THE AMERICAN MINERALOGIST, VOL. 53, JULY-AUGUST, 1968

ECLOGITIC AND OTHER INCLUSIONS IN THE MINERAL BRECCIA MEMBER OF THE DEBORAH VOLCANIC FORMATION AT KAKANUI, NEW ZEALAND

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ABSTRACT

Lapilli tuffs of the Deborah Volcanic Formation formed from two early Oligocene eruptions of basalt or atlantite magma followed by an eruption of melanephelinite magma containing xenoliths of lherzolite, eclogite, hornblendite, pyroxenite and granulite, xenocrysts of hornblende, anorthoclase, ilmenite and coarse grained aggregates of pyrope and augite. Multiphase fluid inclusions, probably dominated by liquid CO_2, occur in almost all phases of the xenoliths and xenocrysts. Most of the xenoliths, except those of hornblendite, have undergone solid-state deformation. Possible partial fusion zones occur along garnet-amphibole and garnet-pyroxene grain boundaries. Compound xenoliths show lherzolite in contact with hornblendite and eclogite. Lherzolite and the melanephelinite show reaction relationships.

The lherzolite, eclogite, granulite, pyroxenite and, possibly, hornblendite are believed to have come from an association of basic and ultrabasic rocks at depth. The melanephelinite magma was probably created from basaltic magma, chiefly by the extraction of anorthoclase, pyrope and clinopyroxene.

Six chemical analyses, optical and X-ray data are presented.

INTRODUCTION

Near Kakanui, east coast, South Island, New Zealand (S. Lat. 45°, E. Long. 171°) basaltic lapilli tuffs of the Lower Oligocene Deborah Volcanic Formation lie between the Upper Eocene Totara Limestone (marine tuffaceous biomicrite) and the Middle Oligocene McDonald Limestone (marine biosparrudite). Details of the regional geology will be found in Gaga (1957), and Coombs and Dickey (1965).

The Deborah Volcanic Formation at Kakanui consists of three units separated by angular unconformities, in downward order:

(3) Mineral Breccia Member
(2) Tuff II
(1) Tuff I

The maximum thicknesses of the three members, as exposed north of the mouth of the Kakanui River, are: (1) 55 feet, (2) 150–200 feet, (3) 150 feet.

Tuffs I and II are composed of glassy and crystalline lapilli of alkaline olivine basalt or atlantite. The Mineral Breccia represents a final eruption of melanephelinite magma. It contains numerous xenolithic frag-

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ments of lherzolite, pyroxenite, hornblendite, eclogite, granulite and large xenocrysts of hornblende, anorthoclase and ilmenite. The pyroclastic deposits are altered to palagonite, zeolites (phillipsite group), calcite and montmorillonoid. The Mineral Breccia, first described by Mantell (1850) and Thomson (1905, 1907), is discussed in later papers by Turner (1942), Benson (1944), and Mason (1966).

This paper presents results of an investigation of the Mineral Breccia undertaken in 1964–1965 at the University of Otago, Dunedin, New Zealand. Additional mineralogical data and details of the investigation are described in Dickey (1965).

Inclusions in the Mineral Breccia Member

At Kakanui, the interesting inclusions are restricted to the Mineral Breccia. Many have streamlined forms and polished surfaces. (Fig. 1). Frequently, polished specimens are mantled by melanephelinite (Fig. 2)

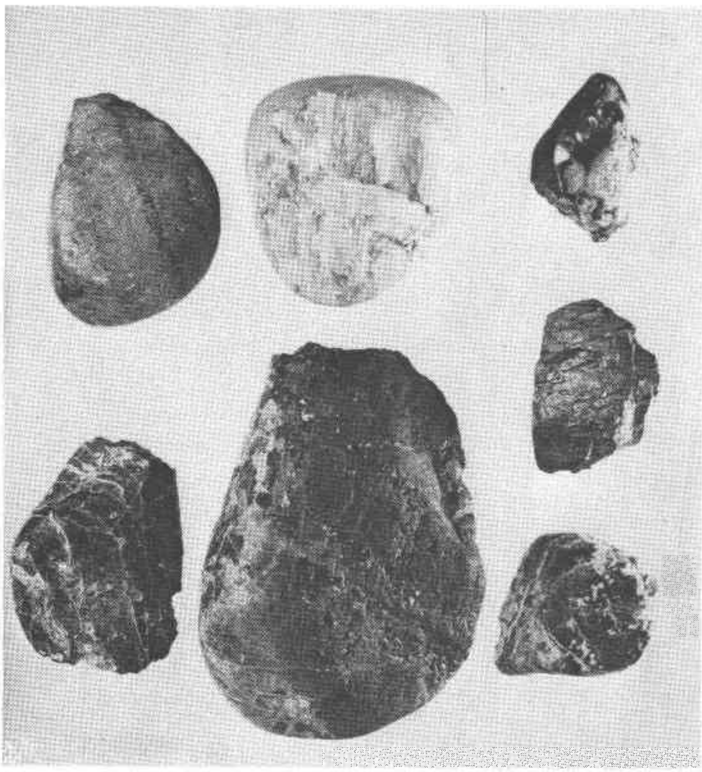


Fig. 1. Polished xenocrysts from the Mineral Breccia Member. Center top: anorthoclase. Right top: augite. Right center: hornblende. Others: pyrope. Length of largest crystal: 7 cm. Photo by R. Hardie.

