

# Phase Relationships of Hydrous Alkalic Magmas at High Pressures: Production of Nepheline Hawaiitic to Mugearitic Liquids by Amphibole-Dominated Fractional Crystallization Within the Lithospheric Mantle

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*Experimental melting studies were conducted on a nepheline mugearite composition to pressures of 31 kbar in the presence of 0–30% added water. A temperature maximum in the near-liquidus stability of amphibole (with olivine) was found for a water content of 3–5 wt % at a pressure of 14 kbar. This is interpreted to have petrogenetic significance for the derivation of nepheline mugearite magmas from nepheline hawaiite by amphibole-dominated fractional crystallization at depth within the lithospheric mantle. Synthetic liquids at progressively lower temperatures range to nepheline benmoreite compositions very similar to those of natural xenolith-bearing high-pressure lavas elsewhere, and support the hypothesis that continued fractional crystallization could lead to high-pressure phonolite liquids. Independent experimental data for a basanite composition modeled on a lava from the same igneous province (the Newer Basalts of Victoria) permit the inference that primary asthenospheric basanite magmas undergo polybaric fractional crystallization during ascent, and may evolve to liquids ranging from nepheline hawaiite to phonolite upon encountering cooler lithospheric mantle at depths of 42–50 km. Such a model is consistent with the presence in some evolved alkalic lavas of both lithospheric peridotite xenoliths indicative of similar depths and of megacryst suites that probably represent disrupted pegmatitic segregations precipitated from precursor alkalic magmas in conduit systems within lithospheric mantle.*

KEY WORDS: *experiment; high pressure; alkalic magmas; amphibole; nepheline mugearite; basanite; lithosphere*

## INTRODUCTION

Alkalic volcanic rocks can be subdivided into two main lineages or series (e.g. Coombs & Wilkinson, 1969): (1) alkali olivine basalt → hawaiite → mugearite → benmoreite → trachyte; (2) basanite → tephrite → nepheline hawaiite → nepheline mugearite → nepheline benmoreite → phonolite. The petrology and geochemistry of these lava series have been studied in many areas, such as the Hebridean province (Muir & Tilley, 1961; LeBas, 1965; Tilley *et al.*, 1967; Thompson *et al.*, 1972; Macdonald, 1975), Hawaii (MacDonald & Katsura, 1964; Tilley & Muir, 1964), New Zealand (Coombs & Wilkinson, 1969; Price & Chappell, 1975; Price & Taylor, 1975), Germany (Ficke, 1961; Huckenholz, 1965; Wörner & Schminke, 1984), the Czech Republic (Macháček & Shrubný, 1970; Shrubný & Macháček, 1973), east Africa (Civetta *et al.*, 1974; Baker *et al.*, 1977; Price *et al.*, 1985), Saudi Arabia (Camp *et al.*, 1992), Reunion (Zielinski, 1975), the Comoro Islands (Flower, 1971, 1973), Antarctica (Sun & Hanson, 1976; Panter *et al.*, 1997), Iceland (Jakobsson *et al.*, 1973) and

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Tristan da Cunha (Le Roex *et al.*, 1990). Although some of these provinces contain basanites and alkali olivine basalts carrying mantle-derived peridotite xenoliths, the more evolved hawaiitic to trachytic or phonolitic lavas typically are devoid of such xenoliths. Furthermore, the majority of chemically analyzed evolved alkalic lavas from these provinces exhibit negative europium anomalies in their rare earth element patterns. This indicates that feldspar subtraction was important in the crystal–liquid fractionation processes that produced the evolved liquids, and implies that these processes operated at low crustal pressures (consistent with the lack of high-pressure xenoliths).

In contrast there are other hawaiitic, mugearitic, benmoreitic and phonolitic lavas that are labeled as high-pressure liquids by their content of Cr-diopside lherzolite xenoliths and/or aluminous pyroxene megacrysts. Although not volumetrically abundant, such high-pressure lavas are widespread throughout eastern Australia (Wilkinson & Binns, 1969; Binns *et al.*, 1970; Green *et al.*, 1974; Sutherland, 1974; Irving & Green, 1976; Stephenson *et al.*, 1980; Wass, 1980; Stolz, 1984; Johnson, 1989; O'Reilly & Zhang, 1995; Zhang & O'Reilly, 1997; Everard, 2001; Zhang *et al.*, 2001). Other examples of mantle xenolith-bearing hawaiitic and mugearitic lavas are found in the Auckland Islands (Green & Hibberson, 1970*a*), Japan (Kuno, 1964; Uchimizu, 1966), SE Asia (Barr & Macdonald, 1981), Sudan (Almond, 1974), and the SW USA (Baldrige, 1979; Evans & Nash, 1979). Xenolith-bearing nepheline benmoreites and phonolites are rarer, but several occur in New Zealand, Nigeria, Germany, Saudi Arabia and eastern Australia (Wright, 1966, 1969; Green *et al.*, 1974; Irving & Price, 1981; Coleman *et al.*, 1983; Camp *et al.*, 1992). As none of these lavas has a sufficiently high Mg/(Mg +  $\Sigma$ Fe) ratio to be a direct partial melt of normal mantle peridotite, they therefore must represent either high-pressure fractionated liquids from more primitive precursors (e.g. alkali olivine basalts and basanites) or else direct partial melts derived from previously enriched mantle sources. The widespread occurrence of kaersutitic or titaniferous pargasitic amphibole megacrysts in these types of lavas (e.g. Kuno, 1964; Irving, 1974*b*; Wass & Irving, 1976) implies an important role for amphibole–liquid equilibria in their petrogenesis.

In an effort to assess whether amphibole fractionation at mantle pressures is a viable mechanism for producing evolved alkalic liquids, we have determined experimentally the phase relationships and phase compositions for a natural nepheline mugearite over a range of pressure–temperature conditions in the presence of varying but controlled amounts of water. We utilize these results to assess the genetic relationship over a specific range of pressure and water content in the melt between this nepheline mugearite and its spatially associated nepheline hawaiitic and basanite lavas, and also to demonstrate that continued

fractional crystallization of such nepheline mugearite liquids at mantle pressures can lead to residual liquids of nepheline benmoreite and phonolite compositions.

## EXPERIMENTAL METHODS

The majority of experiments reported in this paper were conducted on nepheline mugearite 2102 from The Anakies (east), a Quaternary scoria cone within the Newer Basalts province of Victoria, southeastern Australia (Irving & Green, 1976). Xenoliths of Group I Cr-diopside, spinel lherzolite, Group II Al-pyroxene-rich ultramafic rocks and garnet-bearing granulites, as well as megacrysts of anorthoclase, kaersutite, ferrokaersutite, Ti-phlogopite, Ti-biotite, apatite and rare magnetite, are present at this locality (Irving, 1974*a*, 1974*b*; Wass & Hollis, 1983).

The starting material for most experiments on 2102 was homogeneous glass (ground to  $<10\ \mu\text{m}$ ) prepared by fusing the natural powdered rock in a nitrogen atmosphere. Two batches of glass prepared at different times during the course of the study are very similar in composition (except for Fe<sub>2</sub>O<sub>3</sub>/FeO ratio) to the volatile-free natural lava (Table 1). The high-pressure portion of the curve limiting amphibole stability below 1000°C was reversed by carrying out runs on a crystalline starting material (a fine-grained assemblage of clinopyroxene + garnet with trace amounts of mica) obtained by reacting dry 2102 glass in a large unsealed graphite capsule at 24 kbar and 1000°C. Defocused beam microprobe analysis of this crystalline starting material confirmed a composition virtually identical to that of the glass (Table 1). To overcome difficulties in nucleation of feldspar several runs were conducted on homogeneous mixtures of glass seeded with 2% natural labradorite or anorthoclase crystals (grain size  $<5\ \mu\text{m}$ ).

