Ultrabasic eruptives with alnöitic–kimberlitic affinities from Malaita, Solomon Islands

With Plates I and II

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Summary. A detrital assemblage of magnesian ilmenite, pyrope, chrome-diopside, rutile, and zircon has been traced to outcropping ultrabasic alkaline rocks, hitherto unknown in the Melanesian region. Analyses and descriptions of these 'kimberlite indicator minerals' are given. The host rocks comprise alnöite, an alnöite breccia with calcite matrix, and a magnesian ankaratrite, which are described, with chemical analyses. Emphasis is laid on the abundance of ultrabasic inclusions and xenocrysts and the replacements and transformations they have undergone. Malaita Island promises to contribute significantly to the understanding of the relations between alnöite, melilite basalts, and kimberlites.

GEOLOGICALLY Malaita is perhaps the least known of the larger islands of the Solomons. The part of the island which concerns us, the northern half, was first investigated in 1951 by F. K. Rickwood, whose map and description (University of Sydney (1957), pp. 300–305) show it to consist of volcanic rocks, termed the Alite Volcanics, predominantly basaltic, including dolerites, pillow lavas, and basaltic tuffs cemented with zeolites and carbonates, overlain by mudstones and limestones, which are probably of Upper Tertiary Age. Boulders in stream beds suggested that ultrabasic intrusive rocks might occur in the interior, perhaps comparable with the harzburgites and serpentinites which are widespread in other parts of the Solomons (see Thompson, 1960), but this has yet to be confirmed. The next geologist to visit the island, in 1956, was J. C. Grover, Chief Geologist of the British Solomon Islands Protectorate, who found several occurrences of coarse ilmenite gravel, both alluvial and eluvial, in predominantly limestone areas. Red and white minerals accompanying the shining black ilmenite prompted thoughts of gem gravels, but they proved to be pyrope garnet, rutile, and zircon, and of little value. The source and origin of these minerals remained a puzzle, but attracted little attention for some time until Dr. D. R. Grantham suggested that they might be indicative of kimberlites. Detailed examination of the samples strengthened this suggestion, as the ilmenite was found to be magnesian, and chrome-diopside, enstatite, and olivine were added to the list of associated minerals. Accordingly Dr. E. Gerryts, a diamond company geologist, and Dr. R. B. M. Thompson of the Geological Survey Department, British Solomon Islands Protectorate, paid a brief visit to Malaita in 1962 to examine the gravels and try to identify the source rocks. Hopes of diamond finds were not strengthened by the visit, but at two points the gravels were traced back to ultrabasic rocks of a type quite new to the Pacific region, and these form the subject of this paper.

It must be emphasized that this is a preliminary account, as only four specimens of the ultrabasics were brought back for examination, some of them quite small, and their field relations remain rather obscure. Naming of the rocks has also proved difficult, as they are rather unusual types intermediate between melilite basalts, alnöites, and kimberlites, with varying proportions of xenocrysts and inclusions of deep-seated origin. A more extensive and detailed examination of this difficult jungle-covered area is to be made in 1964 by the Geological Survey Department, and this should provide comprehensive collections and more information leading to better naming and a fuller understanding of these rocks. Apart from brief descriptions by Glaessner (1915) of trachydolerites, including nosean-bearing and limburgitic types, from the islands of Feni (Anir) and possibly Lihir, north-east of New Ireland and 600 or 700 miles from Malaita, this would appear to be the first record of alkaline rocks in the Melanesian region.

Field relations

The sketch-map, fig. 1, indicates the location and distribution of both the ilmenite gravels and the ultrabasic rocks discovered to date. The ilmenite gravels are fairly widespread, and although mainly in stream beds, small isolated patches have also been found in pockets on the limestone, presumably shed from source rocks very close by. In a small tributary of the Upper Auluta River (locality 1) a trail of ilmenite led to the outcrop of the ankaratrite, which appeared to be fairly extensive. Two miles to the north-east, in the Hohomela River (locality 2), ilmenite and plentiful pyrope led to an outcrop of alnöite breccia, with alnöite occurring immediately adjacent, and although exposures were poor, alnöite was seen along the stream bed for about 300 yd to the east of the breccia. It was not evident whether the ultrabasics intruded the limestones or were overlain by them, but the presence of limestone

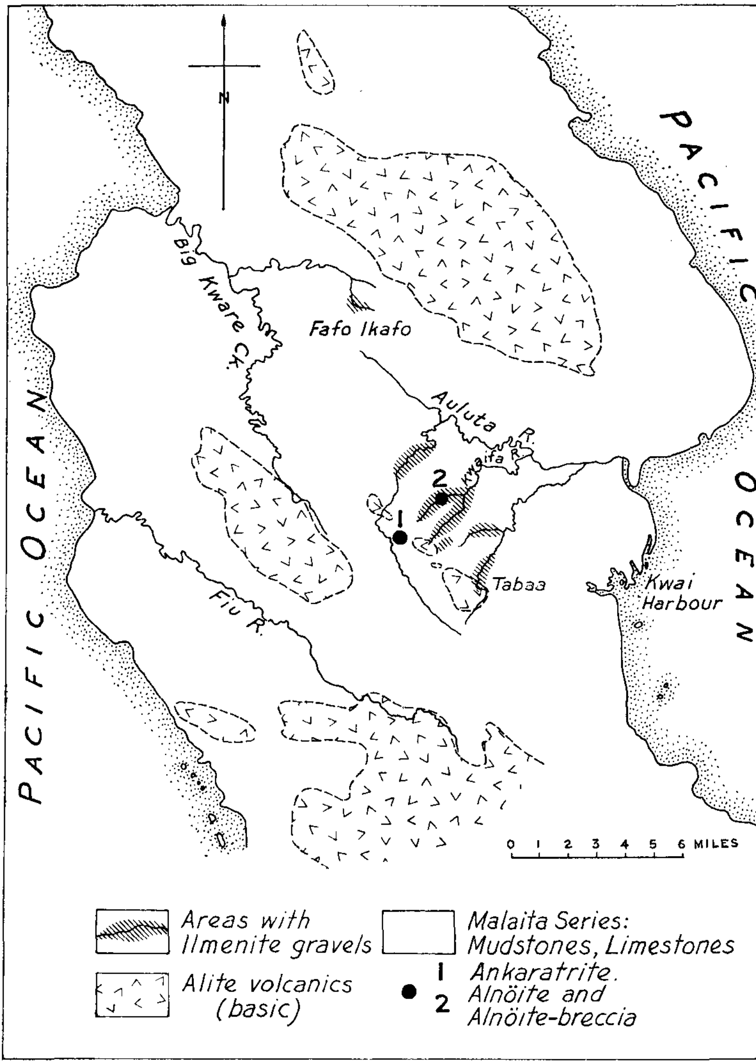

FIG. 1. Sketch-map of part of Malaita.

