a discontinuity at the boundary between the upper and lower crust. This is a consequence of the assumption that there is a change of fusion temperature at this boundary. Inspection of equation (4) shows that melting rates increase as the fusion temperature of the wall rock decreases. Thus contamination will be selective towards rocks with lower fusion temperatures, which tend to be concentrated in the upper crust. This concept is reflected in our calculations by the abrupt increase in melting rate at the lower–upper crust boundary. However, ascending magma is hotter and more fluid at depth; this will tend to selectively assimilate lower crustal material. The net result is illustrated in our calculations by the steady decrease of melting rate with height in both the lower and upper crust segments. The relative role of these competing effects can be assessed by calculating the amount of lower crust in the contaminant in the two-layer model (Fig. 7).

An additional principle is illustrated in this diagram: higher temperature magmas are less selective than lower temperature magmas.

In the calculations the komatiite is contaminated by a larger proportion of lower crust than upper crust. This is because komatiite has a much higher temperature than the fusion temperatures of most crustal rocks, and therefore the influence of Reynolds number on the amount of selective contamination is paramount. The largest difference between the fusion temperature of the wall rocks and the temperature of komatiite occurs at the base of the crust and results in a larger proportion of lower crust being assimilated. The bias towards lower crust assimilation decreases with increasing flow rate. In the case of the picritic basalt, contamination of the two halves is approximately equal with the competing effects counterbalancing one another.

In contrast, basaltic magma is much closer in temperatures to the fusion temperatures of crustal rocks. Indeed, there are many mafic rocks in the crust which may have higher fusion temperatures than the basalt and so could not be assimilated. Basalts are thus likely to be highly selective, being contaminated preferentially by rocks with low fusion temperatures. This principle is illustrated in Fig. 5 by the lower melting rates in the lower crust due to the small difference between the basalt temperature and fusion temperature of the wall rocks. Consequently in the model calculations, the basalt is selectively contaminated with upper crust (Fig. 7).

In reality, continental crust contains a complicated variety of rock types ranging from those with low fusion temperatures, such as pegmatite and granite, to those with refractory compositions, such as gabbros, amphibolites and ultramafics. However, the same principles illustrated in the calculations will hold in a geologically complex crust. Rock types with low fusion temperatures also have lower heats of fusion since they generally contain a higher proportion of minerals with low heats of fusion such as alkali feldspar and sodic plagioclase. Such rock types would be preferentially assimilated. Contamination would be most selective for lower temperature and more evolved magmas such as basalt. These considerations suggest that in regions where magmas at different stages of evolution and thus with different temperatures are ascending through the crust, a contamination by a single end-member composition is unlikely. Evolved magmas might be contaminated with the most fusible rock types, whereas high temperature primitive magmas will contain a greater proportion of more refractory materials in the contaminant.

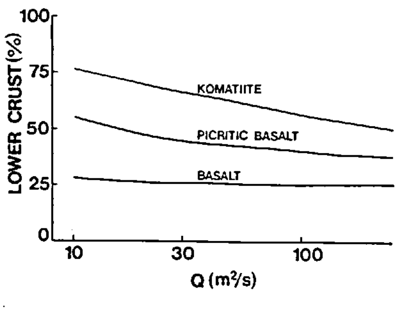

Fig. 7. The percentage of lower crust in the contaminant as a function of the flow rate for the three magma types.

The influence of the geothermal gradient on contamination is illustrated in Fig. 8 for a komatiite with $Q = 100$ m^2/s. The melting rate increases significantly as the geothermal gradient increases and thus results in larger values of the total contamination. If the geothermal gradient becomes large enough, some rocks can become partially molten. Those rocks with the lowest fusion temperatures should contain the highest proportion of partial melt. As far as the contamination process is concerned, partial melting has the effect of reducing the heat of fusion and increasing the melting rate. Consequently, there should be an even greater bias in favour of low fusion temperature rocks if the crust becomes incipiently partially melted. As partial melting is likely to begin at the base of the crust, rock types with low fusion temperatures in the lower crust should be preferentially assimilated.

Melting rates of the dyke side wall are calculated at typically a few metres to a few tens of metres per day. Though the calculations have embodied a prescribed dyke width, D, the gradual increase in that width can be followed by allowing D to vary in the steady-state method. The calculated melting rates are sufficient to cause considerable widening of the dyke fracture either along its length or locally. Some of the major dykes crossing large continental regions can be ten to several

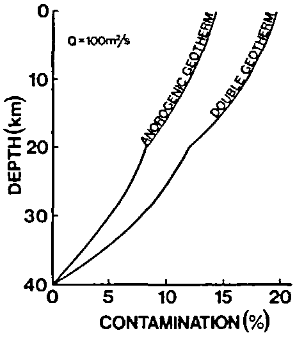

Fig. 8. The variation of contamination with depth for a komatiite at $Q = 100\ m^2/s$. The curves are for the modern average anorogenic geotherm [19] and a geotherm with double this gradient (i.e. the temperature is twice that of the anorogenic geotherm at any depth).

hundred metres wide. It is worth speculating that some of the wider dykes owe their dimensions to thermal erosion during a prolonged period of magma flow.