For experimental runs at 1 atm, welded iron capsules sheathed in ceramic and graphite within sealed platinum capsules were suspended in a vertical furnace with an argon atmosphere, and were drop-quenched in water. High-pressure experiments were performed in a ½ inch piston-cylinder apparatus, employing talc as the pressure medium for runs containing added H<sub>2</sub>O and a combination of talc, fired BN and fired pyrophyllite for nominally dry runs (Green & Ringwood, 1967*a*). The piston-in technique was used, with a –10% correction to nominal pressures (Essene, 1971). Sealed Pt capsules were used for about one-third of the runs and sealed Ag<sub>75</sub>Pd<sub>25</sub>, Ag<sub>77</sub>Pd<sub>23</sub>, Ag<sub>70</sub>Pd<sub>30</sub> or Ag<sub>50</sub>Pd<sub>50</sub> capsules for the remainder. The capsules (0.090" o.d., 0.006" wall) contained 10–15 mg of compacted, powdered sample. For wet runs, requisite amounts of water were added by microsyringe (with an accuracy of  $\pm 0.2\ \text{wt}\ \%$ ), and the welded, crimped ends of the capsules folded double. Weighings before and after each run confirmed no loss of water.

Table 1: Experimental natural and experimental starting compositions

Material:	2102 Natural scoria (volatile-free)	2102 Glass 1	2102 Glass 2	2102 Crystallized glass	2650 + 10% ol Glass 1	2650 + 10% ol Glass 2
SiO <sub>2</sub>	48.80	49.10	49.80	49.60	44.6	44.9
TiO <sub>2</sub>	2.19	2.17	2.23	2.21	2.9	2.8
Al <sub>2</sub> O <sub>3</sub>	15.38	15.40	15.80	15.80	11.7	12.2
Cr <sub>2</sub> O <sub>3</sub>	0.04	0.04	0.04	0.04	0.05	0
Fe <sub>2</sub> O <sub>3</sub> *	4.65	1.11	1.50	2.03		
FeO	5.80	9.00	8.80	8.50	12.1	12.3
MnO	0.16	0.18	0.17	0.17		
MgO	7.19	7.10	6.90	6.90	13.9	13.6
CaO	6.51	6.30	6.40	6.40	7.7	7.5
Na <sub>2</sub> O	5.73	5.60	5.70	5.90	3.65	3.75
K <sub>2</sub> O	2.87	2.90	2.90	2.70	2.0	2.0
P <sub>2</sub> O <sub>5</sub>	0.68	0.68	0.68	0.68	1.0	1.0
Sum	100.00	99.58	100.92	100.93	99.60	100.05
Fe <sub>2</sub> O <sub>3</sub> /FeO	0.80	0.12	0.17	0.24		
Mg/(Mg + ΣFe)	0.562	0.559	0.548	0.544	0.672	0.663

\*Spectrophotometric analyses of Fe<sub>2</sub>O<sub>3</sub> by E. Kiss.

Typical run times ranged from 30–60 min (at near-liquidus temperatures) to 1–7 days (at 600–700°C). Oxygen fugacity in most experiments was buffered only by the intrinsic oxygen fugacity of the furnace assembly, which varies with pressure and temperature but is slightly less than that of the Ni–NiO buffer (Boettcher *et al.*, 1973). Near-liquidus experiments at 14 kbar with 3.5 wt % added H<sub>2</sub>O were repeated using a double-capsule technique with quartz–fayalite–magnetite (QFM) and magnetite–hematite (MH) solid buffers.

Run products were identified by optical and X-ray methods, supplemented in many cases by electron microprobe analyses. Large euhedral amphiboles (up to 150 μm across) were produced in high-pressure reversal runs from crystalline clinopyroxene–garnet starting mixtures. Quench mica was readily distinguishable from primary mica by its occurrence as very thin plates with irregular internal growth patterns and as ‘beards’ on other phases, as well as by its relatively high Ca, Na and Ti, low K, and lower Mg/(Mg + ΣFe) compared with coexisting olivine or clinopyroxene. Quench clinopyroxene, characterized by an arborescent or fine skeletal form, appeared especially in runs above 25 kbar, and in some runs formed optically continuous rims (markedly enriched in iron) on primary clinopyroxene crystals. Evidence of similar quench overgrowths on amphibole crystals was found in several runs. In some runs with 30 wt % H<sub>2</sub>O, laths of a feldspar-like mineral corresponding approximately to Ab<sub>52</sub>An<sub>36</sub>Or<sub>11</sub> with about 15 wt %

H<sub>2</sub>O (see Table 3) were observed and probably represent a quench phase from vapor.

For the purposes of this study we have not conducted any experiments in the presence of CO<sub>2</sub>, as experimental studies of basanite magmas (Green, 1973*a*; Nickel & Green, 1984), as well as the field evidence of amphibole and mica megacrysts within basanite and related lavas, suggest that H<sub>2</sub>O is the predominant volatile species involved. A role for CO<sub>2</sub> (in addition to H<sub>2</sub>O) has been demonstrated in the generation of olivine melilitite liquids (Brey & Green, 1975), but such magmas (or even the rare olivine analcimitic lavas found in the Newer Basalts province—Irving & Green, 1976) are not considered to be parental liquids to the nepheline mugearites.

## PHASE RELATIONS FOR NEPHELINE MUGEARITE AS A FUNCTION OF H<sub>2</sub>O CONTENT

The nepheline mugearite composition was studied under nominally dry conditions and with 2, 3.5, 5, 7, 10 and 30 wt % water added. A supplementary data file with details of more than 200 experimental runs is available for downloading from <http://petrology.oxfordjournals.org>. Most runs were with 2% and 5% water added, and phase relations for these are illustrated in pressure–temperature section in Figs 1 and 2. Only the near-liquidus region was studied with 3.5, 7, 10 and 30% water added (see Figs 3–5).

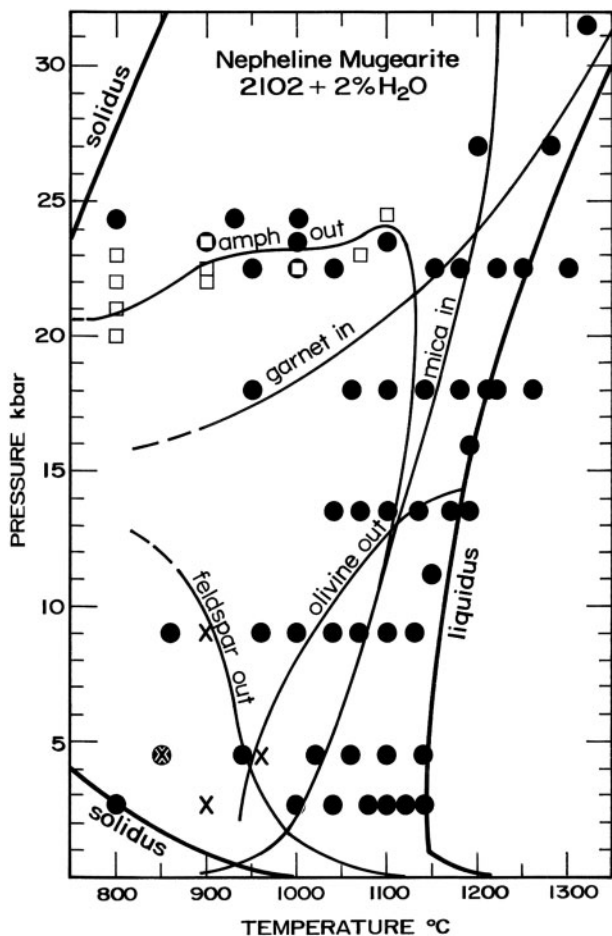


Fig. 1. Phase relationships as a function of temperature and pressure for nepheline mugearite with 2 wt % added water. Starting materials were glass (●), crystallized glass containing garnet + clinopyroxene (□), or glass seeded with 2 wt % feldspar (×).