inclusions in the alnöite breccia suggests an intrusive relationship. A small sill intrusive into the limestone a mile to the east of the alnöite proved to be a sub-ophitic olivine basalt, presumably unrelated to the ultrabasics.

The mineralogy of the ilmenite gravels

The gravels provide better information on several of the significant accessories of the ultrabasic rocks than can be gleaned from the few available specimens of the latter, and this will be summarized briefly before the rocks are considered. The coarser samples are predominantly from 2 mm to 1·5 cm in grain size, and finer ones from 1 to 2 mm.

Ilmenite predominates, and occurs as coarse grains and pebbles up to 1 cm or even 1·5 cm in diameter. The grains are anhedral and usually angular, but worn smooth, and the surfaces are usually lustrous, although sometimes dull and roughened. Small spherical or tubular hollows are not uncommon. It is a magnesian ilmenite, as indicated by the specific gravity range 4·58–4·63, cell parameters *a* 5·07 Å, *c* 13·97 Å, and by the following chemical analyses:

Locality	TiO_2	Fe_2O_3	FeO	MgO	MnO	V_2O_5	Cr_2O_3	Total
Tabaa	48·38	15·68	32·11	4·03	0·01	0·18	0·016	100·41
Fafo Ikafo	50·42	13·44	29·95	5·88	0·18	0·20	0·001	100·07

Analysts: L. C. Chadwick and P. J. Moore
The Tabaa sample contains 0·11 % Nb_2O_5.

In polished section the ilmenite is usually polycrystalline and often rather coarse-grained and free from intergrowths, but sometimes shows strain-slip twinning.

Magnetite is a very minor constituent in some samples, but chromite appears to be absent.

Pyrope is rather variable in abundance, but is conspicuous as orange-red to wine-red grains, mainly 0·5 to 5 mm in diameter, with s.g. 3·70–3·74, *n* 1·735–1·745, and *a* 11·535–11·54 Å. Analysis of a sample from Tabaa is shown below, together with that of a pyrope from eclogite ejected with nepheline basalt from a volcanic cone in Oahu, Hawaii (Yoder and Tilley (1962), p. 482), and one of a pyrope nodule from a Basutoland kimberlite (Nixon *et al.* (1963), p. 1104).

Locality	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	MnO	TiO_2	Cr_2O_3	Total
Malaita	40·82	23·56	0·70	10·70	19·04	4·70	0·30	—	0·03	99·85
Hawaii	41·19	23·69	1·66	10·15	17·81	5·28	0·41	0·28	—	100·47
Basutoland	42·04	21·84	1·97	7·47	20·51	4·37	0·24	0·92	0·43	99·96

Rutile, a relatively minor constituent, occurs as rectangular grains up to 3 mm across, black in colour, but deep orange-brown when crushed fine. It contains a significant amount of niobium, an analysis showing 0·60 % Nb_2O_5, and 0·31 % FeO.

Zircon is colourless, usually water clear, mostly anhedral, but when crystal form is preserved it is the bipyramidal type, with prism short or absent, characteristic of alkaline rocks.

Pyroxenes are of several types, including pale green *enstatite*, pale brown *bronzite*, a dark green *diopsidic* variety, and emerald green *chrome-diopside* (check analysis of this variety from the Kwaifa River showed 0·75 % Cr_2O_3).

The alnöite

The alnöite is a compact black rock with dark phenocrysts of olivine and clinopyroxene together with occasional 'olivine nodules' of composite mineralogy up to 1 cm in diameter. As well as 'nodules' in varying stages of disruption and other altered xenocrystal material, thin sections of the host-rock when viewed under low power present a fragmented structure due to the accretion or welding together of previously consolidated alnöite fragments. This fragmented appearance is suggestive of highly explosive conditions at the time of emplacement, and the occurrence nearby of alnöite breccia cemented with calcite should be borne in mind, although there is no sign of carbonate in the alnöite itself. The rock is moderately magnetic, small fragments being readily attracted to a strong hand magnet.

In thin section, olivine, melilite, and clinopyroxene occur in a partly glassy groundmass containing abundant phlogopite together with much magnetite and perovskite. A modal analysis obtained by point-counts on thin sections of the analysed material is given in table I.

Olivine, which ranges from 0·07 to 1 mm in diameter and is fresh apart from a peripheral zone of speckled blue serpentine, tends to be enclosed in granular phlogopite and may present irregular outlines due to corrosion by the groundmass. Undulose strain extinction is general, and occasional grains show fine twin-lamellae. It is magnesia-rich, with β around 1·680 and a large negative $2V$ with dispersion ($r < v$), indicating a composition around Fo_{85}.

The melilite, uniaxial negative, with ω averaging 1·642, is plentiful in zoned tabular laths which range from 0·03–0·3 mm in length and tend to have a parallel orientation. The central areas of the laths have low anomalous birefringence and grade into narrow margins of more normal and higher birefringence. The melilite is often bordered by small bluish granules, isotropic and of low refractive index which suggest a feldspathoid, and less commonly aggregates of melilite are associated with the small bluish globules or granules.

