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Mineralogy of Cumulus and Non-Cumulus Ultramafic Rocks from Eastern Papua

by

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MINERALOGY OF CUMULUS AND NONCUMULUS ULTRAMAFIC ROCKS FROM EASTERN PAPUA

ABSTRACT

Ultramafic rocks in the Papuan Ultramafic Belt can be divided into two categories on the basis of their fabric: (1) rocks which have originated by crystal settling from presumably basaltic magma (cumulus ultramafics) and (2) rocks with texture which suggests recrystallization in the solid state (noncumulus ultramafics). From field and petrographic evidence it is thought that the cumulus ultramafics have formed by crystal settling from basaltic intrusions which are now represented by the overlying gabbro zone of the Ultramafic Belt, and that the noncumulus ultramafics are pre-existing upper mantle and formed a floor for the basaltic intrusions (Davies, 1971). The object of this investigation was to determine the mineralogy of the two groups of ultramafics. Olivine, orthopyroxene, clinopyroxene and chrome spinel from rock specimens were analysed by electron probe. Olivine and orthopyroxene from 13 samples of noncumulus ultramafics have compositions in the ranges $Fo_{91.6-93.6}$ and $En_{92.1-93.4}$ whereas the same minerals in the cumulus ultramafics have compositions in the ranges $Fo_{78.3-89.6}$ and $En_{81.2-90.5}$. The tight grouping of compositions for the noncumulus rocks and the wide range of compositions for the cumulus rocks strongly suggest that the two groups have separate origin. The large volume of noncumulus ultramafics coupled with their uniformly highly magnesian character argues against origin by crystal settling from basaltic magma, but is compatible (with some reservations) with origin as a refractory residue formed by partial melting of primitive mantle material.

INTRODUCTION

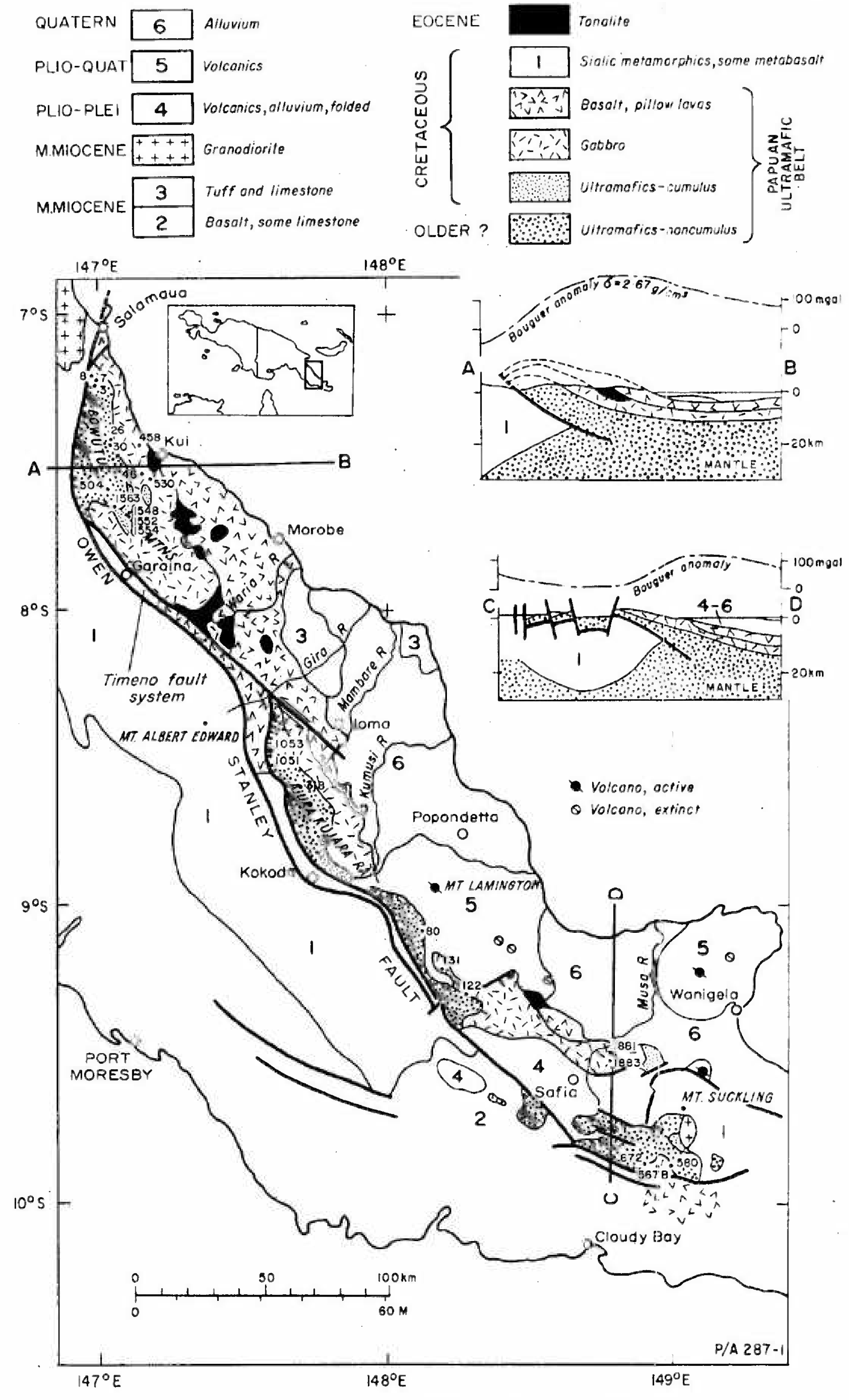
The Papuan Ultramafic Belt is exposed on the northeastern side of the Owen Stanley Range in eastern Papua between 7 and 10°S and 147 and 149°E approximately; length is 400 km (NW-SE) and width is up to 40 km. The belt is thought to be part of an overthrust plate of Mesozoic oceanic crust and upper mantle which was emplaced on a low-angle fault at some time after Upper Cretaceous and before Middle Miocene (Thompson and Fisher, 1967; Davies, 1968).