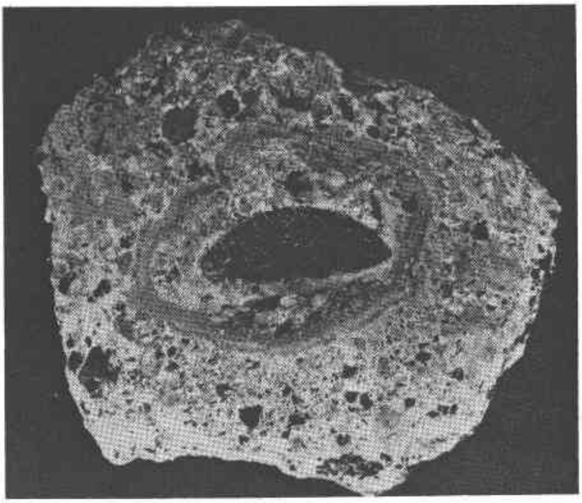


FIG. 2. Streamlined pyrope xenocryst with a mantle of altered melanephelinite, now largely carbonate and zeolite, embedded in tuff consisting of melanephelinite lapilli (light gray) and crystal fragments of hornblende and clinopyroxene (black) in a matrix of calcite and zeolite (white). Length of crystal: 5 cm. Photo by R. Hardie.

indicating that they were polished before eruption, probably by abrasion in the pipe.

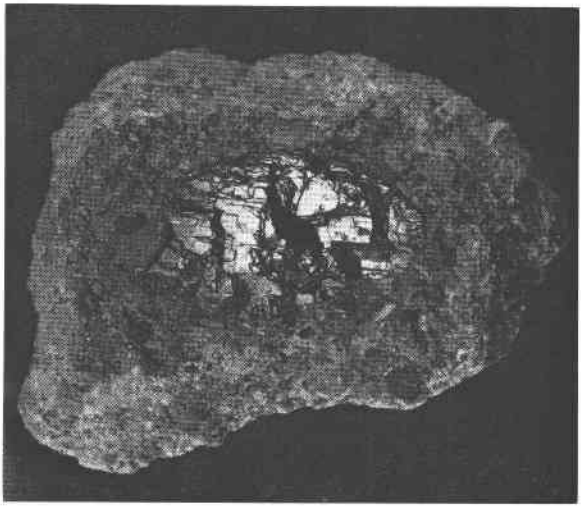
The entire suite of inclusions is characterized by minute fluid inclusions, arrayed either on crystallographically oriented planes or on irregularly curving surfaces. Some of the inclusions are negative idiomorphs, others have less regular forms. Except for the very late secondary phases, calcite and zeolites, fluid inclusions have been observed in almost all translucent phases. Roedder (1965) has determined that the liquid in fluid inclusions of a lherzolite nodule from Kakanui is chiefly CO_2. Approximate filling temperatures for other fluid inclusions in the suite suggest that CO_2 generally predominent.

There are two sorts of inclusions: medium grained, polycrystalline xenoliths, and minerals which occur as large single crystals (Figs. 1, 2, 3) or, rarely, in coarse aggregates. It has been stated (Mason, 1966) that the garnet and hornblende of the polycrystalline xenoliths are equivalent to those occurring as independent xenocrysts. They are, however, quite different. The nature of these and other minerals and mineral assemblages in the Mineral Breccia is outlined in Appendix 1 and in Tables 1 through 4.[1]

[1] Specimen numbers refer to the collection of the University of Otago. Refractive indices, unless otherwise noted, are precise to ± 0.003. X-ray diffraction measurements were repeated 6 times at $\frac{1}{4}° \ 2\theta$ per minute with internal standards, shifting the sample slightly for each scan.

In addition to the properties tabulated above and in Appendix 1, three features of particular interest were obxerved in the suite of inclusions. These are: a reaction relationship between melanephelinite and lherzolite (assemblage 4); evidence of fusion between coexisting garnets, pyroxenes and amphiboles; and compound xenoliths containing more than one assemblage.

Reactions between lherzolite nodules and alkaline olivine basalt are well documented (Wilshire and Binns, 1961), but unlike these, the lherzolite-melanephelinite relationship includes a strong reaction of olivine in the lherzolite with the melanephelinite. The olivines are em-



Fɪɢ. 3. Hornblende xenocryst with a mantle of altered melanephelinite embedded in tuff. Length of crystal: 8 cm. Photo by R. Hardie.

bayed by zones of optically coincident, remnant olivine and tiny crystals of secondary clinopyroxene. The reaction zone lacks opaque grains; however, a thin opaque-rich band occurs in the adjacent melanephelinite. Bronzite grains are similarly embayed, the reaction zone containing remnant bronzite, secondary clinopyroxene and possibly glass. Diopside grains are sieved, especially around their edges, by tiny blebs of glass and altered to titanaugite along the melanephelinite contact. Opaque rims separate picotite grains from the melanephelinite.

