The Canadian Mineralogist
Vol. 35, pp. 291-312 (1997)

PRIMITIVE ANKARAMITIC MAGMAS IN VOLCANIC ARCS: A MELT-INCLUSION APPROACH

FERNANDO N. DELLA-PASQUA[1] AND RICK VARNE[1]

Department of Geology, University of Tasmania, GPO Box 252-79, Hobart, Tasmania 7001 Australia

ABSTRACT

Ankaramite is more mafic than basalt, commonly porphyritic, and generally interpreted as a variety of picrite or olivine basalt that has been enriched in clinopyroxene crystals rather than a product of crystallization of an ankaramitic magma. Samples of ankaramite from the Ulakan Formation, Bali, and Rinjani volcano, Lombok, both in the Sunda arc, and from Merelava and Epi, in the Vanuatu arc, contain olivine and clinopyroxene phenocrysts with vitreous and crystalline inclusions. Heated and homogenized silicate melt inclusions hosted by olivine with $Fo_{>90}$ have CaO/Al_2O_3 (wt%) values > 1, and are rich in Mg (>14 wt% MgO) and Ca (>13 wt% CaO), and therefore have ankaramitic affinities and are quite unlike picrites. Although the composition of the inclusions provides evidence that primitive ankaramitic melts exist, they are consistently more silica-undersaturated than the ankaramitic bulk-rock compositions. Primitive ankaramitic melts are substantially higher in their normative diopside contents than the compositions of experimental melts of dry lherzolite at all pressures up to 4 GPa, which typically are picritic. Olivine fractionation of primary komatiite-like melts with CaO/Al_2O_3 (wt%) values > 1, derived by partial melting of lherzolite at high pressures (>5 GPa), could produce compositions similar to primitive ankaramitic bulk-rock compositions. Alternatively, melting of lherzolite in the presence of mantle fluids bearing H_2O and CO_2 could produce compositions similar to those of the silica-undersaturated melt inclusions trapped in the olivine ($Fo_{>90}$) of ankaramitic samples. Such melts would be likely to react with mantle during ascent to become less silica-undersaturated and more like ankaramitic bulk-compositions.

Keywords: melt inclusion, primitive melts, ankaramite, komatiite, Sunda arc, Indonesia, Vanuatu arc.

SOMMAIRE

Une ankaramite est une roche plus mafique qu'un basalte, couramment porphyritique, et interprétée, en général, comme une variété de picrite ou de basalte à olivine qui s'est enrichie en cristaux de clinopyroxène, plutôt que comme un produit de cristallisation d'un magma à tendance ankaramitique. Les ankaramites de la Formation Ulakan, sur l'île de Bali, et du volcan Rinjani, à Lombok, tous deux dans l'arc de Sunda, en Indonésie, et de Merelava et Epi, dans l'arc de Vanuatu, contiennent des phénocristaux d'olivine et de clinopyroxène contenant des inclusions vitreuses ou bien cristallines. Les inclusions vitreuses, chauffées et homogénéisées, ont été piégées par l'olivine ($Fo_{>90}$); elles ont des valeurs de CaO/Al_2O_3 (base pondérale) supérieures à 1, et sont riches en Mg (>14% MgO) et Ca (>13% CaO). Le magma possède donc une affinité ankaramitique, et diffère sensiblement d'un magma picritique. Malgré l'appui qu'apportent ces compositions de reliquats magmatiques à l'hypothèse de l'existence d'un magma ankaramitique, celui-ci s'avère systématiquement plus sous-saturé en silice que les compositions globales des roches. Les magmas primitifs à tendance ankaramitique sont sensiblement plus enrichis en diopside normatif que les compositions de liquides obtenus dans les expériences à sec sur les lherzolites à toutes pressions jusqu'à 4 GPa, qui sont typiquement picritiques. Le fractionnement de l'olivine à partir d'un magma à tendance komatiitique, ayant un rapport CaO/Al_2O_3 supérieur à 1, dérivé par fusion partielle d'une lherzolite à pression élevée (>5 GPa), pourrait produire des compositions semblables à celles de nos roches. En revanche, la fusion d'un socle lherzolitique en présence d'une phase fluide contenant H_2O et CO_2 pourrait produire des compositions semblables à celles des inclusions vitreuses piégées. De tels magmas réagiraient probablement avec les roches du manteau lors de leur mise en place, pour devenir moins sous-saturés en silice et davantage comme les compositions ankaramitiques observées.

(Traduit par la Rédaction)

Mots-clés: reliquat magmatique, magma mantellique primitif, ankaramite, komatiite, arc de Sunda, Indonésie, arc de Vanuatu.

INTRODUCTION

The origin of ankaramite is of general interest because its bulk composition differs from the picritic compositions of experimentally produced partial melts in equilibrium with mantle peridotite assemblages; yet, ankaramite shares some of the "primitive" characteristics of picrite. Both picrite and ankaramite have similarly Fo-rich olivine, both are rich in Mg, with high Mg# values [Mg# = 100Mg/(Mg + ΣFe)], and, in many cases, both also have high Ni and Cr contents.

---

[1] *E-mail addresses:* u926115@postoffice.utas.edu.au, rick.varne@geol.utas.edu.au

Although one rock type grades into the other, ankaramite has commonly been distinguished from picrite by its richness in clinopyroxene phenocrysts (Lacroix 1916, Hess & Poldervaart 1967, Arculus 1976, Krishnamurthy & Cox 1977, Hawkesworth *et al.* 1979, Foden & Varne 1983, Tomkeieff 1983, Mitchell 1985, Bowes 1989, Le Maitre *et al.* 1989, Barsdell & Berry 1990). Because of this characteristic, most investigators have concluded that ankaramitic bulk compositions never existed as magmas, and that their bulk compositions are the result of the accumulation of clinopyroxene phenocrysts in picritic or basaltic magmas (*e.g.*, Gunn *et al.* 1970, Hughes 1982). However, others have argued for the existence of ankaramitic magmas (*e.g.*, Dawson *et al.* 1970, Thompson & Flower 1971). Maaløe *et al.* (1986) distinguished Jan Mayen ankaramites whose bulk compositions are representative of melts from Jan Mayen ankaramites whose bulk compositions had been affected by crystal accumulation. Maaløe *et al.* (1986) estimated that primitive ankaramitic melt contains 13.5 wt% MgO and 13.5 wt% CaO, with CaO/Al_2O_3 (wt%) = 1.31. Barsdell (1988) and Barsdell & Berry (1990) also presented evidence that ankaramite might not simply be the result of crystal accumulation. They used the nature of Fe–Mg partitioning between olivine and clinopyroxene to investigate the near-liquidus crystallization histories of suites of ankaramitic volcanic rocks from Merelava and Western Epi, both in the Vanuatu island arc, and argued that the parental magmas were saturated in forsteritic olivine and diopsidic clinopyroxene, and had contents of 13.7 and 14.5 wt% MgO, 13.7 and 14.7 wt% CaO, and CaO/Al_2O_3 (wt%) values of 1.33 and 1.34, respectively.

In this study, we attack this problem more directly by investigating the compositions of homogenized melt inclusions in phenocrysts of forsteritic olivine and clinopyroxene from ankaramites from Indonesia and Vanuatu. We argue that if the rocks crystallized from ankaramitic magmas, the compositions of the melt inclusions should have ankaramitic affinities, with characteristically high CaO/Al_2O_3 (wt%) values (>1).

THE ANKARAMITIC HOSTS

Ankaramites with olivine and clinopyroxene phenocrysts containing vitreous and crystalline inclusions were sampled from four localities in two volcanic island arcs: two localities are in the Sunda arc of Indonesia (Fig. 1a), where ankaramites occur in the Ulakan Formation of eastern Bali, and in the Rinjani volcano, Lombok, and two in the Vanuatu arc (Fig. 1b), where ankaramites occur in Merelava and Epi, as well as in several other localities, not investigated here. These four ankaramitic suites are already known to have characteristically high CaO/Al_2O_3 (wt%) values (>1) compared with chondritic CaO/Al_2O_3 (wt%) values of 0.8 (Frey *et al.* 1978) and picritic CaO/Al_2O_3 (wt%) values <1 [*i.e.*, *Ulukan* Formation (Bali): Whitford (1975), Whitford *et al.* (1979), Wheller (1986); Rinjani (Lombok): Foden (1979), Foden & Varne (1981a, b), Varne & Foden (1986); Merelava (Vanuatu): Barsdell (1980, 1988); Epi (Vanuatu): Barsdell & Berry (1990)] (Fig. 2).

The Late Miocene ankaramitic volcanic rocks of the Ulakan Formation are the oldest known volcanic rocks exposed on Bali and are mildly *ne*-normative (Wheller 1986; Table 1). Younger Balinese volcanic sequences lack ankaramite, although basalts are present (Whitford 1975, Whitford *et al.* 1979, Wheller 1986). On Lombok, the island immediately east of Bali, ankaramite represents the most primitive composition among the abundant mafic rocks of the Rinjani volcano. These ankaramitic volcanic rocks form a group compositionally unrelated to

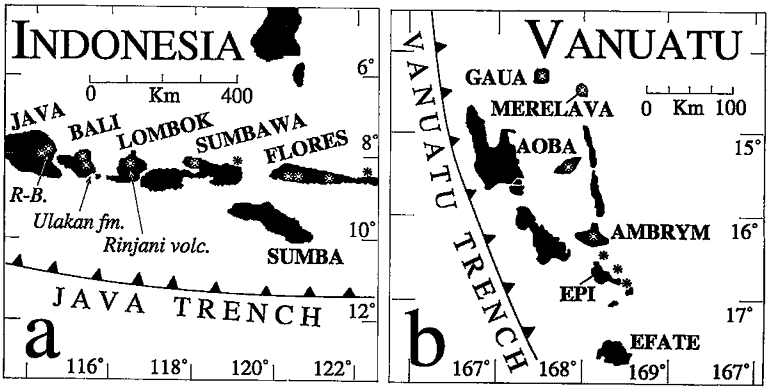


FIG. 1. Location map showing position of (a) Rinjani volcano in Lombok, Ulakan formation in Bali and Ringgit-Beser volcano (R–B) in Java, in the Sunda arc, Indonesia, after Foden (1983), and (b) Merelava and Epi in the Vanuatu arc, Vanuatu, after Greene *et al.* (1988). Stars indicate position of active volcanoes.

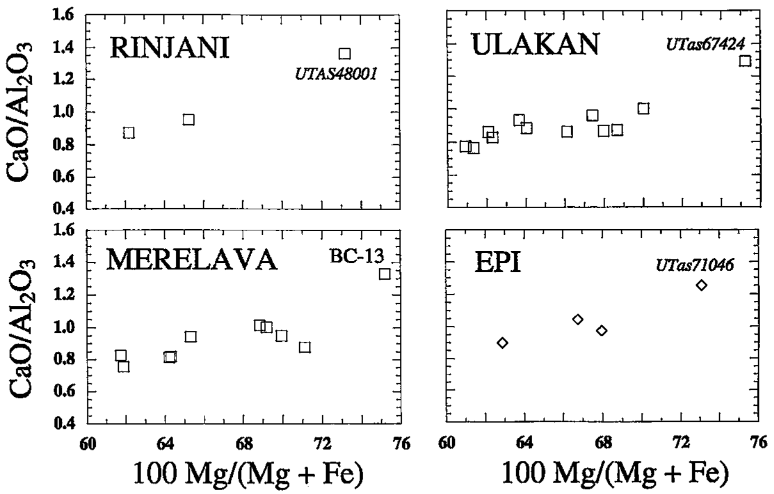


FIG. 2. Bulk-rock CaO/Al_2O_3 *versus* 100 Mg/(Mg + ΣFe) of four ankaramite suites: Ulakan Formation (Bali) and Rinjani volcano (Lombok), in the Sunda arc, and Merelava and Epi, in the Vanuatu arc.

the Rinjani basaltic rocks (Foden 1983) and constitute, as on Bali, a distinct, *ne*-normative rock-type (Table 1). Foden & Varne (1981a) concluded that at least two primary or primitive mafic magmas must be present in the Rinjani volcano, one parental to the basalt – andesite – dacite fractionation sequence, and the other ankaramitic. Sr, Nd and Pb isotopic ratios of ankaramite UTas48001 (Varne & Foden 1986), which is the only Rinjani ankaramite so far isotopically analyzed, are unlike those of the Rinjani basalts, but resemble those of *ne*-normative shoshonitic olivine trachybasalts from the Tambora volcano on Sumbawa, to the east.

In the volcanic suites of Merelava and Epi, in the Vanuatu arc, ankaramite is interpreted to be the primitive end-member of differentiated sequences ranging from ankaramite to basaltic andesite and dacite (Barsdell 1980, 1988, Barsdell & Berry 1990). In these suites from the Vanuatu arc, the ankaramites are *ol*- and *hy*-normative (Table 1), in contrast with the Sunda rocks.

Considered as a group, all these ankaramitic rocks are highly porphyritic, and characteristically contain abundant phenocrysts of euhedral to subhedral clinopyroxene up to 1 cm in diameter, together with scarcer, smaller, phenocrysts of olivine. Whether from Merelava and Epi, or from Rinjani and Ulakan, the clinopyroxene that crystallized early is Ca- and Mg-rich, and its compositions fall mainly within the diopside compositional field (Foden 1983, Wheller 1986, Barsdell 1988, Barsdell & Berry 1990, our unpublished data), although the composition of Merelava clinopyroxene ranges to lower Ca contents, in keeping with the tholeiitic affinities of these suites. The most Mg-rich compositions of clinopyroxene contain inclusions of titaniferous magnetite, in addition to glass inclusions described

TABLE 1. PRIMITIVE ANKARAMITE: BULK-ROCK COMPOSITIONS

	Sunda Arc				Vanuatu Arc			
Location	*(Rinjani volc.)* *Lombok*		*(Ulakan Fm.)* *Bali*		*Merelava*		*Epi*	
Sample #	*48001*	*48002*	*67424*	*67422*	*BC-13*	*31551*	*71046*	*71041*
SiO2 wt%	48.32	47.95	46.44	46.86	50.20	51.33	48.20	47.80
TiO2	0.69	0.83	0.56	0.79	0.46	0.59	0.39	0.43
Al2O3	10.53	13.78	9.12	11.84	10.30	13.10	11.50	13.60
FeO*	9.19	10.16	10.30	10.20	8.08	8.20	8.91	9.54
MgO	14.02	10.61	17.48	13.30	13.71	10.67	13.50	10.70
CaO	14.38	13.14	11.78	11.84	13.69	12.45	14.40	14.20
MnO	0.17	0.17	0.20	0.19	0.17	0.22	0.16	0.18
Na2O	1.50	1.78	1.22	1.59	1.60	1.78	1.05	1.29
K2O	0.90	1.20	0.61	0.94	0.38	0.35	0.31	0.35
P2O5	0.15	0.21	0.21	0.28	0.05	0.07	0.07	0.09
LOI			0.41	0.42	0.90	0.62	0.10	0.31
H2O-			0.37	0.40				
rest			0.33	0.31				
total	99.85	99.83	99.03	98.96	99.54	99.38	98.59	98.49
Mg#	73.1	65.1	75.2	70.0	75.2	69.9	73.0	66.7
Ni (ppm)	151	125	392	246	137		172	97
Cr (ppm)	510	307	1055	618	695		820	448
CaO/Al2O3	1.37	0.95	1.44	0.99	1.33	0.95	1.25	1.04
CIPW norm (mol%)								
Or	4.04	5.61	2.69	4.36	1.68	1.45	1.40	1.64
Ab	5.24	8.25	7.16	9.76	10.78	11.22	7.19	9.21
An	14.70	20.63	13.16	17.60	14.85	18.76	19.64	24.08
Ne	4.99	4.40	1.02	1.46				
Di	38.78	29.88	29.49	27.13	35.85	24.29	34.49	31.46
Hy					13.25	36.66	10.04	8.66
Ol	30.26	28.73	44.81	37.24	22.33	6.12	26.14	23.67
Ilm	1.83	2.29	1.46	2.16	1.20	1.44	1.04	1.19
Ap	0.15	0.22	0.21	0.29	0.05	0.06	0.07	0.09
Phenocryst modes								
Cpx	36.5		37.5		36.0		78.0†	
Ol	12.0		13.9		8.2		28.0†	
Pl	4.5							

Samples were taken from Rinjani (Foden 1979, 1983), Ulakan (Wheller 1986), Merelava (Barsdell 1988), and Epi (Barsdell & Berry 1990). * All iron is expressed as FeO. † Indicates the modal proportion of olivine relative to clinopyroxene. Abbreviations: clinopyroxene Cpx, olivine Ol, plagioclase Pl.

below, but generally lack inclusions of olivine, as well as chromian spinel, which occurs in the olivine phenocrysts.

