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# Plagioclase Lherzolite-Residual Mantle Relationships within Two Eastern Mediterranean Ophiolites

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*Abstract.* The ophiolites of Othris, northern Greece, and Troodos, Cyprus, are of mixed lherzolite-harzburgite and harzburgite sub-type respectively. Within both ophiolites an entire spectrum of harzburgite, plagioclase harzburgite, lherzolite and plagioclase lherzolite interpreted respectively as residual and highly, moderately and slightly modified upper mantle has been recognised. Plagioclase lherzolite frequently contains gabbroic segregations generated by partial melting and incomplete extraction. Othris shows the full range of mantle peridotites while Troodos is dominated by harzburgite with very minor occurrences of plagioclase harzburgite and lherzolite. Chemically, the plagioclase lherzolites have low contents of the basaltophillic minor elements, and a composition slightly more residual than postulated upper mantle compositions, suggestive of a preceding phase of minor depletion. The Othris and Troodos ophiolites seem to have formed under fundamentally different environments—Othris as a marginal ophiolite at the inception on rifting of continental crust, and Troodos later in such an event when spreading was well established.

## Introduction

The field relationships and chemistry of the partial fusion and crystallization of aluminous peridotite have been investigated in varying pressure—temperature fields. Such peridotites, of presumed upper mantle origin, and displaying partial fusion products exist under (a) garnet peridotite facies at Kalskaret, Norway (Carswell, 1968), (b) spinel peridotite facies at Ronda, Spain (Dickey, 1970), Beni Bouchera, Morocco (Kornprobst, 1969), and Lherz, France (Conquéré, 1971), and (c) plagioclase peridotite facies at Lanzo, France (Boudier and Nicolas, 1972) and Makrirrakhi, Greece (Menzies, 1973). Basaltic magmas are thought to be generated by the partial fusion of aluminous peridotite upper mantle (of which Ringwood's (1966) pyrolite model is an approximation) at pressures (depths) of 5–13 kbs (15–35 km) in the plagioclase peridotite field, 10–20 kbs (35–70 km) in the spinel peridotite field, or 18–27 kbs (65–100 km) in the garnet peridotite field (Fig. 1).

Suitable areas for field studies of upper mantle partial melting beneath the continental crust are virtually restricted to alpine belts where tectonic intrusion of peridotite mantle has resulted from plate collision (Nicolas and Jackson, 1972), or diapir—like intrusion in orogenic root zones (Kornprobst, 1969; Loomis, 1972). Evidence relating to the partial melting of upper mantle beneath oceanic crust is widely available from ophiolite complexes where oceanic crust has been thrust up onto continental margins (Dewey and Bird, 1971; Coleman, 1971).

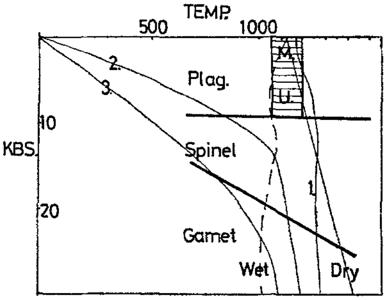

Fig. 1. Peridotite mineral facies. Positions of divariant reaction intervals are marked by heavy lines separated by *Plag.* = plagioclase lherzolite, *spinel and garnet* = spinel and garnet lherzolite respectively. The thin solid and broken lines represent the dry and wet solidus respectively and curves *1*, *2*, *3* (after Verhoogen, 1973) represent ridge axis and points successively further away from the ridge. They give some idea of the possible paths that ascending melt cycles would follow (Turcotte and Oxburgh, 1969). The hatched area represents the approximate position of the Othris mafic (*M*) and ultramafic (*U*) rocks (Menzies, unpublished) and within this field are the rocks of Troodos analysed by Moores and MacGregor (in press)

## Ophiolite Genesis

Ophiolite complexes in which the downward stratigraphic succession pillow lava —dike complex—gabbro—cumulate ultramafic may be recognized commonly contain, at the base, a tectonic peridotite floor (usually harzburgite-dunite) interpreted as depleted mantle, on which the cumulate sequence is developed (Moores and Vine, 1971; Irvine and Findlay, 1972; England and Davies, 1973; Greenbaum, 1972; Montigny *et al.*, 1973; Blake and Landis, 1973). Chemically and texturally similar tectonite ultramafics in alpine peridotite complexes are also identified as depleted upper mantle (Loney *et al.*, 1971; Himmelberg and Loney, 1973; Thayer, 1969). An assemblage of olivine plus orthopyroxene (harzburgite) is the expected residual phase of moderate degrees of partial melting of aluminous peridotite upper mantle (O'Hara, 1968).

Ophiolite complexes permit easy study of partial melt products, and occasionally partial melt processes. Primary and fractionated melt products separated from the residue may be represented by a sequence of extruded pillow lavas, massive flows and injected feeder dikes; subsequent thermal insulation allows the development of a full igneous suite of cumulate ultramafics, olivine and pyroxene gabbros and felsic differentiates onto a floor of depleted mantle as modeled by Greenbaum (1972).

