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HIGH-PRESSURE MEGACRYSTS IN BASANITIC LAVAS NEAR ARMIDALE, NEW SOUTH WALES

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ABSTRACT. Analcime basanites and basanitoids from near Armidale, New South Wales, contain ultrabasic xenoliths and unusually large crystals ("megacrysts") of aluminian augite, ferrian pleonaste, kaersutite, anorthoclase, and rare ilmenite, zircon, and aluminian bronzite. In the light of experimental data, the megacrysts are interpreted as high pressure crystallization products, probably cognate with the enclosing lavas. Unzoned megacrysts with varying Fe/Mg ratios occur in close association, and rare composite megacrysts permit the interpretation of a high pressure crystallization sequence. Separation of these phases from likely parental liquids would apparently give rise to fractionation trends similar to those that might be developed from comparable melts at low pressures.

INTRODUCTION

Certain aspects of inter-relationships between the more important basaltic magma types have recently been clarified by experimental studies carried out at high pressures (compare, Yoder and Tilley, 1962; O'Hara, 1965; Green and Ringwood, 1967; O'Hara and Yoder, 1967). To some extent, the feasibility of fractionation schemes suggested by these experiments must depend on data obtained from natural occurrences of cognate inclusions with high pressure mineralogy in a variety of host rocks and on evaluations of the compositions of liquid residua developed by the extraction of such inclusions from likely "parental" magmas.

This article deals specifically with an assemblage of megacrysts in a sequence of some five or six lava flows capping a hill within the University of New England site at Armidale, New South Wales. These flows, which dip very gently toward the west and have a combined thickness of 35 meters, belong to a volcanic province with predominantly alkali olivine basaltic affinities, ranging in age from early Oligocene to early Miocene (McDougall and Wilkinson, 1967).

HOST ROCKS

Apart from slight differences in texture, individual flows in the sequence show little petrographic variation. Euhedral olivine microphenocrysts up to 0.3 mm are scattered through a fine-grained groundmass (10-100μ) consisting of olivine, plagioclase laths, granules or prisms of pale pinkish clinopyroxene, titanomagnetite, interstitial analcime, and alkali feldspar. Apatite needles are a prominent accessory, and some specimens contain small red-brown crystals of (?) kaersutite. Most flows are massive and holocrystalline, but one in the middle of the sequence shows an irregular color banding in which some of the darker patches contain pale brown intersertal glass instead of analcime and alkali feldspar. Extensively weathered vesicular or amygdaloidal zones cap most flows.

Bulk compositions of a holocrystalline sample from the topmost flow and of a glass-bearing variant from the banded flow are listed in table 1. Chemical similarity between the two is striking, and on the

TABLE 1

Chemical analyses and norms of basanite, etcetera

	Analyses				Norms		
	1	2	3		1	2	3
SiO_2	44.48	44.94	44.90	Or	13.2	9.0	10.0
TiO_2	2.42	2.52	2.13	Ab	14.0	19.8	14.7
Al_2O_3	13.47	14.65	14.97	An	11.8	15.5	13.3
Cr_2O_3	0.09	0.02	...	Ne	11.1	9.7	15.0
Fe_2O_3	3.50	4.53	2.62	Di	17.8	15.8	20.2
FeO	9.09	8.17	8.26	Ol	17.9	15.9	15.1
MnO	0.24	0.19	0.15	Mt	5.1	6.6	3.7
MgO	9.43	8.94	8.45	Il	4.7	4.8	4.0
NiO	0.04	0.06	...	Chr	0.1	0.0	...
CaO	8.12	8.13	9.08	Ap	2.3	1.8	2.4
Na_2O	4.08	4.45	5.02	H_2O	1.7	1.4	1.6
K_2O	2.23	1.52	1.72				
H_2O^+	1.29	1.35	1.21	Total	99.7	100.3	100.0
H_2O^-	0.38	0.03	0.38				
P_2O_5	0.97	0.78	0.97	An*	44	43	46
				F*	25	21	26
Total	99.83	100.28	99.86				

*An = mole percent An/(An + Ab) in normative plagioclase. F = mole percent Fe/(Fe + Mg) in normative femics.

1. Analcime basanite from topmost flow, University site, Armidale, New South Wales (Wilshire and Binns, 1961).

2. Basanitoid, near middle of sequence, University site, Armidale (analyst: G. I. Z. Kalocsai).

3. Analcime-olivine theralite, Square Top intrusion, Nundle, New South Wales (Wilkinson, 1965).

basis of their normative compositions they may be classified respectively as analcime basanite and basanitoid (that is, containing occult normative nepheline, compare Macdonald and Katsura, 1964, p. 86).

The average olivine composition measured from broad X-ray diffraction peaks is Fa_{27}(d_{136} = 2.784 Å, compare Yoder and Sahama, 1957). Individual olivine microphenocrysts are zoned from Fa_{19} to Fa_{28} (β = 1.689-1.709).[1] Groundmass clinopyroxenes show color zoning; β ranges from 1.715 to 1.720. Plagioclase laths are zoned in a normal, non-oscillatory fashion from An_{72} to An_{44} (β-1.570-1.555). Titanomagnetite is optically homogeneous in reflected light, but the X-ray diffraction pattern shows broad, unresolved back reflections suggesting compositional zoning. Assuming it to be an ideal Fe_3O_4–Fe_2TiO_4 solid solution, the average cell dimension (8.435 ± 0.005 Å) indicates an ulvöspinel content of approximately 30 mole percent (Lindsley, 1962). Untwinned alkali feldspar (β = 1.534-1.535) is probably an anorthoclase.