Olivine ranges from compositions as magnesian as Fo_{91-93} down to Fo_{75}. Ca contents in olivine in ankaramite from Merelava and Epi mostly vary from 0.15 to 0.30 wt% CaO (Fig. 3), whereas in ankaramite from Rinjani and Ulakan, Ca contents in olivine increase from 0.25 to 0.40 wt% CaO, with maximum values around Fo_{90} where clinopyroxene joins olivine in the crystallization sequence (Fig. 3).

Some olivine phenocrysts also contain crystals of spinel (Della-Pasqua *et al.* 1995) and, more rarely, clinopyroxene. Values of 100 Cr/(Cr + Al) in the spinel are generally high: they range from 72 in ankaramites from Rinjani up to 87 in ankaramites from Epi. Very rarely, Al-rich spinel grains coexist with the more common Cr-rich spinel: their origin is discussed in Della-Pasqua *et al.* (1995). Clinopyroxene inclusions in Mg-rich olivine are rare: in olivine with $Fo_{90.1}$ from Ulakan, clinopyroxene Mg# is 82.1 and mg# [= 100Mg/(Mg + Fe^{2+})] = 94.0, whereas in olivine with $Fo_{85.2}$ from Rinjani, clinopyroxene Mg# = 85.8 and mg# = 91.0. [The proportion of Fe^{2+} and Fe^{3+} in clinopyroxene is calculated by assuming perfect stoichiometry following the method of Robinson (1980)]. In Merelava assemblages, in common with the clinopyroxene phenocrysts, many olivine phenocrysts have a reversely zoned internal rim (Barsdell 1988) with a typical core-to-rim variation in Fo of 90.5 to 91.3, but reverse zoning is not present in olivine from Epi. Plagioclase phenocrysts in ankaramite from Rinjani are as calcic as An_{90}, but are absent from the most magnesian rocks. In ankaramite from Ulakan, rare microphenocrysts of plagioclase attain An_{75}. In ankaramite from Merelava and Epi, plagioclase phenocrysts are again absent from the magnesian ankaramites and appear only late in the crystallization sequence, coexisting with olivine of composition $Fo_{81.6}$. The groundmass in these rocks is composed of olivine, clinopyroxene, plagioclase, and titaniferous magnetite. Plagioclase compositions in the groundmass range up to An_{70} in Ulakan, An_{90} in Rinjani (Foden & Varne 1981a), An_{93} in Merelava (Barsdell 1988), and An_{94} in Epi (Barsdell & Berry 1990).

In the Rinjani suite, the ankaramites have Al_2O_3 contents less than 16 wt%, high Mg (8–14 wt% MgO), and high CaO, Cr, Ni and Sc contents. Compositional variation within the suite is characterized by simultaneous depletion of Cr, Ni, Sc, MgO, CaO and decreasing Mg#, accompanied by enrichment in Al_2O_3, K_2O, TiO_2, Rb, Sr, Zr, and Nb, and relatively invariant SiO_2 and total Fe. These features are consistent with crystal fractionation involving the clinopyroxene-dominant plagioclase-free phenocryst assemblage of the ankaramites (Foden 1983).

Barsdell (1988) and Barsdell & Berry (1990) showed that ankaramitic bulk-rock compositions from Merelava and Epi define differentiation trends that could also be consistent with fractionation of olivine + clinopyroxene involving observed phenocryst abundances (clinopyroxene:olivine approximately 3 to 4:1), and concluded that the Merelava and Epi rocks evolved down olivine–clinopyroxene cotectics. Olivine occurs together with clinopyroxene even in the Epi rocks with highest Mg contents and Mg# (UTas 71046 and 71041, Table 1), in which olivine (mg# = 92) coexists with clinopyroxene (mg# = 94). It is notable that in all four ankaramite suites, CaO/Al_2O_3 (wt%) values are highest in the most

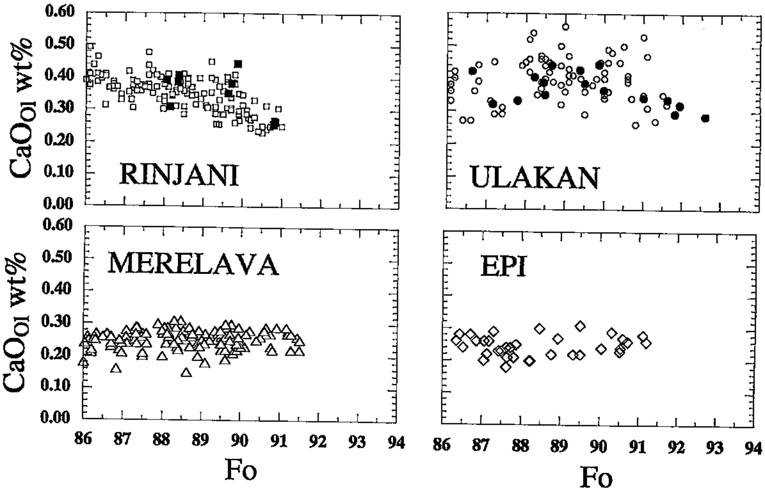


FIG. 3. Concentration of Ca (wt% CaO) in olivine *versus* Fo content. Electron-microprobe data; open circles: standard analytical conditions, filled circles: special analytical conditions. For fuller explanation, see text.

Mg-rich volcanic rocks, and decrease with decreasing Mg# (Fig. 2). Fractionation of an assemblage with clinopyroxene:olivine of approximately 3 to 4:1 would cause CaO/Al_2O_3 (wt%) values to fall even in the most ankaramitic melts.

The somewhat higher Ca contents in olivine from Rinjani and Ulakan ankaramites may be a reflection of the *ne*-normative character of their host rocks (Stormer 1973), but the early increase in Ca content in olivine and subsequent decline with fractionation within each of these suites (Fig. 3) may also simply be due to changing Ca contents in the melts (Sigurdsson 1994). If the most magnesian olivine in the Rinjani and Ulakan melts crystallized before clinopyroxene appeared, Ca contents of the melts would first increase as their Mg# decreased, and Ca contents would increase concomitantly in olivine, then decrease after clinopyroxene joined olivine as a crystallizing phase.

EXPERIMENTAL METHODS

In this article, we have focussed on the compositions of silicate inclusions interpreted as primary melt inclusions in olivine and clinopyroxene phenocrysts from ankaramite samples with "primitive" compositions. These ankaramite samples are characterized geochemically by high Mg# numbers, 73 to 74, high Mg and Cr contents (Table 1), and high CaO/Al_2O_3 (wt%) values, > 1. They include samples UTas48001 and 48002 from Rinjani (see also Foden 1983, Varne & Foden 1986), UTas 67424 and 67422 from the Ulakan Formation of Bali (Wheller 1986), BC–13 and UTas 31551 from Merelava (Barsdell 1988), and UTas 71046 and 71065 from Epi (Barsdell & Berry 1990).

Primary melt inclusions are formed when melt is trapped in a growing crystal as a result of growth irregularities, and are commonly distinguished from secondary melt inclusions, which tend to occur along fracture planes in the host crystal (Roedder 1979, 1984, Sobolev *et al.* 1991). Primary melt inclusions were selected for experimental work following the criteria of Sobolev *et al.* (1991) and Roedder (1979, 1984).

Primary inclusions observed in the olivine and clinopyroxene phenocrysts include "crystalline", "combined" and "vitreous" types, following the classification of Sobolev *et al.* (1989). Microphotographs to illustrate the various types of inclusion are presented in Figure 4. In "crystalline" melt inclusions (Figs. 4a, b), the daughter mineral phase is clinopyroxene, and olivine has nucleated on the inclusion wall. The combined type commonly consists of spinel ± silicate glass ± bubble (Figs. 4c, d). A vapor bubble is common in silicate glass inclusions (Fig. 4e). Some of the cavities that were investigated by infrared spectroscopy are empty, and may have leaked or formed by shrinkage during quenching, but others contain traces of CO_2 and CH_4 (our unpublished data).

The samples of ankaramite were crushed and sieved, and olivine and clinopyroxene grains hand-picked from the crushed material, mounted in epoxy, polished, and analyzed by electron microprobe. Those grains with primary melt inclusions were then extracted from the probe mounts for further study.

Homogenization experiments were carried out on primary melt inclusions hosted in olivine and clinopyroxene grains using a heating-stage based on the design of Sobolev *et al.* (1980), which allows visual monitoring and manual control during heating. As each inclusion-bearing grain was progressively heated, the melting behavior of the inclusion was observed, and the temperature at which the various phases disappeared was recorded.

Bubbles may persist to high temperatures in the ankaramitic melt inclusions, possibly as a result of volatile oversaturation (Danyushevsky *et al.* 1992, Gurenko *et al.* 1992), and as suggested by the presence in magnesian olivine of inclusions containing crystals of chromian spinel, to which bubbles of fluid are attached (Fig. 4c). This possibility made inappropriate the use of techniques of melt inclusion homogenization that use bubble disappearance as an indicator of homogenization; we used the "optical homogenization" technique, in which the melt inclusions are heated up to temperatures at which the last daughter crystals are observed to melt and the melt inclusion becomes optically homogeneous (Gurenko *et al.* 1988, 1992, Hansteen 1991, Sobolev *et al.* 1990).

Once optical homogenization of the inclusions has been achieved, the host grains of olivine and clinopyroxene are quickly cooled, and the molten inclusion quenched to glass (Fig. 4f). The host grains are then mounted in epoxy and individually sectioned and polished to expose the homogenized melt inclusions within them for electron-microprobe analysis.

Homogenized melt inclusion and host grain were analyzed using a CAMECA SX–50 electron microprobe (CSL, University of Tasmania) calibrated with natural standards (PAP data reduction). San Carlos olivine USNM111312/444, basaltic glass VG–A99 USNM113498/1, augite KA USNM122142, and spinel USNM117075 were used as standards, following Jarosewich *et al.* (1980). Analytical conditions were: accelerating voltage 15 kV, beam current 20 nA (minerals) and 10 nA (glass), and beam sizes 1–4 μm (minerals) and 4–10 μm (glass). Some grains of olivine in ankaramites from Rinjani and Ulakan were also re-analyzed for trace elements Ca, Ni, Mn and Cr using longer counting-times (120 seconds), 200 nA, 20 kV and a 20-μm beam size (olivine compositions plotted as filled circles on Fig. 3).

The beam size used on these melt inclusion glasses was restricted by the size of the inclusions, which attains 100 μm and averages 30 to 50 μm. The risk that the excited volume of the electron beam might interact with

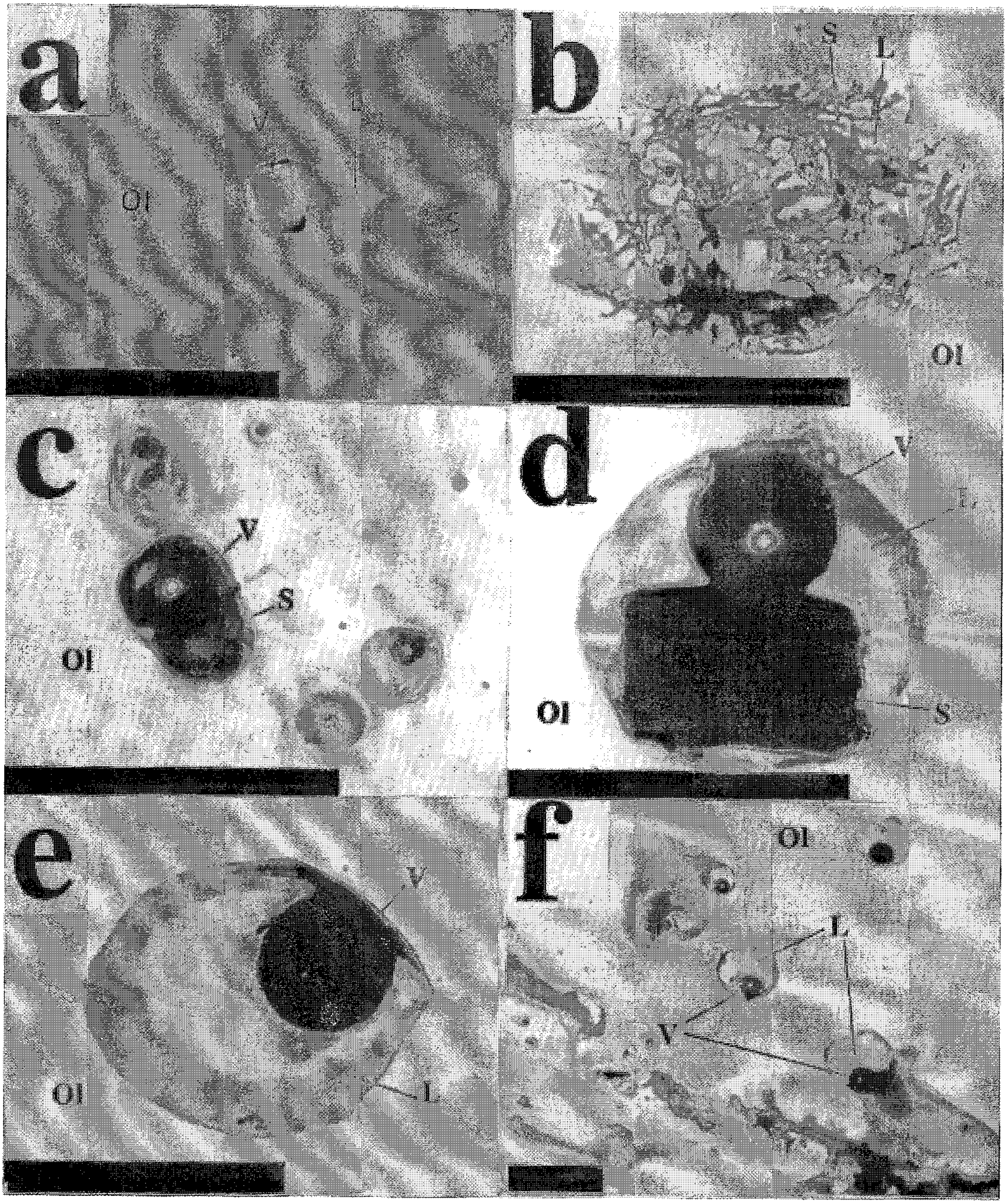


FIG. 4. Types of melt inclusion found in ankaramite, following classification of Sobolev *et al.* (1989). a. "Crystalline" melt inclusions with clinopyroxene daughter crystals. b. Exposed "crystalline" melt inclusion. c. Inclusion of chromian spinel with fluid bubble attached. These types of inclusions are a strong indication of fluid saturation in the melt (Danyushevsky *et al.* 1992). d. "Combined" melt inclusion with an accidentally trapped crystal of chromian spinel. e. "Vitreous" melt inclusion. f. "Crystalline" melt inclusions after heating. Vitreous melt inclusions (4e) are absent in magnesian olivine ($Fo_{>90}$), whereas "crystalline" melt inclusions (4a, b) are common. "Crystalline" melt inclusions in Mg-rich olivine are heated until melting of all daughter crystals is achieved, and quenched to glass (4f). Persistence of a vapor bubble after heating may be due to fluid saturation of the melt, as suggested by combined type (S + V) inclusions (4c). S = solid, L = liquid, V = vapor. Host mineral is olivine. 4b, reflected light. 4a and c to f, transmitted light. The length of the scale bar is 100 μm.