4. Geological consequences

4.1. Continental basalts

Recent investigations of continental basalt provinces have emphasised that two styles of crustal contamination are commonly encountered [26]. In one, contamination is accompanied by fractionation and is widely considered to occur in magma chambers where the heat released by fractional crystallization allows fusion of the wall rock of the magma chamber. In the other, the most primitive lavas are the most contaminated, whereas more differentiated lavas show less contamination.

Assimilation and fractional crystallization (AFC) in magma chambers have been analysed by DePaolo [9] under the assumption that the magma in the chamber is spatially uniform. The AFC model has been widely used [27–29] to interpret geochemical variations in suites of volcanic rocks. AFC is characterised by systematic changes in indices of differentiation, such as SiO_2 and $Fe/(Fe + Mg)$, with incompatible trace element ratios and isotopic parameters which reflect increasing contamination. We note in passing that, although DePaolo [9] analysed the mathematics of AFC processes, the geochemical relationships have yet to be quantitatively related to the thermal and fluid dynamic processes that cause contamination in magma chambers.

The other style of contamination has been recognised in the plateau lavas of the Hebrides [4,5] and in the Deccan trap lavas [30–32]. Workers in the Hebrides [2,4,5,22,33] have particularly emphasised the idea that contamination occurred in a plexus of sills and dykes and that the contamination is highly selective. Some of the geochemical characteristics of the SMLS were acquired after differentiation of the magmas in deep magma chambers within or below the lower crust [22]. The isotopic data in particular [2,4] require that a substantial proportion of the Pb and Nd and some of the Sr is derived from the lower crust, which is usually assumed to be granulite-facies Lewisian gneiss. Smaller proportions of amphibolite-facies Lewisian gneiss are also admissible. Trace element "spidergrams" of SMLS [22,32] give convincing circumstantial evidence of contamination by granulite. In the Deccan lavas positive correlations between Mg number and $^{87}Sr/^{86}Sr$ and between Ni and K_2O [30,32,34] indicate that the most primitive magmas are the most contaminated by continental crust.

The geochemical effects of contamination during magma ascent contrast in several ways with contamination during AFC in a magma chamber. The various effects on major elements, trace elements and isotopes are now discussed, specifically those related to the situations where magma is variably fractionated in deep magma chambers and then periodically ascends to the surface.

4.1.1. Major elements

The geochemical effects sometimes linked with crustal contamination include increases in SiO_2 and alkalis. However, the most primitive, hottest, and therefore most SiO_2 and alkali-poor magma can become more contaminated than an evolved magma. Consider the hypothetical case of contamination of a primitive magma containing 46% SiO_2 and 0.2% K_2O with granite containing 70% SiO_2 and 5% K_2O. 50% fractional crystallization of the primitive magma without contamination might produce a magma with a K_2O content of 0.4% and an SiO_2 content of 50% (Fig. 9). Contamination of the picritic magma by 10% granite would produce a magma with 0.65% K_2O but only 48.4% SiO_2. Magmas with compositions between the primitive and highly fractionated basalt would

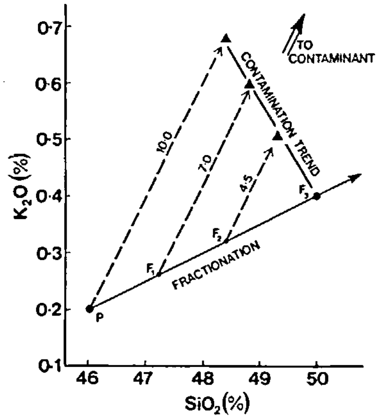

Fig. 9. Illustration of how contamination during turbulent ascent could affect the relationship between K_2O and SiO_2. A primitive magma, P, would produce a positive correlation between the two elements by fractional crystallization (say of olivine) in a subcrustal magma chamber. During the subsequent ascent of magmas with compositions between P and F_3 contamination occurs. The amount of contamination is greatest for the most primitive magma. Magmas P, F_1 and F_2 are transposed to new positions by 10%, 7% and 4.5% contamination of granite with 70% SiO_2 and 5% K_2O, producing a negative correlation and a trend which points neither to the contaminant nor to the most primitive magma. The amounts of contamination chosen are arbitrary and a contamination trend need not be a straight line.

be able to assimilate intermediate amounts during ascent. In this simple example, an *anticorrelation* would be observed between K_2O and SiO_2. We note that on such a diagram the geochemical trend points neither to the primitive magma nor to the crustal contaminant. In this particular case the trend is at right angles to mixing lines connecting basalts and contaminants.