The Ultramafic Belt consists of an ultramafic zone 4-8 km thick, overlain by a gabbro zone about 4 km thick, which is in turn overlain by a basalt zone 4-6 km thick. Rocks of the ultramafic zone are of two textural types. The majority (more than 90 percent) have a tectonite fabric which records recrystallization in the solid state. The smaller group has textures which indicate origin by crystal settling, presumably from basaltic magma. The two types are here referred to as noncumulus and cumulus ultramafics respectively; this follows the usage of Davies (1969; 1971). The cumulus ultramafics form a discontinuous layer up to 0.5 km thick at the top of the ultramafic zone, and are probably genetically related to the overlying gabbros. The noncumulus ultramafics are thought to be pre-existing upper mantle.

The purpose of this paper is to present mineral analyses of the two types of ultramafic rock and to briefly discuss alternative hypotheses of origin.

The noncumulus ultramafics are predominantly harzburgite with minor dunite and orthopyroxenite. The harzburgite consists of olivine with 20-40% orthopyroxene and disseminated accessory chronite. Grainsize is commonly 4-10 mm and grains are interlocking anhedra with strain lamellae (Plate 2). The dunite is a similar rock but with little or no orthopyroxene. The pyroxenite consists of orthopyroxene anhedra with or without accessory chromite; grainsize is variable from 5 mm to 15 cm. Chromite concentrations

FIG. 1



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PAPUAN ULTRAMAFIC BELT

are rare and clinopyroxene concentrations are not known. Most of the harzburgite is homogeneous with orthopyroxene distributed randomly throughout but some is layered with alternating pyroxene-rich and pyroxene-poor layers. Dunite is closely associated with harzburgite in these layered rocks, in irregular interfingering masses or, less commonly, as dunite dykes and veins. Orthopyroxenite forms veins, dykes, and irregular bodies up to 5 m thick, always intrusive into the other rocks.

The cumulus ultramafics (Plate1, Figs. 1 & 2) are made up of the same minerals as the noncumulus rocks but clinopyroxene is much more common and a little plagioclase is present in some rocks. Rock types are dunite, harzburgite, wehrlite, lherzolite, websterite, ortho- and clino-pyroxenite, and rare chromitite. All of the minerals except plagioclase occur as cumulus phases, though in any one rock specimen some of the minerals may be present only as postcumulus interstitial phases. Compositional layering is common, in contrast to the more homogeneous noncumulus ultramafics. Rocks which contain more than a few percent of plagioclase, or which form part of an outcrop which includes plagioclase-rich layers, are consigned to the gabbro zone and are not included in this description of the cumulus ultramafics. In these rocks plagioclase is commonly a cumulus phase.

For the mineralogical study representative samples were selected from the noncumulus ultramafics (13), cumulus ultramafics (7), probable cumulus ultramafics (2), layered cumulus gabbro (2) and ganular gabbro (1). The two probable cumulates are rocks in which the textural evidence of cumulus origin is not conclusive. One specimen of granular gabbro (458) shows evidence of possible partial recrystallization in the solid state: plagioclase grains are only weakly twinned and form a mosaic texture with 120° triple-point intersections. All of the specimens numbers have the prefix 6552.

PLATE 1

Fig. 1: Cumulus ultramafics: layered ultramafic rock consists of cumulus olivine, orthopyroxene, clinopyroxene and chrome spinel in varying proportions. Pyroxene-rich layers are more resistant to erosion. Wele River South, 7°42'S, 147°07'E.

Fig. 2: Thin section from the above outcrop shows contact between olivine-chrome spinel cumulate (bottom) and orthopyroxene-olivine-clino-pyroxene cumulate (top). Overgrowth has disguised the original shapes of the settled grains; cumulus origin is suggested by orientation of c-axes of orthopyroxene grains parallel to the contact. Average grain size is 1 mm top and 5-7 mm bottom. Specimen 1548. Crossed nicols.

