

Petrogenesis of alnöitic rocks from Malaita, Solomon Islands, Melanesia

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SUMMARY. Aphanitic and fragmental alnöitic rocks from Malaita contain ultrabasic xenoliths and discrete nodules (megacrysts) of pyroxenes and garnets. Primary minerals in the alnöites are olivine (Fo_{85}), clinopyroxene (diopside-sahlite), natro-melilite (1/3 melilite-2/3 åkermanite), phlogopite (1-9% TiO_2), perovskite, spinel (ulvö spinel-magnetite series) and accessory nepheline, melanite, and apatite. Alnöite olivines and clinopyroxenes are compositionally different from those phases in the xenoliths and megacrysts. Rare earth element distribution patterns are linear and indicate strong enrichment in the light rare earths ($\text{La}/\text{Yb} = 42-49$). The alnöites are possible primary melts of a pyrolite-type mantle formed by approximately 4% partial melting at depths greater than 120 km, under high carbon dioxide pressures. Despite containing a mantle xenolith assemblage similar to that found in kimberlites, the host Malaita rocks are mineralogically and geochemically different from kimberlite.

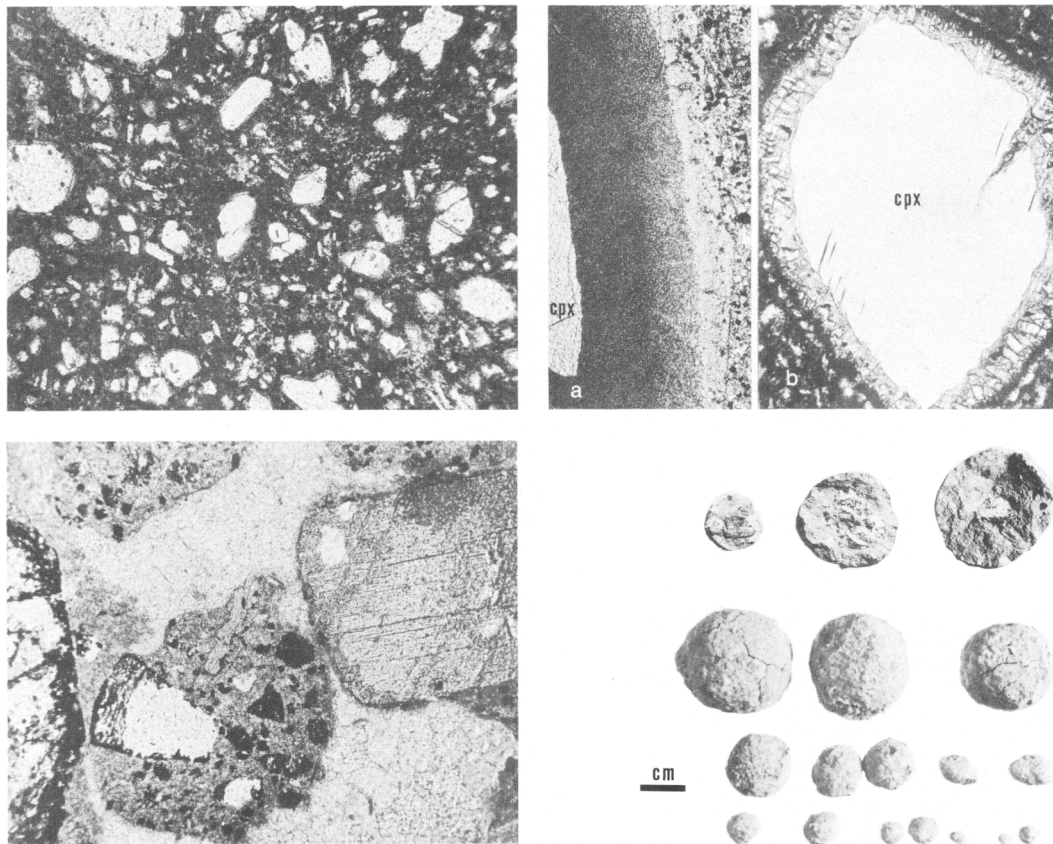
AN alnöite intrusion from Malaita Island, in the Solomon Islands, described by Allen and Deans (1965) contains a suite of deep-seated garnet-bearing lherzolites and discrete nodules, similar to those in kimberlites, which give information about mantle composition and geothermal gradient in a supposedly oceanic environment (Nixon and Boyd, 1979). The alnöite has been emplaced near the margin of the Ontong Java Plateau, an oceanic plate having a crustal thickness of up to 42 km and which has continental characteristics (Kroenke, 1972; Nixon and Coleman, 1978). The purpose of the present study is to compare the petrography and genesis of these unusual rocks with their alnöite and kimberlite counterparts found in more typical continental areas. Xenoliths have previously been described (Nixon and Boyd, 1979) and we are here

concentrating on the phlogopite, melilite, olivine, clinopyroxene, spinel-bearing host alnöite which until now has only been known from a handful of small specimens from Malaita (Allen and Deans, 1965; Dawson *et al.*, 1978).

