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Mineralogy and Partial Melt Textures within an Ultramafic-Mafic Body, Greece

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Abstract. Ultramafic-mafic rocks from Makrirrakhi, Central Greece exhibit features of an original ophiolite sequence which contains depleted mantle material, ultramafic containing partial melt textures and possibly the mafic "pluton" which resulted from the coalescing of these partial melt segregations. Considerable mineralogical variation exists: unzoned olivine crystals range in composition from Fo_{78-84} (mafics) to Fo_{88-92} (ultramafics), plagioclases An_{64-79} (mafics) to An_{80-90} (ultramafics) and spinel varies from a chromian spinel (ultramafics) to a more aluminous-titaniferous spinel (mafics). Pyroxenes from the ultramafics display a limited range: $En_{89-92}\,Fs_{9-8}\,Wo_{0-2}$ (orthopyroxene) and $En_{48-54}\,Fs_{1-10}\,Wo_{38-50}$ (clinopyroxene). Mafic rocks display a greater range being richer in ferrosilite $En_{36-65}\,Fs_{3-20}\,Wo_{33-51}$. Pyroxenes from within the partial melt segregations have chemical affinities with those from the gabbro-troctolite series. A model of partial melt within the upper mantle, and, a set of criteria to distinguish partial melt textures from cumulate textures, are developed from analytical data and textural evidence.

Introduction and General Geology

The ultramafic-mafic belt is situated around Makrirrakhi village in the Othris Mountains Greece, at an altitude of 800–1000 metres (Fig. 1). Geologically Greece can be sub-divided into several N. W. trending facies zones (Auboin, 1965). This body lies within the Sub-Pelagonian zone; a zone occupied mainly by a Mesozoic ophiolite-radiolarian chert sequence. This is overlain unconformably by Upper Cretaceous limestone and Eocene flysch (Hynes, 1972). The complete assemblage is thought to represent (Fig. 2) part of a Mesozoic oceanic crust-upper mantle which was tectonically emplaced onto the continental margin during the Upper Jurassic-Middle Cretaceous interval. During emplacement serpentinisation occured along major thrusts and fractures.

The purpose of this paper is to:

(1) Present mineral data on the complex, essentially the pyroxenes, discuss the chemical variation and to examine the implications.

(2) Report the presence of possible partial melt textures and tabulate the criteria used to distinguish these textures from primary cumulate magmatic textures.

Petrology and Textural Relationships

The lower part of this thrust sheet carries a mixture of mafic-ultramafic rocks which can be sub-divided into the following units: [Photomicrographs a) to d) (Fig. 3a–d) correspond to units 1) to 4).]

(1) Pillow lavas and upper dike complex (Hynes, 1972).