The foliated harzburgite is believed to represent mantle from which the melt fractions have been almost completely extracted (Viljoen and Viljoen, 1969; Carswell, 1968; Boudier and Nicolas, 1972; Himmelberg and Loney, 1973). Minor inhomogeneities are present as foliated or non-foliated patches of dunite and lherzolite, pyroxenite veins, and gabbroic veins. In some ophiolites, mixed areas of tectonite plagioclase lherzolite and lherzolite appear to be intimately associated, and closely related genetically, to this residual harzburgite. The plagioclase lherzolite, which represents possible primary mantle material (Nicolas and Jackson,

1972) commonly displays evidence of an incomplete extraction process in which basaltic liquid was being removed. Such liquids have crystallized as pods or schlieren of gabbroic (ol + plag + cpx + opx) assemblage in a host of lherzolite or plagioclase lherzolite (Menzies, 1973). Incomplete separation and in-situ crystallization of a generated basaltic extract has also been recorded within garnet lherzolites as garnet + clinopyroxene peridotites (Carswell, 1968; Kornprobst, 1969).

## Purpose of This Paper

Recent field work on the Western Othris ophiolite, Greece (Hynes, 1972), the ultramafics and mafics of this complex (M. M.), and the Troodos plutonic complex, Cyprus (C. A.), has identified variable amounts of plagioclase lherzolite, lherzolite, plagioclase harzburgite, dunite, and harzburgite. The purpose of this paper is to describe the petrology of these ultramafic units and their field relations, and to discuss their chemical characteristics and relationships. The broad evolutionary aspects of the two complexes will be discussed and related to the presence or absence of certain modified and/or depleted mantle tectonites.

## Field Relationships within the Othris Ophiolite

In the Western Othris region, and within a sequence of imbricate thrust sheets, a complete ophiolite sequence has been recognized (Hynes *et al.*, 1972; Hynes, 1972; Menzies, 1973). Cumulate mafic and ultramafic rocks of limited extent are in thrust contact with extensive underlying tectonite ultramafics. These latter ultramafics are dominated by a dunite—harzburgite association which is intimately associated with lesser amounts of plagioclase lherzolite, gabbroic schlieren, and lherzolite.

The harzburgite (ol : opx : sp = 79 : 20 : 1) is homogeneous except for the occasional transgressive pyroxenitic and anorthositic veins. Pervasive foliation in harzburgite, defined by pyroxene megacryst and spinel elongation, is often accompanied by small scale compositional layering [Dickey's (1970) metamorphically differentiated layering] where dunite and pyroxenitic material display a sheeted aspect. Alternatively, dunite and harzburgite occur as adjacent masses displaying an irregular contact. Across the contact a parallel foliation is recognized in the dunite, which is defined by strung out chromian spinels within an olivine host. Occasional euhedral spinels are visible in a xenoblastic groundmass of strained olivine and minor exsolved and kinked orthopyroxene. The dunite is easily distinguishable because the scarcity of pyroxene prevents the development of obvious foliation. The small size of comminuted orthopyroxene makes mylonitized harzburgite difficult to recognize in the field.

No pockets or islands of plagioclase lherzolite have been located within the harzburgite unit. The only plagioclase bearing phase are the infrequent gabbroic veins (ol + cpx + plag) varying from 2 cm to 15 cm across. These veins tend to be bordered by harzburgite, and dunite (Boudier and Nicolas, 1972) containing large megacrysts of orthopyroxene. Vein boundaries are irregular but sharply intrusive.

The transition between harzburgite and plagioclase lherzolite, noticeable over several tens of meters, is a zone of gradual increase in plagioclase and clinopyroxene. Intermediate members of the sequence are plagioclase harzburgite, plagioclase-poor lherzolite, and plagioclase lherzolite with gabbroic schlieren. Close association of primary and depleted mantle within the garnet lherzolite field (Carswell, 1968) revealed sheared or possibly interdigitating contacts of garnet peridotite (modified mantle) and dunite (residue). Plagioclase lherzolite contains basaltic extract which exists as either (a) interstitial material closely associated with minor segregations and residual, or as (b) more dominant larger segregations and veinlets (Menzies, 1973).

(a) This type is generally represented by plagioclase lherzolite of uniform appearance and strong foliation. Interstitial plagioclase elongated parallel to the foliation imparts a distinctive fabric to the rock. These felsic pockets, of variable size, are invariably wholly or partially rodingitized to a deuteric aggregate of epidote, zoisite, and hydrogarnet. Green diopside and glomeroporphyritic olivine are found within the larger segregations (Fig. 2). Examples have been found which are enriched in diopside megacrysts, and co-existing with irregular blebs of altered plagioclase in a dunitic host tectonite. As the segregation: residue ratio increases, it eventually produces schlieren of gabbroic composition. The true composition of the primary melt cannot be assessed soly from the mineralogy of the segregations as the actual composition probably includds some fraction which has been removed plus a combination of interstitial and segregation phases. If olivine occurs within these schlieren it is either genetically related to the surrounding residual tectonite, or it is an early precipitate from the first formed melt. Intimate intermingling of the depleted ultramafics and the separated mafic fraction occurs at the margin of these segregations. Enrichment in pyroxene is visible along this "contact" and minute pockets of mafic material join the larger segregations. These islands of plagioclase + clinopyroxene within the ultramafic parent occur on a small scale. Conversely, dunitic and harzburgitic patches are frequently located within the mafic extract.