Contamination is, of course, associated with crystallization in the ascent model, and thus the trend illustrated in Fig. 9 is of *whole rock compositions*. Liquid compositions produced by contamination during ascent will inevitably be more evolved than the original primitive magma, since crystallization has provided part of the thermal energy for wall-rock fusion. However, the contaminated residual liquid of the primitive magma can still be less evolved than an uncontaminated differentiated magma.

In practice, the variations in crustal rock types, flow rates, and variation in the composition and temperature of uncontaminated mafic magma would cause dispersion and scattered rather than tight trends. Further dispersion and scatter could also be anticipated in a crustal magma system by other kinds of crustal contamination processes [7–11]. Absence of correlations between major elements such as SiO_2 and indices of contamination cannot be construed as convincing arguments against contamination.

Contamination of the primitive magma would not significantly change the Fe/Mg ratio, but would increase the SiO_2 content. For example, if the uncontaminated primitive magma were nepheline normative, the contaminated magma could become silica saturated with little change in Fe/Mg ratio. The correlation between ϵ_{Nd} and saturation indices in Skye [4] suggests that contamination is a contributing factor to the range of basalt types in this area.

4.1.2. Trace elements

In this style of contamination, incompatible trace element abundances could become more enriched in primitive magmas than in evolved magmas. Such elements would behave in the same way as K_2O (Fig. 9). Primitive and uncontaminated magmas tend to have lower concentrations of incompatible trace elements. Consequently, contamination effects are accentuated since a given amount of contamination has a larger influence in a primitive lava than in an evolved magma, already enriched in trace elements by fractional crystallization.

One consequence of this style of contamination is that positive correlations between highly compatible and highly incompatible trace elements might be expected. This effect is illustrated in Fig. 10a for Ni and K_2O and an example of such a correlation from the Deccan trap lavas is given in Fig. 10b. In the Deccan lavas considerable scatter in the correlation is to be expected given the many variables that might influence the contamination of any individual lava and the possible influences of other processes such as fractionation and partial fusion on both Ni and K_2O contents. The nickel-rich lavas also tend to be those richest in ^{87}Sr [32,34,35] which supports the interpretation that this trend is associated with crustal contamination.

On diagrams of trace element ratios against other trace elements or isotopic parameters, mixing between two end member compositions (a magma and a contaminant) define a mixing hyperbola. In this style of contamination, however,

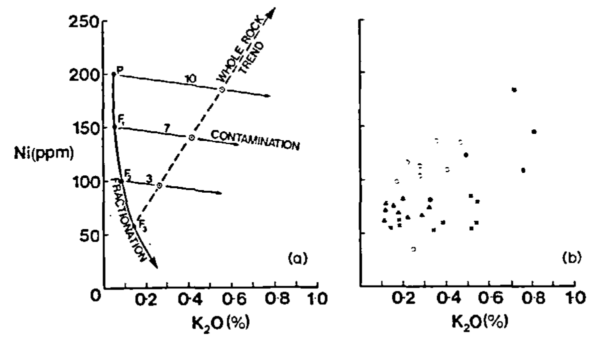

Fig. 10. Plots of Ni versus K_2O. (a) Hypothetical example of trends produced by fractional crystallization and contamination. A primitive magma, *P*, would generate a steep trend of declining Ni with increasing K_2O content by fractional crystallization. During subsequent ascent magmas *P*, F_1 and F_2 are transposed to new positions by 10%, 7% and 3% contamination of granite with 10 ppm Ni and 5% K_2O. The systematic increase in total contamination with increasing Ni content results in a positive correlation in whole rock compositions. (b) Scattered positive correlation in Deccan trap lavas. Unpublished data kindly communicated by K.G. Cox. Lavas described in reference 32. Each symbol represents a different stratigraphic package of lavas. Legend: ● = Bushe lavas; ○ = Upper Poladpur; × = Lower Poladpur; ▲ = Ambenali.

As suggested by the ascent model, the most primitive magma is the most contaminated, but is less selective, so might be contaminated by a higher proportion of intermediate gneiss. The more evolved magmas will be less contaminated but might be contaminated by a higher proportion of leucogneiss with strongly negative ϵ_{Nd}. Each contaminated magma will thus fall on a different mixing hyperbola and will also involve a different amount of contaminant. A well-defined trend can be generated in the ascent model since there are systematic relationships between bulk composition of contaminant, the amount of contamination, and magma temperature. Construction of the compositional trend is shown in Fig. 11. This trend does not point towards the end member composition of the contaminant and does not represent a mixing hyperbola. We emphasise that we have no grounds for preferring this model to that of Thirlwall and Jones [4] and indeed the specific model may well be inconsistent with other geochemical data on SMLS. The purpose of Fig. 11 is to illustrate that curved trends on such diagrams may not represent a hyperbola and need not point towards the end member contaminant. This point is illustrated with a hypothetical example on a plot of ϵ_{Nd} versus K/Zr (Fig. 11). The trend shown is similar to that shown by lavas of the SMLS [4] which plots on a curve which trends to a constant value of ϵ_{Nd} of approximately -10 at large K/Zr ratios. Thirlwall and Jones [4] suggest that this is a mixing hyperbola and that the crustal end member is an intermediate tonalitic Lewisian gneiss with $\epsilon_{Nd} = -10$ to -15. This interpretation may well be correct, but the contamination model presented here allows alternative interpretations of such a diagram and is illustrated in Fig. 11. The potential contaminants are assumed to be Lewisian granulite ranging from an intermediate tonalitic gneiss with Nd = 23 ppm and K/Zr = 63 to a leucogneiss with Nd = 40 ppm and K/Zr = 70. These values are consistent with published geochemical data [4,36], but we note that plotting individual rock specimens on such a diagram would probably produce a scattered set of data rather than a tight trend. We assume that the initial Nd content of the primitive lava is 3 ppm and that the K/Zr ratio is 23 and is not changed by fractionation.