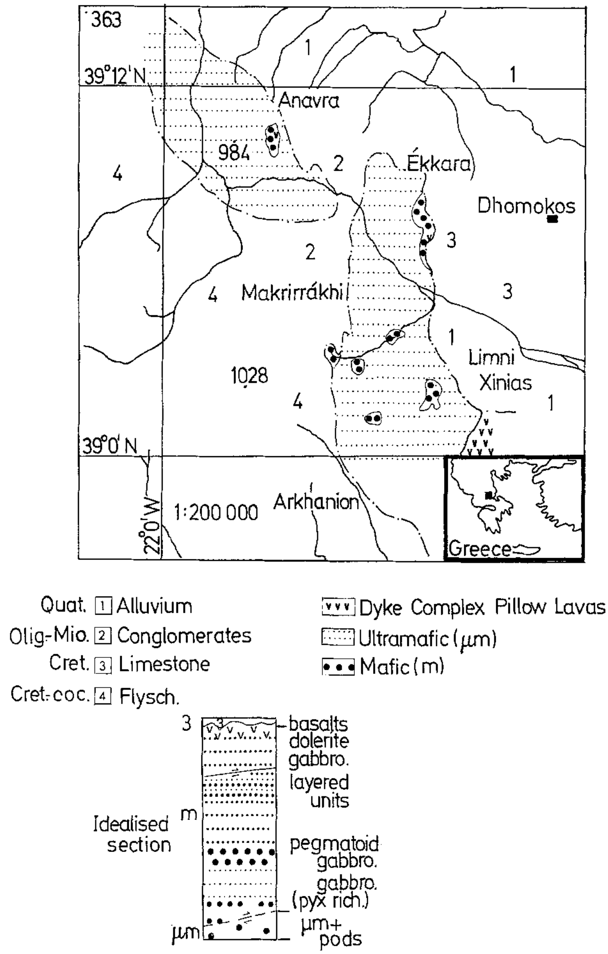


Fig. 1. Ultramafic-mafic belt, Central Greece

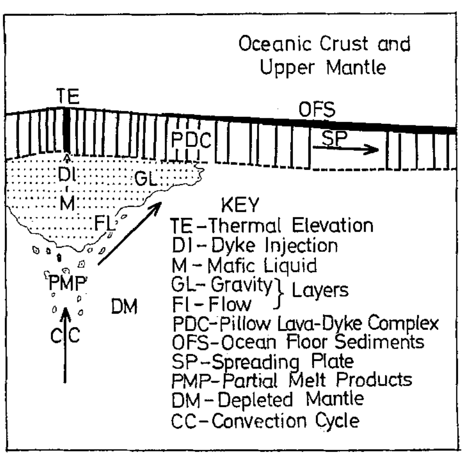


Fig. 2. Upper mantle and oceanic crust (after Moores and Vine, 1971). Illustration of the formation of a mafic pluton from the gradual accumulation of partial melt product from the underlying mantle ultramafic

Table 1. Bulk rock analyses and comparison with 1:3 pyrolite (Green and Ringwood, 1966)

	1.	2.	3.	4.	5.
SiO_2	40.32	43.19	44.87	44.61	45.16
TiO_2	0.00	0.10	0.09	0.22	0.71
Al_2O_3	0.53	3.10	19.69	21.11	3.54
FeO[a]	8.91	10.00	2.72	5.80	8.52
MnO	0.15	0.18	0.07	0.10	0.14
MgO	49.01	35.23	14.11	14.83	37.47
CaO	0.88	7.66	16.46	12.36	3.08
Na_2O	0.16	0.13	1.77	1.02	0.57
K_2O	0.05	0.02	0.03	0.03	0.13
Totals	100.01	99.61	99.81	100.08	99.32

[a] Total Fe as FeO.
1. Depleted ultramafic-harzburgite from dunite-harzburgite series.
2. Plagioclase lherzolite with partial melt textures.
3. Segregation, from the dunite-harzburgite series, of the magmatic type with the composition of an anorthositic gabbro.
4. Anorthositic gabbro from the gabbro-troctolite series.
5. 1:3 Pyrolite (Green and Ringwood, 1966).

(2) Gabbro-troctolite. An assemblage of anorthositic gabbros, gabbros, troctolites and coarse gabbro pegmatites. The most ultramafic magmatic cumulate is represented by troctolites (England and Davies, 1973) within layered units.

(3) Plagioclase lherzolite, metamorphic.

(4) Dunite-harzburgite, metamorphic.

The gabbro-troctolite is approximately 1 km thick and at least 6 kms of ultramafics are exposed (Fig. 1).

The stratigraphically highest member is a series of basalts and dolerites. Randomly oriented plagioclases range in size from 0.05 mm to 2.00 mm. Pyroxenes have been optically determined as augite and pigeonite.

Modal variation of plagioclase, in the gabbro-troctolite unit, produces an assemblage of gabbros and anorthositic gabbros (percentage plagioclase, pyroxene and olivine varies from 70:8:22 to 41:1:58). The plagioclase laths exhibit a considerable range in size from 1–10 mm reaching 16 mm in the very coarse gabbros. Small layered units, 10.00–16.00 cm, occur occasionally within the gabbro-troctolite.

Adjacent to this unit there exists a plagioclase lherzolite (Table 1 and Fig. 4). Which carries segregations and schlieren of a gabbroic composition. The lower ultramafics are mainly dunite, lherzolite and harzburgite; they are homogeneous rocks except where pyroxene content varies producing a "layered" appearance. Gabbroic segregation veins and gabbro pegmatites occur within these ultramafics.

Textural Relationships

Despite serpentinisation many of the textural features have been preserved. The basalt-dolerite display a sub-ophitic texture. Plagioclase phenocrysts occur in those basalts with an extremely fine groundmass of pyroxene and plagioclase.