PLATE 2

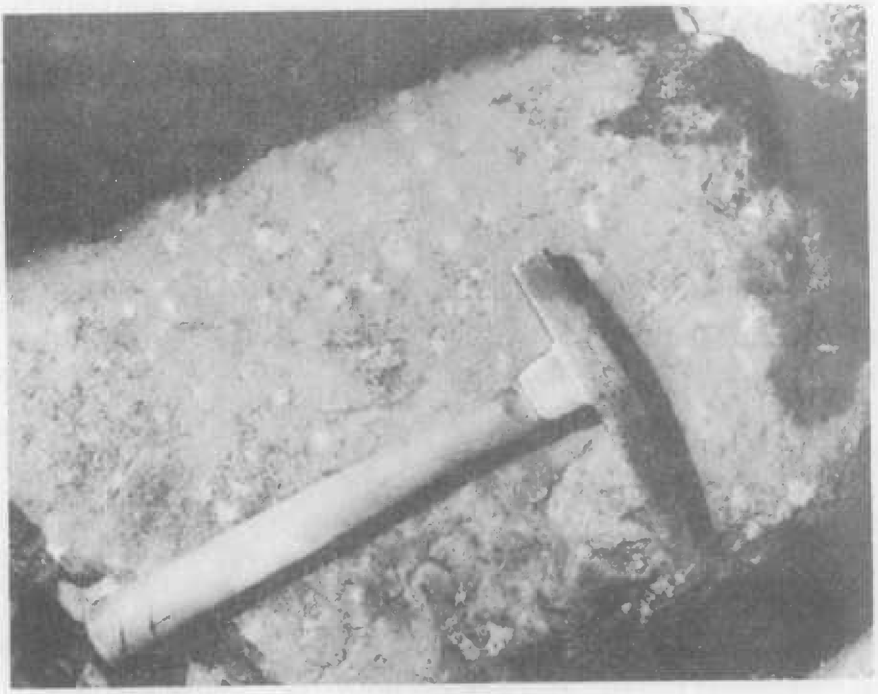

Fig. 1: Noncumulus ultramafics: Typical harzburgite consists of orthopyroxene grains (lighter colour) randomly distributed in olivine-rich rock.

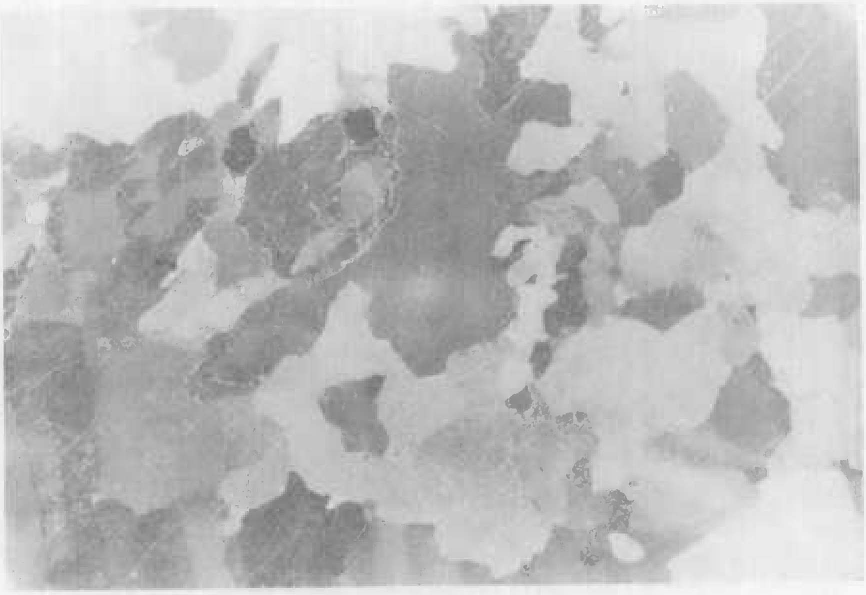

Fig. 2: Typical harzburgite (noncumulus ultramafics) shows tectonite fabric of interlocking anhedra of olivine and minor orthopyroxene. Both minerals show strain lamellae. The larger grains are about 4 mm across. Crossed nicols.

Electron Probe Analyses

Olivine, orthopyroxene, clinopyroxene and chromite were analysed on a JEOL JXA-3A Electron Probe using a specimen current of 0.1 uA. Analysed mineral standards were used in order to keep errors in absorption, fluorescence and atomic number corrections to a minimum. Corrections for absorption and fluorescence were computed using a program modified from Frazer et al. (1966).

Most grains were analyzed for SiO_2 and MgO but the accuracy of the analyses in the case of silicate minerals is considered to be doubtful because of errors due mainly to the low take-off angle of the instrument (20^o). Values for wt%MgO were calculated assuming wt% ($MgSiO_3 + CaSiO_3 + FeSiO_3 + Al_2O_3 + Cr_2O_3$) = 100 for pyroxenes. Errors in calculated MgO due to components unaccounted for are probably less than 0.5 wt%. Total Fe is expressed as FeO. The estimated uncertainty for FeO analyses is about 2-4% of the amount present but light elements in very small concentrations may be in error by as much as 15% of the amount present. Some of the cumulus ultramafics, are zoned with Ca and Al up to 10% higher in rims than in cores. In these cases, the analysis presented is the average of 4-6 points.