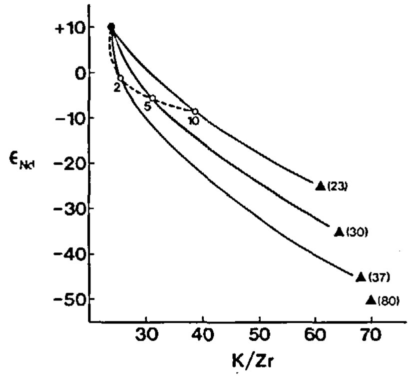

Fig. 11. A hypothetical trend of ϵ_{Nd} versus K/Zr produced by contamination of magma by granulite facies gneiss. A similar trend has been documented for the SMLS by Thirlwall and Jones [4]. The uncontaminated basalt magmas plot at a single point at $\epsilon_{Nd} = +10$ and K/Zr = 24. The potential contaminants range from an intermediate gneiss (Nd = 23 ppm, $\epsilon_{Nd} = -25$ and K/Zr = 61) to a leucogneiss (Nd = 80 ppm, $\epsilon_{Nd} = -50$ and K/Zr = 70). Assuming that the basaltic magmas have 3 ppm Nd, a series of mixing hyperbolae connect compositions between the intermediate gneiss and leucogneiss. The three circles represent compositions of contaminated lava, each of which fall on different mixing hyperbolae. The most primitive magma is contaminated by a greater proportion of intermediate gneiss and also has a larger total contamination. A trend produced in this way is not itself a mixing hyperbola and does not point towards any of the end member contaminant compositions.

it cannot be assumed that curved trends on such diagrams necessarily represent mixing hyperbolae.

4.1.3. Isotopes

Preferential addition of ancient crustal rocks to primitive magmas rather than evolved magmas should produce distinctive isotopic signatures. In the case of Sr, most primitive magmas have lower Sr contents than evolved magmas, so that the effects of contamination would be enhanced. For example, in the Hebrides, lower crustal rocks typically contain 400–600 ppm Sr, primitive uncontaminated basalts 100 ppm Sr, and evolved magmas several hundred ppm Sr [37]. If the primitive magmas are more contaminated, then they should have the highest $^{87}Sr/^{86}Sr$, although the increase in total Sr content might not be great. An inverse correlation between Sr and $^{87}Sr/^{86}Sr$ has been documented in the Skye lavas [37]. Moorbath and Thompson [37] argue that the ^{87}Sr contamination must have occurred *after* the magmas had been fractionated to varying degrees. An AFC model would produce an increase in ^{87}Sr with total Sr. The ascent model thus provides a consistent explanation of the relationships observed in the Skye lavas.

The Sr, Pb and Nd isotopic compositions of Skye lavas are widely interpreted as the consequence of selective contamination of the magmas, predominantly with leucocratic granulite facies gneiss [32,36]. Such rock types have low fusion temperatures and heats of fusion. The selective character of contamination on Skye appears to be what would be expected in the present model.

In the Deccan Trap lavas Cox and Hawkesworth [32] have observed that increases in Mg-number coincide with increases in $^{87}Sr/^{86}Sr$.

4.2. Petrography of lavas

The calculations allow predictions to be made on the petrographic features of erupted lavas which can be compared with observations. Turbulent ascent is likely to be common in hot, low-viscosity primitive magmas, which inevitably have olivine as the only major liquidus phase at crustal pressures. The calculations suggest that high-magnesia lavas, such as picritic basalt and komatiite, should erupt in a porphyritic condition if they ascend along fractures a few metres in width. The olivines grown during ascent would have crystallized while suspended in the liquid. High-magnesia lava sequences are typically porphyritic and Cox [38,39] has demonstrated that their high crystal content cannot always be explained by accumulation. Cox rather suggests that the crystals have grown from high-magnesia liquids without loss of phenocrysts. Advanced crystallization or contamination during turbulent ascent provides an explanation of Cox's petrographic observations.