The significant features of these phase relationships may be summarized as follows.

(1) The temperature stability of amphibole in the presence of melt reaches a maximum for a bulk water content between 3.5 and 5 wt %. The geometry of the phase relations in temperature– $H_2O$  section (Fig. 4) indicates that the actual maximum value is near 3.8 wt %  $H_2O$ . We have no direct evidence that the maximum in amphibole stability actually intersects the  $H_2O$ -undersaturated liquidus. The geometry as drawn for 14 kbar in Fig. 4 shows that amphibole crystallizes within 10°C of the liquidus, and olivine is shown as the actual liquidus phase. However, it is plausible, given the experimental uncertainties, that there is a small range of pressure ( $14 \pm 1$  kbar) and bulk  $H_2O$  content ( $4.0 \pm 0.2$  wt %) for which both amphibole and olivine are simultaneously on the liquidus of the nepheline mugearite. For water contents less than 4 wt % at 14 kbar clinopyroxene and/or olivine are the near-liquidus phases, whereas for greater water contents

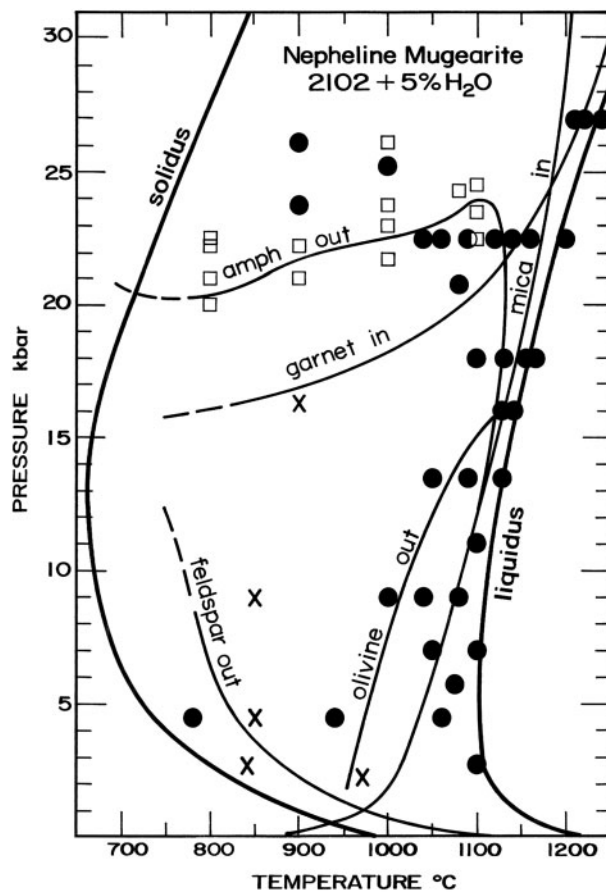
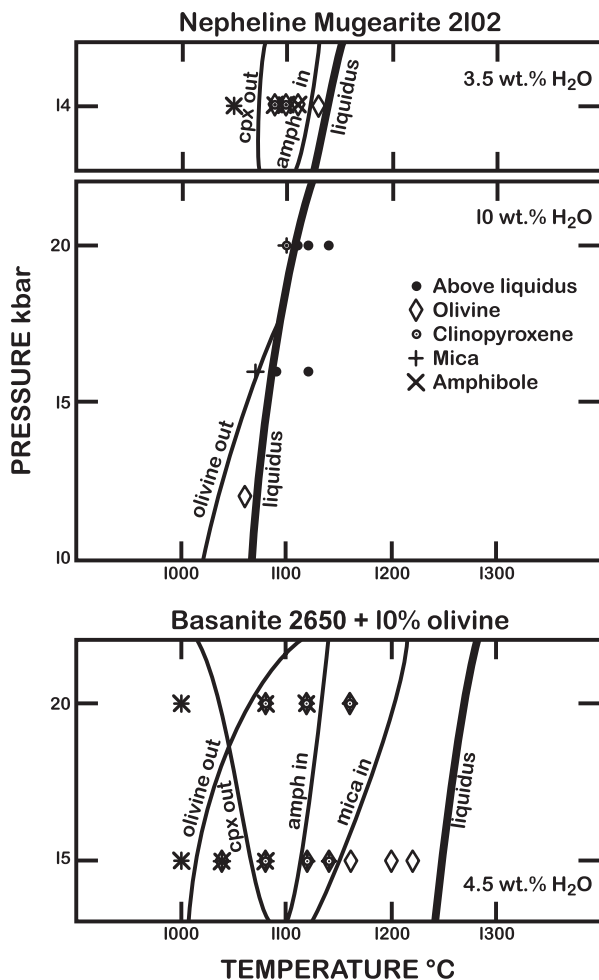


Fig. 2. Phase relationships as a function of temperature and pressure for nepheline mugearite with 5 wt % added water. Starting materials were glass (●), crystallized glass containing garnet + clinopyroxene (□), or glass seeded with 2 wt % feldspar (×).

at 14 kbar olivine appears on the liquidus and mica is the second phase to crystallize. A maximum in amphibole stability as a function of  $H_2O$  activity was also reported by Egger (1972) for an andesite composition and by Holloway (1973) for pure pargasite.

(2) The reversed high-pressure portion of the curve limiting amphibole stability at temperatures less than 1100°C has an overall positive  $dP/dT$  slope. This geometry is consistent with reversed phase equilibria for other alkalic basaltic compositions (Essene *et al.*, 1970; Allen *et al.*, 1975; Allen & Boettcher, 1978), but contrasts with the negative  $dP/dT$  slope reported in unreversed experiments (Millhollen & Wyllie, 1974; Merrill & Wyllie, 1975). Two independent unreversed experimental studies on Kakanui kaersutite (Merrill & Wyllie, 1975; Yagi *et al.*, 1975) yielded somewhat different results for the upper pressure stability limit of this mineral (30 kbar and 25 kbar, respectively). The reversed experiments on basaltic compositions have established conclusively that kaersutite and titaniferous pargasite are not stable at pressures above 25 kbar.





**Fig. 5.** Details of run products and phase relationships as a function of temperature and pressure for nepheline mugearite (top two panels) and basanite 2650 + 10% olivine (bottom panel).

and make comparisons with those for nepheline mugearite 2102. From Fig. 5 it can be seen that for a  $\text{H}_2\text{O}$  content of 4.5 wt % in the pressure interval 15–20 kbar olivine is the liquidus phase joined with decreasing temperature by mica + clinopyroxene and then amphibole. By comparison with phase relationships for 2102 at the same pressure and similar  $\text{H}_2\text{O}$  content (Fig. 2), the liquidus for the basanite is about  $100^\circ\text{C}$  higher and the mica-in phase boundary is about  $30^\circ\text{C}$  higher. However, the amphibole-in boundaries for both compositions almost overlap in this pressure range. Given the projected coexistence of amphibole and olivine on the liquidus of nepheline mugearite 2102 at  $14 \pm 1$  kbar for a  $\text{H}_2\text{O}$  content near 4 wt %, it follows that residual liquids for the basanite composition (with 4.5 wt %  $\text{H}_2\text{O}$ ) at about 15 kbar near the amphibole stability curve might be expected to be of nepheline mugearite composition, if these two magma types are related by amphibole fractionation.

## COMPOSITIONS OF NEAR-LIQUIDUS CRYSTALS AND LIQUIDS

Near-liquidus crystalline phases and coexisting glasses were analyzed by electron microprobe in many nepheline mugearite charges (Table 2) and in a small number of basanite charges (Table 3). Accurate petrogenetic application of these data requires assessment of and correction for the well-known effects of iron loss to noble metal capsule materials (e.g. Merrill & Wyllie, 1973) and of volatilization of Na from glasses during microprobe analysis. We have utilized bulk analysis and mass-balance calculations to make appropriate corrections to our data.