Fawn-coloured augite occurs in phenocrysts ranging from 0·5–3 mm in length. Although idiomorphic in outline, pronounced corrosion effects are general in the cores of the phenocrysts. The larger phenocrysts are often zoned with a colourless core of diopsidic pyroxene surrounded by a clearer rim of augite as in plate I, fig. 1. A spongy 'honeycomb' area has resulted from this corrosion, within which pale brown glass, phlogopite, and magnetite have been precipitated. Polysynthetic twinning is also displayed by the augite. In addition to the internal corrosion effects noted above, an occasional area of augite has been corroded by melilite and now presents scalloped margins to the surrounding tabular melilite which is associated with magnetite. Groundmass augite is fairly abundant and occurs as small acicular prisms which may make up tightly felted aggregates in the glassy base.

The pale reddish-brown mica, which occurs in granular aggregates of stumpy laths ranging from 0·01–0·03 mm in length, is pseudo-uniaxial negative with γ close to 1·600. These optical properties overlap with those of biotite; however, the pale body colour and weak absorption are considered to be consistent with phlogopite.

Perovskite is idiomorphic in golden-brown cubic crystals averaging around 0·003 mm in diameter. Magnetite is more frequent than perovskite and occurs in octahedra ranging from 0·005 to 0·03 mm in diameter. Apatite occurs in slender prisms which resemble the groundmass augite in habit.

The interstitial glass is somewhat variable in appearance but is generally turbid, with refractive index around 1·54, and is charged with augite needles and magnetite. In some areas the glass has a purple colouration and is speckled with small dark inclusions, elsewhere a cryptocrystalline low birefringence is discernible, while small inclusions of a pale blue isotropic mineral of low refraction suggest a feldspathoid.

An 'olivine nodule', 1 cm in diameter, containing an olivine–clinopyroxene–spinel assemblage shows some interesting reaction effects with the enclosing alnöite. This fairly coarse-grained nodule, has areas of olivine attaining 4 mm in diameter with penetrations of granular phlogopite along grain boundaries. Areas of colourless clinopyroxene adjacent to the host rock show relict unaltered cores surrounded by spongy pyroxene in optical continuity. Anhedral yellowish-brown spinel, which is moulded around and encloses small grains of olivine, has acquired a rim of magnetite adjacent to the host rock. Elsewhere along the margins of the nodule reaction effects are more complex. On one edge a granular aggregate of olivine occurs accompanied by turbid glass containing inherited narrow exsolution (?) lamellae of pale green clinopyroxene, to which bladed prisms of colourless clinopyroxene, polysynthetically twinned, are also parallel and are similarly associated with glass and granular olivine. Adjacent to the host rock olivine has been converted either to a granular aggregate of olivine in phlogopite, or to narrow stringers of granular olivine in a pale brown glass.

Elsewhere in the rock, rounded nodular areas of granular reaction products are frequent. One rounded area, 1 mm in diameter consists of a granular aggregate of olivine enclosed ophitically in plates of phlogopite (an individual phlogopite lath attaining 0·4 mm in length), together with some glass, and is enclosed in polysynthetically twinned, optically continuous augite. Small inclusions of perovskite and magnetite are present in the augite which has itself been corroded by the groundmass. In another example an elongated aggregate, 2 mm in length, consists of granular olivine and melilite with some intergranular phlogopite, heavily peppered with small magnetites and surrounded by granular phlogopite.

Fragmented spinel xenocrysts, 1 mm in diameter and rimmed with dark magnetite occur sporadically in the alnöite, while a rounded inclusion, of similar size, consisting of brownish-black glass contains augite and is margined by granular olivine and augite.

A consideration of the foregoing observations and the corrosion phenomena shown by the olivine and clinopyroxene in this rock suggests that at least some of the olivine and augite phenocrysts have arisen from the disruption of olivine nodules and other cognate inclusions of presumed deep-seated origin. Such material, in disequilibrium with the host magma under the conditions prevailing during emplacement, has reacted to give the various resorbed aggregates that have been described. Wilshire and Binns (1961) have figured and discussed identical reaction effects in relation to ultrabasic xenoliths in alkali-basalts. They cite corrosion of clinopyroxene xenocrysts whereby a spongy structure is developed which is later enclosed in a rim of euhedral salite, the precipitation of magnetite rims around spinel xenocrysts, and the conversion of orthopyroxene by incongruent melting to a granular aggregate of olivine with glass which is later enclosed in euhedral salite. There can be little doubt that the granular aggregates of olivine occurring in the 'olivine-nodules' and elsewhere in the Malaita alnöite have been formed from original orthopyroxene.

The alnöite breccia

Two specimens of this unusual breccia, from the same outcrop, are similar carbonated agglomerates consisting of rock and mineral fragments from 1 to 3 cm in diameter set in a fine-grained matrix of pale greenish-white calcite. Apart from infrequent angular inclusions of a fine-grained yellow to white calcite rock, possibly derived from the limestone country rock, all the rock fragments are sub-rounded and consist of a porphyritic medium-grey rock identified as altered alnöite. Enclosed within the latter are conspicuous crystals of dark reddish-brown mica, red pyrope, and dark green orthopyroxene and clinopyroxene—the latter in one case being intergrown with coarse plates of magnesian ilmenite. A few unaltered fragments of these minerals also occur in the fine-grained calcite matrix (see plate II, fig. 3). It is noteworthy that pyrope was not seen in the first specimen to be examined, but was conspicuous in the second.

The mineralogy of this alnöite, dealing first with the crystal inclusions, is as follows:

The *mica* which is reddish-brown under the microscope and pseudo-uniaxial with γ near 1·64, has optical properties and an X-ray pattern corresponding to an intermediate member of the phlogopite-biotite group. The body colour and environment suggest that it is an *iron-rich phlogopite.*

The orthopyroxene is dark green but is iron-stained on weathered surfaces. It shows faint pleochroism with β around 1·685, properties consistent with the X-ray powder pattern and identifying the mineral as *bronzite.*

The clinopyroxene, dark grey-green to emerald green in the hand specimen, is colourless when crushed, with a moderate to large positive $2V$, distinct dispersion ($r > v$) and β around 1·700. These properties suggest a diopside or diopsidic augite similar to that from the Kwaifa River gravels which contained 0·75 % Cr_2O_3, i.e. a *chrome-diopside.* The mineral carries prominent reaction rims, 0·2 mm in width, which are cryptocrystalline and indeterminate.