the host grain when small melt inclusions are being analyzed was reduced by the use of a focussed beam in the center of the inclusion. An allowance of 5 μm was adopted for edge effects on the basis of results of electron-microprobe traverses across melt inclusions by Roedder (1979) and Sullivan (1991). Melt inclusions with a diameter less than 20 μm were not analyzed, and the smallest beam-size used on glass was 4 μm. After each analysis, the correct positioning of analytical points was checked and inspected for any likely interaction of the electron beam with the host grain. Provided the melt inclusions are sufficiently large (>10 μm), the use of transmitted and reflected light images in conjunction with the back-scattered electron image makes the selection and correct positioning of analytical points in exposed melt inclusions a relatively simple procedure.

Volatilization under these beam conditions was assessed following methods, described by Falloon & Green (1986), Sisson & Layne (1993) and Spray & Rae (1995), in which results of spot analyses and broad-area analyses of a glass standard are compared with its known bulk composition. Table 2 shows compositions of glass standard VG–A99 (USNM113498/1; Jarosewich *et al.* 1980) obtained using beam sizes of 1, 4 and 10 μm. Na_2O and K_2O values obtained under focussed beam conditions and 10 μm beam size are in agreement with standard values shown in Table 2. With a 4-μm beam size, Na_2O and K_2O values are only slightly lower than standard, by ~0.1 wt% (Table 2). With a beam size of 1 μm, Na_2O contents are ~0.2 wt% lower than the standard value.

Analytical conditions for glasses adopted in this study may therefore cause some loss of alkalis, but this loss will be insufficient to invalidate the conclusions reached here. These analytical conditions reduce the potential risk of edge effects introduced by the use of a defocussed beam on small melt inclusions. Compositional homogeneity of the glass was confirmed wherever possible by analyzing the center and rim of melt inclusions.

The main experimental uncertainty encountered in our determinations of the composition of the melts originally trapped in the phenocrysts is related to the "optical homogenization" technique that we have adopted. Uncertainty results because olivine and clinopyroxene have crystallized from the trapped melt inclusions during post-entrapment cooling. Much of this olivine was deposited on the melt-inclusion walls, and is difficult to distinguish optically from the primary host olivine. Using the "optical homogenization" technique employed here, some of this post-entrapment olivine might not all be remelted during experimental heating. Alternatively, although much less likely, some of the encapsulating olivine phenocryst might be melted into the melt inclusion because of overheating. Similarly, if a melt inclusion hosted by clinopyroxene were overheated, melt derived from the encapsulating crystal might be added to the melt inclusion, or, conversely, underheating might result in incomplete remelting of post-entrapment clinopyroxene.

A more general difficulty is the phenomenon of Fe loss from inclusions, identified by Gurenko *et al.* (1988, 1992), Danyushevsky *et al.* (1992) and Sobolev & Danyushevsky (1993), whereby Fe and Mg may re-equilibrate between residual melt within an inclusion and its host olivine in such a way as to cause the melt to lose Fe. This re-equilibration involves Fe, Mg diffusion, and is driven by the chemical disequilibrium between the host olivine and the residual melt within the inclusion after the crystallization of post-entrapment olivine on the inclusion walls. A detailed theoretical assessment

TABLE 2. CHEMICAL COMPOSITION* OF BASALTIC GLASS STANDARD VG–A99** USING VARIOUS BEAM–DIAMETERS

	1 μm, 10 nA			4 μm, 10 nA			10 μm, 10 nA			VG-A99**	
	av.		norm	av.		norm.	av.		norm		norm.
SiO_2 wt%	51.13	*0.25*	51.53	50.58	*0.26*	51.57	50.59	*0.21*	51.56	50.94	51.36
TiO_2	3.99	*0.08*	4.02	4.00	*0.12*	4.08	4.04	*0.09*	4.12	4.06	4.09
Al_2O_3	12.35	*0.26*	12.45	12.14	*0.05*	12.38	12.08	*0.41*	12.31	12.49	12.59
FeO*	13.34	*0.63*	13.45	13.38	*0.59*	13.64	13.22	*0.38*	13.47	13.30	13.41
MgO	5.08	*0.55*	5.12	4.79	*0.35*	4.89	5.01	*0.13*	5.10	5.08	5.12
CaO	9.47	*0.58*	9.54	9.25	*0.24*	9.43	9.25	*0.08*	9.42	9.30	9.38
MnO	0.26	*0.03*	0.26	0.24	*0.05*	0.24	0.25	*0.04*	0.26	0.15	0.15
Na_2O	2.44	*0.15*	2.46	2.53	*0.05*	2.58	2.57	*0.12*	2.62	2.66	2.68
K_2O	0.73	*0.08*	0.74	0.76	*0.04*	0.77	0.78	*0.04*	0.80	0.82	0.83
P_2O_5	0.43	*0.02*	0.44	0.41	*0.03*	0.42	0.34	*0.18*	0.35	0.38	0.38
Sum	99.21			98.07			98.12			99.18	

* Focused beam, 15 kV, beam current 10 nA, counting times 20 seconds, except for Na (10 seconds). av.: average result of ten analyses; norm.: average result normalized to 100%. The standard deviation is shown in italics.

** USNM113498/1, Jarosewich *et al.* (1980).

of the possible results of Fe-loss in melt inclusions may be found in Della-Pasqua (1997).

We consider the possible effects of underheating, overheating, and Fe loss in the following sections dealing with the compositions of the melt inclusions.

Compositions of Melt Inclusions in Olivine and Clinopyroxene Phenocrysts from Samples of Primitive Ankaramite

Our main aim is to discover whether the melt inclusions trapped in the earliest-formed phenocrysts in the most primitive ankaramites have compositions with ankaramitic affinities, with characteristically high CaO/Al_2O_3 values (>1). Representative compositions of inclusions in olivine and clinopyroxene phenocrysts from primitive ankaramites are listed in Table 3. These are reported as (1) the compositions of naturally quenched unhomogenized glass from vitreous inclusions, (2) the compositions of heated and homogenized glass from vitreous and crystalline inclusions, and (3) the compositions of heated and homogenized glass following correction for the possible effects of iron loss following post-entrapment re-equilibration.

Compositions of naturally quenched unhomogenized glass from vitreous inclusions

Vitreous melt inclusions in which the only phases are olivine, crystallized on the walls, and quenched glass (Fig. 4e), were found in relatively low-Fo olivine phenocrysts from Rinjani (Fo_{85-88}) and in olivine phenocrysts from Ulakan (Fo_{80-87}). Mg and Fe contents of these naturally quenched unhomogenized glasses from vitreous inclusions (Table 3) are low, compared with ankaramitic bulk-rock compositions (Table 1), but their CaO/Al_2O_3 (wt%) values (Figs. 5a, b) are very similar, are positively correlated with Fo content, and range from ~0.6 up to values of about unity.

Compositions of heated glasses from vitreous and "crystalline" melt inclusions

Crystallized melt inclusions in olivine phenocrysts, analyzed after heating and homogenization, have

TABLE 3. COMPOSITION OF MELT INCLUSIONS IN CLINOPYROXENE AND OLIVINE

Location	*Rinjani (Lombok)*														
Sample #	*48001*	*48001*	*48001*	*48001*		*48001*		*48001*		*48002*		*48002*		*48002*	*48002*
Host	*Olv.*	*Olv.*	*Olv.*	*Olv.*		*Olv.*		*Olv.*		*Olv.*		*Olv.*		*Cpx.*	*Cpx.*
Mg# host	87.7	87.6	87.9	89.7		91.0		90.5		90.4		90.4		87.0	86.2
Run				88/1		83/1		83/3		43/1		43/3		45/1	44/1
Temp. (°C)				1250		1238		1238		1220		1220		1100	1200
Type	*NQ*	*NQ*	*NQ*	*H*	***R***	*H*	***R***	*H*	***R***	*H*	***R***	*H*	***R***	*H*	*H*
SiO2 wt%	46.21	46.27	49.17	45.49	***44.84***	45.79	***44.31***	45.25	***44.15***	43.50	***42.28***	45.00	***43.39***	53.96	56.89
TiO2	1.43	1.26	1.13	0.93	***0.89***	0.88	***0.77***	0.92	***0.80***	1.17	***1.05***	1.27	***1.13***	1.01	0.40
Al2O3	19.43	19.49	20.17	14.23	***13.53***	16.82	***14.75***	16.81	***14.77***	17.73	***15.87***	17.23	***15.35***	17.18	16.26
FeO*	2.66	2.79	2.42	8.70	***9.50***	7.26	***9.50***	6.56	***9.50***	5.72	***9.50***	5.63	***9.50***	5.87	5.81
MgO	1.57	1.19	1.21	9.54	***10.98***	8.63	***12.64***	7.57	***11.99***	8.73	***11.87***	8.78	***11.77***	5.11	3.89
CaO	21.18	20.11	18.27	17.76	***16.90***	16.77	***14.73***	17.07	***15.04***	17.47	***15.66***	17.08	***15.24***	7.70	9.00
MnO	0.00	0.07	0.11	0.14	***0.14***	0.10	***0.11***	0.18	***0.18***	0.11	***0.11***	0.03	***0.05***	0.13	0.07
Na2O	3.14	3.30	3.53	1.85	***1.76***	2.35	***2.06***	2.66	***2.34***	2.77	***2.48***	2.72	***2.43***	3.04	3.74
K2O	1.35	1.82	1.01	1.33	***1.26***	1.16	***1.02***	1.31	***1.15***	1.05	***0.94***	1.10	***0.98***	2.26	3.09
P2O5	1.18	0.92	0.45	0.16	***0.15***	0.09	***0.08***	0.00	***0.00***	0.23	***0.21***	0.18	***0.16***	0.34	0.67
Total	98.14	97.23	97.47	100.13	***99.95***	99.85	***99.95***	98.33	***99.93***	98.48	***99.98***	99.02	***100.00***	96.60	99.82
Mg#	51.25	43.28	47.21	66.19	***67.36***	67.98	***70.38***	67.33	***69.27***	73.16	***69.05***	73.58	***68.87***	60.85	54.45
KD	0.15	0.11	0.12	0.22	***0.24***	0.21	***0.24***	0.22	***0.24***	0.29	***0.24***	0.30	***0.24***	0.23	0.19
FeO	2.09	2.20	1.91	6.85	***7.48***	5.72	***7.48***	5.17	***7.48***	4.50	***7.48***	4.43	***7.48***	4.62	4.58
mg#	57.2	49.2	53.2	71.3	***72.4***	72.9	***75.1***	72.4	***74.1***	77.6	***73.9***	78.0	***73.8***	66.4	60.3
Kd	0.19	0.14	0.16	0.28	***0.30***	0.27	***0.30***	0.27	***0.30***	0.37	***0.30***	0.38	***0.30***	0.30	0.24
CaO/Al2O3	1.09	1.03	0.91	1.25	***1.25***	1.00	***1.00***	1.02	***1.02***	0.99	***0.99***	0.99	***0.99***	0.45	0.55
CIPW norm (mol%)															
Q														***7.61***	0.79
Or														***9.78***	14.99
Ab														***19.99***	27.58
An				19.97	***18.66***	24.38	***20.22***	23.16	***18.87***	24.54	***20.65***	23.87	***20.05***	***19.45***	15.15
Ne				12.47	***11.66***	16.12	***13.35***	18.40	***15.04***	18.58	***15.63***	18.47	***15.54***		
Lc				5.90	***5.48***	5.24	***4.34***	5.96	***4.86***	4.64	***3.92***	4.92	***4.13***		
Di				34.89	***31.39***	34.78	***25.68***	34.79	***24.42***	24.59	***15.71***	32.37	***22.08***	***6.90***	17.92
Hy														***33.38***	21.69
Ol				18.92	***24.87***	15.08	***31.14***	11.56	***29.79***	17.13	***32.71***	13.36	***29.73***		
Cs				5.26	***5.52***	1.97	***3.25***	3.65	***5.03***	7.25	***8.62***	3.49	***5.52***		
Ilm				2.43	***2.27***	2.34	***1.94***	2.47	***2.00***	3.04	***2.57***	3.35	***2.80***	***2.58***	1.14
Ap				0.16	***0.15***	0.09	***0.07***			0.22	***0.19***	0.18	***0.15***	***0.33***	0.72

CaO/Al_2O_3 (wt%) values that overlap those of naturally quenched glasses in vitreous inclusions (~1, Figs. 5a, b); they range up to values characteristic of ankaramitic bulk compositions (~1.2 to 1.6, Fig. 5). CaO/Al_2O_3 (wt%) values are similar amongst melt inclusions within a single olivine grain (Fig. 6, and Run 83, 43, 64 in Table 3), but vary over a wide range amongst melt inclusions from various olivine phenocrysts, even those extracted from the same rock sample (Figs. 5a, b). CaO/Al_2O_3 values also vary more in inclusion compositions than in ankaramitic bulk-rock compositions.

MgO and FeO* contents of some heated and homogenized melt inclusions in olivine phenocrysts are similar to those of their ankaramitic hosts, but in general are lower (Fig. 5). This may be due to iron loss; the possible effects are considered further in the next section.