### Evaluation of iron loss to capsules

Losses of iron from experimental charges to the various capsule materials were monitored by spectrophotometric microanalysis of entire charges (analyst E. Kiss) and by microprobe analysis of hyperliquidus glasses and near-liquidus crystals. For Pt capsules (used mostly for runs under dry conditions or with 2%  $\text{H}_2\text{O}$ ) losses of 32% and 24% of the original iron were documented in runs of 45 min at  $1130^\circ\text{C}$ , 10 kbar and 3.25 h at  $1040^\circ\text{C}$ , 15 kbar, respectively. The compositions of near-liquidus olivines ( $\text{Fo}_{82.6-85.1}$ ) and clinopyroxenes [ $\text{Mg}/(\text{Mg} + \Sigma\text{Fe})$  0.860–0.894] also reflect equilibrium with a melt with a greater Mg/Fe than the starting material.

In contrast, for  $\text{Ag}_{75}\text{Pd}_{25}$  capsules (used for most runs with 5%, 10% and 30%  $\text{H}_2\text{O}$ , and some with 2%  $\text{H}_2\text{O}$ ) losses of only 4% of original iron were found in 1 h at 1100–1200 $^\circ\text{C}$ , 3–30 kbar, which is consistent with analyzed phase compositions. Despite this finding, other silver–palladium alloys absorbed much more iron, and we can only surmise that our batch of  $\text{Ag}_{75}\text{Pd}_{25}$  tubing fortuitously contained some iron impurity. For  $\text{Ag}_{50}\text{Pd}_{50}$  capsules hyperliquidus glass compositions and mass balance for other near-liquidus runs indicate iron losses of 30–43%. Similarly for  $\text{Ag}_{77}\text{Pd}_{23}$  capsules (used mostly for runs with 3.5% and 20%  $\text{H}_2\text{O}$ ) iron losses of 9–30% occurred in 30–70 min at 14 kbar, 1050–1130 $^\circ\text{C}$  under furnace buffered conditions. In analogous runs on the QFM buffer iron losses were lower (0–9%; probably as a result of shorter run times rather than the more reducing oxygen fugacity conditions), and with the MH buffer no iron loss could be detected (but bulk  $\text{Fe}_2\text{O}_3/\text{FeO}$  ratios were substantially increased to about 1.0).

### Results for nepheline mugearite 2102

#### Olivine

The Fe/Mg exchange coefficient for olivine–liquid is known to be dependent on bulk composition and pressure (e.g. Longhi *et al.*, 1978; Takahashi & Kushiro, 1983; Gee & Sack, 1988; Beattie *et al.*, 1991). By combining the 1 atm compositional dependence measured by Gee & Sack (1988)

Table 2: Compositions of synthetic near-liquidus phases for nepheline mugearite 2102 compared with natural megacrysts

Wt % H <sub>2</sub> O:	3.5	3.5	3.5	3.5	5						
Pressure (kbar):	14	14	14	14	15.9						
Temperature (°C):	1150	1130	1110	1090	1140						
Capsule:	Ag <sub>50</sub> Pd <sub>50</sub>	Ag <sub>50</sub> Pd <sub>50</sub>		Ag <sub>75</sub> Pd <sub>25</sub>		Ag <sub>75</sub> Pd <sub>25</sub>		Ag <sub>75</sub> Pd <sub>25</sub>			
Phase:	Glass	Olivine	Glass	Olivine	Amphibole	Glass	Amphibole	Cpx	Glass	Cpx	
SiO <sub>2</sub>	52.60	38.80	51.90	38.80	43.40	52.50	43.50	52.90	53.70	50.50	
TiO <sub>2</sub>	2.40		2.30		3.20	2.30	3.30	1.10	2.30	0.86	
Al <sub>2</sub> O <sub>3</sub>	16.50		16.50		12.70	16.80	12.10	6.30	17.60	4.90	
Cr <sub>2</sub> O <sub>3</sub>					0.17		0.11	0.19			
FeO	5.80	20.30	7.10	21.60	9.20	6.90	8.60	6.30	6.50	5.90	
MnO	0.15	0.28		0.24					0.18	0.20	
MgO	7.20	40.40	7.20	39.20	15.40	6.20	15.20	14.40	4.70	16.30	
CaO	6.70	0.28	6.50	0.26	10.10	6.00	9.90	17.20	6.10	18.20	
Na <sub>2</sub> O	5.90		5.60		2.90	6.10	2.90	1.40	6.60	1.40	
K <sub>2</sub> O	3.00		3.00		1.60	3.20	1.50	0.20	2.40	0.06	
Sum	100.25	100.06	100.10	100.10	98.67	100.00	97.11	99.99	100.08	98.32	
Mg/(Mg + ΣFe)	0.689	0.780	0.620	0.764	0.749	0.616	0.759	0.803	0.563	0.831	
Wt % H <sub>2</sub> O:	5	5			7	Natural megacrysts*					
Pressure (kbar):	15.9	27			13						
Temperature (°C):	1130	1210			1090						
Capsule:	Ag <sub>75</sub> Pd <sub>25</sub>		Ag <sub>75</sub> Pd <sub>25</sub>		Ag <sub>75</sub> Pd <sub>25</sub>						
Phase:	Olivine	Cpx	Mica	Cpx	Garnet	Olivine	Mica	Glass	Amphibole	Cpx	Mica
SiO <sub>2</sub>	37.70	50.80	37.90	51.30	41.10	38.60	38.50	50.70	40.50	47.90	36.40
TiO <sub>2</sub>		0.56	3.30	0.81	0.71		3.10	2.30	4.90	2.00	7.80
Al <sub>2</sub> O <sub>3</sub>		7.00	15.40	8.70	22.20		15.60	16.20	14.70	10.30	15.80
Cr <sub>2</sub> O <sub>3</sub>											
FeO	21.00	6.10	7.80	6.60	14.30		9.10	9.80	11.30	8.70	13.20
MnO	0.36	0.19		0.17	0.47	0.19			0.12	0.12	0.08
MgO	40.30	15.60	19.30	13.60	14.40	40.00	19.30	5.50	11.50	12.30	13.80
CaO	0.15	18.30		14.70	7.00	0.23		7.10	10.60	16.80	
Na <sub>2</sub> O		1.40	0.97	3.00	0.09		0.83	5.70	3.20	2.10	0.84
K <sub>2</sub> O			9.10				8.80	2.70	1.50		8.10
Sum	99.51	99.95	93.77	98.88	100.27	79.02	95.23	100.00	98.32	100.22	96.02
Mg/(Mg + ΣFe)	0.774	0.820	0.815	0.786	0.642	1.000	0.791	0.500	0.645	0.716	0.651

\*Kaersutite 2110b and included titanphlogopite from The Anakies (east) nepheline mugearite and clinopyroxene F4 from Mt. Franklin nepheline mugearite (Irving, 1974b). Cpx, clinopyroxene.

with the pressure dependence found by Takahashi & Kushiro (1983) we derive a  $K_D$  value of 0.32 for the nepheline mugearite at 15 kbar. Thus the predicted liquidus olivine composition (for Fe<sub>2</sub>O<sub>3</sub>/FeO of 0.1, as determined by microanalysis of experimental charges) should be

Fo<sub>81.4</sub>. Analyzed olivines from runs very near the liquidus in Ag<sub>75</sub>Pd<sub>25</sub> capsules and in Ag<sub>77</sub>Pd<sub>23</sub> capsules on QFM have compositions ranging from Fo<sub>79.2</sub> to Fo<sub>81.0</sub>, consistent with both attainment of equilibrium and negligible iron loss. Near-liquidus olivines from runs in Ag<sub>50</sub>Pd<sub>50</sub>

Table 3: Compositions of synthetic near-liquidus minerals and glasses in experiments on basanite + 10% olivine and comparisons with natural nepheline hawaiite