An unusual intergrowth of magnesian ilmenite was observed in one inclusion of chrome-diopside (see plate II, fig. 4). Elongated euhedral plates up to 1·7 mm in length by 0·2 mm in width are arranged in parallel with an occasional hexagonal cross-section 0·8 mm in diameter. In polished section, all the ilmenite plates possess optical continuity, strongly anisotropic in blue-greys, and are entirely homogeneous up to ($\times$ 1000) magnification. The reaction rim around the pyroxene is clearly seen in the photograph and it is interesting to note that an ilmenite plate, which has been exposed by this corrosion, has acquired a magnetite skin in contact with the host rock. The chrome-diopside is cut by occasional veinlets of limonite, roughly parallel to the ilmenite plates. X-ray work on ilmenite extracted from the polished section gave cell parameters of $a = 5{\cdot}07$ Å and $c = 13{\cdot}97$ Å, similar to those of the analysed magnesian ilmenites from the gravels, demonstrating that the plates in the intergrowth also consist of magnesian ilmenite.

The pyrope is isotropic with a refractive index in the range 1·740–1·745 and a cell-size of 11·534 Å, identical with that from the gravels, of which an analysis is given above (p. 19).

Although in thin section alteration of the rock fragments is seen to be general, there can be little doubt of their identity with the fresh alnöite exposed nearby. Carbonated pseudomorphs after olivine range from 0·2–2 mm in diameter and have a yellowish-brown appearance in the hand specimen due to limonite-staining. Lath-shaped pseudomorphs after melilite are abundant and vary from 0·2–0·4 mm in length. Original zoning has been preserved in the laths which show indications of peg-structure. Some of the laths show clear isotropic cores with a refraction lower than the altered margins. The turbid alteration product is pale brown and cryptocrystalline in most of the pseudomorphs and has no immediate reaction with cold dilute acid. The accessory minerals in the alnöite have survived without alteration. Cubes of golden-brown perovskite and octahedra of black magnetite occur abundantly with an average diameter of 0·02 mm. An occasional shattered xenocryst of yellow-brown spinel, 0·04 mm in diameter, was also observed. Apatite occurs sporadically in prismatic crystals up to 0·1 mm in length and presents an occasional hexagonal cross-section. In addition to the large iron-rich phlogopite crystals already described, occasional flakes of reddish-brown mica occur in the rock.

The matrix of the breccia consists of fine-grained calcite with occasional euhedra of iron-rich phlogopite. A noticeable feature of the brecciation is the manner in which the rock fragments, and also large pyropes, are fractured and invaded by micro-veinlets of the calcite matrix with only slight displacement of the smaller fragments thus created, a feature often regarded as characteristic of gas-drilled (fluidized) intrusions.

The ankaratrite

The ankaratrite is a porphyritic greyish-black rock with unusually large clinopyroxene phenocrysts, dark-greenish in colour with a finely pitted surface, smaller dark olivine phenocrysts and irregular white segregations, several millimetres in length, consisting of zeolites. The rock develops a rough surface on weathering due to differential hardness between the phenocrysts and groundmass. It is fairly magnetic and thin slices may be picked up by a strong hand-magnet.

Under the microscope, the rock consists essentially of abundant clinopyroxene—dominantly augitic, and partially serpentinized olivine together with resorbed areas after probable olivine nodules and other xenocrystal material, in a matrix of phlogopite, acicular augite, accessory magnetite and perovskite, and turbid interstitial glass enclosing segregations of zeolite. Fluxional orientation is absent and the minerals tend to be idiomorphic. The modal composition is shown in table I.

In thin section, olivine is frequent and ranges from 0·3–3 mm in diameter. While the smaller grains tend to be completely serpentinized, the larger grains show a marginal development of serpentine which has a finely speckled bluish appearance and may be isotropic or weakly birefringent in blue-greys. The unaltered olivine has $2V$ close to 90° and β around 1·680, indicative of a composition near Fo_{85}. Undulose extinction is frequent in the olivine phenocrysts—as in the alnöite. The olivine, which has in some cases been corroded by the groundmass, is generally enclosed in phlogopite.

Clinopyroxene is abundant in this rock and ranges from large phenocrysts, 2 cm in diameter, down to microphenocrysts, around 1 mm in grain size, and to acicular prismatic crystals 0·03 mm in length. It consists mainly of pale fawn-coloured augite with occasional polysynthetic twinning and a moderate positive $2V$. Zoning towards a colourless core is general in the augite microphenocrysts and is most noticeable in the occasional large phenocrysts, in which central areas of pale diopsidic pyroxene are surrounded by a rim of fawn-coloured augite, 0·03 mm in width, with higher refractive indices (β around 1·715), lower birefringence, and a more oblique extinction. However, the large diopsidic cores are most notable for their honeycomb structure which gives rise to a pitted or spongy appearance on sliced surfaces. In thin section, the diopsidic cores are seen to be riddled with irregular embayments which have been infilled with phlogopite and altered glassy material demonstrably introduced from the surrounding magma. The augitic rims which have magnetite inclusions show few corrosion effects and would appear to have been more in equilibrium with the magma at the time of consolidation. These altered pyroxene phenocrysts are comparable with those described and figured in the alnöite.

Reddish-brown mica is plentiful and occurs in euhedral plates extending over several millimetres and enclosing olivine, augite, magnetite, and perovskite. While the optical properties, small $2V$ around 10° and β around 1·625, are consistent with an intermediate member of the phlogopite–biotite series, the body colour and absorption suggest an iron-rich phlogopite, and for brevity it is here referred to as phlogopite.