Inclusion compositions in olivine are also more silica-undersaturated than ankaramitic host-rock compositions: inclusion CIPW norms contain *ne*, *lc*, and *cs* (Table 3), whereas Rinjani and Ulukan ankaramites are *ne*-normative, and those from Merelava and Epi are *ol*- and *hy*-normative. We cannot explain why the inclusions would yield these silica-undersaturated compositions on analysis if they actually have compositions like the ankaramite hosts. The analytical conditions for glasses adopted in this study might cause some loss of alkalis, but this would make the compositions less silica-undersaturated, not more. In addition, if the trapped glasses originally had ankaramitic compositions but suffered iron loss, the modified compositions would again have become less silica-undersaturated than the original, not more. And if the inclusions were composed of melt plus trapped crystals of olivine and clinopyroxene, or were subjected to overheating or underheating during experimental homogenization, then the compositions would simply become more or less rich in normative olivine and diopside. We therefore conclude that the silica-undersaturated ankaramitic

TABLE 3. COMPOSITION OF MELT INCLUSIONS IN CLINOPYROXENE AND OLIVINE

Location	*Ulakan (Bali)*						*Merelava*				*Epi*		
Sample #	*67424*	*67424*		*67424*		*67424*	*31551*		*31551*		*71041*		*71041*
Host	*Olv.*	*Olv.*		*Olv.*		*Cpx.*	*Olv.*		*Olv.*		*Olv.*		*Cpx.*
Mg# host	84.8	91.8		91.8		88.2	90.4		90.2		91.6		88.9
Run	52/7-8	2/2		33/1		33/2	64/1		64/2		15/1		37/1
Temp. (°C)		1240		1240		1300	1242		1242		1305		1237
Type	*NQ*	*H*	***R***	*H*	***R***	H	*H*	***R***	*H*	***R***	*H*	***R***	*H*
SiO2 wt%	49.98	47.05	***44.68***	47.52	***44.20***	51.01	48.81	***46.20***	47.94	***45.88***	44.96	***43.14***	53.24
TiO2	1.08	0.81	***0.69***	0.93	***0.76***	0.59	0.56	***0.49***	0.52	***0.46***	0.60	***0.53***	0.35
Al2O3	21.07	13.10	***11.17***	13.28	***10.86***	8.71	15.74	***13.68***	15.90	***14.07***	14.74	***12.94***	9.14
FeO*	2.27	4.94	***10.50***	3.80	***10.50***	8.44	5.42	***9.00***	5.76	***9.00***	5.70	***9.00***	7.74
MgO	0.98	13.10	***16.81***	12.48	***16.81***	11.08	9.03	***12.47***	8.97	***12.18***	11.82	***14.89***	9.82
CaO	18.81	15.36	***13.14***	16.07	***13.18***	18.27	17.84	***15.53***	17.93	***15.89***	19.47	***17.12***	14.33
MnO	0.02	0.00	***0.03***	0.05	***0.07***	0.08	0.07	***0.09***	0.00	***0.02***	0.05	***0.05***	0.00
Na2O	2.88	1.73	***1.48***	2.31	***1.89***	1.34	1.78	***1.55***	1.80	***1.59***	2.00	***1.76***	1.20
K2O	2.12	1.23	***1.05***	1.57	***1.29***	1.02	0.64	***0.56***	0.59	***0.52***	0.45	***0.40***	0.33
P2O5	0.32	0.47	***0.40***	0.41	***0.34***	0.38	0.47	***0.41***	0.42	***0.37***	0.16	***0.14***	0.06
Total	99.53	97.79	***99.94***	98.43	***99.90***	100.92	100.36	***99.96***	99.83	***99.98***	99.96	***99.96***	96.21
Mg#	43.53	82.57	***74.09***	85.42	***74.09***	70.10	74.84	***71.21***	73.55	***70.72***	78.74	***74.71***	69.38
KD	0.14	0.42	***0.26***	0.52	***0.26***		0.32	***0.26***	0.30	***0.26***	0.34	***0.27***	
FeO	1.92	4.18	***8.90***	3.22	***8.90***	7.15	4.78	***7.93***	5.08	***7.93***	5.15	***8.12***	6.99
mg#	47.6	84.8	***77.1***	87.4	***77.1***	73.4	77.2	***73.7***	75.9	***73.3***	80.4	***76.6***	71.5
Kd	0.16	0.50	***0.30***	0.62	***0.30***		0.36	***0.30***	0.34	***0.30***	0.38	***0.30***	
CaO/Al2O3	0.89	1.17	***1.18***	1.21	***1.21***	2.10	1.13	***1.13***	1.13	***1.13***	1.32	***1.32***	1.57
CIPW norm (mol%)													
Q													14.86
Or		5.66		4.29		4.79	3.09	***2.51***	2.83	***2.35***			1.29
Ab		2.04				5.08	5.38	***1.71***	3.27	***0.30***			7.10
An		18.95	***14.68***	16.09	***11.96***	11.72	27.02	***21.99***	27.27	***22.63***	21.91	***18.33***	12.25
Ne		10.09	***9.40***	15.74	***11.69***	4.49	7.67	***8.91***	9.85	***10.60***	13.15	***11.00***	
Lc			***4.38***	2.76	***5.23***						1.95	***1.63***	
Di		38.04	***29.47***	42.33	***26.00***	58.38	42.78	***34.89***	42.77	***35.60***	30.28	***20.90***	34.37
Hy													29.28
Ol		22.55	***39.92***	15.93	***40.19***	13.52	11.96	***28.28***	12.09	***26.93***	22.13	***37.01***	
Cs			***0.07***		***2.80***						8.90	***9.72***	
Ilm		2.20	***1.71***	2.45	***1.82***	1.63	1.59	***1.30***	1.47	***1.22***	1.53	***1.28***	0.80
Ap		0.47	***0.37***	0.41	***0.31***	0.39	0.50	***0.41***	0.45	***0.37***	0.15	***0.13***	0.05

Mg# = 100Mg/(Mg + ∑Fe), mg# = 100Mg/(Mg + Fe), KD = (Mg/∑Fe)glass/(Mg/∑Fe)olv, Kd = (Mg/Fe)glass(Mg/Fe)olv. Fe3+/Fe2+ values as follows: Rinjani - 0.27, Ulakan = 0.18, Merelava = 0.14, Epi = 0.11. Run indicates grain number and the melt inclusion number within that grain. NQ: naturally quenched melt inclusion. Analysis in bold italics indicate recalculated (R) compositions of heated (H) melt inclusions. Temp.: temperature of quenching.

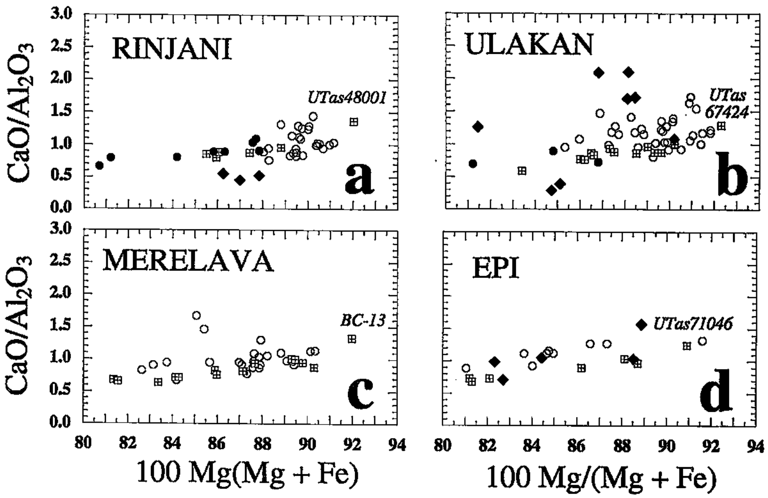


FIG. 5. CaO/Al_2O_3 in melt inclusions *versus* 100 Mg/(Mg + ΣFe) of the host. Open circles: compositions of heated melt inclusions recalculated to be in equilibrium with their host olivine. Filled circles: vitreous melt inclusions hosted by olivine. These consist of three phases: daughter olivine plated on the wall of the melt inclusion, a vapor bubble, and residual glass. During natural cooling of an olivine-hosted melt inclusion, olivine preferentially grows on the wall of its host. As a result, these naturally quenched melt inclusions are significantly depleted in the olivine component. These melt inclusions have very low MgO contents (see Table 3), but their CaO/Al_2O_3 value is unaffected. Filled diamonds: composition of heated melt inclusions hosted by clinopyroxene. Their CaO/Al_2O_3 values are largely modified due to plating of clinopyroxene on the walls of the inclusion. Bulk-rock CaO/Al_2O_3 *versus* 100 Mg/(Mg + ΣFe) of host ankaramite samples are also shown for comparison (square with crosses).

compositions of the inclusions are representative of the melts as trapped, and consider in a later section the implications of this conclusion.

CaO/Al_2O_3 values of clinopyroxene-hosted melt inclusions are also plotted against Mg# content of their host grains. Their CaO/Al_2O_3 values vary much more widely than those of olivine-hosted melt inclusions. In some cases, our homogenization procedure may have remelted some of the host clinopyroxene crystal in addition to the post-entrapment clinopyroxene precipitated on the wall of the melt inclusions: this would produce higher CaO/Al_2O_3 values than those of the original trapped melt. The composition of a reheated homogenized melt inclusion from an Ulakan clinopyroxene (Table 3: sample 67424, run 33/2) may reflect this process. The temperature of homogenization in this experiment was 1300°C, higher than the homogenization temperatures of 1240°C for melt inclusions in olivine from the same rock; its CaO/Al_2O_3 (wt%) value is 2.1, compared with ~1.2 for the olivine-hosted inclusions. Its CaO and normative diopside (~60%) contents are also substantially higher than those of the olivine-hosted inclusions.

If, however, an inclusion were reheated to a temperature lower than its original trapping temperature, some post-entrapment crystals of olivine and clinopyroxene may be left unmelted, which would result in CaO/Al_2O_3 values lower than those of the original trapped melt. Rinjani inclusions 44/1 and 45/1 are likely examples of underheating during homogenization (Table 3).

Therefore, recalling that our main aim is to discover whether the melt inclusions trapped in the earliest-formed phenocrysts in the most primitive ankaramites have compositions with ankaramitic affinities, we have placed most emphasis on the composition of melt inclusions in early-crystallized olivine phenocrysts from ankaramite samples with "primitive" compositions.

Compositions of heated glasses corrected for possible loss of iron

If iron loss has taken place because Fe and Mg re-equilibrated between residual melt within an inclusion and its host olivine, the compositions of heated melt inclusions in olivine will be unlike those of the original melts when they were trapped. We note that

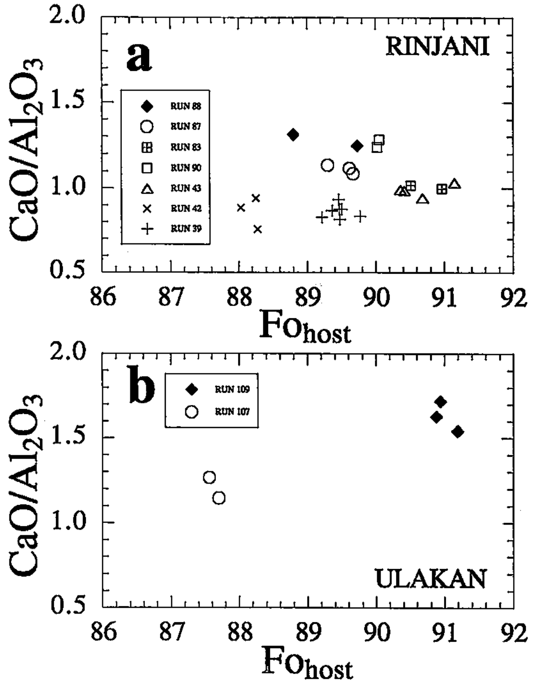


FIG. 6. Similarity in CaO/Al_2O_3 values of coexisting melt inclusion in olivine phenocrysts from (a) the Rinjani volcano, and (b) the Ulakan Formation. Each run represents a separate olivine grain. Note the larger variation in CaO/Al_2O_3 values amongst grains of similar Fo content in Figure 6a, and in Figure 5a and b.

MgO and FeO* contents of heated and homogenized but uncorrected melt inclusions attain values similar to those of the host ankaramites, suggesting that the process of iron loss has not operated uniformly and that iron loss has not markedly affected these MgO- and FeO*-rich compositions. (If material from the encapsulating olivine phenocryst had been added to these melt inclusions as a result of experimental overheating, the composition of the resultant melt would have been much richer in MgO, but its FeO* content would have changed little, so long as it was fairly similar to that of the host olivine, about 8–9 wt%.)

We have recalculated some compositions following a method described in Della-Pasqua (1997), which reverses the re-equilibration process, to evaluate the effect of iron loss on melt inclusion composition. This method assumes a target FeO* content for the original composition of the trapped melt. We have placed an upper limit on the possible amount of iron loss by assuming that melt inclusions in the most magnesian compositions of olivine, Fo_{88} to Fo_{92}, originally had FeO* contents similar to the bulk FeO* contents of the primitive host-rocks. This assumption facilitates the comparison of the compositions of the host ankaramite with recalculated compositions of the melt inclusions. The melt inclusion compositions are recalculated by mass-balanced addition of material with the composition of the host olivine crystal to the composition of the heated homogenized melt inclusion, until the Mg# of the recalculated composition of the inclusion is in equilibrium with the composition of the host olivine, and its FeO* content is that of the ankaramitic host. CaO/Al_2O_3 values are unaffected.

Melt compositions obtained by this recalculation procedure are listed in Table 3, for comparison with uncorrected compositions of inclusions in olivine phenocrysts, after heating and homogenization. FeO*, MgO and SiO_2 contents of the melt inclusions are changed by this correction procedure, and normative *ol* contents increase (Table 3).

RESULTS

Melt inclusions in ankaramite from Rinjani volcano, Lombok, Sunda arc

Heated (1250°C) and homogenized melt inclusions in olivine phenocrysts from Rinjani ankaramites, including both unrecalculated and recalculated compositions, have up to 9.5 wt% MgO and Mg# of 67 to 69, and a high CaO content, about 17 wt%, with high CaO/Al_2O_3 values (Fig. 5, Table 3). The compositions of these melt inclusions generally resemble those of the Rinjani ankaramites, but inclusion compositions are more silica-undersaturated than the bulk-rock compositions. The ankaramitic bulk-rock compositions are *ne*-normative, whereas the inclusion compositions are *ne*-, *lc*-, and *cs*-normative. Melt inclusions in olivine phenocrysts in the most primitive Rinjani ankaramite (UTas48001: $CaO/Al_2O_3 = 1.37$) have CaO/Al_2O_3 values of about 1.25, but some of the inclusions have CaO/Al_2O_3 values that are higher than those of most ankaramites (Fig. 5).

Melt inclusions in ankaramite from the Ulakan formation, Bali, Sunda arc

Heated (1240°C) and homogenized olivine-hosted melt inclusions from Ulakan have about 13 wt% MgO and about 15–16 wt% CaO, with CaO/Al_2O_3 values of 1.2, and an Mg# of about 70. After correction for possible loss of iron, the recalculated compositions of the inclusions have about 17 wt% MgO and 13 wt% CaO.