XENOLITHS

In addition to the megacrysts described in the next section, the analcime basanites and basanitoids contain a variety of xenoliths, predominantly olivine-rich types up to 20 cm across. Lherzolites are most common, but dunites, harzburgites, and orthopyroxenites also occur. These ultrabasic xenoliths are medium- to coarse-grained (1-6 mm) allotriomorphic assemblages with varying proportions of olivine (Fa_{11-12}; β = 1.673-1.675), enstatite (Fs_{12-13}; γ = 1.679-1.681), bright green chrome diopside (β = 1.686, $2V_\gamma = 60°$), and red-brown picotite. Strain bands in olivine (compare Talbot and others, 1963) and exsolution structures in the pyroxenes are typical. The compositions of the essential mineral constituents are comparable with those in ultrabasic xenoliths from other Tertiary basaltic localities in New South Wales (Wilshire and Binns, 1961). Small aggregates of two or three grains and single xenocrysts derived from such xenoliths are abundantly scattered throughout the lavas. These and the xenolith margins display the usual reaction relationships with the host rock (Ernst, 1936; Wilshire and Binns, 1961; White, 1966).

Fine grained pyroxenites (0.2-0.5 mm grain size) are a distinctive but rare type of xenolith. Only three examples, 1 to 2 cm in size, have been observed. They consist of orthopyroxene (Fs_{24-27}; γ = 1.694-1.698) and clinopyroxene (β = 1.689-1.695), each showing complex exsolution structures, with accessory green or grayish spinel. One also contains a little untwinned andesine (An_{38}; β = 1.552). Their significantly different textures and mineral compositions suggest no obvious relationship to the much more abundant olivine-bearing ultrabasic xenoliths.

[1] Refractive indices quoted in this paper were measured on mineral crushes or oriented grains plucked from thin sections, using closely-spaced calibrated immersion oils and Na light. They are believed accurate to within ±0.001 for feldspar, ±0.002 for olivine, pyroxene, and amphibole, and ±0.003 for spinel. Compositions deduced from optical properties are taken from Deer, Howie, and Zussman, *Rock Forming Minerals*, v. 1 to 5, (Longmans, London, 1962-63).

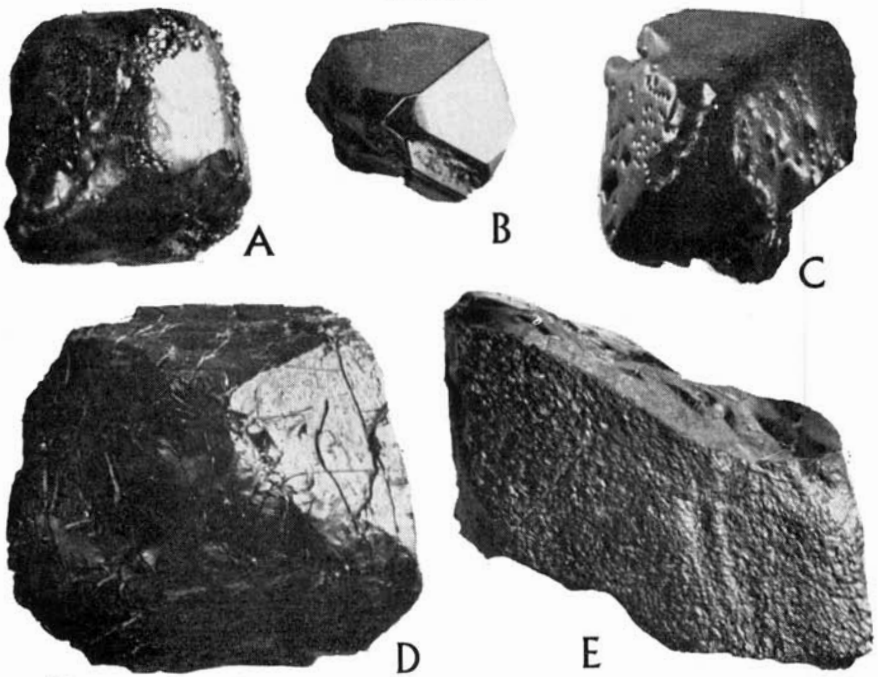
Small xenoliths of teschenite and alkali dolerite, and inclusions of graywacke, siltstone, and shale derived from the underlying Paleozoic basement have also been observed. The more arenaceous types among the latter commonly show areas of pale brownish glass indicative of partial melting and are surrounded by clinopyroxene-rich reaction coronas (compare Wilshire, 1961; Wilkinson, 1962).

MEGACRYSTS

Unusually large crystals, quite distinct in size, habit, and composition from xenocrysts derived from the ultrabasic xenoliths, are scattered throughout all but the topmost flow. They are most abundant in the banded flow at the middle of the sequence and tend to be concentrated toward the eastern end of the exposures (that is, the higher end, presumably closer to the source of eruption). Many of the investigated specimens were collected from decomposed basanites and overlying soil.