Alnöite petrography

The limited exposures within the Hauhaumela stream, at Babaru'u (160° 50½' E, 8° 43' S) in the rain forest of northern Malaita, suggest a pipe-like intrusion several hundred metres across¹ (dated at 33.9 m.y., Davis, 1977) emplaced in steeply folded 'U' Cretaceous mudstones and limestones of the Malaita Group and underlying basalt pillow lavas and tuffs—the Alite Volcanics (Rickwood, 1957; Coleman, 1968). The toughest and least-altered alnöites are dark bluish grey aphanitic boulders and patches occurring within softer, fragmental groundmass. They superficially resemble kimberlitic 'hardebank' and 'blue ground' respectively. They have irregular sculptured weathered surfaces, due to resistant phenocrysts of subhedral olivine up to 5 mm across, with a median size of 0.2 mm and a modal variation of 22-35 (fig. 1). The groundmass contains stumpy crystals of melilite up to 1 mm long, some with eight-sided cross sections, which make up to 30% or more of the rock. The mineral is uniaxial negative and shows median crack and peg textures. All our specimens contain melilite, or its pseudomorphs, thus excluding them from the

¹ Since this report was prepared a smaller intrusion has been located at Kwaikwai 3½ km to the NNW.



FIGS. 1-4. FIG. 1 (*top left*). Alnöite with microphenocrysts of olivine, some cruciformly twinned, in groundmass containing melilite laths and opaque spinels. Ordinary light; width of section is 2 mm. PHN 3544. FIG. 2 (*top right*). (*a*) Turbid alteration rim in clinopyroxene in fine-grained alnöite (*left*). (*b*) Fringe of secondary olivine and melilite around clinopyroxene (*right*). Ordinary light; width of complete section is 2.3 mm. FIG. 3 (*bottom left*). Tuff with lapilli in carbonate matrix in which late-formed phlogopite (*right*) has developed. Ordinary light; width of section is 2 mm. FIG. 4 (*bottom right*). Autoliths of alnöite. The top three specimens are broken to reveal cores of mineral or rock fragments.

ankaratriite group (biotite-rich olivine melanephelinites), which was described from another intrusion nearby (Allen and Deans, 1965). The remainder of the groundmass consists of euhedral perovskite, magnetite, spinel, apatite, rare patches of nepheline, equant grains of (?) haüyne, glass, and microphenocrysts of late-formed poecilitic, very pale brown, mildly pleochroic phlogopite (mode 5-55%). Modal variations of phlogopite and melilite occur within the same thin section and it appears that these minerals intrude patches rich in darker minerals and, thus, represent final products of crystallization. Coarse minerals derived from fragmented ultrabasic nodules and discrete nodules (megacrysts) include olivines, pyropes, spinels, ilmenites, orthopyroxenes and clinopyroxenes

(Nixon and Boyd, 1979). In hand specimens there are taxonomic problems posed by the abundance of these minerals, in particular the several varieties of cpx, but a specific alnöite cpx (see below) has been identified in most specimens (one exception is PHN 3542). These cognate cpx occur as small grains but can be acicular (PHN 3566).

Magmatic reaction at the margins of the pyroxene megacrysts has produced a turbid or spongy zone (fig. 2*a*) in which isotropic blebs of glass and phlogopite can be spattered, and which may have resulted from a sudden release of pressure accompanying intrusion. Secondary olivine and melilite are arranged internally in a herringbone fashion or as a peripheral radiating fringe (fig. 2*b*). The pyroxenes of lherzolite xenoliths are similarly affected

but the component olivine and spinel are not. Some deep-seated inclusions have been completely replaced by sheaf-like aggregates of secondary clinopyroxene with some orthopyroxene, interstitial zeolite, calcite, analcime and incipient yellow mica with ilmenite plates.

The *fragmental* rocks grade from tuffs to breccias with increasing coarseness and angularity of fragments. The origin of the former appears to have been highly turbulent and fluidized, and that of the latter, disruptive auto-brecciated. The coarsest breccias are simply alnöites veined with slickensided calcite. Some varieties consist of fragments

of porphyritic lava (Alite Volcanics), others of alnöite lapilli, in a cream calcite matrix with some gonnardite, mottled with MnO₂ and containing coarse rounded phlogopite (> 1 cm) of late stage origin (fig. 3). Such lapilli tuffs, in which carbonate exceeds 50% of the rock, could have resulted from silicate-carbonate liquid immiscibility.

Autoliths, in which alnöite magma has wrapped around inclusions (fig. 4) resemble those found in kimberlites (Ferguson *et al.*, 1973). Two studied in detail are 24 mm and 19 mm in diameter with subangular cores of cpx (7 mm) and sp lherzolite

TABLE I. *Chemical composition of alnöite and associated rocks from Babaru'u, Malaita, compared with average melilite ankaratrite*