(b) The eventual outcome of this segregation mechanism is the production of a high percentage of segregations and schlieren. These vary from 3 to 50 cm across and frequently occur in swarms. Plagioclase lherzolite, containing foliated lenticular pockets of plagioclase and plagioclase plus pyroxene surrounds these segregations. Apparent leaking or migration of these minute pods have produced, on coalescence, mafic schlieren. The contact with the host ultramafic is either gradational or sharp within the plagioclase lherzolite and plagioclase harzburgite respectively.

## Field Relationships within the Troodos Ophiolite

The Troodos complex is a well developed ophiolite believed to represent a fragment of Upper Cretaceous oceanic crust (Gass and Smewing, 1973; Greenbaum, 1972; Lort and Matthews, 1972; Moores and Vine, 1971). Recently proposed origins, consistent with the theories of plate tectonics, invoke generation at a spreading oceanic ridge (Moores and Vine, 1971) or spreading interarc basin (Miyashiro, 1973). The plutonic complex, underlying the sheeted complex, shows

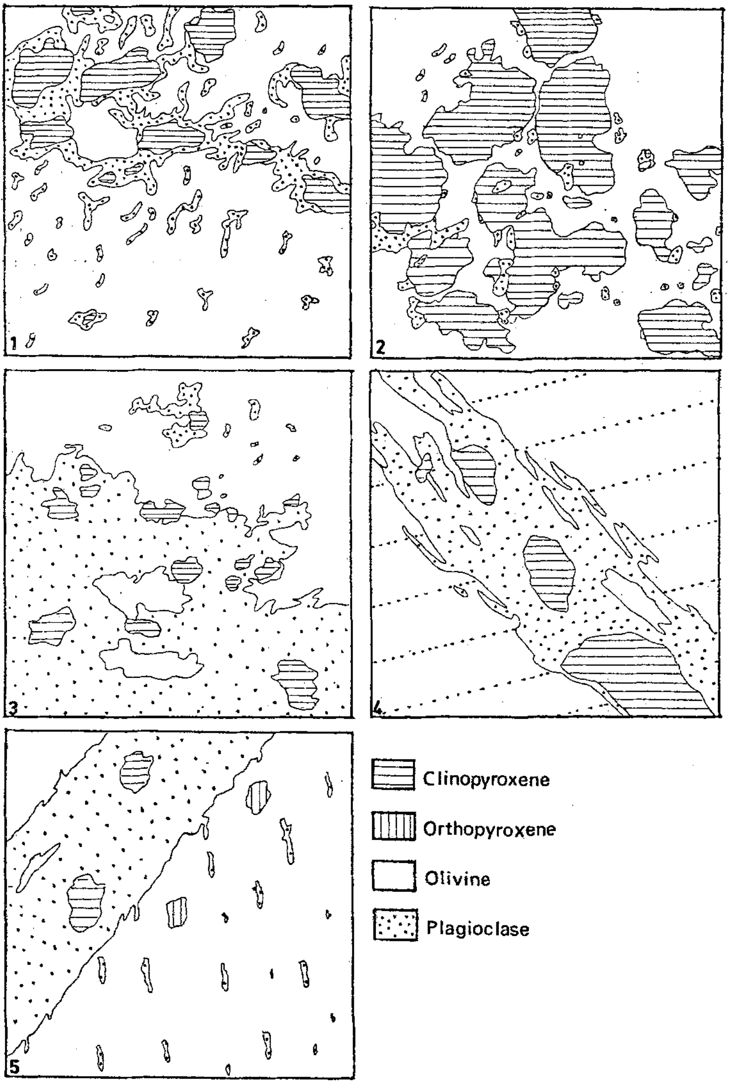

Fig. 2. Textures with the plagioclase lherzolites and harzburgites of Othris. The dotted lines in no. 4 show a possible fabric within the harzburgite

a quasi-stratiform distribution of trondhjemites and high level uralite gabbros underlain by cumulate pyroxene and olivine gabbros, pyroxenites, wehrlites, and dunites lying on a tectonite harzburgite basement. The crystallization sequence of the cumulate series has been determined as (i) cr, (ii) cr + ol, (iii) ol + cpx, (iv) ol + cpx + opx + plag, and (v) cpx + opx + plag (Greenbaum, 1972).

Whereas all other nontectonic igneous contacts are gradational where not intrusive, field evidence shows a profound discontinuity at the dunite-harzburgite contact, where the transition is very abrupt. Chromite deposits are localized within the dunite at, or very near, to this contact. Moores and Vine (1971) identified the dunite and harzburgite as tectonite material below a cumulate sequence and postulated an origin as residual upper mantle. Greenbaum (1972) identified the dunites and chromitites as adcumulates and the harzburgite alone as residual mantle.

The central harzburgite core of the complex occupies an area of 40 sq. km (Wilson 1959). Massive to well foliated harzburgite is remarkably homogeneous, comprising olivine ($80 \pm 5\%$), enstatite + exsolved diopside ($20 \pm 5\%$) and minor intergranular, irregular reddish brown spinel. Textures are xenomorphic granular, with grain size ranging from 0.5 to 10 mm. Serpentinization is prevalent, often approaching 80 to 100%. The major, and rarely a minor second, foliation is defined by flattened and elongate enstatite and spinel lying in the foliation plane. Well foliated harzburgite often shows a one to ten cm compositional layering. The olivine harzburgite fabric shows a strongly developed $\gamma$ axis point maximum in the foliation plane, and a $\alpha$ axis partial girdle (R. P. George, Jr., pers. comm.). The general trend of the major foliation is north-south and subvertical, parallel to the trend of the sheeted dike complex.