Textures in some eclogite specimens (assemblage 9) and possibly in pyrope-augite aggregates (assemblage 6) suggest quenching of an intergranular liquid, formed probably by decompression during eruption. Along pyroxene-garnet and amphibole-garnet contacts are zones, up to 0.4 mm wide, containing spinel, clinopyroxene and plagioclase. The

TABLE 1. COMPOSITION OF HORNBLENDES FROM THE MINERAL BRECCIA MEMBER

	Weight Percent		Cations Per 24 (O, OH, F)					
	1.	2.		1.		2.		
SiO_2	40.2 (1)	40.42	Si	6.01	8.00	6.02	8.00	
			Al	1.99		1.98		
TiO_2	3.98	4.43	Al	0.26		0.45		
Al_2O_3	12.7 (8)	13.90	Ti	0.45		0.50		
Fe_2O_3	6.28	4.84	Fe^{3+}	0.71	5.17	0.54	5.24	
FeO	9.71	6.85	Fe^{2+}	1.21		0.85		
MgO	11.3 (0)	12.95	Mg	2.52		2.89		
CaO	9.86	10.28	Mn	0.02		0.01		
MnO	0.13	0.10	Na	0.81		0.88		
Na_2O	2.79	3.04	Ca	1.58	2.73	1.64	2.91	
K_2O	1.79	2.05	K	0.34		0.39		
H_2O^+	1.5	0.96						
H_2O^-	0.01	0.00						
F	—	0.15						
Total	100.34	99.97						

Optical and Physical Data

1.	2.
α (iight tan) $=1.674$	α (pale yellow) $=1.676$
γ (dark brown) $=1.702$	β (brown) $=1.687$
$2V_x=80\pm3°$	γ (brown) $=1.695$
$Z:c=20\pm3°$	$2V=80°$
Dispersion: $r<v$ distinct	$Z:c=15°$
	$D=3.22$ g/cc
	$a=9.870$ Å
	$b=18.058$ Å
	$c=5.307$ Å
	$\beta=105°\ 12'$

1. Kaersutitic hornblende (OU20237), analyst: Dickey (1965).
2. Hornblende, Mason (1966).

spinel forms purple-gray octahedra and is concentrated in the centers of the zones. The clinopyroxene occurs as stout, purple-brown laths, up to 0.05 mm long; its known properties are: weak pleochroism, $2V_Z$ 40° to 60°, distinct dispersion $r>v$. The plagioclase, according to extinction angles on (010), is at least 60 percent anorthite. Its laths, which are most abundant along the edges of the zones tend to lie at high angles to the edges of the bounding primary grains. The zones at garnet-amphibole contacts are wider than those at garnet-pyroxene contacts, probably because of the fluxing action of water from the amphibole.

TABLE 2. COMPOSITION OF ANORTHOCLASE FROM THE MINERAL BRECCIA MEMBER

Weight Percent		Cations Per 8 Oxygens		
SiO_2	67.4 (2)	Si	2.97	4.99
R_2O_3[a]	20.1 (8)	R	1.05	
CaO	0.79	Ca	0.04	
K_2O	2.05	Na	0.81	
Na_2O	9.44	K	0.12	
H_2O^-	0.03			
Total	99.91	Component Percent		
		Albite	84.0	
		Orthoclase	12.1	
		Anorthite	3.9	

Optical Data
$\alpha=1.526$
$\beta=1.533$
$\gamma=1.535$
$2V_x=40\pm2°$
Dispersion $r>v$ moderate

[a] Includes minor Fe_2O_3.
Anorthoclase (OU20310), analyst: Dickey (1965).

Compound xenoliths have been found which demonstrate the pre-eruptive association of lherzolite with hornblendite (assemblage 5) and with amphibole eclogite (assemblage 9). Most common are fragments of deformed lherzolite, intruded or enveloped by undeformed hornblendite. Typically, the hornblendite-lherzolite contacts are sharp and show no reaction relationship. At the contact the lherzolite is of normal grain size; the hornblendite grain size, however, decreases from 5 mm to 2 mm. Rarely, the contact between lherzolite and hornblendite is gradational. In one such specimen (OU20263) chrome diopside dominates a zone, 5 mm wide, along the contact and appears in the adjacent hornblendite. Within the lherzolite are subidiomorphic grains of phlogopite and amphibole, up to 2 mm, which are usually associated with, and often mantled by, chrome diopside. As usual the hornblendite shows a decrease in grain size, to 2 mm, at the contact. The contact association of lherzolite and eclogite is based upon one specimen (OU20273) which shows a 1.5 cm band of eclogite within lherzolite. No reaction relationship or reduction of grain size is apparent. Amphibole is abundant in the eclogite and penetrates the lherzolite along grain boundaries near the contact. Much of the garnet is concentrated in a 2 mm band which parallels the lherzolite contacts