Magnetite is abundant in small octahedra, averaging 0·02–0·03 mm while yellow-brown perovskite is also very frequent in isotropic cubes of similar grain size. The turbid pale-brown glassy base, which is cryptocrystalline with a low birefringence and an average refractive index around 1·53, is associated with white patches of fibrous radiating zeolite. On the specimen, the glassy base occurs in soft greenish areas, and an X-ray photograph of a sample removed with a sharp needle gave a mixed pattern interpreted as that of a zeolite, identified as gonnardite (natrolite group), intermixed with a sheet silicate possessing a 14·5 Å basal spacing indicative of either a chlorite or a montmorillonoid clay. The latter would appear to be the more probable. White zeolite segregations line cavities in the rock, and delicate acicular crystals may be developed in an occasional cavity. X-ray photographs show that a mixture of zeolites is present, thomsonite being the most important, while gonnardite appears to be another component. The original glassy base of this rock would thus appear to have been converted to a mixture of zeolites of the natrolite group accompanied by probable montmorillonoid material. Apart from this alteration and development of zeolite, the rock is fresh but for partial serpentinization of the olivine that was almost certainly magmatic.

As in the alnöite, rounded resorbed patches are present and one example of a probable olivine-nodule was noted. The latter occupies a dark rounded area of the section, 6 mm in diameter, and presents a fairly sharp contact to the host ankaratrite. While individual grains of olivine around the periphery attain 3 mm in diameter, the greater part of the nodule is made up of phlogopite heavily peppered with magnetite and enclosing irregular lobate patches of reddish-brown spinel almost 0·2 mm in length and showing thick rims of magnetite. Prisms of augite and patches of serpentine and interstitial glass also occur within this area of phlogopite and magnetite.

As well as sporadic xenocrysts of magnetite-rimmed spinel appearing elsewhere in the ankaratrite, rounded resorbed patches are fairly frequent and consist generally of granular olivine enclosed by augite. A typical example is figured in plate I, fig. 2, and shows part of a resorbed area 2 mm in diameter. In other resorbed areas, a more distinct aggregate of granular olivine and granuloprismatic clinopyroxene with minor interstitial phlogopite is observed. While the amount of xenocrystal material occurring in this rock is conjectural, the corroded spongy diopsidic cores to the large augite phenocrysts appear to have been in disequilibrium with the magma at the time of consolidation, and some of the corroded olivine phenocrysts and the spinel xenocrysts could have originated from the disruption of olivine-nodules. Analogy with the work of Wilshire and Binns (1961), previously noted, leaves no doubt as to the xenocrystal character of this rock. Original orthopyroxene of stumpy outline, exceeding 0·5 mm. in length, is now represented by areas of granular olivine, 0·02–0·05 mm in diameter, containing abundant globules of bluish glass, together with some platy clinopyroxene, the whole assemblage being enclosed in phlogopite. A composite coarse-grained inclusion was observed to consist of an area of corroded pale clinopyroxene rimmed with augite, in contact with a granular aggregate of olivine after orthopyroxene enclosed in twinned augite, the whole assemblage suggesting a websterite inclusion or a disrupted 'olivine-nodule'. Indeed, as the zoned clinopyroxene is identical with the zoned phenocrysts which characterize this rock, it may be suggested that all the clinopyroxene phenocrysts are xenocrystal.

Chemistry and nomenclature

Chemical analyses of the Malaita specimens are shown in table I, together with the corresponding modes and normative calculations. The small size of the specimens and the heterogeneous assortment of large phenocrysts and inclusions (e.g. olivine nodules) made representative sampling very difficult. The portion of the alnöite used for analysis, weighing 27 g, was selected to exclude unusually large phenocrysts or inclusions which might have had a disproportionate influence on the composition, and in the case of the ankaratrite a clinopyroxene phenocryst 2 cm in diameter was excluded, the analysed material weighing only 18 g. Although this procedure cannot be regarded as entirely satisfactory, it appeared likely to give the best approximation to the average composition of the rocks which circumstances allowed. From the alnöite breccia an inclusion-free alnöite fragment, weighing 0·75 g, from which the surrounding calcite of the matrix had been removed mechanically, was used for a partial analysis. The modes are based on point-counts of sections cut immediately adjacent to the analysed material, counting 2350 points for the alnöite and 2900 for the ankaratrite, and must also be regarded as only approximations owing to the

TABLE I. Analyses of ultrabasic eruptives from Malaita

	Chemical analyses		
	A	B	C
Reference No.	3639D	3297	3411
	Alnöite	Ankaratrite	Altered alnöite
SiO_2	36·73	37·78	31·39
Al_2O_3	7·14	8·42	8·32
Fe_2O_3	5·85	5·22	11·14 (Fe₂O₃ + FeO)
FeO	6·12	6·99	
MgO	19·11	17·70	11·10
CaO	12·27	12·36	18·43
Na_2O	2·66	0·81	1·00
K_2O	2·31	1·30	2·32
H_2O^+	2·46	4·10	12·73* (H_2O^+, H_2O^-, CO_2)
H_2O^-	0·33	1·08	
CO_2	0·17	0·18	
TiO_2	2·89	2·88	2·69
Nb_2O_5	0·01	0·008	
P_2O_5	1·11	0·86	0·60
SO_3	tr.	0·39	
Cl	0·26	0·02	
F	0·21	0·24	
Cr_2O_3	0·11	0·10	
MnO	0·13	0·24	0·11
BaO	0·11	0·12	
SrO	0·12	0·04	
Less O ≡ Cl, F	0·15	0·105	
Total	99·95	100·73	99·83
Specific gravity	3·06	2·92	

* Loss on ignition

Modes—Volume %	A	B
	3639D	3297
	Alnöite	Ankaratrite
Melilite	13	—
Phlogopite	30	14
Clinopyroxene	10	30
Olivine	13	7
Serpentine	2	10
Magnetite	11	8
Perovskite	7	6
Apatite	1	1
Glass	13	20†
Zeolite	—	4

† Includes ? feldspathoids

Norms—Weight %	A	B
Anorthite	0·83	16·68
Leucite	10·46	6·10
Nepheline	12·21	2·27
Diopside $CaSiO_3$	9·78	15·54
Diopside $MgSiO_3$	8·20	12·50
Diopside $FeSiO_3$	0·53	1·19
Olivine Mg_2SiO_4	27·72	22·26
Olivine Fe_2SiO_4	1·02	2·24
Monticellite	8·43	—
Magnetite	8·58	7·66
Ilmenite	5·47	5·47
Apatite	2·69	2·02
Fluorite	0·16	0·31
NaCl	0·47	—
Na_2SO_4	—	0·71
Calcite	0·40	0·40
Water	2·79	5·18

A. Alnöite, Hohomela River. Analyst: G. M. Harral.
B. Ankaratrite, Upper Auluta River. Analysts: D. C. Hinge and P. J. Moore.
C. Altered alnöite from breccia, Hohomela River. Analysts: D. C. Hinge and P. J. Moore.

limitations indicated above, and the difficulty of identifying all the groundmass components with certainty.

