Patent mantle-metasomatism: Inferences based on experimental studies

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Abstract. K, Na and Ca are the most common elements transported during mantle metasomatism and result in formation of phlogopite (K), amphibole (Na) and clinopyroxene (Ca) by various reactions. This review presents models for this type of metasomatism based on experiments on the pyrolite- K_2CO_3 - H_2O , pyrolite- Na_2CO_3 - H_2O systems and on the pyrolite- $CaCO_3$ system. The addition of K_2CO_3 and Na_2CO_3 lowers the liquidus of pyrolite providing a low temperature, alkali-rich hydrous melt which may ascend and metasomatize overlying mantle regions. Several reactions are proposed for the formation of phlogopite and amphibole (pargasite-edenite) in these systems. The compositions of amphiboles correspond to those found in metasomatized mantle xenoliths. In contrast, Ca-metasomatism is considered to be mainly an anhydrous process in which orthopyroxene and carbonate react to produce clinopyroxene, olivine and CO_2 . High pressure liquids in this model system are of carbonatitic composition and this low viscosity melt can ascend converting harzburgite mantle assemblages to olivine-rich wehrlite.

Based on an inverse experimental approach, moderately high degrees of partial melting of a model metasomatized alkali clinopyroxenite xenolith yield liquids at 30 kb which are very comparable in composition to the lavas enclosing such types of xenoliths.

Experimental modelling of mantle metasomatism produces assemblages which are in good agreement with the mineral assemblages and textural relationships found in metasomatized mantle xenoliths from areas such as West Eifel and South-West Uganda.

Keywords. Mantle metasomatism; pyrolite systems; phlogopite; amphibole; clinopyroxene; xenolith.

1. Introduction

The idea of mantle metasomatism is relatively recent. Harte and Gurney (1975) discussed changes in upper mantle-derived xenoliths in some South African kimberlites. Lloyd and Bailey (1975) suggested that the absence of garnet and orthopyroxene in alkali clinopyroxenite xenoliths in the ultrapotassic provinces of South-West Uganda and Eifel, West Germany was caused by alteration resulting from metasomatic fluids. The concept of mantle metasomatism is being widely accepted as one of the causes of mantle heterogeneity (c.f. Bailey 1982, 1987; Menzies and Hawkesworth 1987).

Dawson (1984) subdivided metasomatic processes into patent and cryptic types. Experimental modelling can only deal with patent metasomatism in which new mineral assemblages can be readily recognized petrographically.

The concept of mantle metasomatism is important with respect to the source regions for kimberlites and other alkaline mafic-ultramafic magmas. Variation in the chemistry of melts may be associated with the processes of rifting or it may be the result of mantle heterogeneities caused by metasomatism. The nature of the metasomatic fluid is a subject of debate, but melts seem to be the most likely media.

Bailey (1987) considered metasomatism to occur by fluids under subsolidus conditions. Spera (1987) suggested that during cooling the metasomatizing agent may evolve from a volatile-saturated melt to a solute-saturated supercritical fluid.

Bailey (1987) subdivides the characteristic lithophile-element-bearing minerals found as a result of metasomatism of peridotitic mantle assemblages into major minerals, which include phlogopite, amphibole, clinopyroxene, and carbonates; and minor minerals comprising phosphates, titanates, oxides and sulphides. The elements introduced by the metasomatic fluids include H, C, F, Ne, Al, P, S, Cl, K, Ca, Ti, Fe, Rb, Y, Zr, Nb, Ba and the rare earths (Bailey 1982). This metasomatic material is usually introduced along grain boundaries and veins and hence evidence of the amount and the types of elements removed are not apparent.

Experiments designed to model mantle metasomatism are much simpler than the natural process. Two approaches have been pursued—determination of the solubility of major and trace elements by metasomatic fluids (note particularly the review by Eggler 1987); and experiments designed to determine the conditions and concentrations under which characteristic metasomatic minerals such as phlogopite, clinopyroxene and amphibole form. The latter experiments have not been as detailed as those designed to determine the solubility of elements in metasomatic fluids, done principally by D H Eggler and co-workers. Experiments to model the conditions of formation of characteristic metasomatic minerals include investigations of the pyrolite- $\text{K}_2\text{CO}_3\text{-H}_2\text{O}$ system at 20 and 30 kb, 850–950°C by Edgar and Arima (1984), and similar experiments at 20 kb, in the pyrolite- $\text{Na}_2\text{CO}_3\text{-H}_2\text{O}$ system described by McNeil and Edgar (1987). More recently, we have carried out experiments in the pyrolite- CaCO_3 system between 20 and 30 kb at 900–1300°C. An experimental study on the nature of carbonatitic melts in the system (pyrolite-40% olivine)- $\text{H}_2\text{O-CO}_2$ and on the potential role of these melts in metasomatic processes has been undertaken by Wallace and Green (1988) and Green and Wallace (1988). An inverse approach to these experiments in which the compositions of liquids (as glass) from partial melting of a model-metasomatized mantle source are compared with the natural lavas believed to be derived from such a source was undertaken by Lloyd *et al* (1985).