Plagioclase harzburgite, containing 1–2% interstitial and highly altered 0.3 mm plagioclase grains, and lesser spinel, occurs as a minor variant of harzburgite only in relative proximity to the dunite contact and is underlain by the dominant plagioclase free spinel bearing harzburgite. Foliated and massive harzburgite is frequently cut by discordant orthopyroxenite veins up to 30 cm across. These veins are rooted in harzburgite and extend upwards cutting chromite deposits and dunites. Vein contacts are sharp or gradational (1–2 cm) with harzburgite, but invariably sharp with the overlying cumulates. In this connection may be mentioned a peculiar orthopyroxene fabric in the harzburgites (Fig. 3), where small discrete enstatite grains occur slightly branching interstitial to olivine, or show poikilitic overgrowth on the larger xenoblastic enstatites. Less frequently, small diopside grains not of exsolution origin may show a similar interstitial habit.

The dunites are adcumulates containing on average 2% euhedral opaque spinel. Away from the harzburgite contact dunite changes gradationally into poikilitic wherlite with the advent of intercumulus diopside. The unfaulted westerly harzburgite contact is poorly defined across 0.5 km owing to outliers and inliers of dunite and harzburgite included within the other, possibly due to large scale infolding. Within the harzburgite core and far removed from the major dunite contact, isolated dunite pods to several hundred meters across are found showing abrupt contacts with bordering harzburgite, and occasionally containing small associated chromite deposits.

Plagioclase lherzolite has been found within harzburgite only as a series of small outcrops west of the summit of Mt. Olympus in close proximity to the dunite contact. This lherzolite possesses a tectonite fabric, and a foliation concordant to that of the neighbouring harzburgite. Texturally, olivine (65%), diopside (10%), and enstatite (15%) show xenomorphic granular habit, and plagioclase and anhedral spinel (8% and 2%) show elongation in the foliation plane. The contacts with the regional harzburgites are not well exposed but appear to grade through nonfeldspathic lherzolite, and wehrlite with varying ol:cpx ratios. This wehrlite is also found cutting the plagioclase lherzolite as a 15 to 20 cm wide

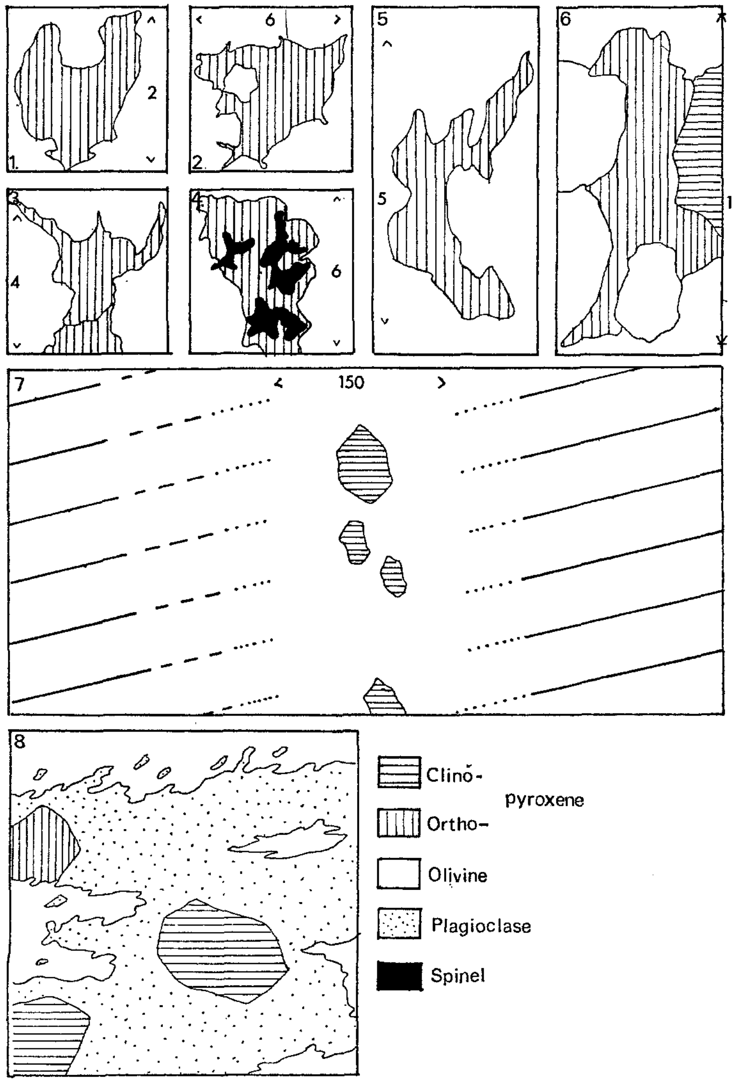

Fig. 3. Textures within the Troodos ultramafics. The six sketches at the top are visible under the microscope, scale marked in mm. Sketch 8 is actual size. The foliation is marked as parallel lines: — plagioclase lherzolite foliation; - - - plagioclase poor ultramafic foliation; ... dunite foliation

band, containing a central zone of large 1 to 3 cm clinopyroxene megacrysts, and margined by dunitic material. Away from the contact the plagioclase component is absent from the lherzolite for a distance of 8 to 10 cm (Fig. 3). This occurrence is identical to Boudier and Nicolas' (1972, Fig. 2) "in-situ" formed dykes with depleted walls in the Lanzo lherzolite, with the central gabbroic fraction being absent on Troodos.