Minerals occurring as megacrysts are described separately below, but the following comments apply in general. 1. Most megacrysts are single crystals devoid of inclusions. Many show somewhat corroded euhedral or subhedral habits (pl. 1). 2. They rarely display deformational

PLATE 1



Megacrysts from decomposed analcime basanite and basanitoid; twice natural size. A. ilmenite crystal showing corroded rhombohedral (?) habit. B. zircon with hyacinth habit and pitted prism face (lower right). C. corroded spinel octahedron. D. portion of a euhedral clinopyroxene crystal. E. corroded prism face on a clinopyroxene crystal.

or exsolution structures. Although some crystals are fractured, cleavage is lacking or only very poorly developed. Pyroxenes and spinels are difficult to distinguish megascopically because of their similar conchoidal fracture and black vitreous appearance. 3. Although careful optical and X-ray measurements fail to reveal any compositional zoning in individual megacrysts, separate crystals in all flows, even adjacent megacrysts in the one thin section, may have substantially different compositions.

Clinopyroxene megacrysts up to 4 cm in size are by far the most abundant type. Euhedral varieties have well developed prism faces and dome terminations. They are colorless in thin section, but crushed material examined in oil shows a pale smoky-brown non-pleochroic color. The β refractive indices of separate megacrysts range from 1.692 to 1.707, higher values correlating with a slightly deeper color. Dispersion of the optic axes ($r>v$) is distinct to strong. A few clinopyroxene megacrysts contain tiny rectangular orthopyroxene inclusions, presumably developed by exsolution.

Chemical analyses of two megacrysts (table 2), with refractive indices representing almost extreme values in the observed range, show this clinopyroxene to be aluminian augite. Most of the aluminum is contained as Tschermak's molecule, $CaAl_2SiO_6$. Sodium is also comparatively high, but since Fe^{+++} is not sufficient to satisfy Na entirely as acmite, a small jadeite component is indicated. Disregarding the effects of Ti, the variations in refractive indices of these and other clinopyroxene megacrysts evidently reflect differences in Fe/Mg content.

Spinel is the next most abundant type of megacryst, occurring as corroded octahedra or fragments up to 1.5 cm across. These are distinctively gray in thin section or crush, but the color of separate megacrysts varies from pale gray to almost opaque. A systematic relationship exists between color intensity, refractive index, and cell dimension. Extreme values are as follows:—

color	—	light gray	very deep gray
n	—	1.765	1.805
a ($\pm$0.003Å)	—	8.114	8.145

The chemical analysis of a medium gray variety with intermediate properties is given in table 3. The insoluble nature of this mineral prevented reliable determination of FeO, but the calculated formula clearly requires much of the iron to be trivalent. The spinel is a ferrian pleonaste with a small ulvöspinel content, for which the relationship between composition, *n*, and *a* corresponds well with those presented by Deer, Howie, and Zussman (1962, fig. 6). It is apparent that differences between individual megacrysts again reflect variation in Fe/Mg ratios. Darker gray crystals may also be relatively enriched in ferric iron.

Poorly-cleaved prismatic or corroded megacrysts of *kaersutite* up to 5 cm in length are comparatively scarce. Megascopically black and vitreous, these are deep red-brown and strongly pleochroic in thin section and crushes. Assuming reasonably uniform Ti contents, variation in Fe/Mg ratio between different megacrysts is once more suggested by a

TABLE 2

Chemical analyses and properties of clinopyroxenes

	Analyses 1	2	3
SiO_2	48.12	49.52	46.95
TiO_2	1.95	0.77	2.12
Al_2O_3	8.76	9.10	7.33
Cr_2O_3	0.00	0.08	...
Fe_2O_3	2.20	1.61	2.96
FeO	6.30	5.18	4.60
MnO	0.16	0.15	0.10
MgO	14.21	16.06	12.95
NiO	0.05	0.00	...
CaO	16.68	16.28	21.42
Na_2O	1.55	1.35	0.69
K_2O	0.05	0.13	tr.
H_2O^+	0.06	0.00	0.47
H_2O^-	0.02	0.00	0.16
P_2O_5	0.05	0.08	...
Total	100.16	100.31	99.75

Cation contents (6 oxygens, Z = 2.00)	1	2	3
Si	1.770	1.796	1.758
Al^{iv}	0.230	0.204	0.242
Al^{vi}	0.149	0.185	0.082
Ti	0.054	0.021	0.060
Cr	0.000	0.002	...
Fe'''	0.061	0.044	0.083
Fe''	0.194	0.157	0.144
Mn	0.005	0.005	0.003
Mg	0.778	0.868	0.723
Ni	0.002	0.000	...
Ca	0.657	0.632	0.859
Na	0.110	0.095	0.050
K	0.002	0.006	tr.
Σ (X + Y)	2.012	2.015	2.004
Mole % Ca	38.8	37.1	47.4
Mole % Mg	45.9	50.8	39.9
Mole % ΣFe	15.3	12.1	12.7
α	1.700	1.689	1.695
β	1.705	1.694	1.699
γ	1.725	1.714	1.720
$2V\gamma$ ($\pm 2°$)	47°	50°	46-54
γ:c	46°	42°	...
D	3.38 gm/cc	...	...