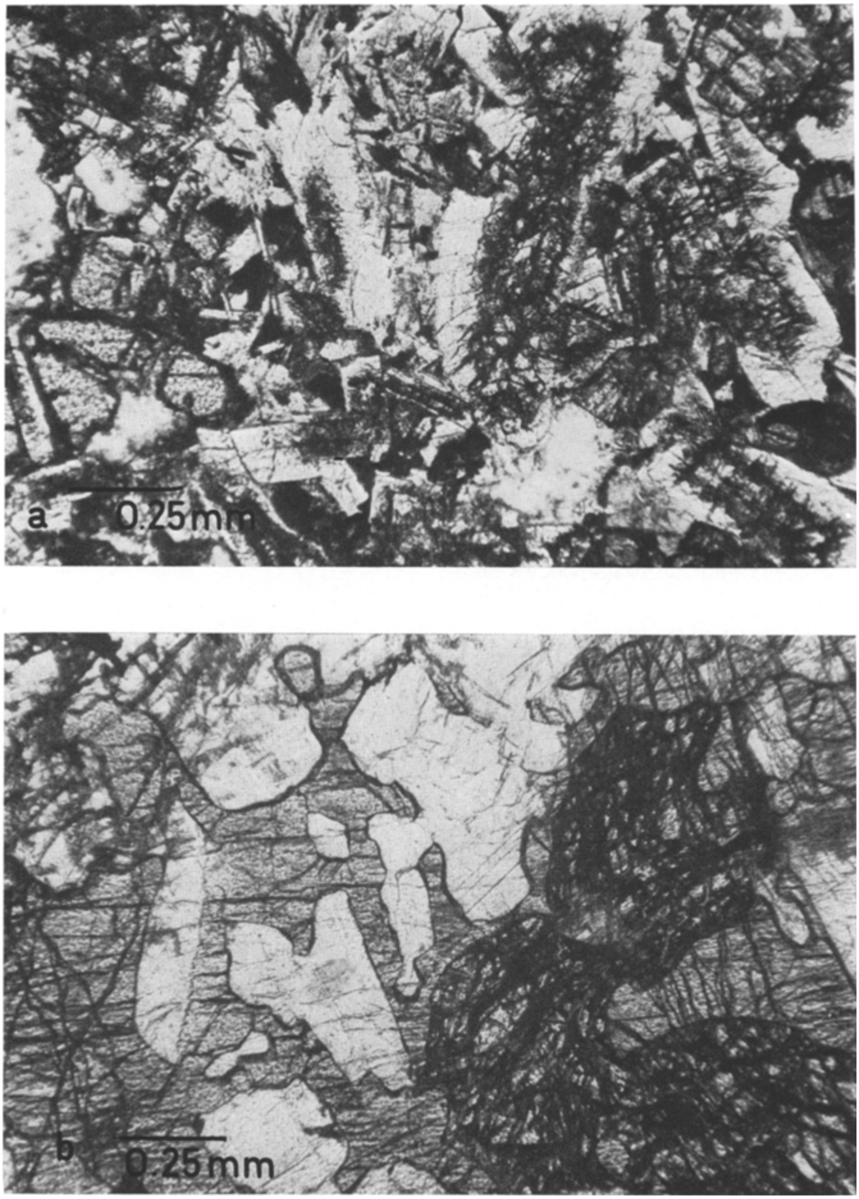
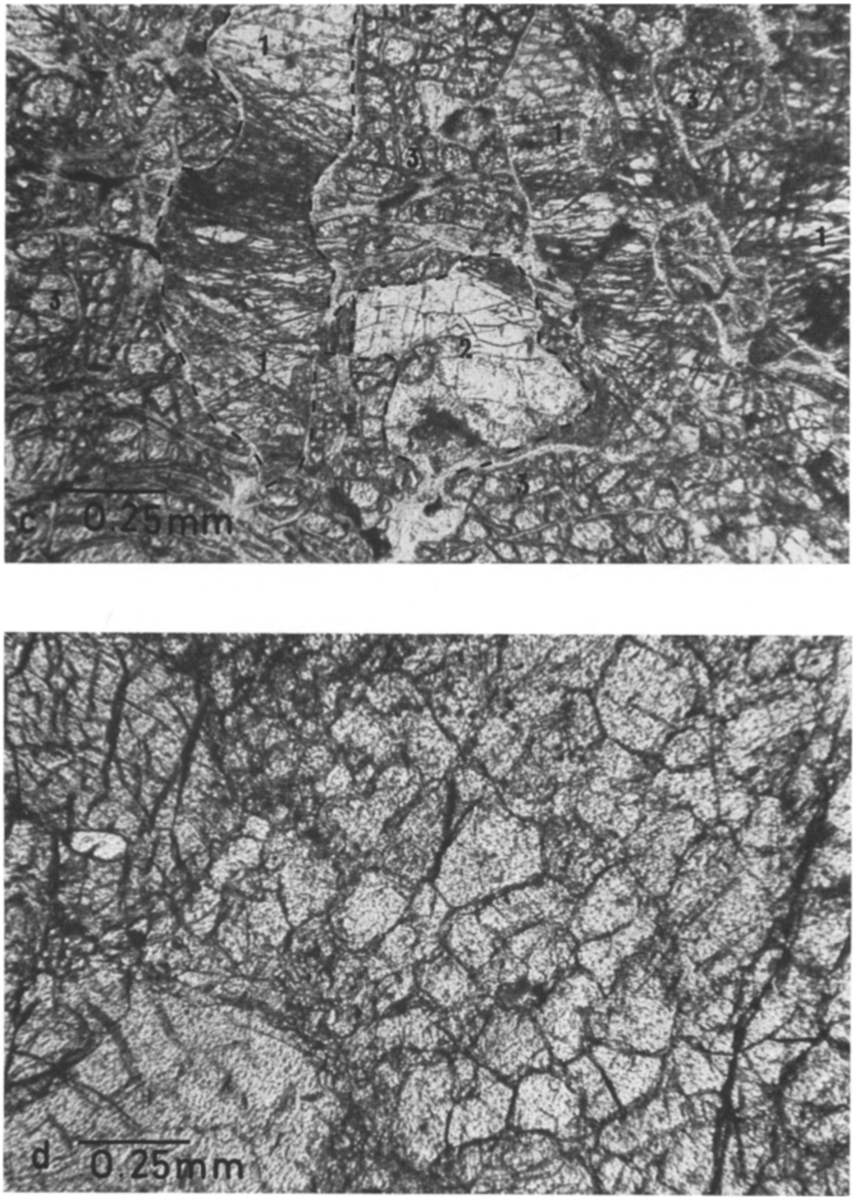