2. Experimental techniques

All experiments were done in a 1.27 cm piston-cylinder apparatus (Boyd and England 1960) using a “hot-piston out” technique in which the starting material together with the requisite amounts of H_2O were sealed in Pt, $\text{Ag}_{75}\text{Pd}_{25}$ or $\text{Ag}_{50}\text{Pd}_{50}$ capsules. The choice of capsule material was dictated by the temperature used, with Pt capsules being required above 1250°C. The well-known loss of iron by alloying with these capsule materials, particularly with Pt, is not significant in the experiments of Edgar and Arima (1984) or McNeil and Edgar (1987) which were done at relatively low temperatures but is more important in the experiments described by Lloyd *et al* (1985) and those for the pyrolite- CaCO_3 system described in this paper. Temperatures in this type of experiment were $\pm 5^\circ\text{C}$ and pressures to within $\pm 5\%$ of stated values. No frictional correction was made in the measurement of pressure. The e.m.f. variation related to pressure during temperature measurements with Pt-Pt₉₀Rh₁₀ thermocouples was also not taken into account.

Establishment of equilibrium, normally examined by reversing the experiment over a phase boundary, is difficult for subsolidus experiments in which there is a fluid of changing composition. McNeil and Edgar (1987) consider that the consistency of proportions of phases probably indicates equilibrium. Of equal importance is the establishment of the relative amounts and changes in composition of the new minerals or of the glass in experiments designed to model metasomatic processes. Edgar and Arima (1984) determined the *relative* (but not absolute) amounts of the "metasomatic" minerals by their X-ray diffraction intensities relative to the other phases. A more sophisticated method in which a weighed amount of an internal calcite standard is introduced, was used by McNeil and Edgar (1987) to assess *relative* proportions of 'metasomatic' minerals. In the experiments of Lloyd *et al* (1985) the proportions of glass representing the degree of partial melting of the model-metasomatized mantle source were established optically by point-counting each run, and by a least squares calculation based on the compositions of the run products as determined by electron microprobe. A least-squares method was also used in the pyrolite-CaCO₃ system described below.

The compositions of the phases in these experiments were determined by electron microprobe except for those found in Edgar and Arima's (1984) study in which they were too fine-grained. Distinction between 'primary' (equilibrium) and 'quench' (non-equilibrium) minerals was based on their textural and compositional relationships.

3. Results and implications

3.1 The pyrolite-K₂CO₃-H₂O system

This study was originally designed to model K-metasomatism of the pyrolite model mantle composition at P-T conditions (20–30 kb, 850–950°C) near that of the continental geotherm. Thus the reactions primarily represent subsolidus ones.

Figure 1 shows that at 30 kb, 850 and 950°C the amount of phlogopite relative to olivine, orthopyroxene and clinopyroxene systematically increases with concentration of K₂O in solution up to about 3.5 g K₂O/10 g solution, and decreases at higher concentrations in which a melt forms. Such a low temperature melt may form by the decomposition of phlogopite to olivine + liquid or more probably represents the beginning of melting of a highly K-enriched pyrolite. The latter conclusion is supported by the experiments of Takahashi and Kushiro (1983) on the melting of a K-enriched peridotite which lowered solidus temperatures by 70° and 150°C at 20 and 30 kb respectively. The importance of Edgar and Arima's (1984) experiments is that they show that phlogopite is the only characteristic phase resulting from this type of subsolidus K-metasomatism at 30 kb and that the olivine/clinopyroxene and olivine/orthopyroxene ratios decrease (figure 1). The Al for the formation of phlogopite is obtained from decreasing stability of garnet as phlogopite increases. Edgar and Arima (1984) propose the reaction:

Results of this system at 20 kb (figure 2a) show a similar trend of increasing phlogopite relative to olivine and pyroxenes with increasing K₂O concentration in

Figure 1. Ratios of X-ray diffraction intensities of phlogopite (phl) relative to clinopyroxene (cpx), orthopyroxene (opx) and olivine (ol); of ol relative to opx and cpx; and of opx relative to cpx with increasing concentration of g K₂O/10 g solution in the system pyrolite-K₂CO₃-H₂O at 30 kb and 950°C (solid circles) and 850°C (open circles) (after Edgar and Arima 1984).

solution, but at this lower pressure no melt occurs even at extreme concentrations of K₂O. Amphibole occurs in the 20 kb runs. This mineral progressively decreases relative to olivine, orthopyroxene and clinopyroxene with increasing K₂O in solution and is not present at greater than 1.8 g K₂O/10 g solution (figure 2a). The composition of this amphibole is likely to be pargasitic in composition.

Figure 2b shows the relative variations of olivine to orthopyroxene and clinopyroxene and of orthopyroxene to clinopyroxene. In contrast to the 30 kb experiments (figure 1), there is a suggestion that the olivine/orthopyroxene ratio

Figure 2a. Ratios of X-ray diffraction intensities of phlogopite relative to cpx, opx, ol and of amphibole (amph) to phl with increasing concentration of $g K_2O/10 g$ solution in the system pyrolite- K_2CO_3 - H_2O at 20 kb and $950^\circ C$.

increases with increasing K_2O in the system. The orthopyroxene/clinopyroxene in the 20 kb runs exhibits a systematic decrease with increasing K_2O (figure 2b). As in the 30 kb experiments, the olivine/clinopyroxene ratio decreases with increasing K_2O .

Edgar and Arima (1984, pp. 530–534) suggest a number of hypothetical reactions at 20 kb to explain the early formation of amphibole and its disappearance with increasing concentration of K_2O , when phlogopite becomes the only diagnostic mineral (figure 2a). At low concentrations of K_2O :

with K_2O in solution produces a rapid increase in phlogopite, along with increasing amounts of olivine and clinopyroxene and decreasing orthopyroxene as amphibole

Figure 2b. Ratios of X-ray diffraction intensities of ol relative to cpx and opx and of opx relative to cpx with increasing concentration of g K₂O/10 g solution for results shown in figure 2a (after Edgar and Arima 1984).

and spinel are consumed. With increasing concentrations of K₂O the substantial increase in the amount of phlogopite relative to olivine and pyroxenes (figure 2a) is produced by the reaction of K₂O in solution with olivine, orthopyroxene and clinopyroxene. Al for the phlogopite is from residual spinel and from clinopyroxene which incorporates some of the Al from the amphibole present in the experiments at lower K₂O concentrations.

The formation of very low temperature, K-rich melts in these experiments at 30 kb indicates the potential of such melts to rise and induce K-metasomatism in nature at depths between 70 and 100 km (20 to 30 kb). These experiments also suggest that simple patent K-rich metasomatism at these depths will rapidly result in the disappearance of garnet, and a decline in the amounts of spinel, amphibole and orthopyroxene.

The antipathetic relationship between amphibole and phlogopite in the 20 kb experiments, and the fact that the composition of this amphibole is not the typical K-richrichterite implies that the diagnostic K-rich metasomatic mineral at depths equivalent to 20 kb is also phlogopite.

3.2 The pyrolite-Na₂CO₃-H₂O system

To model the effects of Na-metasomatism McNeil and Edgar (1987) studied the systems pyrolite-Na₂CO₃-H₂O and pyrolite-Na₂CO₃-K₂CO₃-H₂O in which the K/(K + Na) is fixed as 0.1 (molar) at 20 kb and 950°C. The run products in this system were large enough for probe analysis and the relative proportions of different phases were determined by X-ray diffraction using an internal calcite standard.