TABLE 3. COMPOSITION OF CLINOPYROXENES FROM THE MINERAL BRECCIA MEMBER

Weight Percent				Cations Per 6 Oxygens						
	1	2	3		1		2		3	
SiO_2	49.8 (6)	50.73	50.69	Si	1.82	2.00	1.827	2.000	1.878	2.000
TiO_2	0.93	0.74	0.95	Al	0.18		0.173		0.122	
Al_2O_3	6.98	7.86	7.68	Al	0.12		0.160		0.213	
Fe_2O_3	3.36	3.69	2.50	Ti	0.03		0.020		0.026	
Cr_2O_3	—	—	0.076	Fe^3	0.09		0.100		0.070	
FeO	5.15	3.45	8.43	Fe^2	0.16	2.01	0.105	1.983	0.261	
MgO	16.3 (8)	16.65	12.28	Mg	0.89		0.895		0.678	
CaO	15.8 (8)	15.82	13.34	Mn	0.01		0.003		0.005	1.982
MnO	0.18	—	0.17	Ca	0.62		0.610		0.530	
Na_2O	1.25	1.27	2.57 (2.15)[a]	Na	0.09		0.090		0.185	
K_2O	tr	0.00	0.13 (0.05)[a]	K	—		—		0.006	
P_2O_5	—	—	0.07	P	—		—		0.002	
H_2O^+	—	0.04	0.74	Cr	—		—		0.006	
CO_2	—	—	0.20							
Total	99.97	100.25	99.95							

Component Percent

	1	2	3
Acmite	9.1	9.2	7.2
Jadeite	0.0	0.0	11.8
Hedenbergite	17.2	12.0	27.2
Diopside	45.4	49.9	27.0
Enstatite	13.1	12.0	15.5
Mg-Tschermak	15.2	16.9	11.3

Optical and Physical Data

	1	2	3
α	1.688	1.686	1.696
β	1.695	1.691	1.702
γ	1.710	1.713	1.717
$2V_z$	55±3°	55°	56±3°
D		3.33 gm/cc	
a		9.70 A	
b		8.89 A	
c		5.26 A	
β		106° 55′	

[a] Independent partial analysis by G. I. Z. Kalocsai.
1. Augite (OU8387), analyst: Dickey (1965).
2. Augite, Mason (1966).
3. Omphacitic pyroxene (OU19865), analyst: H. Asari *in* Dickey (1965).

TABLE 4. COMPOSITION OF GARNETS FROM THE MINERAL BRECCIA MEMBER

Weight Percent

	1	2	3
SiO_2	41.3 (0)	41.45	39.11
TiO_2	0.28	0.51	0.25
Al_2O_3	22.0 (0)	23.50	22.47
Fe_2O_3	2.81	0.76	2.06
Cr_2O_3	—	—	0.029
FeO	10.0 (8)	10.08	18.35
MgO	18.1 (7)	18.80	11.57
CaO	5.33	5.09	5.05
MnO	0.44	0.33	0.54
Na_2O	tr	—	0.20 (0.15)[a]
K_2O	0.00	—	0.23 (0.05)[a]
P_2O_5	—	—	0.00
H_2O^+	—	—	0.51
H_2O^-	0.00	—	0.17
CO_2	—	—	0.00
Total	100.41	100.52	100.539

Cations Per 12 Oxygens

	1	Σ	2	Σ	3	Σ
Si	2.97	3.00	2.915	3.000	2.943	3.000
Al	0.03		0.085		0.057	
Al	1.84		1.885		1.936	
Ti	0.02		0.025		0.014	
Fe^3	0.15		0.040		0.116	
Fe^2	0.61		0.600	4.960	1.155	
Mg	1.95	5.01	2.000		1.298	5.013
Ca	0.41		0.390		0.407	
Mn	0.03		0.020		0.034	
Na	0.00		—		0.029	
K	0.00		—		0.022	
Cr	—		—		0.002	

Component Percent

	1	2	3
Pyrope	65.0	66.4	44.8
Almandine	20.3	20.0	39.9
Spessartine	0.9	0.6	1.2
Grossularite	6.1	10.9	7.9
Andradite	7.6	2.1	6.0
Uvarovite	—	—	0.2

Optical and Physical Data

	1	2	3
n	1.748	1.741	1.770
a, Å	11.531	11.536	11.545
D g/cc		3.72	

[a] Independent partial analysis by G. I. Z. Kalocsai.

1. Pyrope (OU20308), analyst: Dickey (1965).
2. Pyrope, Mason (1966).
3. Pyrope-almandine (OU19865), analyst: H. Asari *in* Dickey (1965).

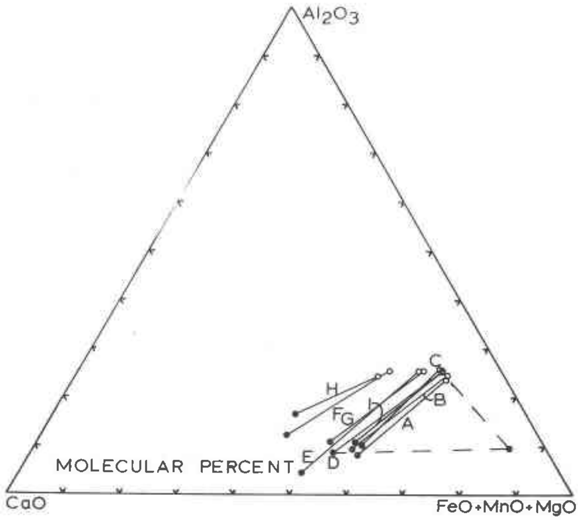


FIG. 4. A C Fm plot of coexisting garnets and pyroxenes from the Mineral Breccia Member and elsewhere. Filled circles: pyroxenes. Open circles: garnets. See key on facing page.