1. Megacryst in basanitoid (table 1, no. 2), University site, Armidale (analyst: G. I. Z. Kalocsai).

2. Megacryst in analcime basanite, University site, Armidale (analyst: G. I. Z. Kalocsai).

3. Phenocrysts in analcime-olivine theralite (table 1, no. 3), Square Top intrusion, Nundle, New South Wales (Wilkinson, 1966).

TABLE 3

Chemical analysis and properties of spinel megacryst

from University site, Armidale, New South Wales

		Cation contents (32 oxygens)	
SiO_2	0.17	Si	0.035
TiO_2	0.76	Ti	0.119
Al_2O_3	59.48	Al	14.602
Cr_2O_3	0.02	Cr	0.003
Fe_2O_3	7.67	Fe'''	1.202
FeO*	14.84	Fe''	2.584
MnO	0.12	Mn	0.021
MgO	17.21	Mg	5.340
ZnO	0.12	Zn	0.019
NiO	0.08	Ni	0.014
CaO	0.01	Ca	0.003
Total**	100.48	Σ(R''' + R'''')	15.96
		ΣR''	7.98
		Mole % ulvöspinel	1.5
		Mole % magnetite	7.8
		Mole % spinel	68.5
		Mole % hercynite	22.2
		n	1.790±0.003
		a	8.131±0.003 Å
		D	3.84 gm/cc

*Total iron (Fe_2O_3) = 24.16; FeO calculated to make R''' = 2R''.

**Pb, Cu, Co, V not detected.

Analyst: G. I. Z. Kalocsai.

range in optical properties from $\beta = 1.695$ ($\gamma - \alpha = 0.035$) to $\beta = 1.707$ ($\gamma - \alpha = 0.038$). The analysis of one crystal shows high Fe^{+++}/Fe^{++} ratio and low structural water content (table 4), features that are consistent with its comparatively high birefringence and low extinction angle (compare Wilkinson, 1961).

Anorthoclase is present in roughly equal abundance to kaersutite, as water-clear uncleaved crystals up to 2 cm in size. Unlike other megacrysts, these show no recognizable crystal form. Fine cross-hatched twinning is characteristic, and the β refractive index (1.536) does not vary. Partial analysis of one crystal by G. I. Z. Kalocsai gave $K_2O = 2.60$ percent, $Na_2O = 9.04$, $CaO = 0.76$ wt percent, corresponding to $Or_{15}Ab_{81}An_4$ mole percent. Qualitative X-ray fluorescence study indicated the presence of iron and traces of strontium.

Rare *ilmenite* megacrysts occur as highly corroded equant crystals, probably rhombohedra, up to 2 cm in size. Partial analyses by G. I. Z. Kalocsai of two megacrysts ($Fe_2O_3 = 9.60, 9.70$; $FeO = 34.20, 35.35$;

TABLE 4

Chemical analysis and properties of kaersutite megacryst from University site, Armidale

		Cation contents (24 O, OH)	
SiO_2	40.14	Si	5.976
TiO_2	6.05	Al^{iv}	2.024
Al_2O_3	14.50	Al^{vi}	0.519
Cr_2O_3	0.04	Ti	0.677
Fe_2O_3	5.92	Cr	0.005
FeO	6.05	Fe'''	0.664
MnO	0.12	Fe''	0.753
MgO	12.03	Mn	0.015
NiO	0.00	Mg	2.667
CaO	10.14	Ca	1.617
Na_2O	3.00	Na	0.866
K_2O	1.71	K	0.325
H_2O^+	0.46	OH	0.456
H_2O^-	0.05		
P_2O_5	0.09	ΣY	5.300
		ΣX	2.808
Total	100.30		
		α	1.681, pale yellow brown
		β	1.704, deep reddish brown
		γ	1.719, deeper brown
		$2V\alpha$	$75° \pm 2°$
		$\gamma:c$	$2°$