Figure 3 shows that amphibole increases relative to calcite and olivine, and decreases relative to orthopyroxene for both experiments in which the concentration

Figure 3. Ratios of X-ray diffraction intensities of amph, ol, opx, cpx relative to calcite (ct) standard with increasing concentrations of g Na₂O/10 g solution (A) and g Na₂O + K₂O/10 g solution at a fixed molar K/K + Na = 0.1 (B) in the system pyrolite (Na, K)₂CO₃-H₂O at 20 kb, 950°C. Double circles represent two data points (after McNeil and Edgar 1987).

of Na₂O, as g Na₂O/10 g solution, and of K₂O + Na₂O, as g(K₂O + Na₂O)/10 g solution, for a fixed molar K/K + Na ratio of 0.1 increased. The exact trend in clinopyroxene in these experiments is difficult to assess as there is an overlap between the main clinopyroxene and secondary olivine peaks on the X-ray diffractograms. Based on mass balance calculations McNeil and Edgar (1987) consider that clinopyroxene may be reduced to zero at high alkali fluid concentrations. Spinel and magnetite, present only in minor amounts, decrease with increasing concentrations of alkalis. At concentrations greater than about 3.0 g alkalis/10 g solution for both the Na₂O and K₂O + Na₂O added experiments, the amounts of amphibole and olivine decrease (figure 3), and at these concentrations glass can be observed in the run products, suggesting that the solidus has been reached.

Based on microprobe analyses, McNeil and Edgar (1987) were able to suggest reactions responsible for the amphibole formation and to calculate likely compositions of the fluid phase in each run. Edenite to pargasite amphibole compositions show an increase in Si and Na and decrease in Al and Ca with increasing concentrations of alkalis (figure 4).

From the probe analysis of each mineral, X-ray intensity data and calculated mineral proportions based on least squares analysis, McNeil and Edgar (1987) were able to assume a fluid composition. With increasing concentration of Na (as g Na₂O/10 g solution), the Na₂O in the fluid increases from 1.13% at the lowest bulk Na₂O concentrations in the system to 4.42% in runs with 3.0 g Na₂O/10 g solution.

Figure 4. Variations in Si, Al, Ca and Na (as cations per 23 oxygen) for amphiboles crystallized in the pyrolite- Na_2CO_3 - H_2O system plotted against concentrations of g Na_2O /10 g H_2O (closed circles) and g Na_2O + K_2O /10 g solution ($\text{K}/\text{K} + \text{Na} = 0.1$) (open circles) (after McNeil and Edgar 1987).

Increasing amounts of amphibole formed at increasing bulk Na_2O concentrations reduced the $\text{H}_2\text{O}/\text{H}_2\text{O} + \text{CO}_2$ ratio in the fluids from 1.00 with solutions in which no Na_2O was present to 0.91 for fluids in experiments with 3.0 g Na_2O /10 g solution.

Based on their X-ray intensity data (figure 3) mineral and fluid compositions, McNeil and Edgar (1987) proposed that the formation of amphibole was the result of a reaction

This reaction is similar to that proposed by Olafsson and Eggler (1983) and Schneider and Eggler (1986) based on experiments with measured K-bearing fluids in which least

Figure 5. Plot of $\text{Ca} + \text{Al}$ vs $\text{Na} + \text{K} + \text{Si}$ (as cations per 23 oxygen) for natural amphiboles from metasomatized mantle xenoliths. Ti-rich pargasites—vertically lined field, pargasites—enclosed open field. Closed circles represent amphiboles produced in the pyrolite- Na_2CO_3 - H_2O system at 20 kb, 950°C using concentrations as g $\text{Na}_2\text{O}/10\text{g}$ solution given after each data point. Closed squares represent end-member amphibole compositions (after McNeil and Edgar 1987).

square calculations suggested that clinopyroxene + orthopyroxene + spinel could be converted to K-pargasite + olivine at about 20 kb.

The applicability of these experiments to actual Na-dominant mantle metasomatism was demonstrated by comparing the compositions of amphiboles in the experiments with those of natural amphiboles formed under comparable depths. The decrease of $\text{Ca} + \text{Al}$ with increasing $\text{Na} + \text{K} + \text{Si}$ in the experimental amphiboles is very similar to that of natural pargasite-edenite rather than to Ti-pargasites (figure 5), suggesting that the former may be produced by a process similar to that modelled by the experiments of McNeil and Edgar (1987). Similarly the experimental amphiboles correlate with natural pargasite-edenite rather than with Ti-pargasite on a plot of the $\text{Mg}/(\text{Mg} + \text{Fe})$ ratio vs Si (figure 6). McNeil and Edgar (1987) consider that variations in natural amphiboles from Ti pargasite to pargasite-edenite may indicate a transition between precipitation from a residual liquid which is silicate-dominant to one which is H_2O -dominant.