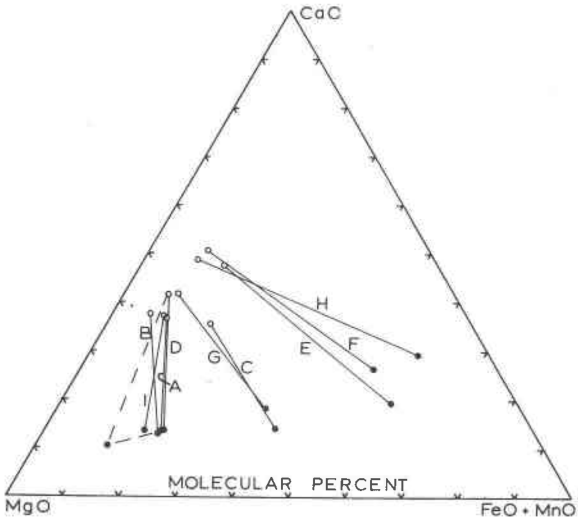


FIG. 5. C F M plot of coexisting garnets and pyroxenes from the Mineral Breccia Member and elsewhere. Filled circles: garnets. Open circles: pyroxenes. See key on facing page.

TABLE 5. CIPW NORMS OF HORNBLENDE AND AUGITE XENOCRYSTS

	1	2	3	4
Or	0.00	0.00	10.58	5.46
Ab	10.58	10.75	0.88	0.00
An	13.44	15.75	17.06	18.23
Lc	0.00	0.00	0.00	5.22
Ne	0.00	0.00	12.32	13.94
Di	51.56	49.11	25.32	24.78
Hy	7.43	11.29	0.00	0.00
Ol	10.33	6.58	16.01	15.59
Mt	4.87	5.35	9.10	7.02
Il	1.77	1.41	7.56	8.41
F	0.00	0.00	0.00	0.31
Residue	0.00	0.04	1.50	1.02
Total	99.97	100.25	100.33	99.97

1. Augite (OU8387)
2. Augite (Mason, 1966)
3. Hornblende (OU20237)
4. Hornblende (Mason, 1966)

In Table 5 CIPW norms are listed for the hornblende and augite xenocrysts (assemblages 2 and 6). The hornblende, which may approximate the composition of the magma in which it formed, has normative nepheline; the augite, in contrast, contains hypersthene in the norm.

DISCUSSION

The suite of inclusions in the Mineral Breccia contains a fragmentary record of the events which preceded the melanephelinite eruption. Some characteristics of this suite will now be reviewed and interpreted.

Key to Figures 4 and 5:

A. Augite (OU8387) and pyrope (OU20308) from the Mineral Breccia Member (Dickey, 1965).[1]
B. Augite and pyrope from the Mineral Breccia Member (Mason, 1966).[1]
C. Omphacitic pyroxene and garnet in amphibole eclogite (OU19865) from the Mineral Breccia Member (Dickey, 1965).
D. Garnet, clinopyroxene and orthopyroxene in hypersthene eclogite (66118) from Salt Lake Crater, Oahu (Yoder and Tilley, 1962).
E. Garnet and clinopyroxene in eclogite (35083) from Loch Duich, Scotland (Yoder and Tilley, 1962).
F. Garnet and clinopyroxene in eclogite (35090) from Glenelg, Scotland (Yoder and Tilley, 1962).
G. Garnet and clinopyroxene in eclogite (E4) from the Kao kimberlite pipe, Basutoland (Nixon, *et al.*, 1963).
H. Garnet and clinopyroxene in eclogite (100-RGC-58) from Tiburon Penninsula, California (Coleman, *et al.*, 1965).
I. Garnet and clinopyroxene from Elie Neck, Fyfeshire, Scotland (Heddle, 1901).

[1] The garnet and pyroxene of assemblage A are not from the same specimen. Specimen OU8387, from which the pyroxene was obtained, however, did contain small garnet crystals, and the analysed garnet, OU20308, was selected because its unit cell edge and refractive index are the same as those of the garnet of OU8387. The analysed minerals, therefore, closely approximate coexisting phases. The analyses quoted from Mason (1966) were carried out on isolated crystals which are believed to represent coexisting phases.

Lherzolite xenoliths, similar to the olivine nodules found in volcanic rocks of the alkaline olivine basalt suite in many parts of the world, dominate the suite of inclusions. Also present are inclusions of eclogite, granulite, pyroxenite and hornblendite. Similarities in texture and mineralogy suggest a genetic connection between the eclogites, granulites and pyroxenites. Probably they and the lherzolite xenoliths came from a solid association of basic and ultrabasic rocks at depth. Similar associations are found in the Pyrenees (Lacroix, 1894; Ave Lallemant, 1967), and elsewhere. The hornblendite (assemblage 5) may also be from this basic-ultrabasic complex. Veins of hornblendite intrude the Pyrenean lherzolites and, like the Kakanui hornblendite, show little or no evidence of solid state deformation, although the adjacent peridotite is deformed. Alternatively, the rising magma might have crystallized as hornblendite around fragments of lherzolite. This interpretation would be more attractive if other kinds of xenoliths had hornblendite mantles.