	Alnöite intrusives			Tuffs		Breccias		Autolith		
	3544	3565	3639D	3545	3553	3541	3543	3552	3297	1
SiO ₂	37.36	36.40	36.73	29.60	27.81	29.45	27.71	28.40	37.78	37.06
TiO ₂	3.36	2.72	2.89	2.91	2.26	2.89	2.77	3.01	2.88	2.91
Al ₂ O ₃	8.06	7.10	7.14	6.60	5.78	6.60	6.03	5.60	8.42	9.48
Fe ₂ O ₃	5.67	4.11	5.85	10.35*	4.48	7.57	6.39	11.70*	5.22	5.56
FeO	5.94	7.13	6.12	—	4.44	3.06	3.20	—	6.99	6.79
MnO	0.18	0.19	0.13	0.16	0.15	0.27	0.17	0.18	0.24	—
MgO	18.76	21.51	19.11	13.70	16.71	20.24	15.17	17.10	17.70	14.13
CaO	10.81	11.85	12.27	16.82	16.16	9.30	16.39	14.21	12.36	15.31
Na ₂ O	3.70	3.20	2.66	0.70	1.11	0.30	1.05	1.60	0.81	2.78
K ₂ O	2.54	2.15	2.31	0.21	1.15	0.18	1.78	1.27	1.30	1.72
H ₂ O+	1.84	1.73	2.46	—	6.61	8.99	5.93	—	4.10	—
H ₂ O-	0.73	0.33	0.33	—	1.67	6.07	2.94	15.40	1.08	2.34
CO ₂	0.64	0.00	0.17	—	9.37	4.62	10.01	—	0.18	—
P ₂ O ₅	1.30	1.40	1.11	1.22	1.19	1.29	1.24	1.93	0.86	1.03
Total	100.89	99.82	99.28	82.27†	98.89	100.83	100.78	100.40	99.92	—

* Total Fe as Fe³⁺. † Partial analysis.

Trace elements p.p.m.

Cr	—	837	—	—	467	437	419	—	—
Co	—	57	—	—	42	54	47	—	—
Ni	—	675	—	—	384	390	352	—	—
Zn	—	—	—	—	96	115	100	—	—
Rb	74	56	—	—	38	12	55	—	—
Sr	1188	1691	—	—	839	306	658	—	—
Ba	—	1589	—	—	968	100	928	—	—
Zr	216	223	—	—	168	205	185	—	—
Nb	103	110	—	—	92	108	96	—	—

Analysts: Alan Gray and Douglas Richardson except where indicated. Except for 3297 and 1 all rocks are from the Babaru'u occurrence.

PHN 3544 Fresh tough alnöite. PHN 3565 Porphyritic olivine-rich alnöite. 3639D Alnöite (Allen and Deans, 1965). PHN 3545, 3553 Soft weathered green alnöite tuff. PHN 3541 Alnöite breccia rich in basalt xenoliths. PHN 3543 Alnöite breccia. PHN 3552 Alnöite envelope from autolith in soft breccia. 3297 Ankaratrite, upper Auluta River (Allen and Deans, 1975). 1 Average composition of melilite-bearing eruptive rocks with Na₂O + K₂O less than 7.25% (173 analyses), Velde and Yoder (1976).

(11 mm). The envelopes are petrographically similar to the lapilli and consist of altered (?) melilite and fresh, but slightly distorted phlogopite arranged concentrically, with subhedral serpentinized olivine pseudomorphs (0.1–0.2 mm) and calcite in a matrix of magnetite, perovskite, and spinel grains and, more rarely, sodalite and melanite.

The bulk chemical composition of the Malaita alnöites is very close to that determined by Allen and Deans (1965)—compare PHN 3544 and 3639D in Table I. They correspond closely to the average 'melilite ankaratrite' group of Velde and Yoder (1976) which is relatively poor in alkalis and rich in MgO (see Table I) compared with their other 'melilite nephelinite' group. The former is rich in olivine and clinopyroxene whereas the latter is rich in feldspathoids. Although the Malaita rocks are highly magnesian they are less so than most kimberlites, but TiO₂ is greater, residing in both ilmenite and ulvöspinel. Combined alkalis are higher than in kimberlites, particularly Na₂O which is slightly greater in amount than K₂O. As in many alkaline basic-ultrabasic volcanic rocks, there are notable amounts of light rare earths (later section), Sr, Ba, Zr, and Nb. The tough fresh alnöite is only relatively slightly affected by hydrous and carbonate alteration unlike the tuffs and breccias (Table I).

Mineral chemistry

Analyses of groundmass *clinopyroxenes* in the alnöites did not frequently match those of the discrete nodules (megacrysts) or the lherzolite nodules (Nixon and Boyd, 1979) indicating that they are not

fragmented members of those suites. These cognate cpx are pale-green diopsides, low in Na and Cr, rimmed by, or showing oscillatory zoning to, brownish ferriferous diopsides or sahlites (Tables II and III, fig. 5). There is also enrichment in Ti and Al but a decrease in Na. Since they are not sub-calcic they have crystallized from the alnöite magma at

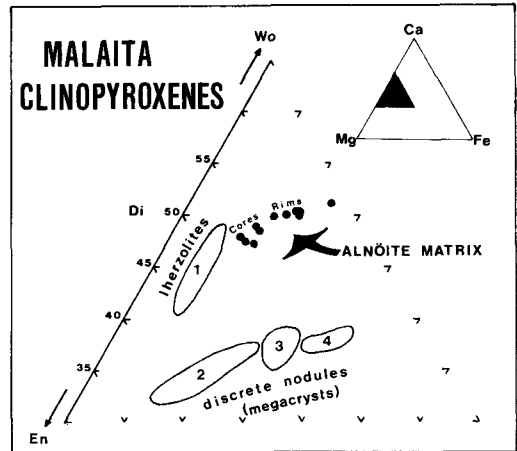


FIG. 5. Plots of compositions of clinopyroxenes from the alnöite groundmass. They are diopsides with sahlitic rims or oscillatory zones. Clinopyroxenes from inclusions within the alnöite suite (Nixon and Boyd, 1979) are also shown for comparison: diopside-subcalcic diopside from the lherzolite xenoliths (field 1), subcalcic diopside/subcalcic augite/augite from the discrete nodule (megacryst) association (fields 2, 3, and 4).