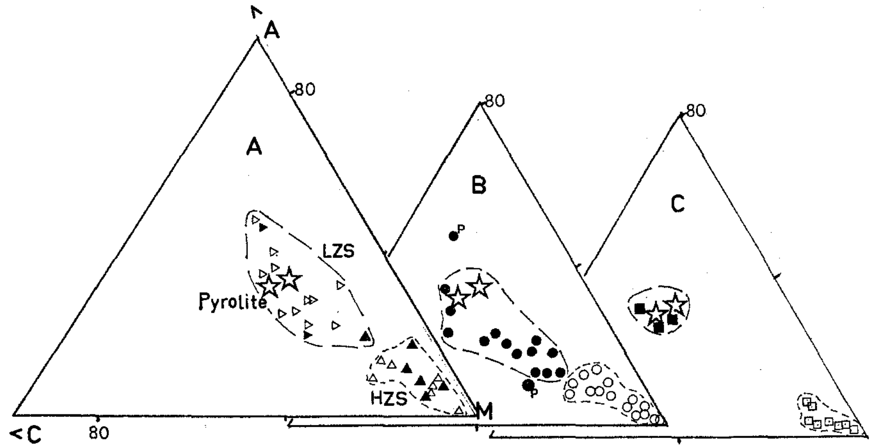

Fig. 4A–C. Portions of the $Al_2O_3$—CaO—MgO diagram indicating the location of various Mediterranean ultramafic complexes. *LZS* Lherzolites, *HZS* Harzburgites. A After Nicolas and Jackson (1972). ▷ Eastern Mediterranean aluminous peridotites; △ Eastern Mediterranean harzburgite type peridotites; ► Western Mediterranean aluminous peridotites; ▲ Western Mediterranean harzburgite type peridotites. Pyrolite—2/3 (Ringwood, 1966; Green and Ringwood, 1967). B Greek Ultramafics. *P* Pindos ultramafics (after Montigny *et al.*, 1973). Othris ultramafics: ● lherzolites and plagioclase lherzolites; ○ harzburgites, dunites and pyroxene rich harzburgites. C Troodos Ultramafics. ■ Plagioclase lherzolites; □ Harzburgites and dunites

Rarely, schlieren of coarse grained gabbroic material (plag + opx + cpx + ol) up to 20 × 8 cm occur in otherwise homogeneous plagioclase lherzolite, lying concordant or slightly discordent to the foliation (Fig. 3). Analogous textures have been described by Menzies (1973) as coalesced gabbroic melt.

## Chemistry and Interpretation

### *Harzburgite*

The high proportion of harzburgite to overlying cumulates precludes the possibility of these peridotites having formed by cumulate processes from a basaltic magma. The plausibility of alpine type peridotites being of cumulate origin is discounted by the low pressure anhydrous ($<5$ kb) olivine—orthopyroxene reaction relationship, which also persists to higher pressures even under very low water contents (Kushiro *et al.*, 1968). This reaction relationship prevents olivine and orthopyroxene from crystallizing simultaneously in the constant proportions of ol:opx = 80:20 as observed in harzburgite. Further, the Troodos and Othris harzburgites exhibit no cryptic mineralogical or bulk variation in Mg/Mg + Fe, Ni, or Cr as might be expected in cumulate systems. Irvine and Findlay show that 2 to 3% Mg/Mg + Fe variation in the Bay of Islands peridotite is largely due to interstitial liquid re-equilibrating with the harzburgite.

Chemically this group is very homogeneous, based on a consistent mineralogy (Fig. 4, Table 1, nos. 1, 12). Harzburgites contain olivine (Othris $Fo_{80-90}$, Troodos $Fo_{90-92}$) and enstatite (Othris $En_{89-90}$, Troodos $En_{90-92}$) and minor amounts of