The gneissic xenoliths (assemblage 13) represent a high grade metamorphic terrane. The presence of exsolution lamellae in the high temperature feldspars is probably due to elevation of the feldspar solvuses with increased pressure (D. S. Coombs, pers. comm., 1964). Experimental data (Bowen and Tuttle, 1950; Yoder *et al.*, 1957; Orville, 1963, 1964) indicate a roughly linear increase of 14C°/kbars.

Distinctly different from the polycrystalline xenoliths are the large crystals of anorthoclase, hornblende and clinopyroxene, which were never found in polycrystalline aggregates. The crystals of augite and pyrope (assemblage 6) which usually occur singly, are rarely associated in coarse grained aggregates and are, in that respect, texturally intermediate.

The analyzed garnets and pyroxenes from the Mineral Breccia are similar in composition to others from including some basalts and kimberlites. This affinity is illustrated in Figures 4 and 5. In view of the number of components neglected, the significance of such diagrams is limited; however, the spatial associations shown in them are consistent with the compositions as a whole and the modes of occurrence. The close relationship between the pyrope-augite pairs of assemblage 6 from Kakanui and of the hypersthene eclogite from Oahu is striking. It is a significant (albeit unexplained) fact that suites of cognate and accidental inclusions in kimberlites included all minerals and mineral assemblages found in the Mineral Breccia, except anorthoclase (Nixon *et al.*, 1963; Williams, 1932). Apparently the melanephelinite and kimberlite magmas have had some common experiences during their evolutions.

The xenocrysts of anorthoclase, hornblende, augite and pyrope are probably cognate inclusions, formed shortly before eruption. If the

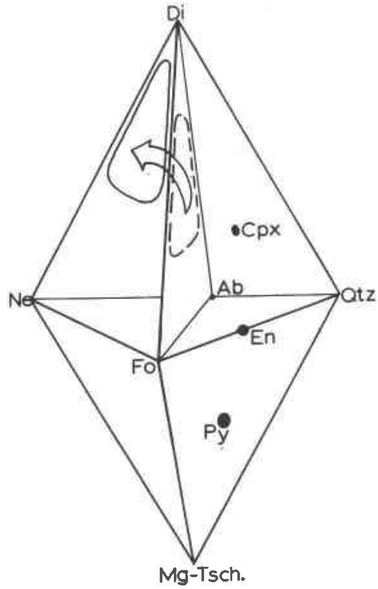


FIG. 6. Simplified trend of a liquid changing in composition from that of alkaline olivine basalt, lying on or near the plane diopside-forsterite-albite, to that of melanephelinite, lying on or near the plane diopside-forsterite-nepheline. The transformation is effected chiefly by the removal of crystals of sodic anorthoclase (closely approximated by Ab), pyrope (Py) and a hypersthene normative clinopyroxene (Cpx). Mg-Tsch. stands for $MgAl_2SiO_6$. The design of the figure is adapted from Yoder and Tilley (1962).

magma from which they precipitated was basaltic, like the magmas of Tuffs I and II, the extraction of anorthoclase, augite and pyrope crystals, perhaps by flotation and settling, might have transformed it (Fig. 6) into the melanephelinite which erupted.

ACKNOWLEDGEMENTS

Professor D. S. Coombs first suggested this study, and to him go warm thanks for his guidance and encouragement. Financial support is acknowledged from the U. S. Government, which supplied a Fulbright Scholarship, and the University of Otago, which provided research facilities and paid for two chemical analyses by the Japan Analytical Chemistry Research Institute. Some of the research equipment at the University of Otago had been purchased with research grants from the New Zealand University Grants Committee. Through the kindness of Professor J. F. G. Wilkinson a partial analysis to check alkali data was carried out in laboratories at the University of New England.

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Manuscript received. November 22 1966: accepted for publication, March 15, 1968.

APPENDIX 1. DESCRIPTION OF INCLUSIONS IN THE MINERAL BRECCIA MEMBER

1. *Ilmenite:* Ragged, embayed fragments in melanephelinite bombs, also rare polycrystalline nodules, up to 4×2 cm, with homogeneous, xenomorphic crystals (5 mm)
2. *Hornblende* (+accessory opaque inclusions). Shiny black cleavage fragments, up to 8

cm, (Fig. 2). Analyses (Table 1, (1) and (2)) are of kaersutitic and hastingsitic affinities and show that significant variations occur between crystals. Relatively high TiO_2 and K_2O are noteworthy.