The presence of clinopyroxene in metasomatized mantle xenoliths containing pargasite-edenite suggests that natural metasomatic processes probably occur under concentrations of Na_2O less than 1.5 g $\text{Na}_2\text{O}/10\text{g}$ solution as modelled by the simplified experiments of McNeil and Edgar (1987). These experiments demonstrated that with increasing intensity of Na-metasomatism, the model proportions of amphibole and their Na-contents progressively increase. A maximum of about 43 wt% amphibole with greater than 5.5 wt% Na_2O can occur in model pyrolite under Na_2O -rich fluid conditions in which $\text{H}_2\text{O}/\text{CO}_2$ is high. Such a hydrated pyrolite can contain 0.8 wt% H_2O and 1.7 wt% Na_2O . In contrast, the maximum amount of calcic amphibole in mantle peridotite is about 15 wt% requiring 0.4 wt% H_2O (Eggler 1978; Wyllie 1978; Schneider and Eggler 1986).

Although the lowering of the pyrolite solidus in the system pyrolite- Na_2CO_3 - H_2O

Figure 6. Relationship between $\text{Mg}/(\text{Mg} + \text{Fe}_T)$ vs Si (as cations per 23 oxygen) for natural amphiboles from metasomatized mantle xenoliths (see figure 5) and for amphiboles from the pyrolite- Na_2CO_3 - H_2O system at 20 kb, 950°C using various concentrations of Na_2O (as g Na_2O /10 g solution). Concentrations are shown after each data point (after McNeil and Edgar 1987).

at 950°C and 20 kb is less than that of the pyrolite- K_2CO_3 - H_2O system, it is still about 50°C lower than in the pyrolite- H_2O system (Green 1973). Thus the addition of both these alkalis provides a mechanism of generating low temperature silicate-dominant, alkali-rich melts which can subsequently metasomatize at shallower mantle levels.

3.3 The pyrolite- CaCO_3 system

The experimental investigation of the pyrolite- CaCO_3 system was undertaken to explain phenomena such as the partial replacement of orthopyroxene by aggregates of olivine and clinopyroxene grains in spinel harzburgite mantle xenoliths of the West Eifel alkaline volcanic province, West Germany. This suggests that some of the olivine-rich lherzolite and wehrlite of the region could be the end product of Ca-dominated metasomatic processes acting on a lithospheric mantle of harzburgitic composition (Edgar *et al* 1989). As CO_2 is an important volatile component in some highly alkaline volcanic provinces associated with continental rifting, a possible mechanism for enhancing the level of Ca could be a fluid flux containing significant CaCO_3 (Bailey 1985). The system was kept dry mainly because of the absence of hydrous phases in many xenoliths of harzburgitic composition showing partial replacement of orthopyroxene. This suggests that the hypothetical Ca-enrichment process can be active in originally dry mantle material.

Results of experiments in the pyrolite + 10 wt% CaCO_3 system are presented in figure 7. A decarbonation reaction divides the subsolidus portion into a low temperature dolomite lherzolite field and a high temperature wehrlite + CO_2 field. Between 25 and 28 kb, the solidus shifts towards lower temperature, intersecting the decarbonation reaction (figure 7).

In the dolomite lherzolite field, run products consist of olivine, orthopyroxene, clinopyroxene, calcitic dolomite and spinel at low and garnet at high pressures.

In the wehrlite + CO_2 field, orthopyroxene and dolomite are absent and the run products consist of olivine, clinopyroxene, spinel and CO_2 vapour. Runs in the pyrolite + 18 wt% CaCO_3 system, have an excess of Ca-rich carbonate (≥ 83 mol%)

Figure 7. Phase relationships for the system pyrolite—10 wt% CaCO_3 . Heavy lines indicate the location of the decarbonation reaction and of the solidus. Dashed lines show the same relations in the simple system $\text{CaO-MgO-SiO}_2\text{-CO}_2$ based on data of Wyllie and Huang (1976) and Wyllie *et al* (1983). Filled and open symbols represent subsolidus and suprasolidus conditions respectively. Squares and circles indicate the presence or absence of orthopyroxene respectively (dol = dolomite; sp = spinel; ga = garnet; W&H = Wyllie and Huang 1976).

CaCO_3) in the wehrlite + CO_2 field in accordance with calcite being stable in wehrlitic compositions in this pressure range (Edgar *et al* 1988).