Wt % H <sub>2</sub> O:	4.5		4.5				4.5							
Pressure (kbar):	15		15						15					
Temperature (°C):	1160		1140				Natural		1120				Natural	
Capsule:	Starting	Ag <sub>75</sub> Pd <sub>25</sub>		Ag <sub>75</sub> Pd <sub>25</sub>				Ne hawaiite	Ag <sub>75</sub> Pd <sub>25</sub>				Ne hawaiite	
Phase:	Glass	Olivine	Glass	Olivine	Cpx	Mica	Glass	69-1027	Olivine	Cpx	Mica	Glass	69-1027	
SiO <sub>2</sub>	44.9	40.13	48.30	38.10	50.95	37.01	47.18	47.22	38.83	50.56	38.03	46.84	47.22	
TiO <sub>2</sub>	2.8	0.00	2.99	0.00	1.39	4.30	3.44	2.28	0.16	1.68	4.04	3.34	2.28	
Al <sub>2</sub> O <sub>3</sub>	12.2	0.00	13.81	0.00	5.69	16.04	15.81	14.96	0.18	6.20	16.04	15.51	14.96	
Cr <sub>2</sub> O <sub>3</sub>					0.19					0.27				
FeO	12.3	14.52	7.03	22.61	6.42	8.11	10.33	10.58	19.57	5.88	8.09	10.51	10.58	
MnO		0.24		0.41	0.24	0.19	0.14		0.35	0.26	0.16			
MgO	13.6	44.80	11.58	38.59	14.43	18.58	6.43	8.95	40.54	14.40	19.32	7.18	8.95	
CaO	7.5	0.30	8.81	0.29	19.51	0.10	8.64	7.91	0.38	19.52	0.18	8.05	7.91	
Na <sub>2</sub> O	3.75		4.14		1.07	0.79	4.57	4.7	0.00	1.12	0.73	4.70	4.7	
K <sub>2</sub> O	2		2.16		0.11	8.51	2.30	2.23	0.00	0.11	8.78	2.42	2.23	
P <sub>2</sub> O <sub>5</sub>	1		1.09				1.26	0.83				1.39	0.83	
Sum	100.05	99.99	98.82	100.00	100.00	93.63	98.84	99.66	100.01	100.00	95.37	98.55	99.66	
Mg/(Mg + ΣFe)	0.663	0.846	0.746	0.753	0.800	0.803	0.526	0.601	0.787	0.814	0.810	0.549	0.601	

Wt % H <sub>2</sub> O:	4.5				4.5				4.5						
Pressure (kbar):	15				5				15						
Temperature (°C):	1080				1040				1000						
Capsule:			Ag <sub>75</sub> Pd <sub>25</sub>				Ag <sub>75</sub> Pd <sub>25</sub>				Ag <sub>75</sub> Pd <sub>25</sub>				
Phase:		Olivine	Cpx	Amph	Mica	Glass	Olivine	Amph	Mica	Glass	Olivine	Amph	Mica	Ilmenite	Glass
SiO <sub>2</sub>		38.36	52.09	43.70	38.51	51.87	36.36	44.25	37.12	47.95	36.06	44.34	38.37	0.52	50.94
TiO <sub>2</sub>			1.12	2.86	3.84	2.55	0.00	2.71	3.74	1.08	0.09	2.48	3.03	49.69	0.98
Al <sub>2</sub> O <sub>3</sub>			4.97	11.94	15.88	16.89	0.00	10.85	15.12	14.41	0.17	10.15	14.37	0.42	16.85
Cr <sub>2</sub> O <sub>3</sub>			0.12	0.14											
FeO		22.95	7.22	9.77	9.09	9.27	29.62	10.72	10.61	4.93	23.79	11.18	11.68	35.83	3.32
MnO		0.43	0.30	0.27	0.17	0.31	0.64	0.39	0.23		0.24	0.39	0.21	0.46	
MgO		38.03	14.78	15.45	19.12	2.12	33.09	15.50	17.86	0.96	35.18	15.02	17.32	5.65	1.70
CaO		0.24	17.88	9.64	0.18	8.49	0.29	9.33	0.20	4.52	0.84	9.29	0.47	0.37	2.30
Na <sub>2</sub> O			1.20	3.04	1.10	4.16		3.20	1.01	5.11		4.02	1.18	4.30	
K <sub>2</sub> O			0.33	1.22	8.55	1.63		1.06	7.80	1.54		1.14	7.95	1.71	
P <sub>2</sub> O <sub>5</sub>						2.47				3.29				1.25	
Sum		100.01	100.01	98.03	96.44	97.29	100.00	98.01	93.69	80.50	96.37	98.01	94.58	92.94	82.10
Mg/(Mg + ΣFe)		0.747	0.785	0.738	0.789	0.290	0.666	0.720	0.750	0.258	0.725	0.705	0.725	0.219	0.477

Cpx, clinopyroxene; Amph, amphibole.

and Ag<sub>70</sub>Pd<sub>30</sub> capsules are not notably Mg-enriched (Fo<sub>76.9-78.1</sub>), despite the evidence for iron loss from the coexisting glasses, which implies that at least in some runs olivines grew early, prior to substantial iron loss from

surrounding melt. Most of the phase compositions reported in Table 2 are from runs in Ag<sub>75</sub>Pd<sub>25</sub> capsules, and where other data are used in calculations below they have been adjusted for iron loss.



### *Amphibole*

All the analyzed amphiboles are kaersutites or titaniferous pargasites [according to the classification of Leake *et al.* (1997)]. There is a systematic variation in amphibole composition with pressure and temperature. With decreasing temperature at constant pressure, there are consistent trends towards decreasing  $Mg/(Mg + \Sigma Fe)$ , Ti and Ca accompanied by increasing  $Al^{VI}$ , Na, K and Mn. Similar trends were reported by Helz (1973) for amphiboles crystallized from basalts at 5 kbar under  $H_2O$ -saturated conditions. With increasing pressure at approximately constant temperature [or constant  $Mg/(Mg + \Sigma Fe)$ ],  $Al^{VI}$  and Na increase at the expense of Ca (as in clinopyroxene). In terms of amphibole end-member molecules, the variation is towards lower Ti-amphibole and higher tschermakite with decreasing temperature, and towards lower edenite and higher glaucophane and tschermakite with increasing pressure.

### *Clinopyroxene*

Near-liquidus clinopyroxenes (for all bulk  $H_2O$  contents) are relatively calcic (16–19 wt % CaO) and contain 4–7 wt %  $Al_2O_3$  and  $\sim 1.5$  wt %  $Na_2O$  in the pressure range 9–20 kbar, but are more subcalcic (12.5–15 wt % CaO) with up to 12 wt %  $Al_2O_3$  and up to 3.7 wt %  $Na_2O$  at pressures of 25–31.5 kbar (reflecting an increase in jadeite component with pressure).

### *Mica*

Mica compositions show trends toward lower mg-value, Ti and  $Al^{IV}$  with decreasing temperature. Data are insufficient to determine the effects of pressure in detail; however, the compositional variation at approximately constant temperature between 2.7 and 24.5 kbar does not appear to be very large. There is a definite trend to lower Ti and Na contents in mica with increasing bulk  $H_2O$  content.

## DISCUSSION

### Constraints on conditions of megacryst formation

The near-liquidus amphiboles produced in the nepheline mugearite at 13.5–14 kbar for bulk  $H_2O$  contents of 3.5% and 5% show some chemical similarities to the magnesian kaersutites occurring as megacrysts in the natural 2102 lava (see Table 2). The natural amphiboles have Ca, Na and K contents comparable with those of the synthetic amphiboles, but have lower Si/Al, lower  $Mg/(Mg + \Sigma Fe)$  values (even if iron loss is taken into account), and higher Ti contents. The megacrysts cannot, therefore, represent liquidus phases of their host lava, but they may have crystallized from a slightly more evolved daughter liquid. This idea that such megacrysts are 'quasi-cognate' with the host magma that brought them to the surface and represent

disrupted crystallization products of earlier but related magma batches within the same conduit system was put forth by Irving (1974*b*, 1984). The pressures of formation of these megacrysts cannot be closely constrained, because amphiboles of generally similar composition have been crystallized from the nepheline mugearite throughout the range 2.7–23.5 kbar. If, however, the geometry of the liquidus and amphibole stability curves in Figs 1, 2 and 4 is significant in the evolution of alkalic magmas at depth, then the maximum pressure for amphibole megacryst crystallization may be about 15 kbar.