3. *Anorthoclase* (±accessory biotite and apatite inclusions). Large, glassy single crystals, up to 700 g, finely twinned on albite law or albite and pericline laws; optically homogeneous; heating (1000°C) shifts $d_{\bar{2}01}$ from 4.07 to 4.06 Å. Analysis (Table 2) gives $Or_{12}Ab_{84}An_4$. Accessories form rare, idiomorphic inclusions; biotite as plates up to 1.5 cm diameter, high Fe, Ti content indicated by intense red-brown color, refractive index and strong x-ray fluorescence peaks; apatite as gray, sometimes bluish or greenish, prisms up to about 2×1.5 cm.
   Biotite (OU20251): $\gamma=1.670$ (JD-Ka-155) to 1.686
   Apatite (OU20251): $\epsilon=1.638$, $\omega=1.643$
4. *Forsterite+bronzite+chrome diopside+picotite.* Lherzolite, most common inclusions in Mineral Breccia, up to 30 cm diameter; xenomorphic granular texture with varying grainsize (2 to 4 mm); typical mode (OU19854) 67.7% forsterite, 17.5% bronzite, 14.3% chrome diopside, 0.5% picotite. Color change from yellow green to brown orange to white caused by deuteric formation of pargasite and iddingsite and later replacement by calcite and zeolites. Solid state deformation indicated by lattice preferred orientation and strain bands of olivine (Turner, 1942) and distortion of bronzite cleavages. Bronzite has monoclinic lamellae exsolved parallel to (100). Diopside is homogeneous, gives strong x-ray fluorescence peaks for Cr. Picotite grains are irregular, occupy intersilicate voids; wide range of refractive index indicates compositional variation.
   Forsterite (Fo_{88-91}) (OU19854): $\alpha=1.651$ $\beta=1.673$ $\gamma=1.691$ $d_{130}=2.770$ Å $2\theta_{062}-2\theta_{LiF220}=2.84°$
   Bronzite (En_{85}) (OU19855): $\alpha=1.669$ $\beta=1.675$ $\gamma=1.682$
   Diopside (OU19855): $\alpha=1.680$ $\beta=1.686$ $\gamma=1.703$
   Picotite (OU19858): $n=1.778$
   (OU19856) $n=1.845\pm0.005$ $a=8.15$ Å
5. *Hornblende+phlogopite* (+opaque oxide). Coarse grained assemblage of brown hornblende (60%), phlogopite (38%), and an opaque oxide (2%) probably ilmenite. Hornblende grains (up to 5 mm) often poikilitically include subidiomorphic phlogopite. Assemblage fresh and undeformed.
   Hornblende (OU19855): $\alpha=1.665$ (light tan) $\beta=1.685\pm0.005$ $\gamma=1.695$ (dark brown) $Z{:}c=11°$ dispersion: $r<v$ distinct
   Phlogopite (OU19855): $\gamma=1.633$ $2V_X=5°$ x-ray diffraction: $I_{004}{:}I_{005}=5.2$
6. *Pyrope+augite.* Usually found as single crystals, but bimineralic xenoliths occur. Pyrope forms wine-red crystals, up to 185 g, streamlined parallel to weak parting (Fig. 2). Black augite crystals equally large, with pronounced cleavage and conchoidal fracture, untwinned and homogeneous. Compositions (Table 3, (1), (2); Table 4, (1), (2)) similar to garnet—pyroxene pair in hypersthene eclogite from Salt Lake Crater (Figs. 4 & 5).
7. *Augite+pleonaste.* Single crystals of black augite with randomly oriented octahedra (up to 3 mm) of nearly opaque pleonaste. Augite resembles that of assemblage (6) but has higher refractive indices. Spinel constitutes 10 percent by weight of the assemblage.
   Augite (OU20252): $\alpha=1.699$ $\beta=1.704$ $\gamma=1.721$
   Pleonaste (OU20252): $n=1.790\pm0.005$ $a=8.14$ A
8. *Augite* (+pleonaste & olivine inclusions): Large (100 cc) crystal of purple-brown augite with poikilitic inclusions of a similar pyroxene and purple-gray pleonaste. Spinel concentrated in linear zones, possibly along fractures. Host crystal also contains patches

(up to 3 mm) of golden-brown glass within which are parallel, idiomorphic olivine pseudomorphs, filled chiefly with zeolites.
Augite (OU20238): $\alpha=1.692$ $\beta=1.702$ $\gamma=1.720$, $2V_Z$ low Dispersion $r>v$ moderate
Pleonaste (OU20238): $n=1.767$ $a=812.$ Å

9. *Garnet+omphacitic pyroxene+brown amphibole* (+accessory ilmenite+oligoclase): Amphibole eclogite, common inclusions up to 15 cm in diameter; xenomorphic granular to poikilitic texture with amphibole enclosing garnet and pyroxene. Garnets, up to 5 mm, are dominantly pyrope—almandine with noteworthy alkali content (Table 4, (3)). Bluish or greenish-gray omphacitic pyroxene, up to 4 mm, is the most abundant phase; shows weak lattice preferred orientation, simple twins and exsolution lamellae parallel to (100). Analysis (Table 3, (3)) has high Na_2O, low CaO and CO_2, which is probably from fluid inclusions. Brown amphibole appears as a late primary phase and as a secondary phase replacing pyroxene. Ilmenite present as a minor accessory, often associated with amphibole. Oligoclase (An_{26}) is a late primary phase constituting 2 percent of rare, amphibole-rich specimens; xenomorphic grains, up to 0.5 mm, moulded around other minerals; high temperature polymorph with polysynthetic twinning. Biotite present as late deuteric phase.
Amphibole (OU19865): $\alpha=1.674$ (light tan) $\beta=1.689\pm0.005$ $\gamma=1.700$ (dark brown) $Z{:}c=17\pm3°$ $2V_X=82\pm3°$ dispersion: $r<v$ distinct
Oligoclase (OU19934): $\alpha=1.542$ $\beta=1.546$ $\gamma=1.551$ $2\theta_{1\bar{3}1}-2\theta_{131}=1.91°$