TABLE 1. PETROGRAPHIC NOTES

No.	Location	Olivine	Ortho-pyroxene (vol.%)	Clino-pyroxene (vol.%)	Spinel (vol.%)	Notes
3	7°14'S, 147°02'E	98			2	Partly serpentinized
7	7°13'S, 147°02'E	98			2	Probable cumulate, partly serpentinized
8	7°13'S, 147°01'E	15	80	4	1	Probable cumulate
26	7°22'S, 147°06'E	10	85		5	Very coarse-grained orthopyroxenite dyke
30	7°24'S, 147°06'E	80	19		1	Undulose ol, kinked opx
46	7°32'S, 147°11'E	90	8	1	1	
80	9°08'S, 148°10'E	93	5		2	
122	9°21'S, 148°17'E	4	95		1	Cumulus opx, slightly deformed
131	9°15'S, 148°13'E	60	35		5	Ultramafic layer in layered gabbro
318	8°40'S, 147°44'E	80	18		2	
458	7°26'S, 147°10'E	5	10	35		Granular gabbro with 50% plag.
504	7°34'S, 147°05'E	80	18	1	1	
530	7°35'S, 147°13'E		15	70		Cumulus ol,opx, cpx, with 15% post-cumulus plag
567B	9°13'S, 148°56'E	10	55	30		5% plag
580	9°52'S, 148°58'E	15	60	25		Cumulus ol, opx, cpx
672	9°52'S, 148°52'E	80	19		1	
1051	8°33'S, 147°36'E	50	50			Undulose ol
1053	8°32'S, 147°36'E	70	28		2	Undulose ol
1425	10°03'S, 150°59'E		60	20		Gabbro with 20% plag
1548	7°42'S, 147°07'E	40	54	5	1	Cumulus ol,opx
1552	7°42'S, 147°07'E	45	45	9	1	
1554	7°42'S, 147°08'E	2	60	38		Cumulus ol,opx, cpx
1563	7°38'S, 147°05'E	80	19		1	
1881	9°30'S, 148°44'E	50		48	2	Cumulus ol, opx, cpx plag
1883	9°31'S, 148°44'E	10	78	5	2	Cumulus ol, opx, cpx with 5% post-cumulus plag
1971	9°50'S, 148°45'E	97	2		1	

TABLE 2: MINERAL COMPOSITIONS

1. Olivine

(a) Olivine from ultramafic rocks with cumulus texture

No.	FeO	NiO	%Fo	No.	Feo	NiO	%Fo
122	12.6	0.3	86.9	1548	10.1	0.1	89.6
567B	18.5	0.2	80.1	1554	7.5	0.04	86.3
580	16.1	0.2	82.8	1883	20.0	0.2	78.3

(b) Olivine from ultramafics with probable cumulus texture

No.	FeO	NiO	%Fo
7	10.1	0.2	89.5
8	9.1	0.3	90.5

(c) Olivine from gabbro

No.	FeO	Nio	%Fo
131	16.9	0.3	82.6
458	18.9	0.2	80.4
1881	11.6	0.3	87.7

(d) Olivine from ultramafic rocks without cumulus texture

No.	FeO	NiO	%Fo	No.	FeO	Nio.	%Fo
3	7.2	0.4	92.3	504	7.5	0.4	92.2
26	6.5	0.4	93.2	672	6.9	0.4	92.8
30	7.7	0.3	92.0	1051	7.7	0.4	92.0
46	7.7	0.4	91.7	1053	7.6	0.4	92.1
80	7.3	0.4	92.3	1552	6.2	0.2	93.6
318	7.8	0.4	91.8	1563	7.5	0.4	92.2
				1971	7.9	0.4	91.6

2. Orthopyroxene

(a) Orthopyroxene from ultramafic rocks with cumulus texture

No.	Al_2O_3	Cr_2O_3	FeO	CaO	$\frac{Mg}{MG+Fe}$	En	Fs	$CaSiO_3$
122	0.8	0.3	7.6	0.7	.888	.876	.111	.012
530	2.0	0.2	11.8	1.4	.816	.793	.179	.028
567B	2.4	0.4	11.3	1.4	.824	.802	.172	.027
580	1.3	0.5	10.24	1.2	.838	.820	.158	.023
1548	1.0	0.7	6.4	0.8	.905	.892	.093	.150
1554	1.1	0.5	7.6	1.4	.840	.874	.111	.025
1883	1.3	0.7	12.3	0.8	.812	.799	.186	.015

(b) Orthopyroxene from ultramafic rocks with probable cumulus texture

No.	Al_2O_3	Cr_2O_3	Feo	CaO	$\frac{Mg}{Mg+Fe}$	En	Fs	$CaSiO_3$
8	0.7	0.4	5.9	0.9	.913	.897	.086	.018

(c) Orthopyroxene from gabbro and norite

No.	Al_2O_3	Cr_2O_3	FeO	CaO	$\frac{Mg}{Mg+Fe}$	En	Fs	$CaSiO_3$
131	1.7	0.4	18.8	0.8	.702	.691	.294	.015
458	1.8	0.3	9.7	0.8	.851	.837	.147	.016
1425	1.7	0.5	13.1	1.5	.793	.770	.204	.050

(d) Orthopyroxenes from ultramafic rocks without cumulus texture

No.	Al_2O_3	Cr_2O_3	FeO	CaO	$\frac{Mg}{Mg+Fe}$	En	Fs	$CaSiO_3$
26	0.1	0.1	4.9	0.1	.930	.928	.070	.002
30	0.3	0.4	4.9	0.3	.929	.924	.071	.005
46	1.0	0.5	4.6	1.1	.932	.912	.067	.021
80	0.5	0.3	4.6	0.4	.934	.927	.066	.006
318	0.5	0.4	5.5	0.5	.921	.911	.079	.010
504	1.5	0.5	4.7	1.1	.930	.906	.068	.021
672	0.9	0.4	4.5	0.5	.934	.926	.065	.009
1051	0.6	0.4	5.0	0.3	.928	.923	.072	.006
1053	0.5	0.3	5.0	0.4	.927	.920	.072	.008
1563	1.1	0.4	5.1	0.9	.925	.909	.074	.017
1871	1.2	0.5	4.9	0.5	.928	.918	.071	.031