In the case of basaltic magmas, in which phases other than olivine are important, the magmas are usually sufficiently viscous that high flow rates along wide dykes are required for turbulent ascent. The flow rates are sufficiently great that little or no crystallization can take place during ascent. As argued in section 3.1, there is also little likelihood of much crystallization or contamination during laminar ascent. Thus if abundant phenocrysts are present, they are likely to have been inherited from the magma chamber. It is interesting to note that if basalts are contaminated during ascent, then the phenocrysts and groundmass should be out of isotopic equilibrium.

4.3. Komatiites

Our calculations show that komatiites are very susceptible to contamination and crystallization during ascent through thick crust. The interpretation of their geochemistry and environment of eruption must therefore be considered with these physical constraints in mind.

There is still considerable doubt about whether komatiites ascended through continental crust, or whether they erupted in an oceanic basin adjacent to a continent. Available evidence [6] indicates that examples of both situations occur. In the case of continental crust, very rapid ascent rates are necessary to avoid extensive olivine crystallization and substantial contamination. The observation [23] that some chilled margins have MgO contents of 30% suggests that komatiites occasionally reached the surface without much crystallization. In a continental environment this requires flow rates in excess of 10^3 m^2/s, dykes of order 50 m wide and therefore very large individual eruption volumes. The observation that komatiite horizons can be traced for hundreds of kilometres [6] supports the idea that komatiites have large volume.

Alternatively, for komatiitic liquids with high MgO contents, less extreme flow rates would be required if they erupted in an oceanic setting with no continental crust and a much steeper geothermal gradient.

Contamination in komatiites has proved to be a contentious issue [40,41]. In some areas, such as the Abitibi belt of Ontario, primitive komatiites have very low abundances of incompatible trace elements [42–44] which, together with their high temperature, makes them very susceptible to contamination by crustal materials. Our calculations indicate that some komatiites could have suffered drastic changes to their chemical composition on traversing the crust. Ascent through the continental crust is also not necessary for crustal contamination to occur. Even in an oceanic setting, komatiite can become contaminated by basalt and sediment derived from neighbouring continental crust during ascent and flow along the ground. Chauvel et al. [45] have shown that the ages of komatiites determined by Sm-Nd studies are sometimes older than the ages determined by other methods on rocks of greenstone belts. This discrepancy could be interpreted as an effect of contamination of an older REE-rich crustal component, producing an initial slope on a $^{143}Nd/^{144}Nd$ versus Sm/Nd ratio diagram.

Our calculations suggest that pristine mantle geochemical characteristics of komatiites are most likely to be preserved in the most primitive and magnesian rocks taken from aphyric chilled margins. The fact that such liquids reached the surface at all must imply that the flow conditions during ascent were such that little crystallization occurred. However, even with a flow rate of about 1000 m^2/s, and little crystallization, we calculate 2% contamination for a 40 km thick crust. Such an amount would have little effect on major element abundances, but could still produce significant changes in trace element abundances.

Another problem in komatiite studies concerns the relationship between komatiites and basaltic komatiites which can often be in close stratigraphic association [6,42,43]. The trace element characteristics of associated komatiites and basaltic komatiites [42,43] can also be very variable in terms of parameters such as Ti/Zr, total REE and Ce/Yb ratios showing much larger variations than could be attributed to fractional crystallization or variable partial melting of a homogeneous mantle source. Cameron et al. [46] have also noted that basaltic komatiites are often unusually silica rich for Mg-rich lavas. One plausible explanation for this variety is mantle heterogeneity, in which case the trace element enrichment observed in basaltic komatiites implies that they cannot be genetically linked to the komatiites despite their close stratigraphic association.

As an alternative, contamination could account for some of the variations in geochemistry and thus the geochemical data may not preclude a genetic link between komatiite and basaltic komatiite. These magma types could be linked in the following way. Consider the case where the primitive komatiite is a 30% MgO melt derived from a depleted mantle source and is required to traverse continental crust. Suppose that such melts derived deep in the mantle traverse the crust at a variety of flow rates. We would anticipate that flow rates would vary substantially even in one eruption due to the interplay between two competing factors. First, the erosion rates of komatiite can often be tens of metres per day and an initially narrow fracture would widen rapidly and allow greater flow. Second, the driving pressure may decrease as magma is discharged and result in a decline in the flow rate. Our calculations suggest that the amount of contamination varies greatly with flow rate. Thus for 10 m^2/s, the komatiite would erupt with a crystal content of 45% and would contain 30% by mass of crust. Such a magma would no longer be a komatiite but a highly porphyritic basaltic komatiite, enriched in incompatible trace elements and silica derived from the crust. Such crystal-rich magmas could well find difficulty in getting to the surface and could become trapped within the crust as sills and magma chambers. Separation of the olivine phenocrysts and further fractionation could yield trace element-rich and silicious basaltic komatiites.