TABLE II. Representative analyses of clinopyroxenes from the Malaita alnöite groundmass

	Ti-Al poor, pale green diopsides					Ti-Al sahlite oscillatory zoned overgrowths					
	1	2	3	4	5	6	7	8	9	10	11
SiO ₂	54.4	54.9	51.5	52.0	52.2	47.6	49.5	46.4	47.6	42.5	47.2
TiO ₂	0.7	0.9	1.3	1.7	1.3	3.2	2.5	3.7	3.2	5.2	3.0
Al ₂ O ₃	0.7	1.2	2.1	2.9	3.2	5.3	3.7	5.8	4.7	8.6	5.0
Cr ₂ O ₃	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0
FeO*	3.8	4.2	4.7	4.3	4.6	5.4	4.9	5.9	6.1	7.1	6.0
MnO	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
MgO	16.4	16.4	15.9	15.8	15.7	14.1	14.7	13.9	13.8	12.1	13.7
CaO	23.7	23.5	24.2	24.2	22.7	23.8	24.1	24.1	23.9	23.3	23.9
Na ₂ O	0.6	0.6	0.6	0.4	0.7	0.5	0.5	0.5	0.5	0.8	0.5
H ₂ O	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NiO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	100.4	101.8	100.4	101.3	100.5	100.0	100.1	100.5	99.9	99.7	99.4

* Total Fe expressed as FeO. Nos. 1, 2 from PHN 3565; No. 3, PHN 3566; No. 4, 3565; No. 5, PHN 3544. Nos. 6–9 and 10–11 are zoned pyroxenes from PHN 3544 and 3566 respectively.

TABLE III. Comparison of the chemical characteristics of clinopyroxenes from the Malaita alnöite

	This study		Nixon and Boyd (1979)		
	Groundmass cpx		Megacrysts		Lherzolites
	Primary	Overgrowth	Augite	Subcalcic di	Diopside
TiO ₂ wt %	0.5-2.0	2.0-5.2	0.5-1	< 1	< 0.5
Na ₂ O wt %		< 1.0	> 2	> 1	0.3-2
Cr ₂ O ₃ wt %		< 0.2	< 0.1	0-1	> 0.5
Mg/(Mg+Fe) %	85-89	75-85	68-78	80-90	91-93.5
Ca/(Ca+Mg) %		> 50	42-48	34-41	43-50.6

temperatures much less than those indicated by the deepest xenoliths (Nixon and Boyd, 1979), presumably at shallower levels. The oscillatory zoning is explained by reaction with alnöite magma (of fluctuating composition due to new injections ?) during later stages of emplacement. The sodium-poor nature of the later cpx may reflect an impoverishment in the magma due to sodium-bearing melilite becoming a stable product at shallow (late stage) depths of intrusion.

The compositions of the diopsides resemble those of the megacrysts in some alkali basalts (Irving, 1974). Given suitable crystallization conditions, similar cognate megacrysts could presumably form in alnöites. The secondary sahlitic varieties are similar to many groundmass cpx in nephelinites and alkali basalts (Scott, 1976).

The melilite laths are of almost uniform composi-

tion (Table IV) and plot close to 1/3 natro-melilite (Ca Na Al Si₂O₇)—2/3 åkermanite (Ca₂ (Mg, Fe) Si₂O₇) reported by El Goresy and Yoder (1974) for many igneous melilites. Velde and Yoder (1976) have emphasized the role of alkalis in the magma which are necessary if melilite is to form. Groundmass nepheline, analysed with difficulty, consisted almost entirely of Na Al SiO₄ end-member, but it is highly altered to zeolitic material. It is conjectured that this reaction may have released sodium for the Na-enriched rims of melilite.

The olivines are of two kinds: aggregate of strained grains, representing disaggregated lherzolites, and subhedral to euhedral liquidus grains, some cruciformly twinned. The abundance of lherzolic olivine is notable since most lherzolites contain heavily serpentinized olivine (Nixon and Boyd, 1979). These olivines are more Mg-rich

TABLE IV. Representative analyses of melilites from the Malaita alnöite suite

PHN	3544		3565		3566		3542	
	1	2	3	4	5	6	7	8
SiO ₂	43.0	43.5	43.9	43.4	43.3	42.5	43.6	43.7
TiO ₂	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1
Al ₂ O ₃	7.4	5.5	6.2	6.4	5.9	6.1	6.7	7.2
Cr ₂ O ₃	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FeO*	2.4	3.5	2.7	3.2	2.8	3.1	2.7	2.6
MnO	0.1	0.1	0.0	0.0	0.1	0.1	0.1	0.1
MgO	8.6	9.1	8.8	8.7	9.1	8.8	8.8	9.0
CaO	34.6	33.9	33.8	33.9	34.4	34.5	35.2	34.7
Na ₂ O	4.0	4.0	3.6	3.9	3.4	4.0	3.5	3.7
K ₂ O	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.2
NiO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	100.2	99.7	99.1	99.5	99.2	99.4	100.9	101.3

* Total Fe expressed as FeO. Analyses 1-2, 3-4, 5-6, 7-8 are cores and rims respectively of individual crystals.