3. Clinopyroxene

(a) Clinopyroxene from ultramafic rocks with cumulus texture

No.	Al_2O_3	Cr_2O_3	FeO	CaO	$\frac{Mg}{Mg+Fe}$	ClEn	ClFs	$CaSiO_3$
530	1.8	0.4	5.1	21.7	.859	.487	.080	.433
567B	2.5	1.0	5.1	21.2	.858	.490	.081	.430
580	2.6	0.8	4.4	21.4	.877	.497	.070	.433
1548	1.0	1.3	2.00	22.3	.941	.528	.031	.442
1554	1.1	0.3	3.1	21.8	.916	.524	.048	.428
1883	2.0	1.4	4.9	22.2	.858	.472	.078	.450

(b) Clinopyroxene from ultramafic rocks with probable cumulus texture

No.	Al_2O_3	Cr_2O_3	FeO	CaO	$\frac{Mg}{Mg+Fe}$	En	Fs	$CaSiO_3$
8	0.7	0.7	2.00	22.3	.943	.539	.030	.435

(c) Clinopyroxene from gabbros

No.	Al_2O_3	Cr_2O_3	FeO	CaO	$\frac{Mg}{Mg+Fe}$	En	Fs	$CaSiO_3$
458	1.9	0.2	3.4	21.9	.906	.512	.053	.434
1425	1.9	0.7	5.7	21.9	.831	.468	.089	.442
1881	2.5	1.6	2.9	21.8	.861	.515	.045	.440

(d) Clinopyroxene from ultramafic rocks without cumulus texture

No.	Al_2O_3	Cr_2O_3	FeO	CaO	$\frac{Mg}{Mg+Fe}$	En	Fs	$CaSiO_3$
46	1.0	0.6	1.50	22.2	.959	.543	.023	.434
504	1.0	0.6	1.60	23.2	.954	.520	.025	.455

4. Chromite

	Al_2O_3	Cr_2O_3	FeO	MgO
9 noncumulus ultramafics	5-16	53-62	16-22	9-13
Cumulate 122	13.6	55.7	20.1	11.1
Cumulate 131	19.9	32.5	37.5	6.1

RESULTS

Analyses are presented in Table 2 and summarized in Figure 2 and 3. The following points are noted.

1) Minerals of the cumulus rocks have a wide range of Mg/(Mg+Fe) whereas those of the noncumulus ultramafics are closely grouped.

2) The compositional ranges of Mg/(Mg+Fe) for cumulus and noncumulus rocks are mutually exclusive; the noncumulus rocks are more magnesian.

3) The probable cumulates (rocks in which the textural evidence for cumulus origin is not conclusive) are more magnesian then most of the cumulates.

4) Tn the noncumulus ultramafics CaO content is low but variable. Clinopyroxene is present in only 2 of the 13 specimens analysed, and then only as exsolution lamellae or rare small exsolved(?) grains. CaO content of orthopyroxene is generally low (maximum 1.1%) and falls off very rapidly with increasing Mg/(Mg+Fe).

5) In the cumulus ultramafics clinopyroxene is common. Compositions are similar to those of clinopyroxenes from layered tholeiitic complexes but are slightly more calcic.

6) The fairly low and variable CaO content of orthopyroxene in the ultramafic cumulates is almost certainly due to the effect of varying amounts of exsolution of clinopyroxene. The low and variable CaO contents of noncumulus orthopyroxenes cannot be attributed to exsolution of clinopyroxene which occurs rarely and then only in the most calcic orthopyroxenes.

7) Al_2O_3 content of orthopyroxene is generally lower in noncumulus than in cumulus ultramafics and varies sympathetically with CaO: noncumulus pyroxenes contain 0.1-1.5% Al_2O_3 whereas cumulus pyroxenes contain 0.8-2.6% Al_2O_3.

DISCUSSION

The noncumulus ultramafic rocks may have originated as:

1) igneous cumulate in which diagnostic textures have been masked by subsequent deformation,
2) a refractory residuum formed after partial melting of less refractory mantle material to yield basaltic magma,
3) an ultramafic body formed independently of basaltic magma evolution, having either crystallized from an ultramafic melt or formed as primitive mantle early in the earth's history.