Fig. 3. a Dolerite containing zoned labradorite and interstitial augite from the basalt-dolerite series. b Olivine gabbro with cumulus resorbed plagioclase and olivine within intercumulus diopsidic augite, from the gabbro-troctolite series. c Plagioclase lherzolite containing inter-

Most of the gabbro-troctolite series have well developed magmatic textures-cumulate layers of plagioclase partly enclosed by variable amounts of intercumulus pyroxene and olivine.



stitial plagioclase (*1*) and pyroxene (*2*) in an environment of residual olivine (*3*). d Lherzolite containing large diopside crystals in a groundmass of interlocking olivine, from the dunite-harzburgite series

The irregular segregation features (Fig. 4) within the plagioclase lherzolite contain clear evidence of a past ability to generate a mafic liquid. The segregations are of variable size ranging from a few millimetres to elongate gabbroic segrega-

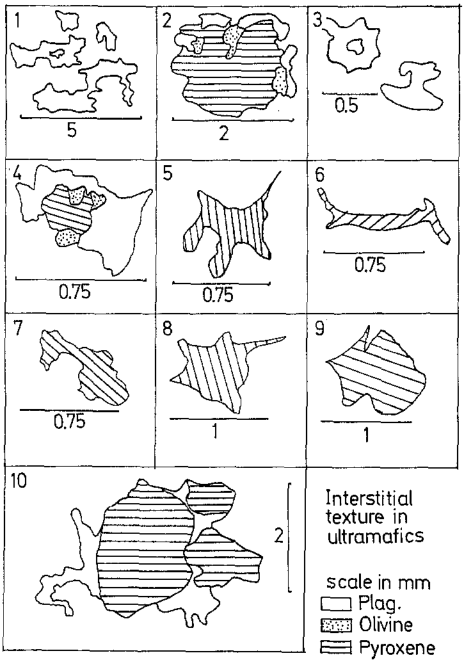


Fig. 4. Partial melt textures within the plagioclase lherzolite group. The irregular anhedral nature of the adjacent crystal phases forms the outline for these sketches

tions of tens of centimetres. These "tectonite", sometimes elongate, schlieren do not exhibit the sharp contacts of the "magmatic" veins found in the dunite-harzburgite group. The latter are parallel sided vein-like anorthositic gabbros, of variable grain size and distribution. Both types contain plagioclase and clinopyroxene (in an environment of depleted ultramafic containing olivine, orthopyroxene and a little plagioclase), which decreases in quantity away from the segregation or vein. Any olivine found within the segregations is very forsteritic and belongs to the residual, surrounding ultramafic, which displays the following textural features:

(a) Granulated pyroxene margins.