TABLE V. Representative analyses of olivines from the Malaita alnöite suite

PHN	3544		3566		3542	
	1	2	3	4	5	6
SiO ₂	40.2	40.5	40.1	40.0	39.9	39.6
TiO ₂	0.0	0.0	0.0	0.0	0.1	0.1
Al ₂ O ₃	0.0	0.0	0.2	0.0	0.0	0.0
Cr ₂ O ₃	0.0	0.0	0.0	0.0	0.0	0.0
FeO*	14.0	14.7	15.3	15.3	13.8	14.3
MnO	0.3	0.2	0.5	0.1	0.2	0.3
MgO	46.5	45.3	45.0	45.5	46.8	46.2
CaO	0.0	0.2	0.4	0.4	0.1	0.3
Na ₂ O	0.0	0.0	0.0	0.0	0.0	0.0
K ₂ O	0.0	0.0	0.0	0.0	0.0	0.0
NiO	0.4	0.2	0.2	0.2	0.3	0.2
Total	101.4	101.1	101.7	101.5	101.2	101.0

* Total Fe expressed as FeO. Analyses 1-2, 3-4, 5-6 are cores and rims respectively of euhedral olivines.

(approx. Fo₉₁) than the euhedral olivines which average Fo₈₅. Table V illustrates that small but significant amounts of Ca are present (especially in the rim) as in some other melilite-bearing eruptives (Mathias, 1949). The euhedral olivines tend to show Ni depletion at the rims.

In a detailed study of a single specimen of Malaita alnöite breccia (Dawson *et al.*, 1978) the micas are divided into two populations: a high-Cr/low-Ti group rich in Mg and a low-Cr/high-Ti group with considerable Mg/Fe variation. The micas from the unbrecciated alnöite are phlogo-

pites with a range of Ti which embraces that of both these populations but which are uniformly low in Cr (Table VI). Micas formed in the breccia can clearly be secondarily derived from compositionally varied minerals, e.g. from relatively Cr-rich mantle xenoliths or Fe-rich Alite volcanics. The phlogopites in groundmass of the unbrecciated alnöite are primary and are compositionally similar to the microphenocrysts, although rims of the latter are enriched in Ti and depleted in Na. A sieve-textured phenocryst, apparently partially melted, is exceptionally enriched in Ti (TiO₂ = 8.6 wt %).

TABLE VI. Representative analyses of phlogopites from the Malaita alnöite suite

	1	2	3	4	5	6	7	8	9	10
SiO ₂	39.6	39.1	39.0	34.6	40.7	41.4	39.5	37.6	38.7	38.7
TiO ₂	1.9	4.4	3.1	8.6	1.2	2.4	3.0	4.0	2.02	5.25
Al ₂ O ₃	14.5	12.9	14.5	13.6	10.5	11.1	12.1	12.8	14.5	14.2
Cr ₂ O ₃	0.2	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.75	0.01
FeO*	8.1	7.6	6.5	7.6	7.3	6.9	7.0	6.8	5.0	13.1
MnO	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.03	0.03
MgO	21.7	21.4	21.1	19.1	24.5	23.8	22.8	21.1	25.0	15.0
CaO	0.0	0.0	0.5	1.5	0.0	0.0	0.0	0.3	0.16	0.00
Na ₂ O	1.0	0.4	0.4	0.5	0.6	0.4	0.1	0.5	1.13	0.63
K ₂ O	8.8	9.2	9.6	8.3	10.1	9.3	9.9	9.9	8.56	8.95
NiO	0.2	0.0	0.3	0.1	0.1	0.1	0.0	0.1	0.20	0.02
Total	96.1	95.1	95.3	94.0	95.1	95.5	94.5	93.2	96.05	95.89

* Total Fe expressed as FeO. Nos. 1-3, rounded phenocrysts PHN 3565, PHN 3566, PHN 3542 respectively. No. 4, sieve-textured phenocryst PHN 3542. Nos. 5-8, groundmass laths PHN 3544. No. 9, representative analysis of high-Mg, high-Cr, low-Ti phlogopite (Dawson *et al.*, 1978). No. 10, representative analysis of high-Fe, low-Cr, high Ti mica (Dawson *et al.*, 1978).

No. 4, Table VI). It thus seems probable that there is an early, high-pressure Ti-enriched phase present.

The mean of twelve analyses of *perovskites* from three specimens gave, in wt %: TiO₂, 55.8; Al₂O₃, 0.41; Cr₂O₃, 0.0; FeO total, 1.79; MnO, 0.05; MgO, 0.29 (rare earths, Nb, and Sr were not analysed). Although mainly Ca TiO₃ there is significant minor element variation; for example, PHN 3566 (4 analyses) and PHN 3542 (5) average: Al₂O₃, 0.22 and 0.36; FeO total, 1.28 and 2.61; MnO, 0.02 and 0.08; and MgO, 0.22 and 0.36 respectively, with no overlap of the ranges.