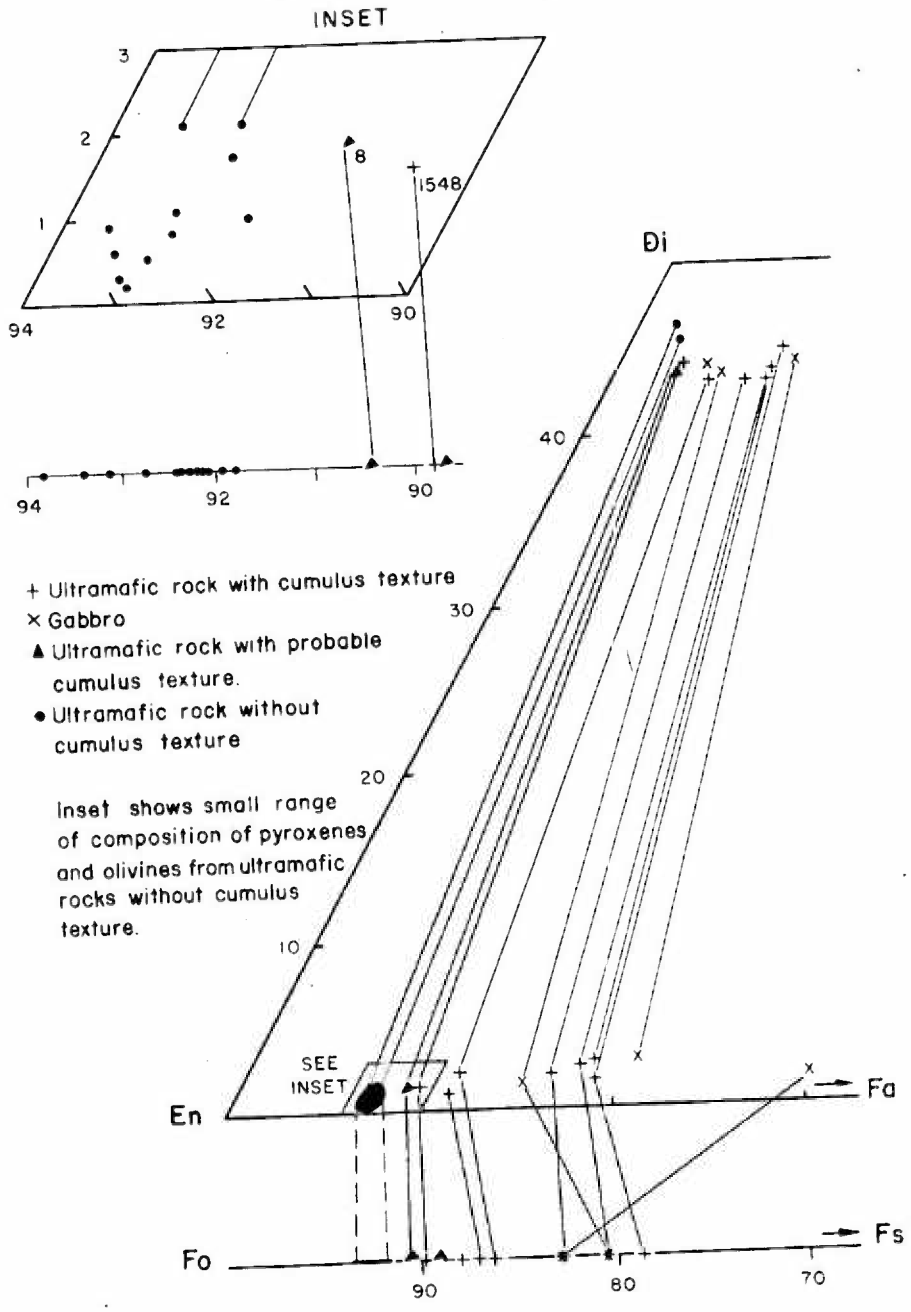

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FIG.2. Pyroxene and Olivine Composition

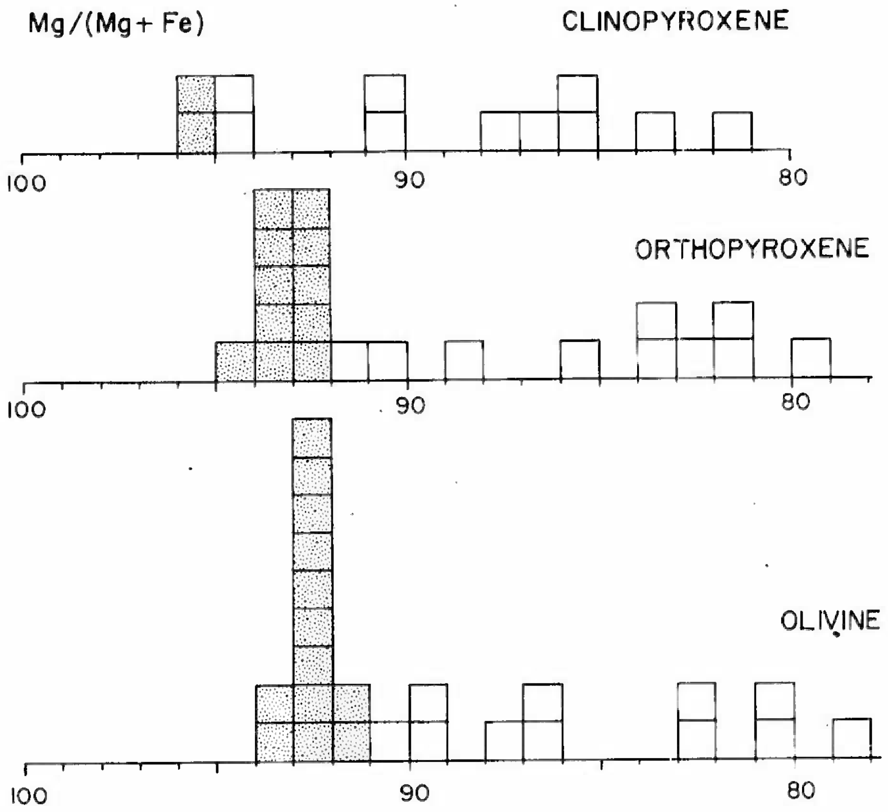

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FIG. 3. Each square represents mineral analyses from from one rock specimen; noncumulus ultramafics shaded, cumulus ultramafics and gabbros not shaded.