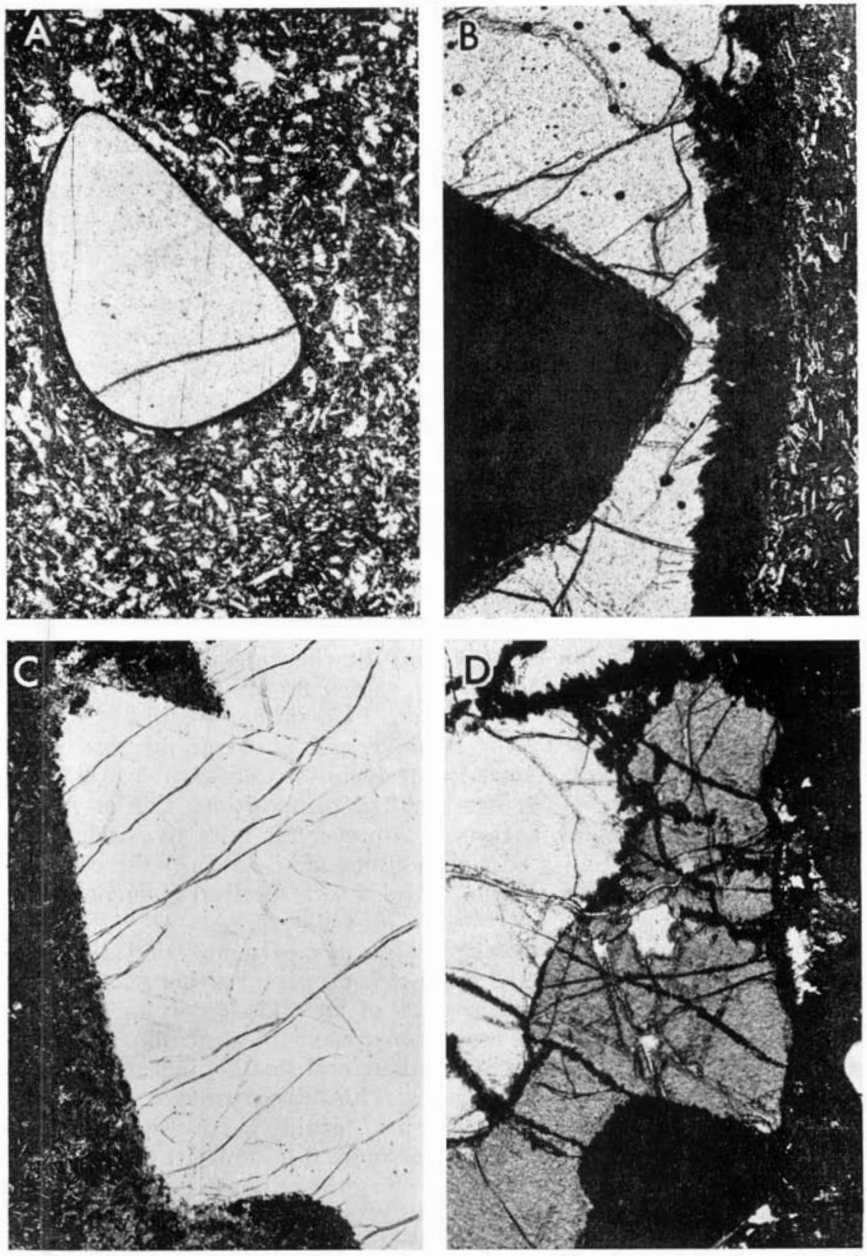
Analyst: G. I. Z. Kalocsai.

MgO = 5.80, 5.92 wt percent) indicate 9 mole percent haematite and 21 percent geikielite in solid solution.

Exceptionally rare *zircon* megacrysts have been observed only among loose material derived from weathered rock. All are deep ruby red in color, and one large crystal shows a well developed, slightly corroded hyacinth habit. To ensure that possible garnet megacrysts were not overlooked, all zircons recovered were tested for anisotropism.

Most large orthopyroxene crystals in the analcime basanites and loose material are pale-green in color, well cleaved, and contain numerous exsolution lamellae. They rarely exceed 2 mm in size, and their compositions ($Fs_{11\text{-}14}$; γ = 1.678-1.682) are comparable with those of enstatites in the lherzolite and other ultrabasic xenoliths, from which they are almost certainly xenocrystal derivatives. Among over 200 glassy pyroxene megacrysts examined optically, however, only one proved to be orthopyroxene. This is an uncleaved, dark green (almost black) prismatic crystal 1 cm in length. Crushed fragments are colorless and free from exsolution lamellae, with a refractive index (γ = 1.692) differing significantly from those of xenocrystal enstatites derived from ultrabasic xenoliths. A partial analysis by G. I. Z. Kalocsai revealed Al_2O_3 = 8.03, FeO (total iron) = 9.57, MgO = 27.75, CaO = 1.60, Na_2O = 0.38 wt percent, indicating *aluminian bronzite* with composition $Ca_3Mg_{81}Fe_{16}$ atom percent.

PLATE 2



Photomicrographs of megacrysts and composite particles in analcime basanite and basanitoid; magnification x 40, ordinary light. A. light gray spinel crystal with narrow magnetite rim. B. dark gray, almost opaque spinel octahedron enclosed by a large clinopyroxene crystal which shows a turbid reaction margin against host basanite (right). The tiny opaque inclusions in pyroxene are pyrrhotite. C. portion of a large irregularly-shaped anorthoclase crystal showing fractures but poor cleavage. D. margin of a composite particle with clinopyroxene (light gray), kaersutite (dark gray), and ilmenite (opaque, lower center). Both pyroxene and kaersutite show fractures but no cleavage. Reaction between the host (right) and the clinopyroxene has extended along fractures at the top of the photograph.

The estimated proportions (by wt) of the various megacrysts are clinopyroxene, 85 percent; spinel, 10 percent; kaersutite, 2 percent; anorthoclase, 2 percent; ilmenite, 1 percent; zircon and bronzite, trace.