In this model the more fractionated liquids are the most contaminated, which is apparently in conflict with the relationships suggested for continental basaltic provinces such as Skye. However, in the model for Skye, the magmas evolve in deep chambers at the base of the crust and then ascend to the surface. In this case the composition and temperature of each batch of ascending magma varies substantially, resulting in a correlation between contamination and primitiveness. Where variable degrees of mantle fusion have resulted in primitive magmas with varying incompatible trace element concentrations (and ratios), the simple relationship suggested will become more complex, as has been documented on Skye [22].

Another kind of situation, however, can be envisaged in which a primitive magma of constant composition periodically ascends directly from the mantle source and no deep crustal reservoirs develop. In this case the principal control on contamination will be the flow rate. As flow rate decreases, the magmas become more contaminated, crystal-rich and the *liquids* evolve towards basaltic komatiite compositions. Separation of olivine phenocrysts from the contaminated magma in shallow sills and in the lavas can produce contaminated basaltic komatiite.

5. Conclusions

The ascent of mafic and ultramafic magmas through the crust under turbulent flow conditions should produce a number of recognisable features in the petrology and geochemistry of the resultant lavas.

(1) For a given flow rate, the phenocryst content should increase as the magma becomes more primitive. Komatiites and picritic basalts have high olivine phenocryst contents unless the flow rates are very high. Tholeiitic basalts, however, form few phenocrysts during ascent. Phenocrysts in basalts would mostly be inherited from the magma chamber.

(2) In some provinces, deep magma chambers can develop at the base of the crust or in the mantle where fractionation can occur. When magmas from these chambers subsequently ascend through the crust, the amount of contamination is greater for those magmas that are more primitive. Thus geochemical parameters that reflect contamination should negatively correlate with those parameters that reflect degree of fractionation. This correlation is opposite to that which would be expected in assimilation fractional crystallization (AFC) within magma chambers, where there is a positive correlation between fractionation and contamination indices.

(3) Trends on many geochemical diagrams are not mixing hyperbolae, because magma temperature and flow rate are involved as additional parameters. Such trends need not point towards the contaminant.

(4) In basalts, AFC processes in magma chambers may be distinguishable from contamination during ascent by studying the isotope geochemistry of phenocrysts and groundmass. In the ascent model, the phenocrysts would be formed largely in the magma chamber before contamination and should be out of isotopic equilibrium with the contaminated groundmass. In AFC processes, the phenocrysts are formed during contamination and are more likely to be in isotopic equilibrium.

(5) Rock types with low fusion temperatures are selectively melted. Primitive magmas are, however, less selective than cooler evolved magmas. Thus the composition of the contaminant could systematically vary as a function of magma temperature. This provides an additional complication in interpreting trends on geochemical diagrams. Rocks with low fusion temperatures tend to be concentrated in the upper crust, while magma is hotter in the lower crust. Calculations on a simple two-layer crust indicate that contamination in basalts will be strongly biased towards low fusion temperature rock types, whereas contamination with the more refractory rocks of the lower crust becomes increasingly important as the magma becomes more primitive and hotter.

(6) Contamination also varies with the flow rate. Maximum contamination occurs at a flow rate corresponding to a Reynolds number of approximately 2000. When the flow is entirely laminar, some of the rising magma solidifies on the dyke wall, preventing contamination of the remainder flowing within the dyke. There should be a bimodality in provinces where flow rates span the critical value: contaminated and relatively uncontaminated lavas would be associated.

(7) Our calculations provide constraints on one aspect of the physical processes involved in genesis of continental basalts. In flood basalt provinces, where the flow rates were probably often high enough for turbulent conditions [14], some crustal contamination seems inevitable. However, the same principles should also apply to magmas traversing the ancient mantle part of the continental lithosphere. Recent studies (summarised in Norry and Fitton [1]) suggest that this mantle has been metasomatised and is extensively veined. The veins,

which are enriched in trace elements and perhaps radiogenic Sr, have compositions which imply low fusion temperatures compared with their mantle host. Thus magmas ascending from the asthenosphere should also assimilate these veins selectively. The geochemical complexity of flood basalt provinces [3,27,30,36,38,47] suggests that both enriched mantle and continental crust can be involved in basalt genesis. In the particular model of contamination treated here, considerable variations in the contributions of these two sources could arise just from variations in the flow rate and magma temperature. Other mechanisms, such as AFC in magma chambers [9] or selective element contamination [10,11], would contribute even further to the diversity encountered.

(8) If primitive magma ascends directly to the surface, the geochemical effects of contamination will be different from that in situations in which deep magma chambers develop. If the primitive magma has a constant composition, then the main control on contamination will be flow rate. The most contaminated magmas will thus be crystal-rich and contain contaminated and fractionated *liquids*. If erupted *liquid* compositions are investigated, the contamination will increase with fractionation as in AFC. Komatiites are examples of magmas that are likely to have ascended directly from deep within the mantle. The process might account for the enrichment of trace elements observed in associated siliceous basaltic komatiites, which could be liquids derived by separation of olivine, either in lavas or in shallow sills.