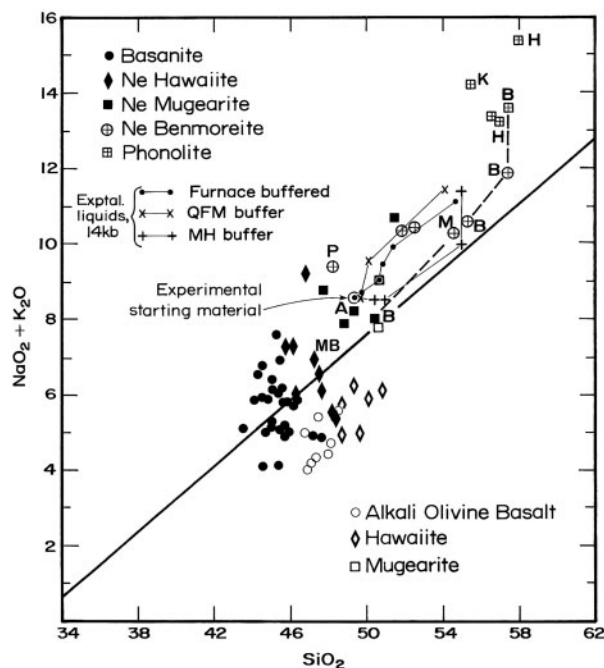
No clinopyroxene megacrysts have been found at The Anakies (east); however, clinopyroxene megacrysts are abundant within nepheline mugearites of very similar composition at Mt. Franklin in the same province (Irving, 1974*b*; Irving & Green, 1976). Nevertheless, these natural pyroxenes differ from the synthetic near-liquidus pyroxenes in having lower Si and  $Mg/(Mg + \Sigma Fe)$  coupled with higher Ti and also higher Al and Na than those crystallized from nepheline mugearite 2102 at pressures less than 25 kbar (see Table 2). Based on such arguments, Irving (1974*b*) concluded that the Mt. Franklin clinopyroxene megacrysts may have crystallized from a less evolved parental liquid similar to Victorian basanites. Some synthetic pyroxenes crystallized from the olivine-enriched basanite are very similar in composition to the megacrysts, and thus provide support for this hypothesis. As with the amphiboles, the pressures of crystallization can only be specified very generally as probably less than 30 kbar (Green, 1973*a*), although Green & Hibberson (1970*a*) were able to duplicate pyroxene megacrysts as near-liquidus phases of an Auckland Islands host hawaiite at 14–16 kbar.

The synthetic near-liquidus micas for the nepheline mugearite are similar in some respects to the titanphlogopite occurring as inclusions within kaersutite megacrysts from The Anakies (east) and forming discrete megacrysts in other alkalic basalts (Irving, 1974*b*; Irving & Frey, 1984), but, as for amphiboles, the synthetic micas differ in having higher  $Mg/(Mg + \Sigma Fe)$  and much lower Ti than the natural micas.

### Fractional crystallization of nepheline mugearite liquids to yield nepheline benmoreites and phonolites

Our experiments on nepheline mugearite 2102 with 3.5 wt %  $H_2O$  at 14 kbar over a temperature range of 80°C below the liquidus using two different oxygen buffers yielded charges containing crystals plus clear glass virtually free of quench products. Microprobe analysis of these glasses (corrected for iron loss, where necessary) gives the equilibrium liquid line-of-descent at 14 kbar for a total  $H_2O$  content of 3.5 wt %.

In Figs 6 and 7 we have plotted these glass compositions on variation diagrams for comparison with the observed



**Fig. 6.** Bulk-rock  $\text{SiO}_2$  vs total alkalis (in wt %) for natural lherzolite-bearing alkalic lavas from southeastern Australia and elsewhere (data mostly from Irving & Green, 1976; Irving & Price, 1981; Table 5) and synthetic glasses in experiments on nepheline mugearite at 14 kbar with 3.5 wt % added water at different oxygen fugacities. The diagonal line is the arbitrary boundary between strongly silica-undersaturated and mildly silica-undersaturated alkalic lavas proposed by Saggerson & Williams (1964). Letters denote geographical localities: MB, Mt. Bunninyong; A, The Anakies (east); B, Bokkos; H, Heldburg; K, Harrat Kishb; M, Mt. Mitchell (Queensland); P, Pigroot.

range of natural lherzolite-bearing alkalic lava compositions. The latter are mostly from southeastern Australia, but also include examples from New Zealand, Germany and Nigeria (Irving & Price, 1981), and a lherzolite-bearing phonolite from Harrat Kishb, Saudi Arabia (Table 4). It is evident that the experimental data define a compositional trend to nepheline benmoreite liquids that closely parallels the trend for natural magmas. This trend is produced by crystallization of olivine + amphibole + clinopyroxene (+ minor magnetite under conditions of the MH buffer), a process consistent also with available trace element data (Irving & Price, 1981). Based on geochemical arguments, further evolution towards phonolite liquids appears to require a change in the crystallizing assemblage to one of clinopyroxene + mica (Irving & Price, 1981).

Our calculations of liquid compositions have been made for a pressure of 14 kbar because there is a near-liquidus multiple saturation point for nepheline mugearite 2102 at this pressure; these experimental charges permitted very reliable analyses of quenched residual liquids. In reality, polybaric fractional crystallization is a more

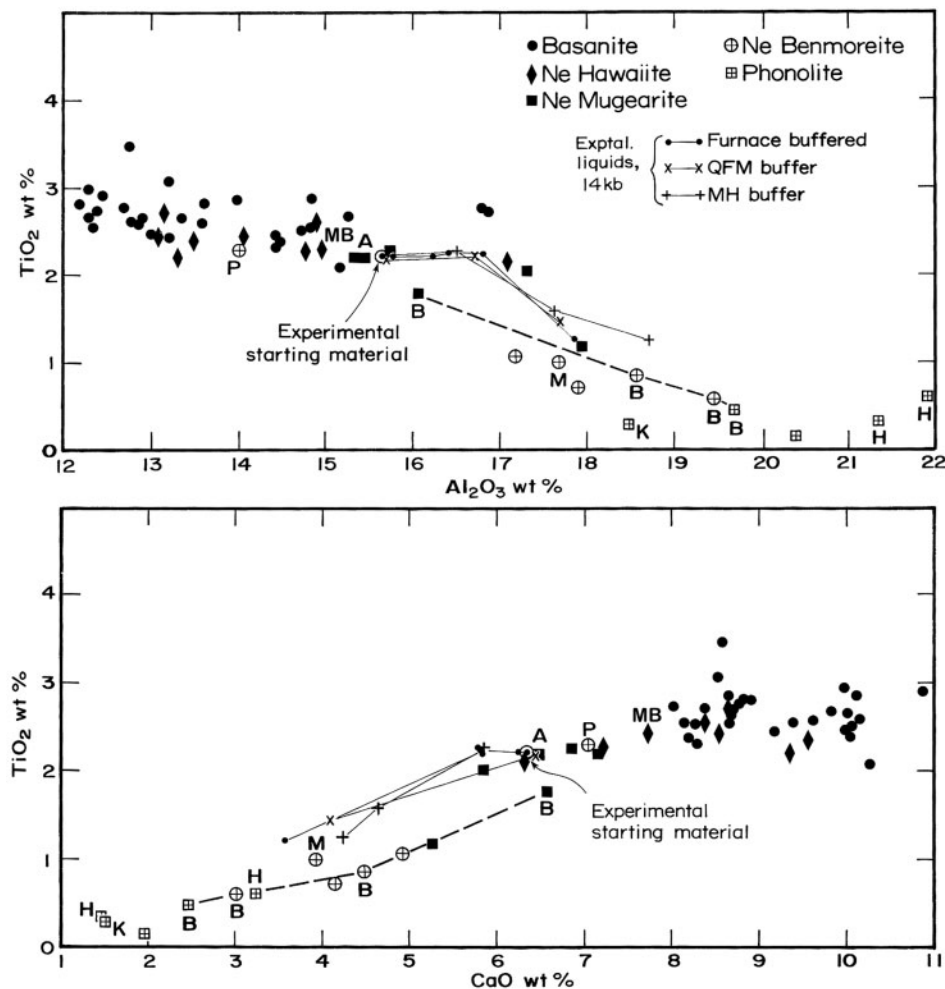
likely process affecting natural magmas during ascent. The best current constraints on the pressures of formation of lherzolite-bearing nepheline benmoreite and phonolite magmas range from a maximum of about 14 kbar to a minimum of about 8 kbar [representing the upper limit of plagioclase stability in lherzolite bulk compositions (Green & Ringwood, 1967; Green & Hibberson, 1970b)]. The absence of Eu anomalies in the rare earth element patterns of such lavas (Irving & Price, 1981) precludes a significant role for feldspar in their evolution, and probably is consistent with a similar pressure range, even though the limits of alkali feldspar stability in phonolitic liquids have not yet been experimentally determined.