The *spinel*s show a wide variation in composition. The abundant euhedral to subhedral opaque spinels are magnesium-rich members of the ulvöspinel-magnetite solid solution series (Nos. 2-6, Table VII). There are irregular dark red, translucent cores (5-10 μ) composed of Cr ceylonite (No. 1, Table VII). In specimen PHN 3542, which

lacks cpx, the spinels are richer in Ti and Mg (magnesian-ulvöspinel-ulvöspinel-magnetite) than those in the alnöites but are similar to those in the alnöite breccia (Dawson *et al.*, 1978) and tuff PHN 3595C (Nos. 11, 12, Table VII). Also in the latter specimen are slightly larger (50-100 μm) euhedral mantled spinels with cores of magnesian aluminous chromite rimmed by ceylonite (Nos. 9 and 10 respectively, Table VII).

Within the alnöites there is an evolutionary trend of spinel composition from Cr-ceylonite cores to ulvöspinel-magnetite rims and then by decreasing Ti and increasing Fe/(Fe+Mg) within the ulvöspinel-magnetite range. This trend is found in lamprophyric and alnöitic diatremes at Fen, Norway and Île Bizard, Quebec (Mitchell, 1979). At Malaita the spinels in the breccia have higher Ti and lower Fe/(Fe+Mg) than those in the aphanitic types and, therefore, represent an earlier fraction of the magma.

TABLE VII. Representative analyses of spinels from the Malaita alnöite suite

PHN	3566		3544		3565		3542		3595C (tuff)			
	1	2	3	4	5	6	7	8	9	10	11	12
TiO ₂	0.6	11.0	11.4	11.4	11.0	11.5	14.5	14.9	2.1	3.5	15.9	16.9
Al ₂ O ₃	36.3	0.8	0.8	0.9	0.8	0.7	3.3	2.8	15.5	43.2	5.5	5.6
Cr ₂ O ₃	26.5	1.3	1.1	0.7	1.3	0.6	2.0	0.7	36.6	0.6	0.5	0.3
FeO*	19.9	74.5	75.2	75.6	76.1	76.2	68.1	68.1	34.1	32.4	66.4	65.1
MnO	0.3	0.9	1.3	1.3	1.0	1.1	0.9	1.0	0.4	0.6	0.6	0.6
MgO	16.7	5.2	5.2	4.8	5.2	4.8	8.1	7.6	9.5	17.7	7.7	8.2
Total	100.3	93.7	95.0	94.7	95.4	94.9	96.9	95.1	98.2	98.6	96.0	96.7
Recalculated analyses†												
Fe ₂ O ₃	8.0	47.3	47.6	47.5	48.5	47.7	40.1	39.7	14.8	20.4	35.9	34.1
FeO	12.9	31.9	32.4	32.9	32.5	33.3	32.0	32.4	20.8	14.1	34.1	34.5
Total	101.3	98.4	99.8	99.5	100.3	99.7	100.9	99.1	99.7	100.1	100.2	100.2
Mol. % end member spinel molecules												
MgAl ₂ O ₄	57.7	1.1	1.2	1.3	1.2	1.1	4.7	4.1	23.5	62.0	7.2	8.0
Mg ₂ TiO ₄	1.9	13.8	13.4	12.4	13.4	12.4	18.1	17.7	6.9	1.7	15.5	16.1
MgCr ₂ O ₄	7.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.0	0.0	0.0	0.0
MnCr ₂ O ₄	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0
FeCr ₂ O ₄	20.7	1.0	1.1	0.6	1.3	0.6	1.9	0.7	34.9	0.6	0.4	0.3
Mn ₂ TiO ₄	0.0	1.5	2.1	2.1	1.5	1.9	1.4	1.6	0.0	0.9	0.9	0.9
Fe ₂ TiO ₄	0.0	15.6	16.1	17.3	15.5	17.8	19.7	21.6	0.0	7.0	27.0	28.6
Fe ₃ O ₄	12.2	66.7	66.1	66.3	67.1	66.1	54.3	54.5	24.6	28.0	49.0	46.2

* Total Fe expressed as FeO.

† Fe₂O₃ and FeO calculated by Carmichael's (1967) method.

Petrological comparison with kimberlites

The mantle xenolith suite of the Malaita alnöites can be matched with those of kimberlites with the exception of a suite of augite megacrysts (Table 3, and Nixon and Boyd, 1979). The host rocks, however, show important divergences which are only partially apparent from a study of their chemical compositions (Table I). These are:

1. Melilite has not been positively identified in kimberlite.
2. Alnöitic micas can usually be distinguished from those in the kimberlite groundmass as they tend to be higher in Ti and $Fe/(Fe + Mg)$.
3. Alnöitic olivines are comparatively enriched in Ca.
4. Compositions of the spinels differ. Kimberlitic spinels tend to be less aluminous and more magnesian for a given Ti content. Kimberlite spinels show an evolutionary trend of increasing Ti at constant $Fe/(Fe + Mg)$ ratios whereas the alnöite ulvöspinel-magnetite spinels show decreasing Ti with increasing $Fe/(Fe + Mg)$.