Table 1

| | 1. | 2. | 3. | 4. | 5. | 6. | 7. | 8. | 9. | 10. | 11. | 12. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 42.41 | 43.63 | 39.92 | 44.27 | 43.67 | 42.30 | 45.16 | 42.75 | 40.41 | 54.10 | 43.24 | 43.47 |
| $TiO_2$ | 0.06 | 0.11 | 0.01 | 0.13 | 0.09 | 0.11 | 0.71 | 0.022 | 0.008 | 0.026 | 0.018 | 0.010 |
| $Al_2O_3$ | 0.48 | 1.85 | 0.11 | 3.58 | 3.11 | 4.60 | 3.54 | 3.63 | 0.14 | 0.81 | 0.99 | 0.47 |
| $Cr_2O_3$ | 0.48 | 0.42 | 0.45 | 0.43 | 0.27 | 0.33 | 0.43 | 0.65 | 0.41 | 0.62 | 0.40 | 0.39 |
| $Fe_2O_3$ | 0.83 | 2.48 | 4.87 | 4.69 | 6.76 | 2.20 | 0.46 | 3.10 | 5.35 | 1.93 | 2.34 | 5.44 |
| FeO | 7.53 | 6.18 | 4.84 | 4.34 | 3.01 | 6.40 | 8.04 | 5.49 | 3.92 | 5.62 | 4.27 | 3.24 |
| MnO | 0.16 | 0.16 | 0.18 | 0.18 | 0.17 | 0.21 | 0.14 | 0.18 | 0.17 | 0.21 | 0.13 | 0.15 |
| NiO | 0.30 | 0.28 | 0.38 | 0.27 | 0.25 | 0.19 | 0.20 | 0.25 | 0.24 | 0.06 | 0.29 | 0.27 |
| MgO | 46.95 | 42.58 | 49.00 | 38.53 | 34.82 | 37.23 | 37.47 | 40.34 | 49.05 | 33.30 | 40.44 | 45.72 |
| CaO | 0.74 | 2.15 | 0.19 | 3.30 | 7.67 | 6.14 | 3.08 | 3.46 | 0.18 | 1.82 | 0.82 | 0.77 |
| $Na_2O$ | 0.05 | 0.14 | 0.05 | 0.11 | 0.12 | 0.20 | 0.57 | 0.061 | 0.005 | 0.036 | 0.027 | 0.006 |
| $K_2O$ | 0.01 | 0.02 | 0.01 | 0.13 | 0.02 | 0.01 | 0.13 | 0.008 | 0.002 | 0.000 | 0.010 | 0.002 |
| S | 0.00 | 0.01 | 0.00 | 0.03 | 0.03 | 0.04 | — | 0.029 | 0.041 | 0.008 | 0.015 | 0.019 |
| $H_2O$ | * | * | * | * | * | * | 0.00 | * | * | 1.97 | 7.20 | * |
| Total | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.53 | 100.20 | 100.0 |
| Mg/Mg+Fe | 0.910 | 0.900 | 0.905 | 0.889 | 0.872 | 0.888 | 0.888 | 0.897 | 0.909 | 0.890 | 0.919 | 0.909 |

Othris
1. average of 7 harburgite
2. average of 6 lherzolites.
3. average of 2 dunites.
4. typical homogeneous plagioclase lherzolite.
5. pyroxene rich plagioclase lherzolite.
6. plagioclase rich plagioclase lherzolite.
7. Pyrolite (Ringwood 1966) $P_2O_5 = 0.06$ wt.%.

Troodos
8. average of 3 plagioclase lherzolites.
9. average of 6 dunites.
10. orthopyroxenite vein.
11. plagioclase harzburgite.
12. average of 8 harzburgites.

$P_2O_5$ in all Othris and Troodos samples $<0.01$ wt. %.
Othris S values determined on only two samples of each type.
* Recalculated $H_2O$, $CO_2$ free to 100% for comparison.

anhedral aluminous Cr spinel. This three phase assemblage produces a highly refractory chemistry with bulk ratios of Mg/Mg + Fe ranging from 0.891–0.905 (Othris) to 0.906–0.911 (Troodos). The total alkali content is less than 1000 ppm and CaO and $Al_2O_3$ are both appreciably less than one percent. Furthermore, Ti, S, and P are also extremely low. Field evidence reveals a difference in structural styles, the harzburgite being foliated while the overlying ultramafic magmatic cumulates are relatively structureless.

For these reasons the harzburgite is thought to represent depleted upper mantle (O'Hara, 1970) produced by partial melting of aluminous upper mantle peridotite and subsequent removal of the basaltic extract (Hamilton and Mountjoy, 1965; Himmelberg and Loney, 1973). The impossibility of further extraction of basaltic liquid is apparent from the low abundance of "liquid accumulative" elements and the highly magnesian nature of the mineral phases. The rather constant ratio of ol:opx 80:20 implies uniform controls on partial melting. A plot of Ca—Al—Mg (Fig. 4) reveals the close chemical similarity of residual peridotites from Othris and Troodos and also the ultramafic complexes studied by Nicolas and Jackson (1973).

### *Plagioclase Harzburgites*

The plagioclase harzburgites and orthopyroxenites of Troodos, and the lherzolites of Othris are intermediate members of the residue-extract series. The plagioclase harzburgite (Table 1 no. 11) is slightly enriched in Ca, Al, Na und K relative to the harzburgite proper, and poorer in $RO/SiO_2$. The presence of plagioclase illustrates the small compositional increment required to stabilize this fourth phase. The absence of plagioclase within the assemblage (ol + opx + sp ± cpx) is not necessarily indicative of the spinel peridotite field (Loney *et al.*, 1971) but merely a reflection of Cr, Al, Ca, and Na concentrations. High Cr and low Na and Ca favour the presence of spinel and the absence of plagioclase (Green and Hibberson, 1970). Consequently the plagioclase harzburgite is interpreted as a residual harzburgite which has retained a small proportion of the generated basaltic liquid, the aluminous part of which is represented as interstitial plagioclase. Perhaps significantly, these plagioclase harzburgites are restricted to the top of the harzburgite very close to the development of the cumulate sequence.