A striking feature of the analyses is the close similarity in chemical composition of the alnöite and the ankaratrite, despite mineralogical differences, but before discussing the rock assemblage the reasons for proposing their present nomenclature will be outlined. Table II shows the Malaita analyses alongside those of selected comparable rocks. First one may note the close chemical similarity of the altered alnöite from the breccia with the alnöite from Alnö which von Eckermann (1948, p. 103) regards as the most typical. Whether the carbonate matrix of this breccia is to be regarded as carbonatite, thereby strengthening the comparison with Alnö, is a point the writers would rather defer until more field-work has been done, but a link with carbonatites seems highly probable. The analysis of the fresh alnöite (No. 1) is

TABLE II. Malaita analyses compared with other rock types

	1	2	3	4	5	6	7	8
SiO_2	36·73	31·39	27·30	36·64	40·32	37·78	39·01	36·33
TiO_2	2·89	2·69	3·68	2·50	2·66	2·88	3·21	1·89
Al_2O_3	7·14	8·32	8·95	7·96	9·46	8·42	7·93	5·09
Fe_2O_3	5·85	11·14	8·87	6·19	4·75	5·22	4·53	7·43
FeO	6·12		7·01	5·59	7·48	6·99	7·83	3·40
MnO	0·13	0·11	0·27	0·17	0·25			0·10
MgO	19·11	11·10	12·34	18·15	18·12	17·70	17·82	26·63
CaO	12·27	18·43	17·18	15·11	10·55	12·36	14·25	6·78
Na_2O	2·66	1·00	0·38	2·85	2·62	0·81	1·96	0·37
K_2O	2·31	2·32	2·99	1·44	1·10	1·30	1·54	2·43
H_2O^+	2·46	12·73	3·95	1·56	1·25	4·10	0·85	7·25
H_2O^-	0·33		1·32	0·03	0·57	1·08	0·19	
CO_2	0·17		2·17	0·53		0·18		1·64
P_2O_5	1·11	0·60	2·90	0·91	0·68	0·86	1·14	0·66
F	0·21		0·17		0·04	0·24		
Cl	0·26		0·07		0·05	0·02		
Total	99·95	99·83	99·94	99·71	100·09	100·73	100·26	—

1. Malaita alnöite (A of table I), abbreviated.
2. Malaita alnöite from breccia (C of table I).
3. Alnöite, Alnö, Sweden, with Cr_2O_3 0·07, BaO 0·25, SrO 0·002, S 0·33 %. Eckermann (1948), p. 103.
4. Olivine-melilite, Hochbohl, Würtemberg, with S 0·1, BaO 0·05, ZrO_2 0·03 % Tröger (1935), p. 172.
5. Nephelite basalt, Uvalde Co., Texas, with SO_3 0·03, S 0·01, NiO 0·06, BaO 0·06, SrO 0·03. Washington (1917), p. 720.
6. Malaita ankaratrite (B of table I), abbreviated.
7. Olivine-rich ankaratrite, Mahanoro, Madagascar. Lacroix (1923), p. 64.
8. Average of four 'micaceous kimberlites'. Nockolds (1954), p. 1023.

comparable with certain magnesia-rich melilite basalts or olivine-melilitites, such as that from Hochbohl (No. 4) and a nepheline basalt from Uvalde County, Texas (No. 5), which is associated with melilite basalt, but mineralogically the highly micaceous character of the Malaita rock appears to be more consistent with alnöite. General usage has tended to associate the term alnöite with dyke rocks and melilite basalt with plugs or flows, but this has little relevance at this stage in our knowledge of Malaita.

The Malaita rock here termed ankaratrite is difficult to match, but in several respects compares well with an olivine-rich ankaratrite from

Madagascar (No. 7), although differing in its greater water content and lower content of soda. Ankaratrite was proposed by Lacroix as a group name for melanocratic nepheline-basalts with essential biotite. Within the group he recognized several types, including ankaratrites with melilite and nepheline, with melilite but without nepheline, as well as olivine-rich and limburgitic varieties. The presence of melilite ankaratrites in Madagascar invites a comparison with the Malaita alnöite to which there can be no doubt that the Malaita ankaratrite is genetically related. Lacroix (1923, p. 63) provides a further point of resemblance when he observes that the olivine in the olivine-rich ankaratrite displays the characteristic undulose extinction of the olivine nodules that are rather ubiquitous in the basic lavas of Madagascar, although he did not observe any fragments of the other minerals which occur in the nodules.

None of the Malaita rocks have the high magnesia contents characteristic of the typical kimberlites of the diamond pipes, but the links between the alnöites, the melilite basalts and the kimberlites are too real to be ignored, especially in the present context of associated pyrope and magnesian ilmenite, the so-called 'kimberlite indicator minerals'. On the evidence of the analyses, however (cf. No. 8), the Malaita rocks cannot properly be styled kimberlites.

Discussion

Certain of the lesser constituents of the Malaita rocks merit brief comment. The proportions of alkalis differ considerably in the two rock types, the alnöite containing 4·97 % total alkalis and soda slightly in excess of potash, whereas the ankaratrite has only 2·11 % total alkalis, with potash predominant. Both rocks contain similar amounts of fluorine, but there is a reciprocal relationship between chlorine and total sulphur estimated as sulphate. The high figure of 0·26 % chlorine in the alnöite, seen in conjunction with the prominence of normative feldspathoids and the presence of blue isotropic granules of low refractive index in the groundmass, strongly suggests that sodalite is present. As no sulphides are visible in the ankaratrite it is tempting to refer the sulphur content to sulphate-feldspathoids, such as nosean or haüyne possibly in an altered condition in the groundmass. The heavy trace of niobium found in both rocks is in keeping with the alnöite–carbonatite association, although, as Dawson (1962) and others have shown, the kimberlites also share this peculiarity.