(9) Magma extrusion temperatures have apparently declined with geological time. If hotter magmas were available in the Archean for ascent through the crust, we can speculate that contamination was more significant then.

Acknowledgements

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References

1 M.J. Norry and J.G. Fitton, Compositional differences between oceanic and continental basic lavas and their significance, in: Continental Basalts and Mantle Xenoliths, C.J. Hawkesworth and M.J. Norry, eds., Shiva Geol. Ser., pp. 5–19, 1983.
2 A.P. Dickin, Isotope geochemistry of Tertiary igneous rocks from the Isle of Skye, Scotland, J. Petrol. 22, 155–189, 1981.
3 C.W. Carlson, G.W. Lugmair and J.D. MacDougall, Columbia River volcanism: the question of mantle heterogeneity or crustal contamination, Geochim. Cosmochim. Acta 45, 2483–2499, 1981.
4 M.F. Thirlwall and N.W. Jones, Isotope geochemistry and contamination mechanics of Tertiary lavas from Skye, Northwest Scotland, in: Continental Basalts and Mantle Xenoliths, C.J. Hawkesworth and M.J. Norry, eds., Shiva Geol. Ser., pp. 186–228, 1983.
5 R.N. Thompson, A.P. Dickin, I.L. Gibson and M.A. Morrison, Elemental fingerprints of isotopic contamination of Hebridean province mantle-derived magmas by Archean sial, Contrib. Mineral. Petrol. 79, 159–168, 1982.
6 E.G. Nisbet, The tectonic setting and petrogenesis of komatiites, in: Komatiites, N.T. Arndt and E.G. Nisbet, eds., pp. 501–518, George Allen and Unwin, 1982.
7 A.T. Anderson, Magma mixing: petrological process and volcanological tool, J. Volcanol. Geothermal Res. 1, 3–33, 1976.
8 N.L. Bowen, The Evolution of the Igneous Rocks, 322 pp., Dover, New York, N.Y., 1928.
9 D.J. DePaolo, Trace element and isotopic effects of combined wall rock assimilation and fractional crystallization, Earth Planetary Sci. Lett. 53, 189–202, 1981.
10 P.J. Patchett, Thermal effects of basalt on continental crust and crustal contamination of magmas, Nature 283, 559–561, 1980.
11 E.B. Watson, Basalt contamination by continental crust: some experiments and models, Contrib. Mineral. Petrol. 80, 73–87, 1982.
12 H.E. Huppert, R.S.J. Sparks, J.S. Turner and N.T. Arndt, Emplacement and cooling of komatiite lavas, Nature 398, 19–22, 1984.
13 H.E. Huppert and R.S.J. Sparks, Komatiites, I. Eruption and flow, J. Petrol. 26, 1985.
14 H.R. Shaw and D.A. Swanson, Eruption and flow rates of flood basalts, Proc. 2nd Columbia River Basalt Symposium, pp. 271–299, 1971.
15 L. Wilson and J.W. Head, Ascent and eruption of basaltic magma on the Earth and Moon, J. Geophys. Res. 86, 2971–3001, 1981.
16 The Laki fissure eruption of 1783 in Iceland erupted 12 km^3 in less than six months and certainly qualifies as a high discharge rate and voluminous lava. However, the observations do not allow any direct assessment to be made of the flow régime of the Laki lava.

17 R.S.J. Sparks and H. Pinkerton, Effect of degassing on the rheology of basalt lava, Nature 276, 385–386, 1978.

18 G. Hulme, Turbulent lava and the formation of lunar sinuous rilles, Modern Geol. 4, 107–117, 1975.

19 G. Hulme, A review of lava flow processes in relation to the formation of lunar sinuous rilles, Geophys. Surv. 5, 245–279, 1982.

20 E.R. Oxburgh, Heat flow and magma genesis, in: Physics of Magmatic Processes, R.B. Hargreaves, ed., pp. 161–194, Princeton University Press, 1980.

21 M.J. Bickle, C.E. Ford and E.G. Nisbet, The petrogenesis of peridotitic komatiites: evidence from high-pressure melting experiments, Earth Planetary Sci. Lett. 37, 97–106, 1977.

22 R.N. Thompson, Primary basalts and magma genesis, I. Skye, North-west Scotland, Contrib. Mineral. Petrol. 45, 317–341, 1974.

23 M.J. Bickle, The magnesium contents of komatiite liquids, in: Komatiites, N.T. Arndt and E.G. Nisbet, pp. 479–494, George Allen and Unwin, 1982.

24 P.T. Delaney and D.D. Pollard, Solidification of a basaltic magma during flow in a dyke, Am. J. Sci. 282, 854–885, 1982.