The compositions of melt inclusions at Ulakan resemble those of the bulk rocks (Tables 1, 3), but they tend to be richer in normative *ne* and, as a group, they tend to have somewhat higher CaO/Al_2O_3 values (Fig. 5). The highest CaO/Al_2O_3 value in olivine-hosted inclusions, 1.75, was found in olivine with Fo_{91}. The most primitive ankaramite in the Ulakan suite (UTas67424) contains

17.5 wt% MgO and 11.78 wt% CaO, with Mg# = 75.2 and CaO/Al_2O_3 = 1.44. It is unlikely that its bulk composition is the result of clinopyroxene accumulation, as it is similar to that of melt inclusions hosted in olivine ($Fo_{91.7}$) phenocrysts from the same rock. It is notable that at similar run temperatures, the differences in composition between Rinjani and Ulakan melt inclusions reflect those between the ankaramite hosts, with the Ulakan compositions richer in Mg, poorer in Ca, and with higher Mg# values.

Melt inclusions in ankaramite from Merelava, Vanuatu arc

Heated and homogenized melt inclusions in Fo_{90} olivine in ankaramite from Merelava contain about 9 wt% MgO, about 5–6 wt% FeO, 18 wt% CaO (Table 3), with CaO/Al_2O_3 = 1.1 and Mg# values similar to those of primitive Merelava ankaramites (Tables 1, 3). They are *ne*-normative and resemble ankaramites from Ulakan more than they do the Merelava ankaramites, which are *ol*- and *hy*-normative. Compositions adjusted for possible loss of iron have about 12 wt% MgO, and somewhat lower Mg# values. Melt inclusions suitable for homogenization experiments have not yet been found in olivine more magnesian than $Fo_{90.5}$, although olivine compositions in Merelava ankaramites range up to Fo_{92}. Two melt inclusions hosted in the same Fo_{85} olivine grain have CaO/Al_2O_3 values of 1.70 and 1.45. An inclusion hosted in olivine with Fo_{88} has CaO/Al_2O_3 of 1.30, similar to that of the whole-rock composition of sample BC–13.

Melt inclusions in ankaramite from Epi, Vanuatu arc

One melt inclusion in Fo_{92} olivine contains 17.12 wt% CaO and 14.89 wt% MgO, and has a CaO/Al_2O_3 value of 1.32, resembling the bulk composition of the most primitive ankaramite sample from Epi, with 14.61 wt% CaO, 13.50 wt% MgO and CaO/Al_2O_3 = 1.25. With the exception of one melt inclusion in clinopyroxene, CaO/Al_2O_3 values for olivine- and clinopyroxene-hosted melt inclusions are mutually consistent and in agreement with bulk-rock compositions, but inclusion compositions are silica-undersaturated, whereas ankaramitic bulk rocks are not (Tables 1, 3).

PETROGENESIS OF PRIMITIVE ANKARAMITIC MAGMAS

Barsdell (1988) and Barsdell & Berry (1990) concluded that ankaramitic bulk-rock compositions from Merelava and Epi define differentiation trends consistent with olivine + clinopyroxene fractionation and with actual abundances of phenocrysts (clinopyroxene:olivine approximately 3 or 4:1), and proposed that the Merelava and Epi rocks evolved down olivine–clinopyroxene cotectics. They inferred that the parental magmas were ankaramitic, saturated in forsteritic olivine and diopsidic clinopyroxene, and had between 13.7 and 14.5 wt% MgO, between 13.7 and 14.8 wt% CaO, and CaO/Al_2O_3 (wt%) values of 1.33 and 1.34, respectively (Barsdell & Berry 1990; Table 3). Barsdell (1988) discussed four possible ways of producing the primitive ankaramites: (1) olivine fractionation from a picritic parent, (2) olivine fractionation combined with assimilation of clinopyroxene, (3) partial melting of lherzolite

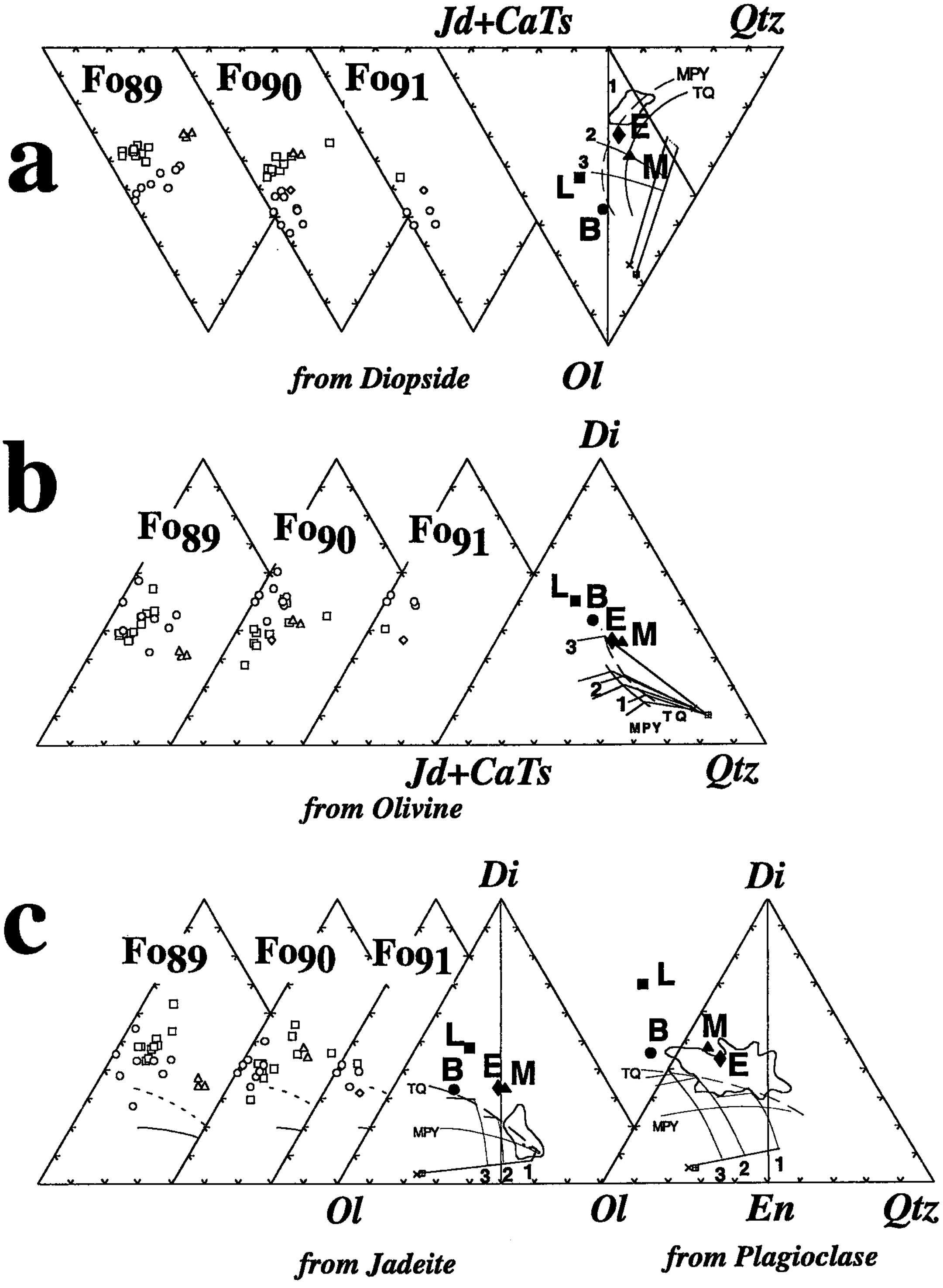
FIG. 7. Compositions plotted in the CIPW molecular normative basalt tetrahedron Ol – Di – (Jadeite + CaTs) – Qtz. A detailed explanation for the projections is given by Falloon & Green (1988). Cotectics for Olivine (Ol) + Orthopyroxene (Opx) + Clinopyroxene (Cpx) ± Garnet (Ga) + liquid; Ol + Opx + liquid; and Ol + liquid, are drawn, for pressures up to 3 Gpa, for partial melts of MORB pyrolite (MPY: cross) and a more depleted mantle composition, Tinaquillo Lherzolite (TQ: square); data from Jaques & Green 1980, Falloon & Green 1987, 1988, Falloon *et al.* 1988. Numbers are pressures in Gpa. Lines labeled MPY and TQ in Fig. 7a and Fig. 7c show where clinopyroxene is eliminated from the residues during partial melting.

Fig. 7a is a projection from Di (= Diopside on the figure) to the tetrahedron face Ol – (Jadeite + CaTs) – Qtz. Fig. 7b is projected from Ol (= Olivine on the figure) to the face Di – (Jadeite + CaTs) – Qtz. Fig. 7c is projected from (Jd + CaTs), shortened to Jadeite on the figure, to the face Ol – Di – Ol – Qtz. For comparison, Fig. 7c also includes cotectics projected to the face Ol – Di – Qtz from Plagioclase.

Filled symbols represent whole-rock compositions of the most primitive ankaramites in each of the four suites. L: Utas48001 Rinjani volcano, Lombok. B: Utas67424 Ulakan Formation, Bali. M: BC-13 Merelava. E: 71046, Epi.

Fig. 7c, projected from Jadeite, best illustrates the discrepancy between whole-rock compositions of primitive ankaramites (filled symbols) and compositions of partial melts that are in equilibrium with mantle lherzolite assemblages. The ankaramies are richer in normative diopside and lie above the Ol + Opx + Cpx ± Ga + L cotectics showing primary melts produced by partial melting of both MORB Pyrolite (MPY, full line) and depleted Tinaquillo Lherzolite (TQ, dashed line) model mantle compositions.

Open symbols are recalculated compositions of melt inclusions hosted in olivine with compositions Fo_{89}, Fo_{90} and Fo_{91} (circles: Ulakan, squares: Rinjani, triangles: Merelava, diamonds: Epi). Melt inclusions have high contents of normative diopside, and are ankaramitic rather than picritic, similar to the whole-rock compositions of their host ankaramite, but more silica-undersaturated. Melt inclusions in olivine with Fo_{89-91} from Rinjani and Ulakan show a wide compositional range. Fewer melt inclusions were available for Meralava and Epi ankaramites. Two melt inclusions in olivine with Fo_{90} from Merelava are more ankaramitic than the host ankaramite. One melt inclusion in Fo_{91} from Epi has lower normative diopside but higher CaO/Al_2O_3 than its host.


a
Jd+CaTs
Qtz
Fo89
Fo90
Fo91
MPY
TQ
1
2
3
E
M
L
B
from Diopside
Ol
b
Di
Fo89
Fo90
Fo91
L
B
E
M
3
2
1
MPY
TQ
Jd+CaTs
Qtz
from Olivine
c
Di
Di
Fo89
Fo90
Fo91
L
B
E
M
TQ
MPY
3
2
1
L
B
M
E
TQ
MPY
3
2
1
Ol
Ol
En
Qtz
from Jadeite
from Plagioclase

at pressures low enough for orthopyroxene to melt incongruently, and (4) a combination of mechanism (3) with addition of a component derived from melting of wehrlite or pyroxenite derived from the lower crust. Two generalized models were tested by Barsdell & Berry (1990) using SILMIN (Ghiorso & Carmichael 1985): an assimilation model involving a low-K picritic melt and wehrlitic or pyroxenitic assimilant, and a partial melting model involving melting of lower-crust wehrlite or pyroxenite with and without the addition of a small amount of picritic melt contaminant.

The assimilation model was found to require about 90% assimilant to match the phase and bulk-rock chemistry of the ankaramitic parental melt, and was therefore considered unrealistic. We note here that our clinopyroxene-hosted inclusion data can also be viewed as a test of the clinopyroxene accumulation–assimilation hypothesis for the origin of ankaramitic melts. Small amounts of experimental overheating (= clinopyroxene addition and assimilation) of inclusions lead to very high CaO/Al_2O_3 values, whereas small amounts of underheating are reflected by particularly low values (= clinopyroxene subtraction). The CaO/Al_2O_3 values of the rock compositions display much smaller and more systematic variations than those of clinopyroxene-hosted inclusions that have undergone clinopyroxene assimilation. Also, although the range of CaO/Al_2O_3 values is similar in rocks and in olivine-hosted inclusions, many of the olivine-hosted inclusions have CaO/Al_2O_3 values higher than those of bulk-rock compositions with similar Mg# values.

Barsdell & Berry (1990) showed that partial melting of typical upper mantle lherzolite compositions at 0.5 GPa also failed to give suitable results, essentially because the starting compositions have high orthopyroxene:clinopyroxene values. Partial melting of a wehrlitic source could yield an appropriate ankaramitic composition, but only small amounts of normative orthopyroxene in the wehrlitic composition are tolerable. In essence, Barsdell & Berry (1990) could see no way of producing primitive ankaramitic magma without recourse to a wehrlitic (ol + cpx) source. They speculated that carbonatite-related metasomatism might convert an upper mantle lherzolite to wehrlite, but noted that this process is restricted to pressures below 2 GPa and involved enrichment in Na of the wehrlite.

Here, we first use more recent experimental work to re-evaluate the possibility that partial melting of upper mantle lherzolite might yield an ankaramitic magma without requiring the involvement of a wehrlite-derived component, and then present two possible schemes for ankaramite petrogenesis.

Anhydrous partial melting of mantle lherzolite in the pressure range 1 – 3 GPa

Experimental studies of the melting behavior of lherzolite provide a guide to the likely compositions of primary mantle-derived magmas. CaO/Al_2O_3 values of partial melts of lherzolitic mantle (olivine + orthopyroxene + clinopyroxene ± spinel ± garnet) are determined mainly by its bulk mantle CaO/Al_2O_3 value (*e.g.*, ~0.8: Frey *et al.* 1978, 1991), and by whether clinopyroxene and garnet occur in the residual assemblage (Herzberg 1992).

The compositional range of partial melts in equilibrium with mantle lherzolite at pressures up to 3 GPa is shown graphically in Figure 7 (dashed and full lines), constructed from the findings of Jaques & Green (1980), Falloon & Green (1987, 1988), and Falloon *et al.* (1988). With increasing pressure in the range 1 to 3 GPa, melts become increasingly *ne*-normative (*i.e.*, richer in Jd and CaTs components, Figs. 7a, b), but do not attain CaO/Al_2O_3 values >1 or the high normative *di* contents typical of primitive ankaramites (Fig. 7c). These partial melts are picritic rather than ankaramitic, and although CaO/Al_2O_3 values increase with degree of melting (Kinzler & Grove 1992b), they do not exceed bulk-mantle values. With greater extent of melting, melts become poorer rather than richer in normative clinopyroxene components, and eventually become picritic. Experiments with fertile and depleted lherzolite up to 3 GPa show that changes in starting compositions do not lead to a shift in composition of the partial melt toward an ankaramitic composition (Green *et al.* 1987, Falloon *et al.* 1988, Baker & Stolper 1994, Hirose & Kushiro 1993).