(b) Interlocking anhedra of olivine which exhibit translation lamellae parallel to (100).

(c) Exsolution phenomena induced by high stress.

(d) Variable spinel habit from relict symplectite with olivine to interstitial.

This fabric may be a direct result of the mode of emplacement or is more probably induced by solid state flow within the mantle (Carter and Ave Lallement, 1970). This tectonite ultramafic forms an inert base onto which crystalline phases, from overlying mafic liquid were precipitated at a later time. Thrust emplacement superimposed a minor granular texture which failed to obscure the primary tectonite fabric.

Electron Probe Analytical Technique

Major mineral phases were analysed using a Cambridge Instruments Geoscan electron probe microanalyser at an accelerating voltage of 20 kv and a specimen current of 0.4 A. Pure element and mineral standards were used, data being corrected using a Fortran Programme called TIM 2. An extensive scanning programme was carried out in an attempt to locate any exsolved or zoned phases. These were found within the pyroxenes and plagioclases respectively. Exsolution lamellae were frame and line scanned for several elements. Full analysis was completed on each phase. Olivines and plagioclases were analysed for Fe—Mg and Ca—Na, the relative amounts of Fo, Fa and Ab, An were calculated using a programme devised by J. Ashworth and A. Arnold (pers. comm.).

Analytical Data

Pyroxenes

Orthopyroxenes from the ultramafic units (3) and (4) contain very little CaO (maximum 1.48 wt %) and exhibit a limited compositional range (Fig. 5). Pyroxenes from the plagioclase lherzolite segregations are enriched in chromium, and ferrosilite. This may be a reflection of the more mafic environment of formation of these pyroxenes. High titanium clinopyroxenes have been observed within experimental partial melt textures (Green and Ringwood, 1967).

Orthopyroxenes, of higher ferrosilite content, from the gabbro-troctolite unit, exist either as reaction rims between olivine and plagioclase or as exsolution lamellae within a clinopyroxene host.

Coexisting clinopyroxenes from the ultramafics lie within the diopside-endiopside field (Poldervaart and Hess, 1951). These exhibit a more limited range in composition than clinopyroxenes from the gabbro-troctolite unit.

	Orthopyroxenes		Clinopyroxenes	
	Ultramafic	Mafic	Ultramafic	Mafic
En	89—92	85—88	48—54	33—51
Fs	8—9	15—12	2—10	3—20
Wo	0—2	—	38—50	36—65

The composition fields of clinopyroxenes from these two divisions display considerable overlap. Clinopyroxenes from the troctolites lie within the field of clinopyroxenes from the ultramafics (Fig. 5) i.e. groups (3) and (4).

Chromium, titanium and manganese oxide weight percent values (Fig. 5) vary within pyroxenes from mafics and ultramafics. Clinopyroxenes from the mafic rocks tend to be enriched in titanium and manganese. Overlap exists due to the high content of these oxides in pyroxenes from within segregations of the plagioclase lherzolite. Orthopyroxenes from the ultramafic rocks are depleted in titanium and chromium relative to coexisting calcium rich pyroxenes (Fig. 6).

A cluster analysis programme, devised and written by E. B. Walsworth-Bell, (Aberdeen UniΛersity) run on these analyses, confirms the close similarity of pyroxenes from the mafics and ultramafics, which is displayed by individual aspects of pyroxene chemistry. The bulk of these pyroxene analyses are enriched in either normative diopside or hypersthene tending towards the quartz normative field.

Two major types of exsolution were found (100), orientation:

a) diopside in enstatite.

b) enstatite in diopsidic augite (Fig. 7).

These occur as exsolved blebs, lamellae or as an inter-growth within intercumulus clinopyroxenes.