Reverting now to the general similarity of the two Malaita rocks, reference to the modal analyses confirms the similarity in respect of olivine/serpentine, magnetite, perovskite, and apatite, and reveals the essential contrasts in respect of melilite, phlogopite, and clinopyroxene contents. The high water content and vesicular character of the zeolite-bearing ankaratrite would suggest that the ankaratrite magma was better able to retain its volatiles than the alnöite, the agglomeratic character of the latter (visible under the microscope) and its occurrence as a breccia, pointing also to the more highly explosive character of the alnöite magma.

Comment has already been made on the extent to which the petrography of these two rocks has been modified by the presence of coarse-grained ultrabasic inclusions, notably olivine nodules with an olivine–clinopyroxene–orthopyroxene (now altered)–spinel assemblage, and possibly websterite nodules in addition. Apart from the more obvious nodules, and granular olivine aggregates after orthopyroxene enclosed in clinopyroxene, the petrographic evidence indicates that the large clinopyroxene phenocrysts, occurring in both rocks, and probably the majority of the olivine phenocrysts together with the magnetite-rimmed fragments of spinel are all xenocrystal. The fact that both these rocks contain a relative abundance of similar xenocrystal material presents a further confirmation of their consanguinity. Present opinion on the origin of the coarse-grained ultrabasic inclusions in melilite and alkali-basalts would appear to be divided. In agreement with the earlier work of Ross *et al.* (1954), Wilshire and Binns (1961) in their review of this problem favoured 'the hypothesis that such xenoliths represent portions of the earth's mantle incorporated in magmas originating from within that zone'. However, in a detailed re-examination of the subject O'Hara and Mercy (1963, p. 293) have pointed out 'that the mineral facies of the (peridotite) nodules and associated gabbro-nodules in basalts makes it impossible for them to be unmetamorphosed fragments of the mantle', and consider that there is a genetic connexion between the nodules and the rocks in which they occur. The latter view that these olivine nodules are cognate rather than accidental may be relevant to the unusual chemistry of the Malaita rocks, as the segregation and bulk removal of cognate material, e.g. by gravitation or settling, would have a profound effect on the original magma. Nixon *et al.* (1963) have suggested (p. 1129) that the removal of omphacitic clinopyroxene in cognate nodules of griquaite type might account for the low soda-content of the kimberlites, a suggestion one might possibly also apply to the low soda contents of the Malaita ankaratrite. In this connexion it is appropriate to compare the Malaita analyses with the average composition for micaceous kimberlite (No. 8).

The magnesian-ilmenite/pyrope assemblage of the gravels which led to the discovery of these rocks, and the subsequent identification of these minerals as xenocrysts in the alnöite breccia (see plate II, fig. 3) provide a major argument for stressing the kimberlitic affinities of the Malaita rocks. Almost all the heavy minerals of the gravels (see pp. 19–20) are to be matched in kimberlite pipes. The pyrope, highly magnesian but with virtually no chromium, is of a type common as pyrope nodules in kimberlites (cf. analysis of Basutoland example, p. 19) or in conjunction with green diopside in griquaite inclusions in kimberlites. Nixon *et al.* (1963) indicate that these nodules and griquaites are cognate inclusions in the kimberlite, and that this type of garnet is to be distinguished from the chromiferous pyropes derived from garnetiferous peridotite (which O'Hara and Mercy (1963) believe are little altered fragments of the mantle) and the pyrope-almandines thought to be derived from eclogite inclusions. There is also a very close similarity between the Malaita pyrope and that from an unusual hypersthene eclogite nodule from Salt Lake Crater in Oahu, Hawaii, described by Yoder and Tilley (1962). Analysis of the rock and other mineral components indicate that the Salt Lake pyrope is similarly chrome-deficient. As nepheline-melilite basalts containing olivine nodules are also present on Oahu, there would seem to be a strong case for close comparison between these two occurrences in oceanic-type settings. That the magnesian ilmenites are most characteristic of kimberlites there is no doubt, and the ilmenite/chrome-diopside intergrowth found in the alnöite breccia (plate II, fig. 4) matches occurrences in kimberlites described and figured by Williams (1932, vol. 2, pp. 384–386). The chrome-diopsides, rutiles, and zircons of Malaita also match those of the kimberlites.

It is now generally recognized that these 'kimberlite indicator minerals' are by no means restricted to kimberlites, diamondiferous or otherwise, but occur also in various breccia pipes (Davidson, 1957) and in basaltic pipes (Okhapkin and Chubugina, 1960), and have a wider significance to the petrologist than to the diamond prospector. The Malaita rocks and minerals in fact appear likely to provide an excellent example of the close relation between melilite-bearing eruptives and kimberlites that so many petrologists have emphasised. Reviewing this topic, O'Hara and Mercy (1963, p. 297) recently stated '. . . these facts are in accordance with the hypothesis that kimberlite is a fluidized system of xenoliths, xenocrysts, melilite basalt liquid and a gas phase intruded explosively at relatively high velocities'. It seems to the present writers that this hypothesis is not inappropriate to the interpretation of the Malaita alnöite breccia.