It seems unlikely, then, that a primary ankaramitic magma, with its characteristic CaO/Al_2O_3 value greater than unity and richness in normative *di*, could be produced by partial melting of anhydrous mantle peridotite at pressures up to 3 GPa. We consider two additional mechanisms: one involving partial melting of mantle lherzolite at pressures below 4 GPa, in the presence of H_2O–CO_2-rich fluids, and a second involving partial melting of mantle lherzolite at pressures above 4 GPa.

Partial melting of mantle lherzolite in the pressure range 1 – 3 GPa in the presence of CO_2-rich fluids

The chemical compositions of silica-undersaturated rocks such as nephelinites and melilitites are commonly characterized by high CaO/Al_2O_3 values (>1), one of the characteristics of ankaramites, and many are similarly rich in clinopyroxene. Such compositions may form by partial melting of lherzolite at pressures less than 4 GPa in the presence of CO_2-rich fluids (Mysen & Boettcher 1975b, Brey & Green 1975, 1977, Frey *et al.* 1978, Brey *et al.* 1983, Adam 1987, Green *et al.* 1987, Taylor & Green 1987). Their high CaO/Al_2O_3 values are considered to reflect the increased stability of garnet in the mineral assemblages of the residual peridotite, as a function of pressure and CO_2 content. CO_2 hence may play a crucial role in the genesis of highly silica-undersaturated ankaramitic melts.

Partial melting of mantle lherzolite at pressures above 4 GPa

In peridotitic systems, the field of stability of olivine on the liquidus contracts with increasing pressure. The shift of the olivine–pyroxene liquidus boundary curve with increasing pressure is illustrated to 14 GPa in Figure 8 (thin lines). This interpretation is based on experimental results of Shibata (1976), Walker *et al.* (1979), Green *et al.* (1986), Takahashi (1986), Falloon *et al.* (1988), Herzberg (1992), Kinzler & Grove (1992a), Hirose & Kushiro (1993), and Baker & Stolper (1994). Assuming that pressure-related trends on the cotectic established to ~4 GPa persist to higher pressures, a possible Ol + Opx + Cpx + Grt cotectic can be extrapolated to ~14 GPa (Fig. 8, dashed line). This

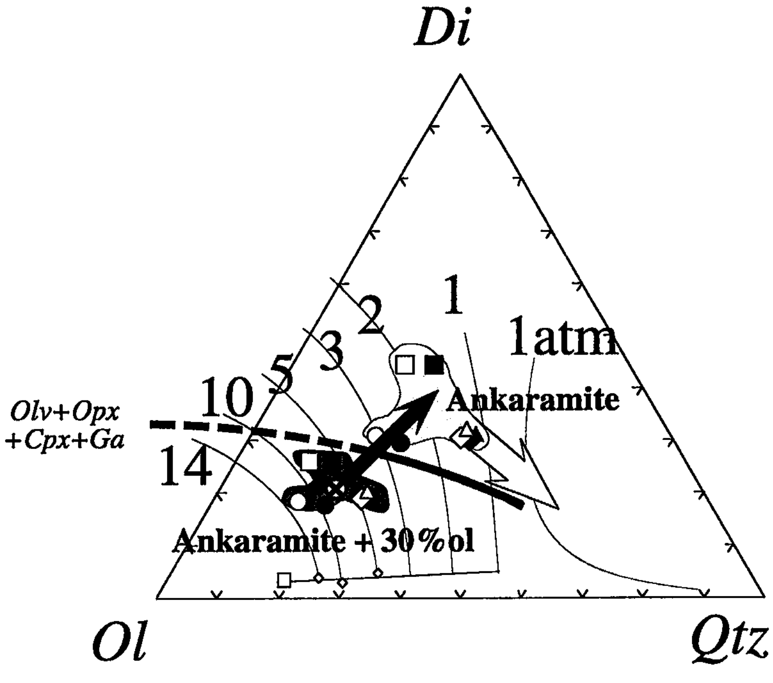


FIG. 8. Projection from Jadeite as in Figure 7, illustrating the likely shift of the olivine–pyroxene liquidus boundary curve with pressure, based on experimental work of Shibata (1976), Walker *et al.* (1979), Green *et al.* (1986), Takahashi (1986), Falloon *et al.* (1988), Kinzler & Grove (1992a), Herzberg (1992), Hirose & Kushiro (1993), and Baker & Stolper (1994). Grid lines above 5 GPa are extrapolated using experimental data of Takahashi (1986), Herzberg (1992), and Hirose & Kushiro (1993), assuming that pressure-related trends on the cotectic established to 4 GPa (full line), persist to higher pressures (dashed line). Central open area includes bulk-rock compositions of the primitive ankaramites studied. Dark-shaded area includes recalculated bulk-rock compositions of the ankaramite samples with 30% equilibrium olivine added. Symbols represent the bulk-rock compositions of the most primitive ankaramite in each suite with and without olivine added. Square: Rinjani; circle: Ulakan; triangle: Merelava; diamond: Epi. Open symbols use Fe^{3+}/Fe^{2+} as determined from olivine – spinel inclusion pairs (Rinjani: 0.27, Ulakan: 0.18, Merelava: 0.14, and Epi: 0.11 after Maurel & Maurel 1984). Filled symbols use all iron as FeO.

Melts generated above 5 GPa (*e.g.*, ⊗) have CaO/Al_2O_3 values greater than 1 (Herzberg 1992). On the way to the surface and as pressure on the melt decreases, the Ol – Px – Grt – melt cotectic will migrate away from composition ⊗, leaving melt composition ⊗ in the olivine liquidus field. Olivine will now precipitate from the melt, thereby shifting the melt composition away from the olivine apex and causing the residual melt to become more and more ankaramitic, until eventually clinopyroxene precipitates. Numbers indicate pressure in GPa.

extrapolation is based on olivine–pyroxene boundary curves to 14 GPa taken from experimental data of Takahashi (1986), Herzberg (1992) and Hirose & Kushiro (1993).

The CaO/Al_2O_3 value of partial melts in equilibrium with peridotite is inherited from the source and controlled by the assemblage of residual minerals (Herzberg 1992). The field of stability of garnet enlarges with increasing pressure, and the appearance of garnet as a residual phase plays a key role in imparting higher CaO/Al_2O_3 values to the partial melts (Takahashi 1986, Kato *et al.* 1988, Wei *et al.* 1990, Herzberg 1992, Moriyama *et al.* 1992, Trønnes *et al.* 1992, Ohtani *et al.* 1995). Herzberg (1992) showed that partial melts in equilibrium with Ol + Opx + Cpx + Grt and generated at pressures above 5 GPa are picritic, but that the shift toward the Ol–Di join of the Ol–Px–Grt cotectic imparts komatiitic (*i.e.*, ankaramitic) CaO/Al_2O_3 values > 1 to the melt (Herzberg 1992).

Consider the evolution of a representative picritic melt with komatiitic affinities, generated at the Ol + Cpx + Opx + Grt cotectic at some pressure above 5 GPa (composition *X*, Fig. 8). Suppose that this representative picritic melt *X* rises through the mantle. As pressure decreases and the liquidus field of olivine enlarges, the location of the Ol + Px + Grt cotectic migrates away from composition X, thereby leaving the melt within the liquidus field of olivine. Olivine will continue to precipitate from the melt as it rises and cools. Olivine crystallization will cause the melt's composition to move away from the olivine apex toward the olivine–pyroxene cotectic; if the melt continues to rise, falling pressure will lead to enlargement of the liquidus field of olivine, and the location of the olivine–pyroxene cotectic will continue to migrate away from the liquid composition, so that it will continue to precipitate olivine, becoming richer in pyroxene components and retaining the high CaO/Al_2O_3 value acquired as a primary melt. A protracted period of olivine crystallization as the melt ascends would cause the residual melt to become more and more ankaramitic, until eventually clinopyroxene joins olivine.

This postulated course of evolution of the primary komatiitic melt supposes that the fractionating liquid reacts little with the mantle through which it is passing. The more the melt reacts with orthopyroxene of the mantle while re-equilibrating to lower pressures, the less ankaramitic it will become.

DISCUSSION AND CONCLUSIONS

We have shown that melt inclusions in forsterite ($Fo_{>90}$) phenocrysts in primitive ankaramites have CaO/Al_2O_3 values about or greater than unity, high contents of Mg and Ca, and high Mg# values, greater than 71. If the host ankaramites crystallized from picritic or basaltic magmas enriched with clinopyroxene crystals, then the melt inclusions in olivine would have lower CaO/Al_2O_3 values. These inclusion compositions clearly have high CaO/Al_2O_3 values and thus ankaramitic affinities, suggesting that the primitive ankaramites of each suite may have been derived from ankaramitic parental magmas.

The heated, homogenized olivine-hosted inclusion compositions are generally *ne*- and *lc*-normative, and some are also *cs*-normative. The primitive ankaramites from Rinjani and Ulakan have *ne*-normative bulk-compositions, and in general the compositions of the inclusions from their olivine phenocrysts resemble those of these ankaramite hosts, but are clearly more silica-undersaturated. It is notable that at similar run temperatures, the differences in composition between Rinjani and Ulakan melt inclusions reflect those between the ankaramite hosts, with the Ulakan compositions similarly richer in Mg, poorer in Ca, and with higher Mg# values. The more silica-undersaturated compositions of the inclusions also resemble leucite basanites and tephrites from the Sangenges, Soromundi and Batu Tara volcanic centers in the eastern Sunda arc to the east, so could well be representative of magmatic compositions involved in the genesis of Rinjani and Ulakan ankaramites. Similarly, we have concluded that the silica-undersaturated ankaramitic compositions of olivine-hosted inclusions from Merelava and Epi are representative of the melts as trapped, despite the *ol*- and *hy*-normative character of their host ankaramites.

Experimental studies suggest that partial melting of mantle lherzolite could yield primary melts with high CaO/Al_2O_3 values by partial melting either in the presence of CO_2-rich fluids at pressures less than 4 GPa, or by anhydrous partial melting at pressures above 5 GPa (Fig. 9, Stage 1a and 1b, respectively), or by some combination of these factors at intermediate pressures. We note that partial melts produced experimentally by lherzolite melting in the presence of CO_2-rich fluids at pressures less than 4 GPa are markedly silica-undersaturated, and thus similar to the compositions of olivine-hosted melt inclusions, whereas the compositions of partial melts produced by anhydrous high-pressure melting of lherzolite are picritic with komatiitic affinities.

We have tested the possibility that the ankaramitic melts represent non-primary but primitive liquid compositions derived by olivine fractionation from a high-pressure picritic melt with komatiitic affinities by addition of equilibrium olivine to the most primitive ankaramitic bulk-rock compositions in each suite. Figure 8 shows that addition of 10–30% olivine is sufficient to bring the hypothetical parental picritic liquid close to the hypothetical 5–10 GPa Ol + Opx + Cpx + Grt cotectic (Fig. 8, dashed line). The compositions of primitive ankaramites with 30% equilibrium olivine added are shown for each suite in Table 4. These calculated hypothetical parental liquids have 24–28 wt% MgO, and an Mg# between 83 and 87. The Fo contents of the equilibrium olivine in equilibrium with calculated parental picritic liquids for Rinjani,

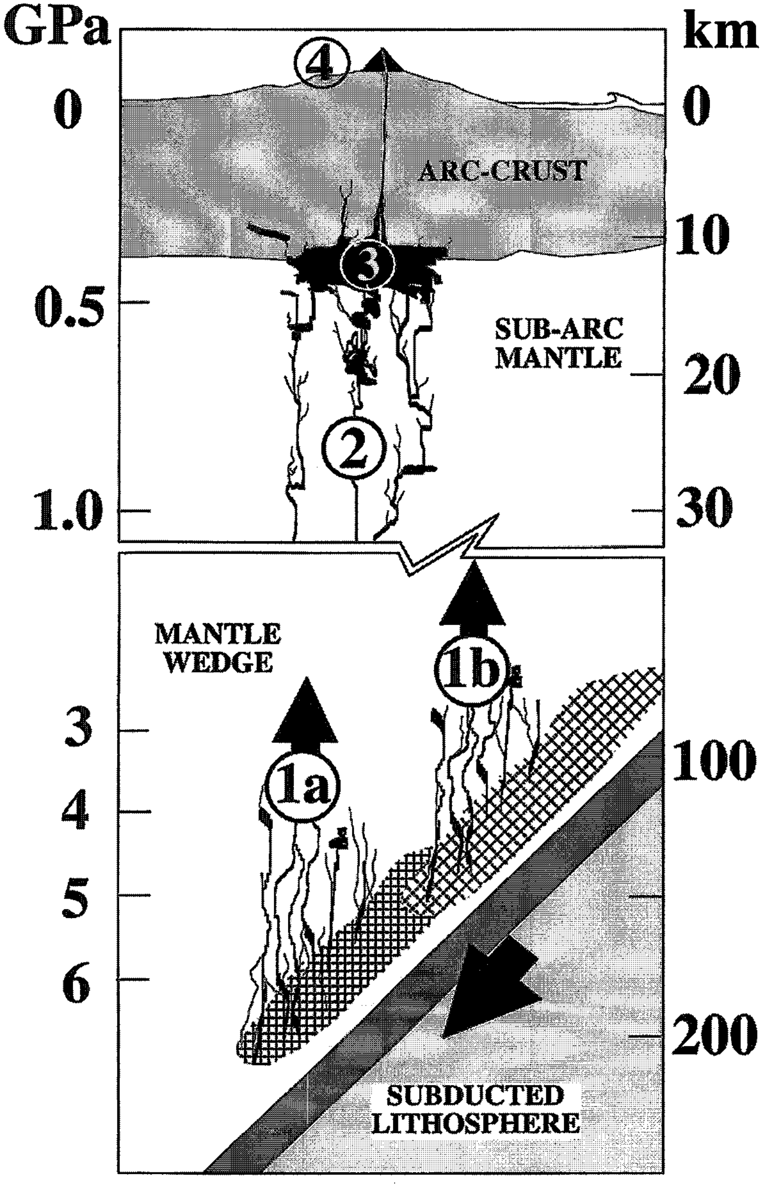


FIG. 9. Schematic model illustrating possible stages in the formation of ankaramitic magmas in volcanic arcs. Stage 1: Generation of primary melts with variable CaO/Al_2O_3 values (*e.g.*, 0.8 to 1.6) by partial melting at pressures greater than 5 GPa (1a, horizontal cross-hatched area), or by partial melting at pressures less than 4 GPa in the presence of CO_2-rich fluids (1b, diagonal cross–hatched area) or by some combination of these conditions. Stage 2: Trapping of ascending primary melts by early-fromed phenocrysts (*e.g.*, $Fo_{>90}$). Stage 3: Aggregation at lower pressures of fractionating melts, possibly accompanied by re-equilibration with sub-arc mantle and magma–mantle reaction (Kelemen *et al.* 1990). Stage 4: Accumulation of melts, accompanied by differentiation in subvolcanic environment, followed by eruption. See text for further discussion.