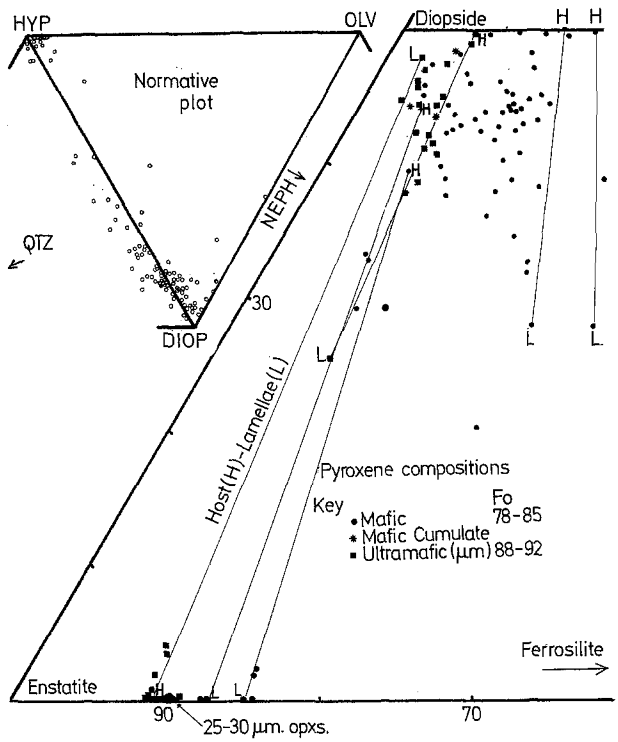


Fig. 5. Pyroxene composition and normative distribution. Clinopyroxenes display a wide compositional variation within the ultramafic and mafic rocks. Orthopyroxenes tend to be rather limited in compositional range falling in a cluster on the Enstatite-ferrosilite join

Cryptic variation occurs within the layered units of the gabbro-troctolite sequence.

Wo	En	Fs (pyroxene)	Fo (olivine)
46	43	9	78
40	51	4	82

Anorthite content is extremely variable within the one section (Hunahashi *et al.*, 1968–1969) reaching a maximum within the plagioclase lherzolites (Fig. 7), the coexisting olivines exhibiting a similar increase in content of forsterite. Weight percent of nickel oxide reaches a maximum in the most magnesium rich olivines, the weight percent of manganese reaching a minimum.

Discussion and Conclusions

The absence of a thermal aureole is an indication that these ultramafics did not originate by accumulation from an intrusive ultramafic liquid. The ratio of mafic: ultramafic, the magnesian nature of the dunite-harzburgite group and the associated

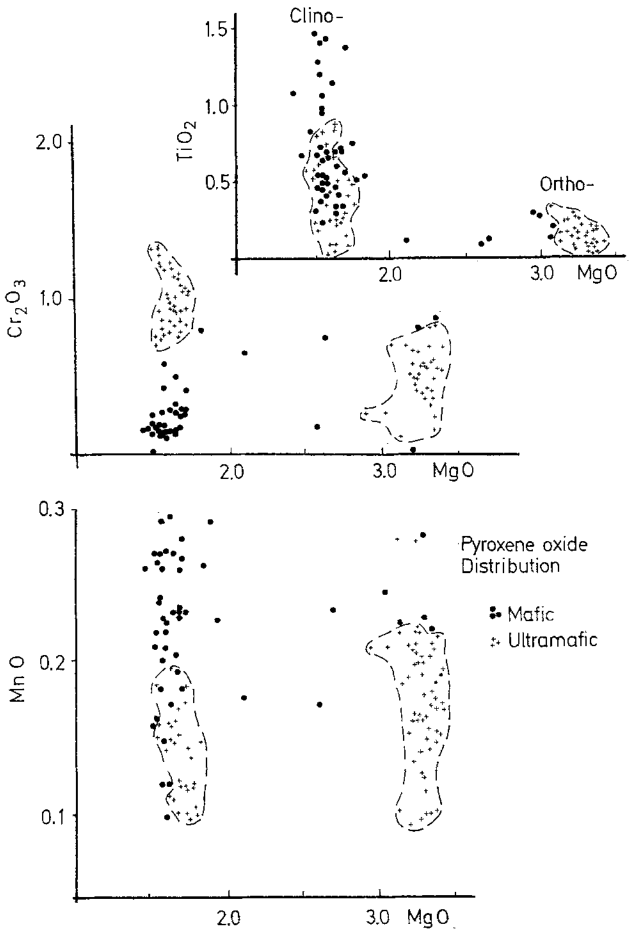


Fig. 6. Plots of TiO_2, Cr_2O_3 and MnO against MgO for pyroxenes from the mafic and ultramafic rocks. (Electron probe analyses)

sequence of oceanic sediments, pillow lavas and intrusive dyke complex indicate origin as a fragment of oceanic crust and upper mantle (Moores and Vine, 1971).