COMPOSITE MEGACRYSTS

Although comparatively scarce, large polymineralic particles regarded as composite megacrysts provide evidence of a genetic relationship between most of the minerals listed above. Assemblages so far observed include:

1. *Clinopyroxene-spinel.*—Some ten of the clinopyroxene megacrysts studied enclose one or more small gray spinel grains, usually euhedral or subhedral octahedra about 0.5 mm in size, at or near their margins pl. 2-B). In one example the clinopyroxene itself consists of several interlocking crystals with spinels concentrated along grain boundaries. The refractive indices of the two components in such particles are systematically related, observed extreme cases being a magnesian association of clinopyroxene ($\beta = 1.692$) with light gray spinel (n = 1.770), and a more iron-rich assemblage of clinopyroxene ($\beta = 1.705$) and deep gray spinel (n = 1.805).

2. *Clinopyroxene-spinel-olivine.*—Two clinopyroxene megacrysts with gray spinel inclusions also contain a small subhedral olivine inclusion near their margins. In one of these the following optical properties were measured: clinopyroxene, $\beta = 1.700$; spinel, n = 1.795; olivine, $\beta = 1.699$. The composition of the olivine, Fa_{23}, differs significantly from that of its analogues in the ultrabasic xenoliths. Large olivine "xenocrysts", especially those lacking picotite inclusions or strain bands, were investigated to ascertain whether any had compositions similar to the olivine in this composite megacryst. However all refractive index and X-ray measurements indicated compositions close to Fa_{11}, thereby supporting the interpretation that such grains were derived from the ultrabasic xenoliths.

3. *Clinopyroxene-kaersutite-spinel-ilmenite.*—One of the clinopyroxene megacrysts encloses a small grain of kaersutite. Furthermore, a large composite particle 2 cm across consists of an allotriomorphic granular assemblage (grain size 5 mm) of clinopyroxene ($\beta = 1.705$) and kaersutite ($\beta = 1.694$, $\gamma - \alpha = 0.034$), with several small spinel (n = 1.805) and ilmenite grains located between and within the pyroxenes and amphiboles. Some clinopyroxene and kaersutite grains in this particle have grown in parallel orientation, but their mutual boundaries are smoothly curved. Judging from the refractive indices, the clinopyroxene and spinel are close to the most iron-rich single crystal equivalents, whereas the kaersutite appears more magnesian than the majority of single megacrysts found elsewhere in the analcime basanites.

4. *Clinopyroxene-orthopyroxene.*—Only one example of a coarse graphic intergrowth of clinopyroxene ($\beta = 1.692$) and orthopyroxene ($\gamma = 1.691$), forming a large composite particle 1.2 cm across, was observed in thin section. Throughout this particle, which essentially consists of one large and several smaller intergrowths, the two minerals

maintain a common orientation (c-axes and cleavages parallel). Clinopyroxene predominates, but orthopyroxene is more abundant than in exsolution intergrowths shown by some other clinopyroxene megacyrsts, and the texture is quite different. Refractive indices indicate that the clinopyroxene compares with the magnesian extreme of single crystal megacrysts, while the orthopyroxene appears similar to the one example of aluminian bronzite.

No composite particles containing anorthoclase or zircon were recorded.

Most megacrysts and composite particles show evidence of reaction with the enclosing analcime basanite or basanitoid. Clinopyroxenes have narrow marginal zones clouded by an abundance of tiny inclusions. Spinels and ilmenites are rimmed by magnetite. Anorthoclases are surrounded by a narrow zone of plagioclase. Kaersutite margins show no pronounced reaction coronas but may be dusted with tiny opaque inclusions. The extent of marginal effects varies considerably in different specimens, but their width rarely exceeds 50-100μ. These reaction relationships were probably developed in part during final consolidation of the host rocks, but the highly corroded outlines and pitted faces on most megacrysts suggest that a state of disequilibrium existed for an appreciable period prior to eruption.

DISCUSSION

Their frequently subhedral to euhedral habit, poorly developed cleavage, and general freedom from exsolution or deformational structures suggest that the megacrysts crystallized directly from a melt. However the corroded faces and marginal reaction relationships imply either that the megacrysts crystallized from the parent magma of the basanitic lavas under pressure-temperature conditions substantially different to those prevailing during the eruptive phase, or alternatively that they are accidental and hence genetically unrelated to their host rocks.

It is pertinent here to examine likely differences in composition between the aluminian augite megacrysts and the groundmass clinopyroxenes of their basanitic hosts, even though the latter are too fine-grained for effective separation and analysis. Kushiro (1960), Le Bas (1962), Huckenholz (1965a, 1965b, 1966), and White (1966) have shown that clinopyroxene compositions in basic rocks depend mainly on the level of undersaturation in their host rocks. Comparing data presented by these authors and by Wilkinson (1966) for clinopyroxenes in theralites from shallow intrusive bodies and for groundmass clinopyroxenes in nepheline basanite and basanitoid lavas, it appears probable that the fine-grained groundmass clinopyroxenes in the Armidale analcime basanites and basanitoids are titaniferous salites, richer in Ti (2.0-3.5 percent TiO_2) and Ca (20-24 percent CaO), poorer in Si (44-47 percent SiO_2), Mg (10-12 percent MgO) and Na (0.5-1.2 percent Na_2O), and comparable in Al (6-10 percent Al_2O_3), relative to the two analyzed megacrysts (compare comparative data for theralite and its clinopyroxene from the Square Top intrusion, tables 1 and 2). The Al content of the groundmass clino-

pyroxene can probably be attributed to enrichment in the $CaTiAl_2O_6$ component (Kushiro, 1960), whereas in the megacrysts it is mainly present as Tschermak's molecule ($CaAl_2SiO_6$). Since Clark, Schairer, and de Neufville (1962) have shown experimentally that solid solution of $CaAl_2SiO_6$ in diopsidic clinopyroxene is favored by high pressure, the compositions of the clinopyroxene megacrysts suggest their high pressure derivation.