### *Orthopyroxenite Veins*

The pure orthopyroxenite veins cutting the harzburgites (Table 1 no. 10) are richer in ferrosilite than the enstatites in harzburgite by several mole percent. Mineralogical and field studies are consistent with these veins being derived from the last fusion product extracted from the harzburgite. This liquid forms the late stage veins, and fills the remaining pore spaces in a harzburgite crystal mush. This crystallises as poikilitic grains or extensions to xenoblastic enstatite (Fig. 3). The infrequent diopside grains in harzburgite seem to have formed from a more calcic, non-aluminous residual pore fluid. Orthopyroxenite veins within the Pindos ophiolite, Greece have similarly been proposed as the last partial melting products from ultramafic material (Montigny *et al.*, 1973).

### *Lherzolite*

Lherzolites which are associated with the harzburgite in Othris are easy to recognize by their enrichment in clinopyroxene in an area of enstatite rich ultramafic. Relative to harzburgite the lherzolites are richer in Al, Ca, and Ti brought about by increase of modal pyroxene, yet lower in these elements than plagioclase lherzolite (Table 1, no. 2). The slightly more iron rich nature of the olivines and pyroxenes (relative to harzburgite) is reflected by the lower NiO content and Mg/Mg + Fe ratio. The pyroxene phases are enriched in Mn, and Ti but lower in Cr than equivalent pyroxenes in harzburgite.

The lherzolites are thought to represent highly modified mantle material which has had the plagioclase component removed. It still retains some evidence of an incomplete extraction process in the form of clinopyroxene and minor plagioclase. Possibly in status it lies between the plagioclase harzburgite and the plagioclase lherzolite in that further melting would produce a harzburgite.

### *Dunite*

The bulk of the dunites on Troodos lie above the harzburgite, but some interfolding is apparent. This also seems to be the case in Othris, but exposure of vast amounts of dunite is not encountered. The dunite pods lying enclosed within the Troodos harzburgite far from the major contact (1–3 km) and exhibiting sharp, contacts are believed to result from crystal settling ofolivine (O'Hara, 1968, 1970) and/or spinel from pockets of olivine basalt magma enclosed within harzburgite, during ascent at a spreading ridge axis. Olivine fractionation would result if the olivine primary phase volume expanded at a greater rate than heating due to adiabatic decompression. There is no evidence on Troodos for residual 100%, or even 90% olivine dunites. Refractory dunites would have much higher contents of Cr, Ni and lower Ti, Fe, Mn and S (Table 1, no. 9) than the refractory harzburgites (Burns, 1973). The Troodos cumulate dunites have $Mg/Mg+Fe$ values of 0.903–0.916, approximately the same as harzburgite. Direct evidence of magmatic origin for these pods is meagre, the invariably euhedral chromites, and rare chromite deposits being the only clue. Within Othris the dunites contain olivine ($Fo_{90-91}$) associated with euhedral to subhedral spinels and infrequent pyroxene. A non-residual origin can be argued for dunites that contain minor concentrations of euhedral chromite strung out parallel to the contact with harzburgite. Dunites with varying orthopyroxene contents (0–10%) and anhedral spinels could possibly represent a further depletion stage of harzburgite.

### *Plagioclase Lherzolite*

Menzies (1973) presented several criteria for distinguishing primary tectonite lherzolite from highly deformed cumulate ultramafic. The possiblity of misinterpretation of the Troodos and Othris plagioclase lherzolite is discounted. No five phase cumulates ($ol+cpx+opx+plag+sp$) have yet been identified in these ophiolites. In the Troodos magmatic ultramafic-mafic transition a two phase poikilitic feldspathic lherzolite cumulate with three intercumulus phases ($plag+cpx+opx$) does occur, but shows considerable modal variations over short distances. These cumulates are distinguished from tectonite by lower Ni, Cr, S and $RO/SiO_2$; higher Na, K, Ti and P; $Mg/Mg+Fe<0.877$; and tiny euhedral Cr, Fe rich spinels.

Plagioclase lherzolite as exposed in Othris and on Troodos is not "pristine" upper mantle, as many major and minor elements show systematic depletion consistent with a preceding phase of magmatic extraction.

Chemical heterogeneity of the Othris plagioclase lherzolites, produced by modal fluctuations of the magmatic segregation material is evident from three typical examples presented in Table 1 (nos. 4, 5, 6). The Troodos plagioclase lherzolites (Table 1, no. 8) are remarkably homogeneous (except for infrequent gabbroic segregations and "in-situ" dikes) and exhibit less than five to ten percent relative variation in oxides. The bulk chemical difference with respect to harzburgite is an increase in Al, Ca, Fe, Ti, Mn, S, Na, and K appearing as modal plagioclase, clinopyroxene and sulphide. Decrease in Ni, Mg, and Cr is due to compositional changes of mafic minerals, the modal decrease of olivine, and the loss of spinel as a significant component. Cr is unaccountably higher in the Troodos plagioclase than in harzburgite. Ca and Al in the Othris lherzolites vary systematically depending on whether clinopyroxene or plagioclase is the dominant segregation phase. Homogeneous lherzolites from both localities have CaO and $Al_2O_3$ contents of approximately 3.3 and 3.6 wt. % respectively. The ratios of Mg/Mg + Fe used a rough index of residuality is distinctly lower than in any of the previously described ultramafics.