Ulakan, Merelava and Epi ankaramites are: 94.5, 94.6, 95.0, and 94.5 (all iron as FeO). If Fe^{3+}/Fe^{2+} values determined from olivine–spinel inclusion pairs are used (Maurel & Maurel 1984), the equilibrium compositions of olivine are Fo$_{95.9}$, Fo$_{95.5}$ Fo$_{95.8}$, and Fo$_{95.2}$, respectively (Table 4).

The highest Ni contents in magnesian olivine (Fo$_{90}$ to Fo$_{92}$) range from 0.21 to 0.34 wt% NiO (Barsdell 1988, Barsdell & Berry 1990; Fig. 10) and extrapolate to a range from 0.4 to 0.5 wt% in Fo$_{94}$ to Fo$_{95}$ (Table 4). This range resembles Ni contents in primitive olivine (Sato *et al.* 1991, Chen 1993) and in olivine from Ringgit-Beser volcano, situated immediately west of Bali (R–B, Fig. 1a), with up to 0.63 wt% NiO in Fo$_{94}$ (Varne, unpubl. data). Adopting a Ni content in olivine of ~0.50 wt% NiO, with a range in D_{Ni}^{ol-liq} values from ~2.0 to ~2.5 (Beattie *et al.* 1991), the Ni content of the hypothetical picritic liquid ranges from ~2000 to ~1600 ppm, much higher than those of primitive ankaramite bulk-rock compositions (~130 to 390 ppm

TABLE 4. PRIMITIVE ANKARAMITE: BULK-ROCK + 30% OLIVINE

	Sunda Arc				Vanuatu Arc			
Sample no.	*UTAS48001*		*UTAS67424*		*BC-13*		*71046*	
Location	*Lombok*		*Bali*		*Merelava*		*Epi*	
Fe3+/Fe2+		*0.27*		*0.18*		*0.14*		*0.11*
SiO2 wt%	46.48	*46.57*	45.82	*45.88*	48.21	*48.25*	46.87	*46.91*
TiO2	0.49	*0.49*	0.4	*0.4*	0.33	*0.33*	0.28	*0.28*
Al2O3	7.42	*7.42*	6.55	*6.55*	7.36	*7.36*	8.22	*8.22*
FeO*	8.64	*8.21*	9.48	*9.18*	7.76	*7.54*	8.53	*8.33*
MgO	24.92	*25.27*	27.67	*27.91*	24.99	*25.17*	24.68	*24.84*
CaO	10.13	*10.13*	8.47	*8.47*	9.79	*9.79*	10.29	*10.29*
MnO	0.12	*0.12*	0.14	*0.14*	0.12	*0.12*	0.11	*0.11*
Na2O	1.06	*1.06*	0.88	*0.88*	1.14	*1.14*	0.75	*0.75*
K2O	0.63	*0.63*	0.44	*0.44*	0.27	*0.27*	0.22	*0.22*
P2O5	0.11	*0.11*	0.15	*0.15*	0.04	*0.04*	0.05	*0.05*
total	100.00	*100.00*	100.00	*100.00*	100.00	*100.00*	100.00	*100.00*
Fe2O3		*1.94*		*1.56*		*1.16*		*0.90*
FeO		*6.46*		*7.78*		*7.76*		*7.52*
equil. Fo	94.5	*95.9*	94.6	*95.5*	95.0	*95.8*	94.5	*95.2*
Kd	0.30	*0.30*	0.30	*0.30*	0.30	*0.30*	0.30	*0.30*
mg#	83.7	*87.5*	83.9	*86.5*	85.2	*87.1*	83.8	*85.5*
D Ni (B)	2.41	*2.42*	1.89	*1.90*	2.45	*2.46*	2.46	*2.47*
CaO/Al2O3	1.37	*1.37*	1.29	*1.29*	1.33	*1.33*	1.25	*1.25*
CIPW norm (mol%)								
Or	2.50	*2.50*	1.71	*1.70*	1.05	*1.05*	0.86	*0.86*
Ab	3.80	*3.80*	4.97	*4.98*	6.71	*6.70*	4.45	*4.45*
An	9.16	*9.14*	8.29	*8.27*	9.29	*9.28*	12.17	*12.16*
Ne	2.60	*2.58*	0.21	*0.20*				
Di	24.13	*24.07*	18.65	*18.62*	22.39	*22.36*	21.36	*21.33*
Hy					9.52	*9.50*	8.21	*8.23*
Ol	56.57	*56.68*	65.13	*65.18*	50.25	*50.32*	52.26	*52.29*
Ilm	1.15	*1.14*	0.91	*0.91*	0.75	*0.75*	0.64	*0.64*
Ap	0.10	*0.10*	0.13	*0.13*	0.03	*0.03*	0.04	*0.04*

Analytical results in italics indicate that the composition is calculated using Fe^{3+}/Fe^{2+} values determined from Ol–Spl pairs. * All iron expressed as FeO. mg# is defined as 100Mg/Mg + Fe); K_d is equal to (Mg + Fe)glass/(Mg + Fe)Ol. D Ni (B) is the partition coefficient for Ni between olivine and liquid, determined using the equation of Beattie *et al.* (1991).

Ni, Table 1), but matching those of ~1000 to 2000 ppm Ni, postulated for highly magnesian (>20 wt% MgO) primary liquids (Clarke 1970, Smith & Erlank 1982, Liang & Elthon 1990, Barnes *et al.* 1995, Lesher & Arndt 1995).

We now consider the implications for ankaramite petrogenesis of the compositional data yielded by our study of melt inclusions.

If the melt inclusions in olivine and clinopyroxene in the aggregated magma (= crystals plus melts) are samples of the melts in contact with the crystals when they grew, these melts would have been at or near their liquidus temperatures when trapped. The earliest phases to crystallize (of those that survive) seem to have been Mg-rich olivine in Rinjani ankaramites, later joined first by chromian spinel, and then by clinopyroxene. The melts trapped in olivine may therefore include some melt fractions in existence at higher temperatures and pressures than those prevailing when the aggregated ankaramitic magmas (= crystals plus melts) adjusted to low-pressure conditions before eruption, and may therefore represent primitive magmas parental to the ankaramites. In Rinjani, the clinopyroxene-hosted melt compositions preserve the fractionation paths of the melts as they evolved at low pressures (Della-Pasqua 1997).

We suggest that ascending primary melts (Fig. 9, Stage 2), similar in composition to the olivine-hosted inclusions with variable CaO/Al_2O_3 values (Fig. 5), collect and mix at low pressures (<0.5 GPa, Fig. 9, Stage 3) while continuing to react and re-equilibrate with the sub-arc mantle. During melt–rock interaction (*cf.* Kelemen *et al.* 1992), primary liquids could become modified by the dissolution of pyroxene from the wall-rock, leading to the silica-enrichment (Kelemen 1990, Kelemen *et al.* 1992) that distinguishes the ankaramite rock compositions from the compositions of primitive melt inclusions trapped in early-crystallized olivine crystals (Table 1 and 3, respectively).

Olivine and clinopyroxene phenocrysts from the ankaramites vary in composition, are zoned, and display resorption textures. In our opinion, these textural features suggest that the conclusion of Barsdell (1988) and Barsdell & Berry (1990), that the Merelava and Epi rocks evolved down olivine–clinopyroxene cotectics, may be too simple an explanation. Instead of being simple differentiates of a parental ankaramitic magma, the rocks might have formed as mixtures of crystals and melts at low pressures. Continued crystallization and reaction in the sub-arc reservoir (Fig. 9, Stage 3) of these aggregated melts could account for their compositional characteristics and for the wide compositional ranges and textural features observed in the phenocrysts of erupted ankaramitic rocks (*e.g.*, olivine ranging from ~Fo_{74} to ~Fo_{92}, and clinopyroxene ranging from Mg# ~80 to ~93), as well as for their relative abundances (Cpx:Ol ~3 or 4:1, Table 1) and the presence of a reversely zoned rim observed in primitive olivine and clinopyroxene phenocrysts of ankaramites from Merelava (Barsdell 1988) and Epi (Barsdell & Berry 1990).

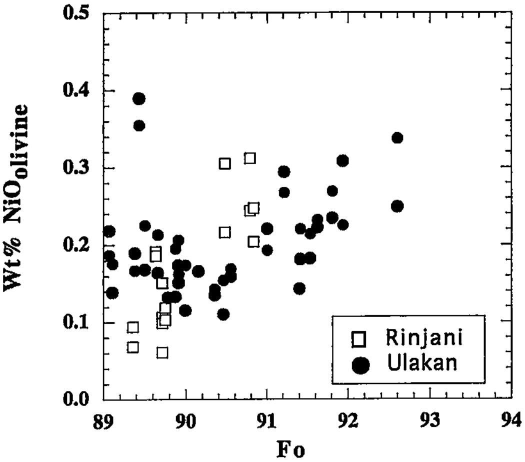


FIG. 10. Concentration of Ni (wt% NiO) in olivine *versus* Fo in ankaramite samples from Rinjani volcano (Lombok), and Ulakan Formation (Bali). These are results of electron-microprobe analyses operating at conditions suitable for trace elements (Ca, Ni, Mn and Cr); current 200 nA, beam size 20 μm, 20 kV and 120 seconds counting time.

In short, we propose that the inclusions of primitive melt, with their variable CaO/Al_2O_3 values, trapped in olivine (Fo_{89-92}) in ankaramite rocks from Rinjani volcano (CaO/Al_2O_3 of 0.8 to 1.5) and the Ulakan Formation (CaO/Al_2O_3 of 0.9 to 1.8) (Fig. 5) represent aliquots of primary melts trapped by early-formed phenocrysts (Fig. 9, Stage 2) before the magmas aggregated, mixed, and re-equilibrated at low pressures in the sub-arc mantle. We view primitive ankaramitic magmas in volcanic arcs as an aggregate of Ca- and Mg-rich silica-undersaturated primary melts with variable CaO/Al_2O_3 values modified by melt–wallrock interaction during crystallization and ascent; they collected in subvolcanic reservoirs in the shallow arc mantle, where they continued to react and re-equilibrate at low pressures.

ACKNOWLEDGEMENTS

This work forms part of a Ph.D. thesis submitted to the University of Tasmania by FNdP, who was supported by an Australian Postgraduate Research Award. The costs of the research were met through grants from the Australian Research Council to RV. We thank D.H. Green for discussions about peridotite melting in the presence of CO_2-rich fluids and the generation of ankaramitic melts. D.V.S. Kamenetsky and L. Danyushevsky are thanked for their guidance with the experimental work on melt inclusions, and for reviewing early drafts of the article. Technical assistance was provided by K.L. Harris. Electron-microprobe analyses were made with the assistance of W. Jablonski. R.F. Berry and M. Barsdell are thanked for providing ankaramitic samples from Merelava and Epi. J. Adam, A.J. Crawford, L. Danyushevsky, K.L. Harris, P. Sedwick and I.A. Sigurdsson provided stimulating advice throughout the project. R.F. Martin, G.T. Nixon and the two reviewers, D. Francis and R.W. Luth, are thanked for their careful reading of this article. Their comments, suggestions and criticism helped improve it.

References

Adam, J. (1987): Dry, hydrous and CO_2-bearing liquidus phase relationships in the CMAS system at 28 Kb, and their bearing on the origin of alkali basalts. *J. Geol.* **96**, 709-719.

Arculus, R.J. (1976): Geology and geochemistry of the alkali basalt-andesite association of Grenada, Lesser Antilles island arc. *Geol. Soc. Am., Bull.* **87**, 612-624.

Baker, M.B. & Stolper, E.M. (1994): Determining the composition of high-pressure mantle melts using diamond aggregates. *Geochim. Cosmochim. Acta* **58**, 2811-2827.

Barnes, S.J., Lesher, C.M. & Keays, R.R. (1995): Geochemistry of mineralised and barren komatiites from the Perseverance nickel deposit, Western Australia. *Lithos* **34**, 209-234.

Barsdell, M. (1980): *Petrological Variation in the Banks Islands, New Hebrides.* Ph D. thesis, Auckland University, Auckland, New Zealand.

________ (1988): Petrology and petrogenesis of clinopyroxene-rich tholeiitic lavas, Merelava volcano, Vanuatu. *J. Petrol.* **29**, 927-964.

________ & Berry, R.F. (1990): Origin and evolution of primitive island arc ankaramites from Western Epi, Vanuatu. *J. Petrol.* **31**, 747-777.

Beattie, P., Ford, C. & Russell, D. (1991): Partition coefficients for olivine–melt and orthopyroxene–melt systems. *Contrib. Mineral. Petrol.* **109**, 212-224.

Bowes, D.R. (1989): *The Encyclopedia of Igneous and Metamorphic Petrology.* Van Nostrand Reinhold, New York, N.Y.

Brey, G., Brice, W.R., Ellis, D.J., Green, D.H., Harris, K.L. & Ryabchikov, I.D. (1983): Pyroxene–carbonate reactions in the upper mantle. *Earth Planet. Sci. Lett.* **62**, 63-74.

________ & Green, D.H. (1975): The role of CO_2 in the genesis of olivine melilitite. *Contrib. Mineral. Petrol.* **49**, 93-103.

________ & ________ (1977): Systematic study of liquidus phase relations in olivine melilitite + H_2O + CO_2 at high pressures and petrogenesis of an olivine melilitite magma. *Contrib. Mineral. Petrol.* **61**, 141-162.

Clarke, D.B. (1970): Tertiary basalts of Baffin Bay: possible primary magma from the mantle. *Contrib. Mineral. Petrol.* **25**, 203-224.

Danyushevsky, L.V., Sobolev, A.V. & Kononkova, N.N. (1992): Methods of studying melt inclusions in minerals during investigations on water-bearing primitive mantle melts (Tonga trench boninites). *Geochem. Int.* **29**(7), 48-62.

Dawson, J.B., Powell, D.G. & Reid, A.M. (1970): Ultrabasic xenoliths and lava from the Lashaine volcano, northern Tanzania. *J. Petrol.* **11**, 519-548.

Della-Pasqua, F.N. (1997): *Primitive Ankaramitic Magmas in Volcanic Arcs.* Ph.D thesis, University of Tasmania, Hobart, Tasmania.

________, Kamenetsky, V.S., Gasparon, M., Crawford, A.J. & Varne, R. (1995): Al-spinels in primitive arc volcanics. *Mineral. Petrol.* **53**, 1-26.

Falloon, T.J. & Green, D.H. (1986): Glass inclusions in magnesian olivine phenocrysts from Tonga: evidence for highly refractory parental magmas in the Tonga arc. *Earth Planet. Sci. Lett.* **81**, 95-103.

________ & ________ (1987): Anhydrous partial melting of MORB pyrolite and other peridotite compositions at 10 Kbar: implications for the origin of primitive MORB glasses. *Mineral. Petrol.* **37**, 181-219.

________ & ________ (1988): Anhydrous partial melting of peridotite from 8 to 35 Kb and the petrogenesis of MORB. *J. Petrol., Lithosphere Special Issue,* 379-414.