An alternative hypothesis for generation of some phonolites by direct partial melting of previously emplaced alkalic basaltic rocks in the lower crust (Hay & Wendlandt, 1995) suffers from difficulties in sustaining a thermal regime to produce melting in solidified mafic rocks in the lithosphere. Furthermore, the strong spatial and temporal association of phonolites with basanites in many provinces plausibly argues for a genetic connection between these magmas, which can be successfully modeled by fractional crystallization processes in batches of ascending and cooling magma.

In our discussion above we drew parallels between the basanite  $\rightarrow$  nepheline hawaiiite and alkali olivine basalt  $\rightarrow$  hawaiiite lineages. However, comparisons between the more evolved lavas of these two lineages are more difficult to make. We are aware of at least one lherzolite-bearing mugearite (from Tasmania—Sutherland, 1974; Everard, 2001), but no examples of lherzolite-bearing benmoreites or trachytes. This may not be surprising in view of the fact that both experimental and geochemical studies (e.g. Frey *et al.*, 1978) imply that primary alkali olivine basalts originate at lower mantle pressures than basanites. Thus, the evolution of mildly undersaturated alkalic magmas beyond the hawaiiite–mugearite stage may nearly always take place in a crustal pressure regime, implying a significant role for feldspar fractionation and gravitational settling of any dense mantle xenoliths.

### Derivation of nepheline mugearites from basanites by fractional crystallization at mantle pressures

Basanitic lavas are commonly the most abundant associate of hawaiiitic, mugearitic, benmoreitic and phonolitic lavas within the eastern Australian Tertiary–Quaternary basalt provinces (Wass & Irving, 1976) and elsewhere. Among the Newer Basalts lavas, the lherzolite-bearing basanites are the most obvious candidates for high-pressure, primary magmas parental to liquids like nepheline mugearite 2102. An alternative hypothesis of generating evolved alkalic magmas by direct partial melting of variably Fe-enriched



**Fig. 7.** Bulk-rock  $\text{Al}_2\text{O}_3$  and  $\text{CaO}$  vs  $\text{TiO}_2$  (in wt %) for natural lherzolite-bearing alkalic lavas from southeastern Australia and elsewhere (data mostly from Irving & Green, 1976; Irving & Price, 1981; Table 5) and synthetic glasses in experiments on nepheline mugearite at 14 kbar with 3.5 wt % added water at different oxygen fugacities. Letters denote geographical localities: MB, Mt. Bunninyong; A, The Anakies (east); B, Bokkos; H, Heldburg; K, Harrat Kishb; M, Mt. Mitchell (Queensland); P, Pigroot.

mantle (Wilkinson, 1977; Wilkinson & Hensel, 1991) is not favored based on the lack of a viable thermal mechanism to generate magmas in relatively cold lithospheric peridotite and on isotopic grounds. The near constancy of Sr and Nd isotopic compositions across the spectrum of evolved lavas both in the Newer Basalts and in some Queensland provinces (McDonough *et al.*, 1985; W. F. McDonough & A. J. Irving, unpublished data) would not be expected if ancient enriched lithospheric mantle (with variably more radiogenic Sr and less radiogenic Nd isotopic compositions) were involved either as a source or an assimilant (see also O'Brien *et al.*, 1995). In particular, the natural nepheline mugearite 2102 is essentially identical in isotopic composition to basanites from the same province (see Table 5), and even more evolved nepheline benmoreite and phonolite lavas from

Queensland (described by Irving & Price, 1981) have notably unradiogenic Sr isotopic compositions.

We have tested the high-pressure fractional crystallization hypothesis in two ways: by calculating the effect of addition of observed near-liquidus phases to the nepheline mugearite, and by analyzing glasses produced in near-liquidus crystallization experiments on a basanite at similar pressures.

For the first calculation we assumed that the multiple near-saturation of the nepheline mugearite with amphibole and olivine for  $\text{H}_2\text{O}$  contents of 2–5 wt % at about 14 kbar has petrogenetic significance. By using a least-squares mixing program similar to that of Bryan *et al.* (1969), we sought to relate the nepheline mugearite to one of the lherzolite-bearing nepheline hawaiites from Mt. Bunninyong in the Newer Basalts province.

We computed a liquidus olivine composition for a  $K_D$  of 0.32, and constructed a liquidus amphibole composition from analyzed synthetic amphiboles, with  $Mg/(Mg + \Sigma Fe)$  adjusted empirically for coexisting amphibole–olivine pairs in our experimental runs, where  $Mg/(Mg + \Sigma Fe)_{\text{amph}} = 0.98 Mg/(Mg + \Sigma Fe)_{\text{ol}}$ . A least-squares solution using both of these phases gave small negative values for olivine, and a better solution was obtained using amphibole alone (see Table 6). A mixture of 24.9% amphibole + 74.7% 2102 approximates a nepheline hawaiiite composition reasonably well, but the total FeO and CaO contents of the calculated best-fit mixture are low by 10%.

Table 4: Composition of lherzolite-bearing phonolite H272b from Harrat Kūshb, Saudi Arabia

SiO <sub>2</sub>	55.92
TiO <sub>2</sub>	0.26
Al <sub>2</sub> O <sub>3</sub>	18.64
Cr <sub>2</sub> O <sub>3</sub>	0.02
Fe <sub>2</sub> O <sub>3</sub> T	7.03
MnO	0.21
MgO	1.32
CaO	1.50
BaO	0.08
SrO	0.17
Na <sub>2</sub> O	11.07
K <sub>2</sub> O	3.30
P <sub>2</sub> O <sub>5</sub>	0.49
LOI	0.58
Sum	100.59
Mg/(Mg + ΣFe)	0.173

Analysis by inductively coupled plasma emission spectrometry at University of Washington, using methods of O'Brien *et al.* (1991).

These discrepancies and the differences in P<sub>2</sub>O<sub>5</sub> contents suggest that the fit could be improved by considering iron oxides and apatite as well. Except for ulvöspinel in runs containing 20 wt % H<sub>2</sub>O and magnetite in runs on the MH buffer, iron oxides were generally not observed in our near-liquidus experiments. Nevertheless, the documented occurrences (e.g. Wilkinson, 1962; Cross & Holloway, 1974; Irving, 1974b; Stuckless & Irving, 1976) of apatite and titanomagnetite as discrete megacrysts or mineral inclusions associated with kaersutite and Ti-pargasite megacrysts at a number of alkalic basalt localities, including The Anakies (east), points to a role for these phases in the evolution of alkalic basaltic liquids. Indeed, a mixture of 76.1% 2102 + 22.4% amphibole + 1.2% apatite + 1.2% ulvöspinel (with a composition based on that of the near-liquidus oxide phase of 2102 with 20 wt % H<sub>2</sub>O) shows a much closer fit to the chosen nepheline hawaiiite composition.