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Explanation to Plates

Plate I

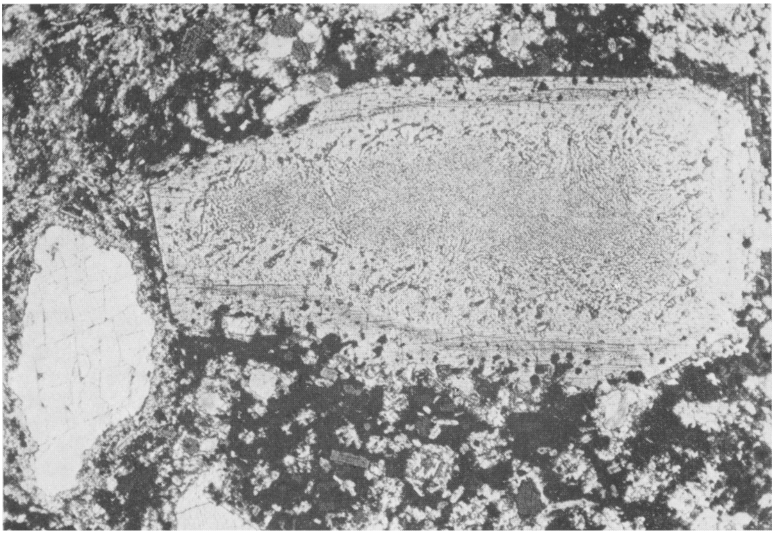
Fig. 1. *Alnöite*: A phenocryst of zoned clinopyroxene shows pronounced corrosion effects in the core and is adjacent to an embayed olivine phenocryst. Melilite laths are prominent in the groundmass. Crossed polars ($\times 49$).

Fig. 2. *Ankaratrite*: An augite crystal (outer edge follows X–Y) encloses a granular aggregate of olivine after orthopyroxene, and magnetite and phlogopite are also associated with the aggregate. Crossed polars ($\times 49$).

PLATE II

FIG. 3. *Alnöite Breccia*: Fragments of altered alnöite in a calcite matrix. G = Pyrope garnet, S = Serpentinized olivine, P = Phlogopite, C = Chrome-diopside, C/I = Chrome-diopside–ilmenite intergrowth. L = Limestone incluson. Glazed slab ($\times 2$).

FIG. 4. *Alnöite Breccia*: A graphic intergrowth of magnesian ilmenite (white) in chrome-diopside. A prominent alteration rim is developed along the embayed margin of the chrome-diopside. Normal incident light ($\times 47$).



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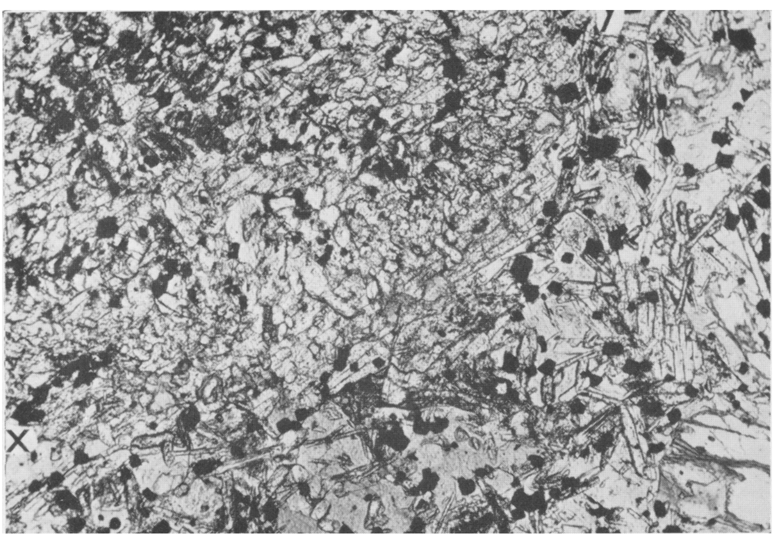

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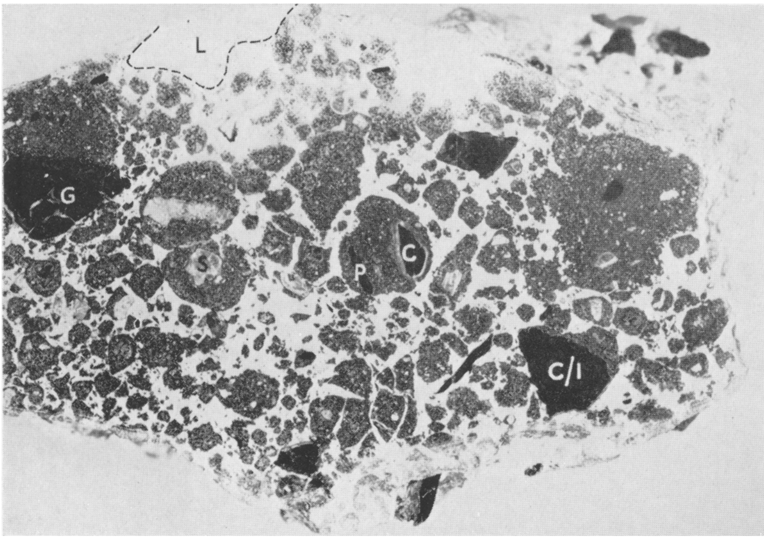

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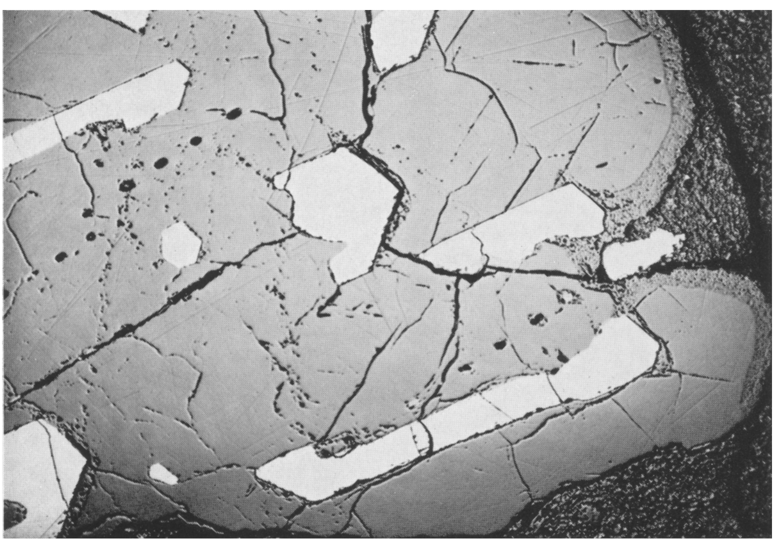

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