Rare earth elements and petrogenesis

The rare earth elements were determined by instrumental neutron activation analysis (Table VIII). From a consideration of counting statistics and BCR-1 results, precision and accuracy, at the 2σ level, are better than $\pm 5\%$ for all elements except Nd and Ho, for which $\pm 10\%$ is a more realistic figure.

Superficially, the alnöites resemble kimberlites in that they show linear, strongly enriched light rare earth patterns with no Eu anomaly (fig. 6). However, the La/Yb ratios (i.e. the extent to which the light rare earths are fractionated from the heavier

elements) are significantly lower than those for kimberlites with comparable Sm abundances (used instead of rare earth elements) see fig. 7. The alnöites bear a greater similarity to the leucitite and phonolitic tephrite series of volcanic rocks from the W. Rift in Uganda (Mitchell and Bell, 1976). The occurrence of Malaita alnöite with ankaratrite and an unusual melanite-ouachitite (Bradshaw, 1968) supports the idea of a genetic relationship with such alkaline volcanic rocks and carbonatites, as noted by Allen and Deans (1965). Fig. 7 shows that despite a 25% increase in Sm from the least rare earth-enriched sample (PHN 3553) to the most enriched (PHN 3565), there is no systematic variation in the La/Yb ratio, the latter lying between the most extreme values of 42 and 49. Fractionation of coarse phenocrystal mica (La/Yb = 27) has played an insignificant role in the development of the rare earth abundance patterns, since separation would have resulted in an increase of La/Yb with Sm.

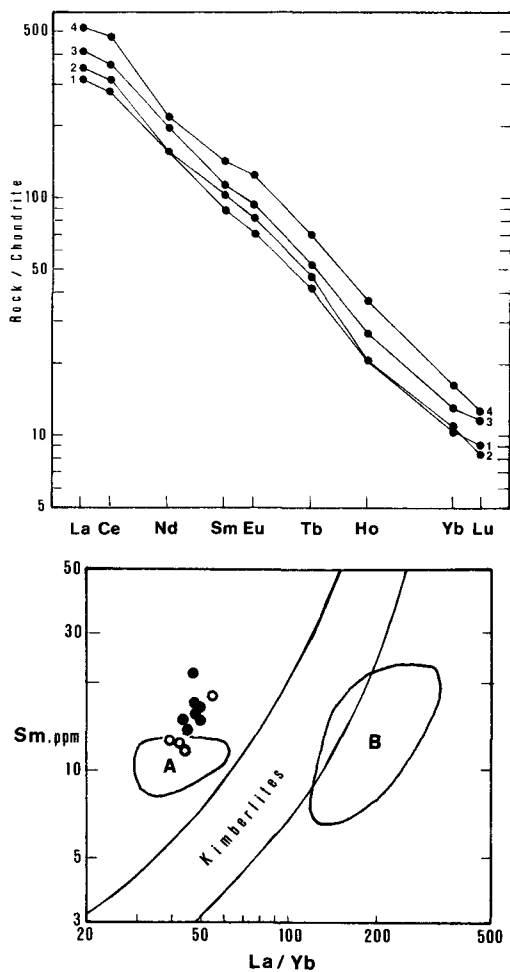
Perovskite is the likely main host for rare earth elements and since this mineral is low in MgO (< 0.5%) fractionation would result in an increase in rock MgO values as the rare earths were reduced. The converse would hold with separation of magnesian phases low in rare earths (olivine, mica, melilite, etc.). However, there is a strong positive correlation of ΣREE with MgO as well as with Al_2O_3 , total Fe and trace elements such as Zr and Nb, all of which show a similar 15–25% increase from samples 3553 to 3565. In contrast, a less well-defined but negative correlation is seen between La and CaO, the latter tending towards higher concentrations in those samples with high CO_2 in Table I.

This can be interpreted as a mixing of two chemically distinct components, the first typically magmatic in origin (richer in Al_2O_3 , MgO, rare

TABLE VIII. Rare earth element analyses

PHN	Alnöite intrusives		Tuffs		Breccias		Autolith	Mica
	3544	3565	3545	3553	3541	3543	3552	3553
La	82.6	101	85.4	76.1	91.8	83.4	125	1.78
Ce	195	229	199	174	201	184	304	1.87
Nd	65.4	92.9	71.9	73.8	82.6	80.5	102	—
Sm	14.91	17.06	15.58	13.74	16.31	14.84	21.74	0.172
Eu	4.65	5.39	4.73	4.16	4.88	4.39	7.05	0.059
Tb	1.84	1.96	1.74	1.57	1.82	1.69	2.62	—
Ho	—	1.52	1.16	1.15	1.15	—	1.37	—
Yb	1.93	2.15	1.79	1.72	1.86	1.68	2.69	0.065
Lu	—	0.30	0.21	0.23	0.28	0.28	0.32	—
La/Yb	42.8	47.0	47.7	44.2	49.4	49.6	46.5	27.4

earths, etc.), the second rich in calcite and apparently deficient in rare earth-rich phases such as perovskite and pyrochlore. The sole effect of the second fraction has been to dilute the components of the first by adding CaCO_3 , but allowing such ratios as La/MgO and La/Yb to remain virtually unchanged. The total effect of the mixing pheno-