Obviously, there are a number of uncertainties inherent in this type of calculation. A reverse fractional crystallization process can only very generally be approximated by considering phases of fixed composition; however, for the relatively small volumes (~25%) of solid phases added here, this procedure should demonstrate the compositional trends towards parental liquids. If, as we believe, Fe–Ti oxides are important minor phases in this process, there is considerable choice in composition, depending on, among other things, estimated oxygen fugacities for the natural process. Furthermore, for the purposes of modeling we have arbitrarily chosen just one specific nepheline hawaiiite lava from a range of examples in the Newer Basalts province. The important conclusions that emerge from this exercise are that kaersutitic amphibole is the major phase controlling the evolution of nepheline hawaiiitic to nepheline mugearitic liquids, and that apatite, Fe–Ti oxides and, possibly in some cases olivine, are minor phases in this process.

Table 5: Sr and Nd isotopic compositions of nepheline mugearite 2102 and selected other lavas

Locality:	Newer Basalts			Queensland	
	Mt. Noorat	Mt. Bunninyong	The Anakies (east)	Mt. Mitchell	Phonolite Hill
Rock type:	basanite	ne hawaiiite	ne mugearite	ne benmoreite	phonolite
Xenoliths:	present	present	present	present	present
Sample:	71-28	69-1027	2102	2943	X-32
<sup>87</sup> Sr/ <sup>86</sup> Sr	0.70382	0.70375	0.70384	0.70391	0.70327
<sup>143</sup> Nd/ <sup>144</sup> Nd	0.51280		0.51281		
ε <sub>Nd</sub>	+3.2		+3.3		

Isotope ratios were measured at Australian National University using the techniques reported by McDonough *et al.* (1985). All lavas are Recent to Quaternary in age and thus no age corrections were applied to measured isotopic ratios. Any such corrections would result in negligible changes with respect to measurement uncertainties.

Near-liquidus glasses produced experimentally for the olivine-enriched Mt. Leura basanite at 15 kbar in the presence of 4.5 wt % H<sub>2</sub>O (see Table 3) have nepheline hawaiite compositions. In runs at 1140°C and 1120°C, equilibrium near-liquidus crystallization of olivine, clinopyroxene and mica produced residual quenched liquids that are similar in composition to the Mt. Bunninyong nepheline hawaiite. The discrepancies for Ti, P and to some extent K result from the fact that the Mt. Leura basanite is anomalously more enriched in these elements than other basanites of the Newer Basalts province (Irving & Green, 1976). The discrepancy in Mg/(Mg + ΣFe) values could be removed if a more magnesian basanite composition was chosen (even basanite 2650 to which more than the arbitrary 10% olivine had been added). Our conclusion from both of the approaches examined here is that progressive fractional crystallization of a primitive water-undersaturated basanite at 14 kbar can indeed yield liquids first of nepheline hawaiite composition and then of nepheline mugearite composition.

If primary basanites are formed by partial melting of garnet lherzolite at ~28 kbar (Green, 1973*b*), then it is likely that fractional crystallization will actually be polybaric. This process cannot be modeled uniquely; however, if the nepheline hawaiite stage involves some amphibole removal (as appears to be required from alkalis-silica systematics—see Fig. 6, and also Irving & Price, 1981, fig. 6), then the pressure-temperature geometry of the amphibole stability field for the basanite essentially

precludes production of nepheline hawaiite liquids at pressures above about 20 kbar. Polybaric fractional crystallization of the Mg-rich primary basanite magma ascending from pressures of 30 kbar may proceed through a derivative basanite or tephrite stage by removal of olivine + clinopyroxene until H<sub>2</sub>O activity in the residual liquids is sufficient to permit amphibole crystallization in the 14–20 kbar pressure range. Evolved basanite lavas [i.e. with Mg/(Mg + Fe<sup>2+</sup>) < 0.65] are found at Mt. Leura (a fact that dictated addition of olivine to the natural samples for experimental studies of primitive liquids). It also may be significant that amphibole megacrysts have never been observed at Mt. Leura and are exceedingly rare at other basanite eruptive centers within the Newer Basalts (Irving, 1974*b*; Ellis, 1976).

It is notable that the calculated compositions in Table 6 do not differ greatly in normative nepheline contents from 2102. This results from the involvement of amphibole, which produces a characteristic change in Ca/Na ratios, but which is comparable with the basaltic liquids in Al<sub>2</sub>O<sub>3</sub> content. Thus, we suggest by analogy that hawaiite magmas (which in the Newer Basalts province differ from the nepheline hawaiites mainly in having lower normative nepheline contents) may be derived from alkali olivine basalt parent liquids by fractional crystallization also dominated by amphibole. The lherzolite-bearing alkali olivine basalt from Mt. Frazer (Victoria) is a potential primary magma that could be parental to such hawaiites.

Table 6: Phase compositions and least-squares mixing solutions relating nepheline mugearite to nepheline hawaiite by equilibrium crystallization

Material:	Olivine	Amphibole	Apatite	Ulvöspinel	69-1027*	Mix 1†	Mix 2‡
SiO <sub>2</sub>	38.80	43.40			47.22	47.50	47.29
TiO <sub>2</sub>		3.20		29.10	2.28	2.42	2.74
Al <sub>2</sub> O <sub>3</sub>		12.70		1.50	14.96	14.70	14.68
FeO	19.20	8.60		64.70	10.58	9.61	10.38
MgO	41.30	16.00		2.40	8.95	9.27	9.02
CaO	0.27	10.10	55.80		7.91	7.20	7.75
Na <sub>2</sub> O		2.90			4.70	4.89	4.91
K <sub>2</sub> O		1.60			2.23	2.56	2.57
P <sub>2</sub> O <sub>5</sub>			42.40		0.83	0.51	1.04
Sum	99.57	98.50	98.20	97.70	99.66	98.66	100.38
Mg/(Mg + ΣFe)	0.793	0.768		0.062	0.601	0.632	0.608
Σr <sup>2</sup> for nine oxides relative to 69-1027						1.96	0.57

\*Nepheline hawaiite lava from Mt. Bunninyong, Victoria (Irving & Green, 1976).

†74.4% nepheline mugearite 2102 + 24.9% amphibole.

‡76.1% nepheline mugearite 2102 + 22.4% amphibole + 1.2% apatite + 1.2% ulvöspinel.

## CONCLUSIONS

High-pressure crystal–liquid phase relationships for nepheline basanite and nepheline mugearite from the Newer Basalts province permit the inference that these magma compositions are related to one another by fractional crystallization of olivine, clinopyroxene, amphibole, mica, apatite and Fe–Ti oxides at mantle depths of ~42 km. Such a model is also consistent with trace element abundances in these lavas coupled with knowledge of crystal–liquid elemental partition coefficients. The presence in both the primitive and more evolved lavas of peridotite and pyroxenite xenoliths with mineral assemblages indicative of similar depths provides further evidence that fractional crystallization operated within the lithospheric mantle, and may have been initiated as basanite magmas encountered cooler rocks there. Additionally, the experimental studies of these alkalic lavas support models for the origin of megacryst suites contained in them that involve disruption of polyphase pegmatites precipitated at elevated pressures (probably in conduits within lithospheric mantle) by episodic pulses of ascending magmas spanning a range of compositions related by fractional crystallization.

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## SUPPLEMENTARY DATA

Supplementary data for this paper are available at *Journal of Petrology* online.

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