Origin as an igneous cumulate seems unlikely. The lithological and chemical homogencity of these rocks, the lack of post-cumulus plagioclase and the virtual absence of clinopyroxene are all features which set the noncumulus utramafics apart from the ultramafic zones of the layered batholiths of Bushveld and Stillwater type. The most compelling evidence against cumulus origin is the highly magnesian character of the noncumulus ultramafic minerals. Olivine and orthopyroxene of such highly magnesian composition occur in equilibrium with basaltic liquid only at or very near the liquidus and would constitute only a very small proportion of the settled crystals from a given volume of magma. However in the Papuan Ultramafic Belt the rocks comprising these highly-magnesian minerals make up over 90% of the ultramafics and about one third of the entire volume of the complex.

Green and Ringwood (1966) have suggested that large bodies of homogeneous ultramafic rock with high Mg/(Mg+Fe) and low Ca and Al content might be formed as a refractory residuum when pyrolite mantle is partially melted to produce basaltic magma. If the Papuan ultramafics originated in this way then partial melting and segregation of magma must have been a very thorough process which produced a remarkably homogeneous residuum and left no trace of feeder pipes, trapped pools of melt etc. The noncumulus ultramafics would represent the refractory residuum, and the cumulus ultramafics the early-formed crystals from the basaltic magma. Is the chemistry of these two groups of rocks compatible with the hypotheses? The plot of Mg/(Mg+Fe) ratios is exactly what would be expected, but the very low Ca and Al content of some of the noncumulus orthopyroxenes requires explanation. If the residual orthopyroxene equilibrated with basaltic melt it should contain about the same amount of Ca and Al as do the earliest formed orthopyroxene crystals from the basaltic melt at comparable pressure. In fact many of the noncumulus orthopyroxenes contain distinctly less Ca andAl than do the cumulus orthopyroxenes. This might possibly be explained if in some cases small amounts of melting and magma segregation continued after the initial segregation of basaltic melt. The last fraction of melt segragated would be much richer than basalt in normative enstatite and both the melt and the residuum would be depleted in Ca and Al. No evidence has been found for the existance of melt of such an unusual composition in the rocks of the Ultramafic Belt but some volcanic rocks of the nearby Cape Vogel area (Dallwitz et al. 1966), which are unusually rich in normative enstatite and very poor in Ca and Al, may have formed by such a process.

Alternatively the lower Ca and Al content of many of the noncumulus orthopyroxenes may be a corollary of their high Mg content, or due to some other factor such as the possible development of Ca-poor protoenstatite in the residuum at high temperatures. Green and Ringwood's (1966) experimental evidence indicates that Ca and Al should decrease slightly with increasing Mg but probably does not show the very sharp decrease observed in the Papuan orthopyroxenes. The development of Ca-poor protoenstatite probably would still not explain the lower Al of the noncumulus orthopyroxenes, because the Al contents of co-existing protoenstatite and orthoenstatite are roughly equal. In any case the protoenstatite would need to have undergone equilibrium inversion to orthoenstatite on cooling. The low Al content could be attributed entirely to equilibration at low pressure, but this seems unlikely because pyroxene in the overlying cumulus rocks is almost invariably richer in Al than the noncumulus orthopyroxene. The low Ca content of orthopyroxene is not obviously due to exsolution of clinopyroxene. Clinopyroxene has been found is only two of the thirteen analyzed specimens and then only in very small amounts. These two specimens (46 & 504) are those in which orthopyroxene is richest in Ca.

If we postulate that the noncumulus ultramafic rocks formed independently of basaltic magma evolution, there is no need to reconcile the data with a hypothetical magma production process. Perhaps the rocks represent a primitive refractory mantle which at no stage has been related to generation of basaltic or other magma. Such a hypothesis places few constraints on the chemistry of the rocks and thus cannot be critically tested using our data. Such hypothesis runs counter to the concept that primitive mantle material is capable of yielding basaltic magmas on partial metting.

There is little evidence to support origin as an intrusive body of ultramafic magma. The noncumulus ultramafics are probably older than the other rocks of the Ultramafic Belt and appear to have acted as a floor for the magma chamber in which the gabbro zone rocks and the ultramafic cumulates crystallized. Gabbro intrudes noncumulus ultramafics in places, but nowhere do the ultramafics intrude gabbro or other rocks. On the other hand it is possible that ultramafic magma existed at some earlier stage. Although no igneous micro-textures are preserved in these rocks, the presence of orthopyroxenite dykes suggests that the noncumulus ultramafics have been subjected to an environment in which ultramafic magma could exist. The dykes might possibly have formed by silica metasomatism of peridotite (cf. Bowen and Tuttle, 1949); the low Ca and Al content or orthopyroxene from the one specimen of dyke rock which has been analysed (26) is compatible with formation by silica metasomatism of olivine. However the field and petrographic evidence argue for magmatic origin; dyke contacts are sharp, there are no replacement textures, and the coarser-grained pyroxenite dykes contain correspondingly coarse-grained accessory chromite, whereas chromite grains in the host peridotite are uniformly fine. In a more detailed study of a Californian ultramafic body, Loney et al. (1970) have concluded that ultramafic dykes within the body were intrusive rather than replacement features.

The textures of the noncumulus ultramafics are at least superficially similar to those which would be produced in a convecting mantle in which movement is accommodated by syntectonic recrystallization (Carter and Ave L'Allement, 1970; Ave L'Allement and Carter, 1970).

Conclusion.