________, ________, Hatton, C.J. & Harris, K.L. (1988): Anhydrous partial melting of a fertile and depleted peridotite from 2 to 30 kb and application to basalt petrogenesis. *J. Petrol.* **29**, 1257-1282.

Foden, J.D. (1979): *The Petrology of some Young Volcanic Rocks from Lombok and Sumbawa, Lesser Sunda Islands.* Ph.D. thesis, University of Tasmania, Hobart, Tasmania.

________ (1983): The petrology of the calcalkaline lavas of Rinjani volcano, East Sunda arc: a model for island arc petrogenesis. *J. Petrol.* **24**, 98-130.

________ & Varne, R. (1981a): The geochemistry and petrology of the basalt – andesite – dacite suite from Rinjani volcano, Lombok: implications for the petrogenesis of island arc, calc-alkaline magmas. *In* The Geology and Tectonics of Eastern Indonesia (A. J. Barber & S. Wiryosujono, eds.). *Geological Research and Development Centre (Bandung), Spec. Publ.* **2**, 115-134.

________ & ________ (1981b): Petrogenetic and tectonic implications of near coeval calc-alkaline to highly alkaline volcanism on Lombok and Sumbawa islands in the eastern Sunda arc. *In* The Geology and Tectonics of Eastern Indonesia (A. J. Barber & S. Wiryosujono, eds.). *Geological Research and Development Centre (Bandung), Spec. Publ.* **2**, 135-152.

________ & ________ (1983): Arc ankaramites, Sangean Api xenoliths and Cordilleran ultramafic to dioritic intrusive complexes: an updated concept of arc growth and development. *In* Sixth Australia Geol. Conv. on Lithosphere dynamics and evolution of continental crust. *Geol. Soc. Aust., Abstr. Ser.* **9**, 153-154.

Frey, F.A., Garcia, M.O., Wise, W.S., Kennedy, A., Gurriet, P. & Albarède, F., (1991): The evolution of Mauna Kea volcano, Hawaii: petrogenesis of tholeiitic and alkali basalts. *J. Geophys. Res.* **96**, 14347-14375.

________, Green, D.H. & Roy, S.D. (1978): Integrated models of basalt petrogenesis: a study of quartz tholeiites to olivine melilitites from south eastern Australia utilizing geochemical and experimental petrological data. *J. Petrol.* **19**, 463-513.

Ghiorso, M.S. & Carmichael, I.S.E. (1985): Chemical mass-transfer in magmatic processes. 2. Applications in equilibrium crystallization, fractionation and assimilation. *Contrib. Mineral. Petrol.* **90**, 121-141.

Green, D.H., Falloon, T.J., Brey, G.P. & Nickel, K.G. (1986): Peridotite melting to 6 GPa and genesis of primary mantle-derived magmas. *In* Fourth Int. Kimberlite Conference. *Geol. Soc. Aust., Abstr. Ser.* **16**, 181-183.

________, ________ & Taylor, W.R. (1987): Mantle-derived magmas – roles of variable source peridotite and variable C–H–O fluid compositions. *In* Magmatic Processes: Physicochemical Principles (B.O. Mysen, ed.). *The Geochem. Soc., Spec. Publ.* **1**, 139-154.

Greene, H.G. Macfarlane, A., Johnson, D.P. & Crawford, A.J. (1988): Structure and tectonics of the central Hebrides arc. *In* Geology and Offshore Resources of Pacific Island Arcs-Vanuatu Region (H.G. Greene & F.L. Wong, eds.). Circum-Pacific Council for Energy and Mineral Resources (Houston, Texas), *Earth Science Ser.* **8**, 377-412.

Gunn, B.M., Coy-Yll, R., Watkins, N.D., Abranson, C.E. & Nougier, J. (1970): Geochemistry of an oceanite – ankaramite – basalt suite from East Island, Crozet Archipelago. *Contrib. Mineral. Petrol.* **28**, 319-339.

Gurenko, A.A., Sobolev, A.V. & Kononkova, N.N. (1992): New petrological data on Icelandic rift alkali basalts. *Geochem. Int.* **29**(4), 41-53.

________, ________, Polyakov, A.I. & Kononkova, N.N. (1988): Primary melt of Iceland rift tholeiites: composition and conditions of crystallization. *Dokl. USSR Acad. Sci.* **301**, 179-182.

Hansteen, T.H. (1991): Multi-stage evolution of the picritic Maelifell rocks, SW Iceland: constraints from mineralogy and inclusions of glass and fluid in olivine. *Contrib. Mineral. Petrol.* **109**, 225-239.

Hawkesworth, C.J., O'Nions, R.K. & Arculus, R.J. (1979): Nd and Sr isotope geochemistry of island arc volcanics, Grenada, Lesser Antilles. *Earth Planet. Sci. Lett.* **45**, 237-248.

Herzberg, C. (1992): Depth and degree of melting of komatiites. *J. Geophys. Res.* **97**, 4521-4540.

Hess, H.H. & Poldervaart, A. (1967): *Basalts. The Poldervaart Treatise on Rocks of Basaltic Composition.* J. Wiley & Sons, New York, N.Y.

Hirose, K. & Kushiro, I. (1993): Partial melting of dry peridotites at high pressures: determination of compositions of melts segregated from peridotite using aggregates of diamond. *Earth Planet. Sci. Lett.* **114**, 477-489.

Hughes, C.J. (1982): *Igneous Petrology.* Elsevier, Amsterdam, The Netherlands.

Jaques, A.L. & Green, D.H. (1980): Anhydrous melting of peridotite at 0–15 Kb pressure and the genesis of tholeiitic basalts. *Contrib. Mineral. Petrol.* **73**, 287-310.

Jarosewich, E., Nelen, J.A. & Norberg, J.A. (1980): Reference samples for electron microprobe analysis. *Geostandards Newsletter* **4**, 43-47.

Kato, T., Ringwood, A. E. & Irifune, T. (1988): Experimental determination of element partitioning between silicate perovskites, garnets and liquids: constraints on the early differentiation of the mantle. *Earth Planet. Sci. Lett.* **89**, 123-145.

Kelemen, P.B. (1990): Reaction between ultramafic rock and fractionating basaltic magma. I. Phase relations, the origin of calc-alkaline magma series, and the formation of discordant dunite. *J. Petrol.* **31**, 51-98.

________, Dick, H.J.B. & Quick, J.E. (1992): Formation of harzburgite by pervasive melt/rock reaction in the upper mantle. *Nature* **358**, 635-641.

Kinzler, R.J. & Grove, T.L. (1992a): Primary magmas of mid-ocean ridge basalts. 1. Experiments and methods. *J. Geophys. Res.* **97**, 6885-6906.

________ & ________ (1992b): Primary magmas of mid-ocean ridge basalts. 2. Applications. *J. Geophys. Res.* **97**, 6907-6926.

Krishnamurthy, P. & Cox, K.G. (1977): Picrite basalts and related lavas from the Deccan Traps of western India. *Contrib. Mineral. Petrol.* **62**, 53-75.

Lacroix, A. (1916): Sur quelques roches volcaniques mélanocrates des possessions françaises de l'océan Indien et du Pacifique. *C.R. Acad. Sci.* **158**, 177-183.

Le Maitre, R.W., Bateman, P., Dudek, A., Keller, J., Lameyre, J., Le Bas, M.J., Sabine, P.A., Schmid, R., Sørensen, H., Streckeisen, A., Woolley, A.R. & Zanettin, B. (1989): *A Classification of Igneous Rocks and Glossary of Terms.* Blackwell, Oxford, U.K.

Lesher, C.M. & Arndt, A.N. (1995): REE and Nd isotope geochemistry, petrogenesis and volcanic evolution of contaminated komatiites at Kambalda, Western Australia. *Lithos* **34**, 127-157.

Liang, Y. & Elthon, D. (1990): Evidence from chromium abundances in mantle rocks for the extraction of picrite and komatiite melts. *Nature* **343**, 551-553.

Maaløe, S., Sorensen, I. & Hartogen, J. (1986): The trachybasaltic suite of Jan Mayen. *J. Petrol.* **27**, 439-466.

Maurel, C. & Maurel, P. (1984): Étude expérimentale de la distribution du fer ferrique entre spinelle chomifère et bain silicaté basique. *Bull. Minéral.* **107**, 25-33.

Mitchell, R.S. (1985): *Dictionary of Rocks.* Van Nostrand Reinhold, Melbourne, Australia.

Moriyama, J., Kawabe, I., Fujino, K. & Ohtani, E. (1992): Experimental study of element partitioning between majorite, olivine, merwinite, diopside and silicate melts at 16 GPa and 2000°C. *Geochem. J.* **26**, 357-382.

Mysen, B.O. & Boettcher, A. (1975): Melting of a hydrous mantle: II. Geochemistry of crystals and liquids formed by anatexis of mantle peridotite at high pressures and high temperatures as a function of controlled activities of water, hydrogen and carbon dioxide. *J. Petrol.* **16**, 549-593.

Ohtani, E., Nagata, Y., Suzuki, A. & Kato, T. (1995): Melting relations of peridotite and the density crossover in planetary mantles. *Chem. Geol.* **120**, 207-221.

Robinson, P. (1980): The composition space of terrestrial pyroxenes – internal and external limits. *In* Pyroxenes (C.T. Prewitt, ed.). *Rev. Mineral.* **7**, 419-494.

Roedder, E. (1979): Origin and significance of magmatic inclusions. *Bull. Minéral.* **102**, 487-510.

________ (1984): Fluid inclusions. *Rev. Mineral.* **12.**

Sato, H., Tchoua, F. & Kusakabe, M. (1991): Olivine phenocrysts in some Cameroonian basalts – implications for primary magma composition. *Mineral. Petrol.* **44**, 253-269.

Shibata, T. (1976): Phenocryst – bulk rock composition relations of abyssal tholeiites and their petrogenetic significance. *Geochim. Cosmochim. Acta* **40**, 1407-1417.

Sigurdsson, I.A. (1994): *Primitive Magmas in Convergent Margins and at Oceanic Spreading Ridges: Evidence from Early Formed Phenocryst Phases and their Melt Inclusions.* Ph.D thesis, University of Tasmania, Hobart, Tasmania.

Sisson, T.W. & Layne, G.D. (1993): H_2O in basalt and basaltic andesite glass inclusions from four subduction-related volcanoes. *Earth Planet. Sci. Lett.* **117**, 619-635.

Smith, H.S. & Erlank, A.J. (1982): Geochemistry and petrogenesis of komatiites from the Barberton greenstone belt, South Africa. *In* Komatiites (N.T. Arndt & E.G. Nisbet, eds.). Allen & Unwin, London, U.K. (347-397).

Sobolev, A.V. & Danyushevsky, L.V. (1993): Petrology and geochemistry boninites from the north termination of the Tonga Trench: constraints on the generation conditions of primary high-Ca boninite magmas. *J. Petrol.* **35**, 1183-1211.

________, Dmitriev, L.V., Baruskov, V.L., Nevsorov, V.N. & Slutsky, A.B. (1980): The formation conditions of the high-magnesium olivines from the monomineralic fraction of Luna 24 regolith. *In* Proceedings of the 11th Lunar Planet. Sci. Conf. (105-116).

________, ________, Tsameryan, O.P., Kononkova, N.N. & Robinson, P.T. (1991): A possible primary melt composition for the ultramafic lavas on the Margi Area, Troodos Ophiolite, Cyprus. *In* Cyprus Crustal Study Project: Initial Report, Holes CY–I and IA (I.L. Gibson, J. Malpas, P.T. Robinson & C. Xenophontos, eds.). *Geol. Surv. Can., Pap.* **90-20**, 203-218.

________, Kamenetsky, V.S. & Kononkova, N.N. (1989): New data on the petrology and geochemistry of the ultramafic volcanites of Valayinskiy Range, eastern Kamchatka. *Geokhimiya* **12**, 1694-1709 (in Russ.).

________, ________, Metrich, N., Clocchiatti, R.N. Kononkova, N.N., Devirts, A.L. & Ustinow, V.I. (1990): Volatile regime and crystallization conditions in Etna hawaiite lavas. *Geochem. Int.* **28**(4), 53-65.

Spray, J.G. & Rae, D.A. (1995): Quantitative electron-microprobe analysis of alkali silicate glasses: a review and user guide. *Can. Mineral.* **33**, 323-332.

Stormer, J.C. Jr. (1973): Calcium zoning in olivine and its relationship to silica activity and pressure. *Geochim. Cosmochim. Acta* **37**, 1815-1821.

Sullivan, G.E. (1991): Chemical evolution of basalts from 23°N along the mid-Atlantic ridge: evidence from melt inclusions. *Contrib. Mineral. Petrol.* **106**, 296-308.

Takahashi, E. (1986): Melting of a dry peridotite KLB–1 up to 14 GPa: implications on the origin of peridotitic upper mantle. *J. Geophys. Res.* **91**, 9367-9382.

Taylor, W.R. & Green, D.H. (1987): The petrogenetic role of methane: effect on liquidus phase relations and the solubility mechanism of reduced C–H volatiles. *In* Magmatic Processes: Physicochemical Principles (B.O. Mysen, ed.). *Geochem. Soc., Spec. Publ.* **1**, 121-138.

Thompson, R.N. & Flower, F.J. (1971): Evidence for upper-crust ankaramitic liquids. *Am. Geophys. Union, Trans.* **52**, 377 (abstr.).

Trønnes, R.G., Canil, D. & Wei, K. (1992): Element partitioning between silicate minerals and coexisting melts at pressures of 1–27 GPa, and implications for mantle evolution. *Earth Planet. Sci. Lett.* **111**, 241-255.

Tomkeieff, S.I. (1983): *Dictionary of Petrology.* J. Wiley & Sons, Chichester, U.K.

Varne, R. & Foden, J.D. (1986): Geochemical and isotopic systematics of eastern Sunda arc volcanics: implications for mantle sources and mantle mixing processes. *In* The Origin of Arcs (F.C. Wezel, ed.). Elsevier, Amsterdam, The Netherlands (159-189).

Walker, D., Shibata, T. & De Long, S.E. (1979): Abyssal tholeiites from the Oceanographer fracture zone. *Contrib. Mineral. Petrol.* **70**, 111-125.

Wei, K., Trønnes, R.G. & Scarfe, C.M. (1990): Phase relations of aluminium-undepleted and aluminium-depleted komatiites at pressures of 4–12 GPa. *J. Geophys. Res.* **95**, 15817-15827.

Wheller, G.E. (1986): *Petrogenesis of Batur Caldera, Bali and the Geochemistry of Sunda-Banda Arc Basalts.* Ph.D. thesis, University of Tasmania, Hobart, Tasmania.

Whitford, D.J. (1975): *Geochemistry and Petrology of Volcanic Rocks from the Sunda Arc, Indonesia.* Ph D. thesis, Australian National University, Canberra, Australia.

________, Nichols, I.A. & Taylor, S.R. (1979): Spatial variations in the geochemistry of Quaternary lavas across the Sunda arc in Java and Bali. *Contrib. Mineral. Petrol.* **70**, 341-356.

Received November 12, 1995, revised manuscript accepted February 25, 1997.