There are at present no high pressure experimental data available for basalts directly comparable with the Armidale basanites (9.7-11.1 percent normative nepheline), but comparisons can be made with the results obtained by Green and Ringwood (1967) and Bultitude and Green (1968) for an alkali olivine basalt (2.2 percent *ne*) and an olivine nephelinite (15.3 percent *ne*). Clinopyroxene and orthopyroxene are liquidus phases in the alkali-olivine basalt at 13.5 kb (anhydrous), the P-T field of orthopyroxene probably being extended by hydrous conditions (Green and Ringwood, 1964, 1967). Orthopyroxene was not observed in anhydrous runs on olivine nephelinite at pressures up to 36 kb, but under wet conditions it is a prominent near-liquidus phase at 18 kb (with minor olivine and clinopyroxene) and 23.5 kb (with minor olivine and garnet). The synthetic pyroxenes are notably aluminous, and the clinopyroxenes are also relatively subcalcic. Compositional similarities with rare aluminian bronzite and abundant aluminian augite megacrysts are therefore evident, supporting the view that the latter are high pressure cognate phases. The absence or rarity of spinel in the experimental studies, compared with its relative abundance among the megacrysts, can probably be attributed mainly to differing oxidation states in the two systems. Although an accidental origin for the megacrysts cannot be completely ruled out, the presence of kaersutite—a phase restricted to undersaturated alkaline rocks (Wilkinson, 1961)—also implies a cognate relationship.

The aluminian augite and bronzite, accompanied by kaersutite and andesine, in "alkali olivine basalt or hawaiite" (normative hyperthene = 8.8 percent) from Taka-sima, Japan (Kuno, 1964) are among the few examples of megacrysts or "phenocrysts" previously assigned a high pressure cognate origin. There are many other references to basaltic rocks containing megacrysts, especially of clinopyroxenes enriched in Tschermak's molecule but including pyrope-rich garnet, kaersutite, titanbiotite, olivine, magnetite, plagioclase, and anorthoclase (Lausen, 1927; Ernst, 1936; Wilkinson, 1962; Brousse and Berger, 1965; Huckenholz, 1965b; Mason, 1965; Vitaliano and Harvey, 1965; Aoki, 1966; White, 1966). Intepretations placed on these vary, and in some cases no data are given for the host rocks, but the possibility that they represent additional occurrences of cognate, high pressure crystallization products deserves further investigation.

If it is assumed that during crystallization at high pressures the precipitating phases trend toward more iron-rich compositions (compare Green and Ringwood, 1967, tables 8, 9) and that the refractive indices of the megacrysts reflect variations in their Fe-Mg ratios, then

it is possible to deduce a high pressure crystallization sequence from the rare composite megacrysts at Armidale. Clinopyroxene, which occurs in most associations, provides the essential key to such an interpretation. Crystallization evidently commenced with precipitation of minor orthopyroxene, either preceding or accompanied by relatively magnesian clinopyroxene. The major phase of crystallization was characterized by abundant clinoproxene and spinel whose compositions, as indicated by optical data, display sympathetic variation in response to differing Fe contents of the parental melt. Two composite particles, one shown to have a clinopyroxene of intermediate iron content, indicate that clinopyroxene and spinel were very occasionally joined by olivine. The most iron-rich clinopyroxene and spinel were joined by relatively magnesian kaersutite and ilmenite. Intratelluric crystallization then concluded with the separation of iron-enriched kaersutite, probably accompanied by anorthoclase.

Experimental studies on a variety of olivine-normative basaltic compositions under both dry and hydrous conditions indicate that olivine and plagioclase are important liquidus or near-liquidus phases at pressures below about 10 kb, whereas pyrope-rich garnet figures prominently near the liquidus above pressures of about 18 kb (compare Yoder and Tilley, 1962; Green and Ringwood, 1964, 1967; Cohen, Ito, and Kennedy, 1967; Bultitude and Green, 1968). The absence of plagioclase and garnet and the scarcity of olivine among megacryst assemblages thus suggest that the main phase of this crystallization sequence took place under pressure conditions broadly equivalent to the topmost mantle or crust-mantle boundary. Later crystallization of kaersutite and anorthoclase may have occurred at somewhat higher levels, possibly within the lower crust.

The occurrence of unzoned megacrysts with different compositions within the one lava flow raises problems. The size and homogeneity of individual megacrysts or the components of composite particles suggest relatively slow growth under conditions permitting continuous equilibrium with the parental melt. If a cognate origin is to be favored, some process whereby successive fractions of megacrysts were effectively removed from further reaction with the liquid, and then remixed, must be invoked. If this were accomplished by accumulation in a temporary magma chamber or on the walls of a conduit, it is perhaps surprising the polycrystalline aggregates are so rare.