The nature of the decarbonation reaction was defined using mineral compositions and proportions calculated by least-squares mass balance for two adjacent runs, close to the determined reaction. The proposed reaction (table 1) is almost similar to the reaction, orthopyroxene + dolomite $\rightarrow$ clinopyroxene + olivine + CO_2 , determined in peridotitic systems with CO_2 added (Wyllie and Huang 1976; Eggler 1978; Brey *et al* 1983). Also a small proportion of spinel reacting with orthopyroxene increases the abundance of olivine and of the Ts component in the clinopyroxene. This is suggested by a systematic decrease in the abundance of spinel on the high temperature side of the reaction. Moreover, as Al enters more easily than Cr in clinopyroxene relative to spinel, the latter is systematically more chromiferous in nature in the wehrlite + CO_2 field.

Of petrological importance is the fact that the decarbonation reaction in the pyrolite + CaCO_3 system is about 100 to 150°C lower than in the simple system modelling dry peridotitic assemblages with CO_2 added (Eggler 1978; Wyllie *et al* 1983; see figure 7).

Using back-scattered imaging, suprasolidus conditions at 30 kb were recognized in the form of interstitial material. The material is not glass but an aggregate of extremely fine grains believed to have quenched from a very low viscosity melt. The exact nature of the melt could not be characterized. However, qualitative probe

Table 1. Proposed decarbonation reaction (in simplified form) in the system pyrolite + 10 wt% CaCO₃.

analyses of the interstitial material for a run at 1200°C and 30 kb yield low totals of about 60% and low silica content (< 4%), with CaO and MgO as the main oxides. This suggests a CO₂-rich dolomitic melt. Therefore the solidus temperature and the carbonatitic nature of the melt at low degrees of partial melting is concordant with Wendlandt and Mysen's (1980) results on dry natural peridotite with CO₂ added.

The sodium content of clinopyroxene decreases significantly at the solidus at 30 kb. Because there is no other Na-bearing minerals and the clinopyroxene abundances do not increase, Na is probably partitioned quantitatively in the CO₂-rich melt. This is in accordance with the experimental results of Wallace and Green (1988) on the phase relationships of a carbonate and amphibole-bearing lherzolite assemblage from which the first satisfying and precise composition of high pressure primary carbonatite magma was determined. Wallace and Green (1988) noted that the melt is strongly enriched in Na₂CO₃ and that the high pressure solidus is defined by the breakdown of dolomite and of the jadeite component of the clinopyroxene to produce an aluminous phase plus melt.

In order to relate these experimental results to Ca-dominant metasomatism of the West Eifel xenoliths, a geotherm shown in figure 8 is applied to the phase relations given in figure 7. This qualitative geotherm is believed to represent a minimum based on geothermometry calculations and geophysical modelling reported by Seck and Wedepohl (1983) and Fuchs and Wedepohl (1983) for the Rhenish Massif. With such a high geotherm, the solidus is crossed in a dry lherzolitic mantle at approximately 100 km depth and therefore a small fraction of carbonatitic melt is formed if CO₂ is supplied or is already available as a carbonate phase (figure 8). Hunter and McKenzie (1989) have shown experimentally that, even at small degrees of partial melting, such a melt will form an interconnected network. Therefore, as predicted by McKenzie (1984, 1985), very small fractions (< 1%) of such a low viscosity melt can efficiently segregate

Figure 8. Tentative geotherm, believed to be applicable to the upper mantle in the West Eifel area, applied to the pressure-temperature relations shown in figure 7. For details refer to text (abbreviations as in figure 7).

from their mantle source. However because the geotherm in the West Eifel is such that the melt crosses its solidus in the wehrlite + CO_2 field (figure 8), it probably becomes highly reactive relative to a dry harzburgitic mantle at a pressure of 25 kb or less, the dolomitic component of the melt reacting with orthopyroxene to form olivine, clinopyroxene and CO_2 vapor. If the melt flux is sufficient, an olivine-rich wehrlite can eventually form. As long as the system is kept dry, the possible addition of Na is limited by its solubility in clinopyroxene. Therefore, we are in agreement with Green and Wallace (1988) and Wallace and Green (1988) that high pressure primary carbonatitic melts are very effective metasomatic agents. In an amphibole-bearing lherzolite the transformation to wehrlitic compositions is restricted to pressures less than 21 kb (Green and Wallace 1988). In contrast our results suggest that a dry harzburgitic mantle could probably be subjected to this type of metasomatism up to a depth corresponding to 25 kb provided, conditions as that of the West Eifel geotherm are reached.