Oceanic crust is generated by dyke injection into fractures on spreading plates, a process fed by underlying mafic "plutons" (Fig. 2). Partial melt processes within the ultramafic upper mantle continually replenish the supply of mafic liquid which becomes depleted due to magma injection. Below the "pluton" there exists a zone of ultramafic containing partial melt segregations of mafic liquid.

The assemblage under discussion can be subdivided on the basis of texture, whole rock and mineral composition (Jackson and Thayer, 1972):

a) Dunite-harzburgite. The low content of aluminium, calcium and alkali oxides, and the magnesian character of the minerals precludes the possibility of this group representing primary undepleted mantle (Steuber, 1965; Fig. 8 and Table 1). The bulk composition is not that generally accepted as representative of primary

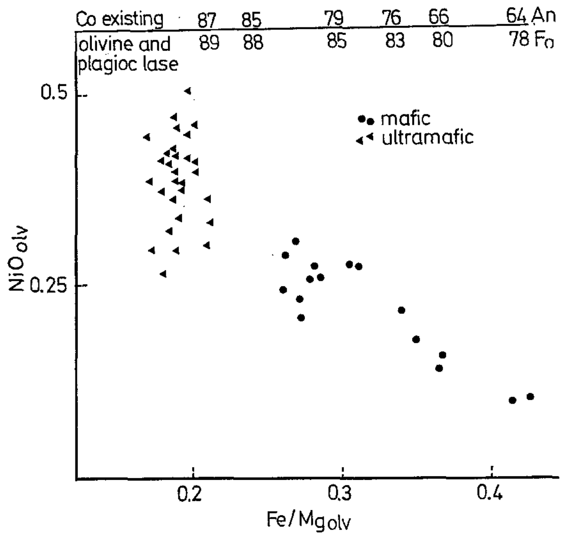


Fig. 7. Variation in olivine composition. Content of NiO varies linearly with the content of MgO within olivines. Also shown is the composition of co-existing plagioclases which increase in anorthite content from the anorthositic gabbros to the ultramafics. A gradual increase in the forsterite component is accompanied by a more definite increase in the anorthite content of the plagioclase

mantle (Green and Ringwood, 1967). The residual oxides (Vinogradov *et al.*, 1971) of manganese and nickel tend to be concentrated in the pyroxenes and olivines respectively.

b) Plagioclase lherzolite. This contains evidence of a past ability to produce mafic liquid in the form of mafic segregations. Local melting of a lherzolitic type ultramafic could lead to simultaneous depletion of plagioclase and pyroxene (Boudier and Nicolas, 1972), producing this type of ultramafic containing gabbroic schlieren. These segregations are surrounded by residual dunite or olivine harzburgite (Thayer, 1969). Physico-chemical models like those produced by Vinogradov (Vinogradov *et al.*, 1971), indicate that local or partial melting produces a residue rich in the oxides of magnesium, manganese, nickel and chromium akin to group a); the dunite-harzburgite. The filtrate or melt product concentrates certain oxides which are found in the schlieren and segregations-calcium, sodium, aluminium, titanium and silicon (Table 3). The plagioclases are more albitic and the pyroxenes enriched in ferrosilite within these schlieren, producing a bulk composition corresponding to an anorthositic gabbro. This may not truly represent the primary product of melting as fractionation or removal of part of the liquid may have occured. The composition of this primary melt is dependent on the original mantle material composition, the degree of melting and the depth of separation of melt from the residual framework.

Assessement of the degree and extent of partial melting is difficult due to the possible mobility of these felsic interstitial globules. Adiabatic decompression of the ultramafic assisted by heat flow and solid state flow leads to upward migration and coalescing of the melt product, eventually producing a mafic "pluton". Crystal precipitation would then proceed onto an inert floor of ultramafic from the overlying liquid.