FIGS. 6 and 7. FIG. 6 (top). Chondrite normalized abundance diagram for four representative alnöite samples. 1. PHN 3553 (tuff). 2. PHN 3545 (tuff). 3. PHN 3565 (alnöite intrusive). 4. PHN 3552 (autolith). FIG. 7 (bottom). Sm vs La/Yb diagram showing the relative positions of the alnöites (●) compared with the fields of leucitites and phonolitic tephrites (A) and mafurites, ugandites and katungites (B) from the W. Rift, Uganda (data from Mitchell and Bell, 1976). Also shown is the band defined by kimberlites (data from Fesq *et al.*, 1975, and Mitchell and Brunfelt, 1975). The four extra points (○) refer to analyses of olivine melilite nephelinites from S.E. Australia (Frey *et al.*, 1978).

menon can be assessed by considering the autolith analysis. Ferguson *et al.* (1973) have suggested that autoliths in kimberlites are representative of a more primary magmatic stage in their evolution. If this is the case with the alnöites then the primary magma has been diluted by as much as 40% in the case of PHN 3553. Furthermore, if the carbonate fraction can be considered to be primary also (i.e. derived with the magma from the mantle) this would imply a physical separation of the two fractions during eruption, possibly by liquid immiscibility, as has been suggested for specimen PHN 3595 on page 589 or by separation of a gaseous phase.

From a consideration of pressures and temperatures of equilibration of lherzolite inclusions, the alnöites have been derived from depths greater than 120 km (Nixon and Boyd, 1979), probably by mantle partial melting. Comparison with olivine melilite nephelinites from S.E. Australia, considered by Frey *et al.* (1978) to be primary, reveals that the alnöites have higher $\text{Mg}/(\text{Mg} + \text{Fe})$ values with Ni abundances of up to 675 ppm as compared with 460 ppm. Such values are quite compatible for co-existence with the mantle. Additionally, Sun and Hanson (1975) suggested that primary alkali basalts usually possess a $\text{P}_2\text{O}_5/\text{Ce}$ ratio of 75 ± 15 . The alnöite values lie between 61 and 69, within the range defined. Collectively, therefore, these features indicate that the alnöites are indeed primary melts, and may be used to extend the range of compositions studied by Frey *et al.* (1978) to a slightly greater degree of silica undersaturation. Employing the criteria of Frey *et al.* (1978), the P_2O_5 abundance of the alnöites indicates that they were formed by 4–4.5% partial fusion (assuming a pyrolytic P_2O_5 abundance in the upper mantle). Even using the extrapolated P_2O_5 abundance of the autolith (1.6%) the required degree of partial fusion is only reduced to 3.7%. These figures are similar to those of the less undersaturated basalts from Frey *et al.* (1978) as are the rare earth abundances (see fig. 7). Consequently, it seems possible that there is an additional factor responsible for silica undersaturated magmas, viz., the higher $\text{CO}_2/\text{H}_2\text{O}$ ratios of the source rocks as proposed by Frey *et al.* (1978) from a consideration of experimental data. A further effect of high P_{CO_2} , they argued, would be to increase the $\text{CaO}/\text{Na}_2\text{O}$ ratio as this becomes less dependent on the jadeite activity in the source material pyroxene. Comparison of the alnöites with the nephelinites and melilitites of Frey *et al.* (1978) reveals that the alnöites do have higher $\text{CaO}/\text{Na}_2\text{O}$ ratios and generally higher CO_2 contents.

Taken together, the rare earth data, the CO_2 and P_2O_5 abundances, and the $\text{CaO}/\text{Na}_2\text{O}$ ratio indicate that the alnöites have been derived by ~4% partial fusion of a pyrolytic mantle with a rare earth

abundance pattern comparable to that proposed by Frey *et al.* (1978), under a high volatile pressure with a high P_{CO_2} . The evidence from the xenoliths further constrains the depth of origin to 120 km +. On eruption the CO_2 was rapidly exsolved resulting in a gas fluidized extrusion, and an abundance of brecciated material, similar to that proposed for kimberlites. At Malaita, largely degassed magma, represented by the aphanitic rocks, illustrate a quieter mode of eruption. The more evolved spinels suggest that these rocks were formed later in the volcanic cycle.

Acknowledgements. We are indebted to Chief Selwyn Wandili and his people for making it possible to collect samples in the Baburu'u area; and Mr William Maelau and Mr Wally Bush of Auki, the capital of Malaita. The assistance of Drs Brian Hackman, Frank Coulson, Wyn Hughes, and Peter Philips and Mr Sam Iko of the Geological Survey is deeply appreciated. We have benefited from correspondence with Dr Tom Deans. We thank Messrs Alan Gray and Douglas Richardson for analysing the rocks in Table I.

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[Manuscript received 28 June 1979;
revised 17 September 1979]

NOTE ADDED IN PROOF

Analysis of the carbonate fractions from samples PHN 3543 and 3593c has confirmed the prediction that the variation in rare-earth abundances is the result of dilution by a carbonate component, poor in the rare earths. The analyses were performed by partly dissolving separated carbonate minerals in dilute acetic acid and analysing the solutions with the usual techniques of gamma-ray spectrometry.

Results:

	La	Ce	Sm	Eu	Yb	Lu
PHN 3543	22.1	12.0	2.39	0.755	1.34	0.15
PHN 3593c	18.5	32.3	2.22	0.754	0.46	0.11

(All figures in ppm.)