Ultramafic cumulates can be distinguished from the noncumulus ultramafics by their texture, in some cases by the presence of layering, by the occurrence of clinopyroxene as a major mineral phase and particularly by the Mg/(Mg+Fe) ratios of olivine and orthopyroxene. The ultramafic cumulates settled out of basaltic magma and are probably related to the overlying gabbro zone rocks. The noncumulus ultramafic rocks may have originated either as a refractory residuum from partial melting of primitive mantle or by some other process independent of basaltic magma generation.

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APPENDIX

A Simplified Model for the Evolution of the Noncumulus Ultramafics by Partial Melting

Partial melting of a peridotite in the system Mg_2SiO_4-$CaAl_2Si_2O_8$-SiO_2 could be used as a rough model for the formation of the noncumulus ultramafic rocks.

i) Low pressure (pressures at which enstatites melts incongruently)

A peridotite Q in Fig. 5 is raised to 1260°C where a liquid of composition R is formed. If the liquid is not allowed to segregate increasing amounts of liquid R are formed until all anorthite goes into solution. At this point the composition of the residue will have reached T and will start to move along TF while the liquid starts to move along RS. Shortly afterwards the maximum temperature is reached and a melt close to quartz-normative basaltic composition is left in equilibrium with a harzburgite residue. Note that, with the beginning of melting at R,P (approximating to pyrolite composition of Green and Ringwood, 1966), does not contain sufficient normative enstatite to produce a residue as rich in orthopyroxene as the Papuan noncumulus ultramafic rocks.

If much of the liquid R is allowed to segragate before partial melting ceases the composition of the late stage liquid would move rapidly from R towards S and possibly beyond. Such a liquid would be quartz-normative, rich in normative enstatite and low in Al and Ca. Orthopyroxene in equilibrium with such a liquid would also be low in Al and Ca.

ii) High Pressure (above pressures where enstatite melts incongruently).

At higher pressures (above about 3Kb) the protoenstatite-forsterite cotectic moves into the olivine-normative region, as does the beginning of melting. The protoenstatite-forsterite residue would here be in equilibrium with an olivine-normative liquid before segregation took place. If early segregation was allowed to take place and was followed by more partial melting and segregation an olivine-normative liquid otherwise similar to case (1) would form.

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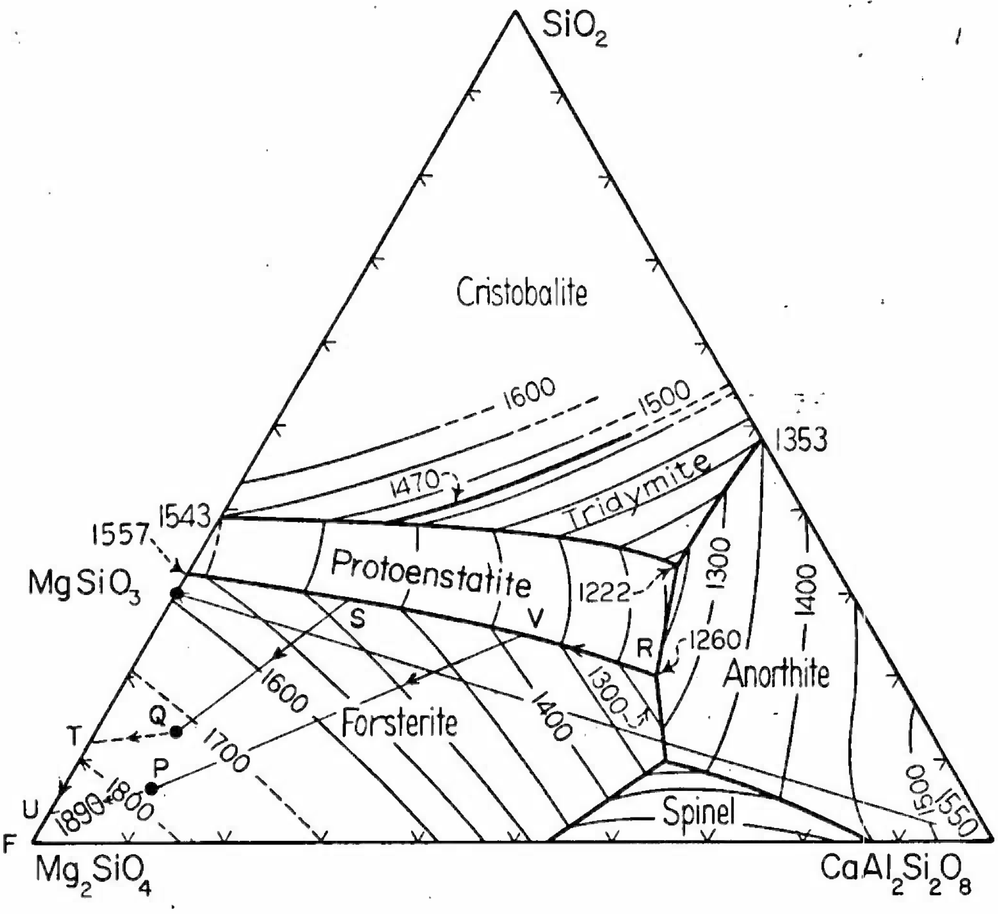

Fig 4 Partial melting behaviour of a peridotite Q in the system Mg_2SiO_4-$CaAl_2Si_2O_8$-SiO_2 at atmospheric pressure. [Modified from O. Anderson, Am. Jour. Sc. 39, 440 (1915)]