Any appraisal of fractionation trends due to the extraction of the megacryst assemblage from their parent liquids is limited by the difficulty of estimating the proportions of the various megacryst phases. In this discussion the abundances obtained by studying thin sections and by weighing material recovered from decomposed basanite will be assumed to represent the ratios in which the megacrysts originally crystallized. The effects of corrosion and selective magmatic transport will be ignored and in view of their scarcity as megacrysts the effects of separating aluminian bronzite and zircon will not be taken into account.

Columns 1 and 2 of table 5 list the calculated bulk compositions of the megacryst assemblage produced during the main phase of high pressure crystallization and of the entire megacryst assemblage, respectively. Both are significantly undersaturated. The main normative constituents are highly calcic plagioclase, magnesian olivine, and diopsidic pyroxene, indicating that the principal fractionation trends arising from separation of the megacryst assemblages from basaltic magmas at high pressures would broadly resemble the more familiar low pressure trends in shallow intrusives, namely depletion in magnesium and calcium, and enrichment in alkalis. At high pressures, spinel clearly plays a most important role. Its removal has the effect of qualifying any tendency toward silica depletion or alumina enrichment.

More specifically, the implications of assuming a cognate relationship between the megacrysts and their host rocks are considered in columns 4 and 5 of table 5. The parental magma from which the Armidale basanites might be derived by even 30 percent crystallization of the megacryst assemblage (much more than is indicated by actual abundances) is itself a liquid of basanitic composition, not differing greatly from the actual host rocks themselves. This is further supporting evidence of a cognate origin.

Although it does not conform to observed abundances, a mixture of 80 percent kaersutite and 20 percent anorthoclase (column 3, table 5) also closely resembles the bulk composition of the host rocks. The differences in titanium and ferrous iron might be reduced by adding some clinopyroxene, spinel, and ilmenite to such a mixture. Thus if kaersutite-rich assemblages were extracted at lower pressures than most of the clinopyroxene and spinel, little additional fractionation need ensue.

Kuno (1964) also concluded that fractionation due to separation of the megacrysts at Taka-sima, which he interpreted as products of crystallization near the crust-mantle boundary, would be similar to that which might arise by separation of olivine, augite, calcic plagioclase, and iron oxide under low pressure conditions. Moreover, Vitaliano and Harvey (1965) indicated that precipitation of what appears to be slightly lower pressure megacryst assemblage (olivine, aluminous clinopyroxene, and andesine) compared with that from Armidale, caused comparatively little fractionation in the host basanitoid ("alkali basalt"). The limited evidence available from three separate localities thus suggests that partial crystallization of basaltic magmas at pressures equivalent to the lower crust or crust-mantle boundary offers no unique explanations for transitions between the more important basaltic magma types. However, fractionation processes at even higher pressures within the mantle might well be responsible for derivation of, for example, alkali olivine basaltic liquids from tholeiitic parents (compare Yoder and Tilley, 1962; Green and Ringwood, 1967; O'Hara and Yoder, 1967). In this connection, further data on garnet-bearing megacryst assemblages such as those in melanephelinite breccia at Kakanui, New Zealand (Mason, 1965; Dickey, 1965) will be awaited with interest.

TABLE 5

Calculated chemical compositions (water free) and norms

	1	2	3	4	5
SiO_2	43.9	43.6	45.5	45.4	44.8
TiO_2	1.4	1.9	4.8	2.5	2.3
Al_2O_3	14.0	14.3	15.7	14.3	14.3
Fe_2O_3	2.5	2.6	4.8	4.1	3.6
FeO	6.7	6.8	4.9	8.8	8.3
MnO	0.1	0.1	0.1	0.2	0.2
MgO	15.3	14.8	9.7	9.3	11.0
CaO	14.8	14.2	8.3	8.2	10.0
Na_2O	1.3	1.5	4.2	4.3	3.4
K_2O	0.1	0.2	1.9	1.9	1.4
P_2O_5	...	...	...	0.9	0.6
Total	100.1	100.0	99.9	99.9	99.9
			Norms		
Or	0.6	1.1	11.1	11.1	8.3
Ab	1.3	2.4	16.5	17.8	12.3
An	32.0	31.7	18.5	14.2	19.5
Ne	5.3	5.5	10.4	10.0	9.0
Di	32.9	30.8	17.7	16.8	21.2
Ol	21.7	21.0	11.1	17.3	18.5
Mt	3.7	3.7	7.0	6.0	5.3
Il	2.7	3.6	5.9	4.7	4.4
Ap	...	...	...	2.0	1.3
Total	100.2	99.8	99.8	99.9	99.8
An	96	93	51	43	56
F	14	13	0	23	20

1. Mixture of 90 percent clinopyroxene and 10 percent spinel megacrysts.
2. Mixture of 85 percent clinopyroxene, 10 percent spinel, 2 percent kaersutite, 2 percent anorthoclase and 1 percent ilmenite megacrysts.
3. Mixture of 80 percent kaersutite and 20 percent anorthoclase megacrysts. Norm includes 1.7 percent excess TiO_2.
4. Average Armidale basanite (table 1).
5. Hypothetical parent basanite obtained by combining 30 percent column 2 with 70 percent column 4.

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