10. *Augite+Bronzite+Pleonaste:* Gray-green pyroxenite, 70 percent xenomorphic augite, up to 1 cm; bronzite largely replaced by iddingsite and carbonate; olive-green pleonaste grains equant, up to 5 mm, or vermiform and moulded around pyroxenes.
Augite (OU20256): $\alpha=1.682$ $\beta=1.689$ $\gamma=1.705$
Bronzite (OU20256): $\alpha=1.673$ $\beta=1.678$ $\gamma=1.683$
Pleonaste (OU20256): $n=1.763\pm0.005$ $a=8.11$ Å

11. *Augite+Oligoclase+Brown Amphibole+Garnet* (+accessory hypersthene, ilmenite & apatite): Garnets, up to 2 mm, lie in a groundmass of equant, xenomorphic, gray augite, oligoclase, and brown amphibole, average grainsize 0.3 mm. Mode (OU20271) is 30% augite, 30% oligoclase, 12% amphibole, 12% garnet, 2.5% ilmenite, 2% hypersthene, 11.5% zeolites, carbonate, etc. Garnets, usually altered, include small crystals of clinopyroxene, an opaque mineral, rare hypersthene and apatite. Augite has lacey appearance, especially near grain edges, possibly due to blebs of glass. Oligoclase (An_{17}) is an high temperature polymorph, unzoned, often twinned. In addition to grains in the groundmass, amphibole forms poikilitic grains up to 2 mm. Amphiboles have opaque rims along contacts with garnets. Also present in groundmass are hypersthene xenomorphs and rounded ilmenite grains.
Garnet (OU20271): $n=1.772$
Augite (OU20271): $\alpha=1.694$ $\beta=1.698$ $\gamma=1.718$
Oligoclase (OU20271): $\alpha=1.537$ $\beta=1.542$ $\gamma=1.546$ $2\theta_{1\bar{3}1}-2\theta_{1\bar{3}1}=1.89°$

12. *Labradorite+Augite+Bronzite* (+accessory apatite & rutile): Subidiomorphic pyroxenes immersed in labradorite. Unveven texture caused by jagged grains and grainsize variation (0.2 to 2 mm). Mode (OU20250) is 50% labradorite, 25% augite, 23% bronzite, 2% accessories. Laboradorite (An_{55}) forms equant grains (0.2 mm) and irregular patches, up to 2 mm; usually zoned, sometimes polysynthetically twinned, often contains fine needles, possibly apatite. Bronzite has exsolved monoclinic lamellae and distorted cleavages. Greenish-tan augite is homogeneous. Minute prisms of apatite and golden-brown rutile (up to 0.1 mm) occur as inclusions.
Labradorite (OU20250): $\alpha=1.554$ $\beta=1.558$ $\gamma=1.565$ $2\theta_{1\bar{3}1}-2\theta_{131}=1.97°$ dispersion: $r<v$ moderate

Augite (OU20250): $\alpha=1.680$ $\beta=1.690$ $\gamma=1.710$ dispersion: $r<v$ weak to moderate
Bronzite (OU20250): $\alpha=1.685$ $\beta=1.693$ $\gamma=1.701$

13. *Garnet+Sanidine+andesine+quartz* (+accessory rutile, apatite, biotite & graphite): Gneiss with garnet and accessories lying in quartzofeldspathic groundmass. Equigranular, subidiomorphic texture with two mutually perpendicular foliations: the older caused by parallelism of garnet microaugen, rutile, biotite and graphite grains and lattice preferred orientation of quartz and feldspars, the younger by chloritic partings. Mode (OU20237) is 41% sanidine, 28% garnet, 16% andesine, 4% quartz, 3% biotite, 8% other accessories. Garnet, 0.08 to 1.5 mm, contains graphite and rutile inclusions. Sanidine is a microperthitic, high temperature polymorph. Exsolved lamellae, up to 0.05 mm long, estimated, by $d_{\bar{2}01}$ (Tuttle and Bowen, 1958), as 15% $KAlSi_3O_8$. Host estimated as 85% $KAlSi_3O_8$; $\bar{2}01$ peak is assymmetrical, suggesting that the host composition ranges to higher K content. Host has optical properties of high sanidine. Heating for 130 hours, 990° to 1100°C, in an open vessel at 1 atm, failed to homogenize the feldspar. Andesine (An_{35}) is an antiperthitic, high temperature polymorph. Crystals are twinned and contain lamellae of potassic (lower refractive index) phase. Rutile forms wine-red prisms up to 0.15 mm long. Graphite as feathery flakes up to 0.15 mm. Subidiomorphic biotite up to 1.2 mm in diameter.

Sanidine (OU20237): $\alpha=1.520$ $\beta=1.525$ $\gamma=1.526$ dispersion: $r<v$ moderate plane of optic axes parallel to (010)
Andesine (OU20237): $\alpha=1.545$ $\beta=1.552$ $\gamma=1.556$ $2\theta_{1\bar{3}1}-2\theta_{131}=1.94°$
Garnet (OU20237): $n=1.779$ $a=11.511$ Å
Biotite (OU20237): $\gamma=1.636$ $2V_X>0$ dispersion: $r<v$ distinct
Apatite (OU20237): $\epsilon=1.635\pm0.005$