25 G.P.L. Walker, Lengths of lava flows, Philos. Trans. R. Soc. London, Ser. A 274, 107–118, 1973.

26 C.J. Hawkesworth and M.J. Norry, eds., Introduction, in: Continental Basalts, Shiva Geol. Ser., pp. 5–19, 1983.

27 M.A. Menzies, W. Leeman and C.J. Hawkesworth, Geochemical and isotopic evidence for the origin of continental flood basalts with particular reference to the Snake River Plain and Columbia River, U.S.A., Philos. Trans. R. Soc. London, Ser. A 310, 643–660, 1985.

28 R.S. Thorpe, P.W. Francis and L. O'Callaghan, Relative roles of source composition, fractional crystallization and crustal contamination in the petrogenesis of Andean volcanic rocks, Philos. Trans. R. Soc. London, Ser. A 310, 675–692, 1984.

29 H. Downes, Sr and Nd isotope geochemistry of coexisting alkaline magmas, Cantal, Massif Central, France, Earth Planet. Sci. Lett. 69, 321–334, 1984.

30 J. Mahoney, J.D. MacDougall, G.W. Lugmair, A.V. Murali, D.M. Sankar and K. Goplan, Origin of the Deccan Trap Flows of Mahabaleshwar inferred from Nd and Sr isotopic chemical evidence, Earth Planet. Sci. Lett. 60, 47–60, 1982.

31 K.G. Cox and C.J. Hawkesworth, Relative contribution of crust and mantle to flood basalt magmatism, Mahabaleshwar area, Deccan Traps, Philos. Trans. R. Soc. London, Ser. A 310, 627–641, 1984.

32 K.G. Cox and C.J. Hawkesworth, Geochemical stratigraphy of the Deccan Traps at Mahabaleshwar, Western Ghats, India, with implications for open system magmatic processes, J. Petrol., 1985 (in press).

33 R.N. Thompson, M.A. Morrison, A.P. Dickin and G.L. Hendry, Continental flood basalts ... Arachnids rule OK?, in: Continental Basalts and Mantle Xenoliths, C.J. Hawkesworth and M.J. Norry, eds., Shiva Geol. Ser., pp. 158–185, 1983.

34 K.G. Cox, personal communication.

35 K.G. Cox and P. Clifford, Correlation coefficient patterns and their interpretation in three basaltic suites, Contrib. Mineral. Petrol. 79, 268–278, 1982.

36 B.L. Weaver and J. Tarney, Rare earth geochemistry of granulite-facies gneisses, north-west Scotland: implications for the petrogenesis of the Archean lower continental crust, Earth Planet. Sci. Lett. 51, 279–296, 1980.

37 S. Moorbath and R.N. Thompson, Strontium isotope geochemistry and petrogenesis of the early Tertiary lava pile of the Isle of Skye, Scotland, and other basic rocks of the British Tertiary Province: an example of magma-crust interaction, J. Petrol. 21, 295–321, 1980.

38 K.G. Cox, A model for flood basalt vulcanism, J. Petrol. 21, 629–650, 1980.

39 K.G. Cox, Komatiites and other high-magnesia lavas: some problems, Philos. Trans. R. Soc. London, Ser. A 288, 599–609, 1978.

40 J.C. Cloué-Long and R.W. Nesbitt, Contaminated komatiites, Nature 313, 247, 1985.

41 H.E. Huppert, R.S.J. Sparks and N.T. Arndt, Reply to contaminated komatiites, Nature 313, 247–248, 1985.

42 N.T. Arndt and R.W. Nesbitt, Geochemistry of Munro Township basalts, in: Komatiites, N.T. Arndt and E.G. Nisbet, eds., pp. 309–329, George Allen and Unwin, 1982.

43 J.N. Ludden and L. Gelinas, Trace element characteristics of komatiites and komatiitic basalts from Abitibi metavolcanic belt of Quebec, in: Komatiites, N.T. Arndt and E.G. Nisbet, eds., pp. 331–346, George Allen and Unwin, 1982.

44 A. Cattell, T.E. Krough and N.T. Arndt, Conflicting Sm-Nd whole rock and U-Pb zircon ages for Archean lavas from Newton Township Abitibi Belt Ontario, Earth Planet. Sci. Lett. 70, 280–290, 1984.

45 C. Chauvel, B. Dupré and G.A. Jenner, The Sm-Nd age of Kambala volcanics is 500 Ma too old!, Earth Planet. Sci. Lett. 74, 315–324, 1985 (this issue).

46 W.E. Cameron, E.G. Nisbet and V.J. Dietrich, Boninites, komatiites and ophiolitic basalts, Nature 280, 550–553, 1979.

47 R.W. Carlson, Isotopic constraints on Columbia River flood basalt genesis and the nature of the subcontinental mantle, Geochim. Cosmochim. Acta 48, 2357–2372, 1984.