The gabbro-troctolite series resulting from this process exhibits limited igneous "layering" giving some idea of the original quantity and temperature of the

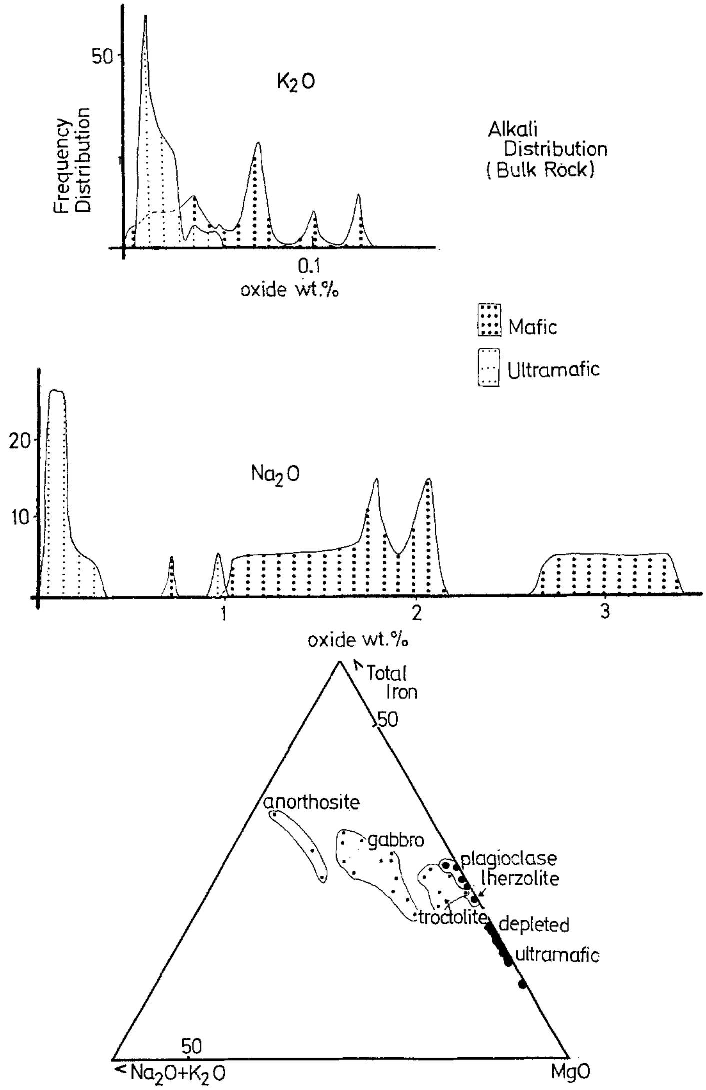


Fig. 8. Frequency distribution of sodium and potassium from forty five wet chemical determinations. Alkali, iron and magnesium diagram illustrates the mild fractionation trend in the gabbro-troctolite series and the affinity of the plagioclase lherzolite to this series. The depleted nature of the residual ultramafic is also illustrated

magma. Nickel partition studies on co-existing clinopyroxene and olivine (Hakli and Wright, 1967) within the gabbros and troctolites can be used as a geothermometer (Hakli, 1968). Despite certain possible limitations to this method—pressure and composition of the melt—a temperature of 1000–1150 was obtained. Olivines within the troctolites contain more nickel than those of the anorthositic gabbros thus producing a range in temperature, the early formed troctolites being higher temperature rocks. Using this range at a depth equivalent to the oceanic upper mantle, these mafics are seen to lie above the pyrolite solidus (Wyllie, 1971) near to the field of incomplete segregation within a gabbro-peridotite complex. Incomplete segregation is visible in the form of certain schlieren but the upper limit of this temperature range would intersect the pyrolite solidus at a greater depth. At this depth a melt fraction could form and separate at a higher level from the residual material. Consequently this complex encompasses ultramafic with evidence of incomplete segregation and an assemblage of mafics with minor cumulates, due to the small amount of gabbroic magma.

Ultramafic rocks which contain these partial melt textures require the use of certain criteria to distinguish them from a cumulate magmatic texture. The latter is characterised by systematic variations in rock types, e.g. troctolite-gabbro-anorthosite layers which in themselves exhibit modal and cryptic variation. The plagioclase lherzolite ultramafics display the following features:

(1) Associated rocks, of tectonite fabric, contain interlocking anhedra of olivine.

(2) Segregations of plagioclase and pyroxene are sometimes elongated parallel to the direction of solid state deformation.

(3) Lack of systematic cryptic or modal variation.

(4) Schlieren contain subhedral phases within a framework of anhedral "residual" crystals.

(5) Bulk chemistry of surrounding ultramafic is low in total alkali, magnesium and iron. Variable content of schlieren produces marked changes in alkali content.

(6) Pyroxene phases within the segregations contain higher oxide percentages of titanium and iron.

The above criteria may only apply in part to each individual ultramafic association, but, nevertheless helps distinguish it from a primary cumulate ultramafic.

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