3.4 Melting of a model metasomatized mantle source

Lloyd *et al* (1985) determined the compositions of liquids produced from partial melting of a model alkali clinopyroxenite composition which they considered representative of the metasomatized xenoliths in the Katwe-Kikorongo and Bunyaruguru volcanic fields of South-West Uganda. This model xenolith contained the metasomatic mineral assemblage of clinopyroxene + phlogopite + magnetite + sphene + apatite (table 2); diagnostic of Ca and K but a little Na metasomatism under mantle conditions. The objectives of the experiments were to determine whether such a model-metasomatized mantle composition could partially melt to produce a liquid whose composition corresponds to that of the principal host lava (katungite) of this area, as inferred from the near-liquidus experiments of Arima and Edgar (1983).

Figure 9 shows the compositions of liquids formed between 1175°C and 1200°C at 30 kb from partial melts of 20 wt% to complete melting, and the incoming minerals

Table 2. Modal and chemical composition of model alkali clinopyroxenite used in Lloyd *et al* (1985) experiments. Compositions of 26 katungites from South-West Uganda and composition of glass from 25% partial melting of average composition of model alkali clinopyroxenite (from Lloyd *et al* 1985).

(Volume %)	A	(wt%)	B	C	D
Clinopyroxene	52	SiO ₂	40.20	39.9	37.1
Phlogopite	35	TiO ₂	4.92	5.28	5.55
Apatite	2	Al ₂ O ₃	7.27	7.84	6.78
Sphene	4	Fe ₂ O ₃	6.69	6.81	—
Magnetite	6.5	FeO	7.12	5.38	11.9
Jadeite	0.5	MnO	0.09	0.21	0.18
		MgO	12.60	10.15	10.1
		CaO	12.21	12.35	12.4
		Na ₂ O	1.21	1.95	1.56
		K ₂ O	4.18	4.96	4.06
		H ₂ O ⁺	1.49	2.27	—
		CO ₂	0.98	0.98	—
		P ₂ O ₅	0.70	0.76	1.41
		Total	99.66	98.84	91.04

A—modal analysis of starting material in model alkali clinopyroxenite.

B—chemical analysis of model composition A.

C—average of 26 katungites from South-West Uganda.

D—composition of liquid from 25% partial melting of compositions A and B at 30 kb.

with decreasing temperature. The correspondence between the compositions of glass determined by microprobe analyses with that obtained by least-squares mass balance calculation is excellent (figure 9). The interpolated composition of glass at 25% partial melting (table 2) corresponds very closely to the average of 26 katungites (table 2) suggesting that metasomatized alkali clinopyroxenite was the source for such a lava.

Partial melting of the model mantle xenolith at 20 kb could not unequivocally show that partial melting at this pressure produce liquids comparable to the natural lavas found in South-West Uganda. However, based on theoretical considerations, Lloyd *et al* (1985) do not consider that any degree of partial melting is likely to produce such magmas.

The greater amount of heat necessitated by the high degrees of partial melting inferred from these experiments may be provided by the K₂O content of the model xenolith used by Lloyd *et al* (1985). As this is 150–200 times greater than that of model pyrolite (Ringwood 1975), the amount of ⁴⁰K (and probably U, Th) necessary to supply this additional heat is available.

4. Conclusions and future studies

In this paper we have attempted to show how experimental petrology can be used to model the major types of mantle metasomatism involving K, Na and Ca which produce phlogopite, amphibole and clinopyroxene as diagnostic mineral phases.

Figure 9. Determined and calculated melt compositions from various degrees of partial melting of alkali clinopyroxenite xenolith (table 1) at 30 kb. Experimentally determined crystallization sequence given at the top of figure. Solid symbols represent determined glass compositions, open symbols represent calculated compositions (see text). Vertical dashed line is interpolated composition of melt at 25% partial melting. Other abbreviations as in figure 1 and Ilm—ilmenite, Ap—apatite (after Lloyd *et al* 1985).

These experiments constrain possible P, T conditions under which these minerals commonly occur in metasomatized mantle-derived xenoliths in South-West Uganda and in the West Eifel region of Germany.

Although these experiments are very simplified relative to the natural metasomatic processes, they can be used to model what appears to be stages of predominance of one type of metasomatism relative to another. Such stages appear to be related to depth in the mantle and availability of a particular fluid species. Studies are in progress to develop an evolutionary metasomatic model for K, Na and Ca metasomatism.

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