On first inspection, the major element chemistry of these plagioclase lherzolites seems compatible with the pyrolite model (Ringwood, 1966; Table 1, no. 7). However, in many respects they show a slightly more residual nature. The ratios of $CaO/Al_2O_3$, $RO/SO_2$, and Mg/Mg + Fe, sensitive to phase proportions and compositions are higher than in pyrolite. Elements such as Na, K, Ti and P (especially in the Troodos lherzolites) show a spectacular decrease.

Although the artificial manner in which the pyrolite model was constructed makes absolute comparisons suspect, these plagioclase lherzolites are obviously incapable of producing primary olivine tholeiite magmas with the requisite Na, K, Ti and P contents. This depletion can best be explained by invoking Green's (1970) two-stage or multi-stage partial melt model for the origin of oceanic ridge basalt. Small quantities of mobile elements are removed by utilizing available pore water (0.1–0.2 wt. %) to instigate partial melting. When the small quantity of water saturates the melt further melting and removal of major components is dependant on increasing temperature. In an environment of semi-solid upward mantle flow beneath constructive plate boundaries removal of less than 5% partial melt might be accomplished by the continuous syntectonic recrystallization of mantle peridotite (Carter *et al.*, 1972) forcing the pore liquid out. This basalt (nepheline normative) could have been removed at an earlier stage of melting and separation, or mixed with extensive melt products of tholeiitic composition generated nearby at the same time.

The partially depleted source rock would be subjected to further melting on intersecting the anhydrous solidus. The basaltic liquid produced from this phase of melting would be chemically different from the earlier phase. The present interstitial liquid in the Othris segregations, and the magma still capable of being generated from both lherzolites is probably a high-alumina ocean-ridge tholeiite (O'Hara, 1968; Green, 1970).

The existence of fossilized extraction processes within these plagioclase lherzolites permits easy study of those elements which are concentrated within either the residuum or the melt medium. As the latter contains plagioclase and pyroxene it is found to be enriched in Na, K, Ca, Fe, Mn, Ti, Al, and S: the residuum, a mixture of olivine and orthopyroxene, concentrates Mg, Ni, and Cr. Considerable mineralogical variation (Menzies, 1973) accounts for this chemical break. This elemental split is in general agreement with physico-chemical models (Vinogradov *et al.*, 1971) and studies of partial melting, except for Mn which we have found to concentrate in the melt fraction (Burns, 1973) in the clinopyroxene and minor olivine.

## Discussion and Conclusion

Othris and Troodos, both showing all the physical features of ophiolite complexes, have significantly different structural styles and chemical trends. Troodos is a typical example of the harzburgite sub-type ophiolite, and Othris intermediate between the harzburgite and lherzolite sub-types (Himmelberg and Loney, 1973; Nicolas and Jackson, 1973). Within these two ophiolites exists a spectrum of mantle types: harzburgite (depleted and residual), plagioclase harzburgite (highly modified), lherzolite (moderately modified), and plagioclase lherzolite (slightly modified). The range of compositions of these mantle types forms a continuous spectrum on a Ca—Al—Mg diagram (Fig. 4). The rocks from Othris reproduce this trend while the Troodos material shows extreme separation of plagioclase lherzolites and harzburgites with non-intervening members. This indicates that the mantle depletion process was more extensive, and has gone further towards completion here than in Othris. Assuming an original homogeneous primary mantle, this implies incomplete extraction of a less basic parent magma or set of magmas from Othris than occurre in Troodos. Generation of an olivine poor basalt in Othris (approximately 15–20% partial melt with incomplete extraction) and an olivine rich basalt (25% partial melt, with almost complete extraction) in Troodos is qualitatively supported by field evidence and chemical depletion parameters.

The general absence of partial melt—segregation features on Troodos, and the absence of trapped basaltic liquid within harzburgite implies that the zone of segregation—separation lies at depth, below the harzburgite unit. If dunite pods formed by accumulation from olivine basalt liquids during ascent at a ridge axis, a substantial pressure differential must have existed between the regime of partial melt—segregation and fractional crystallization in axial magma chambers. Thus the basaltic liquid need not be in equilibrium with harzburgite residue at low pressure conditions. The axis cumulate fractionation sequence (cr + ol + cpx + opx + plag) shows a low pressure reaction relationship, and is significant in that olivine and orthopyroxene, formerly in equilibrium with basaltic liquid in the zone of magma segregation, do not appear simultaneously or sequentially on the liquidus at low pressure. The 6–8 km thick Troodos basalt-generated lithosphere would require 18–24 km of underlying harzburgite to balance the pyrolite mantle model (Fig. 5) (Verhoogen, 1973). Full development of a sequence which includes approximately 2 km of basaltic material, a thick sheeted complex, and an extremely well differentiated plutonic complex was only realized on Troodos. Extensive dunite adcumulates as present in Troodos require large volumes of olivine rich basalt cooling slowly under conditions of high heat flow, or thick crust which would act as an insulator. Alpine-type chromite deposits are also favoured by these circumstances. The Othris complex consists of relatively thin oceanic crust (2–3 km), a poor dike complex, and a limited amount of plutonics. Adcumulate dunites and chromite deposits, both of which are integral parts of harzburgite sub-type ophiolite deposits (Thayer, 1969) are absent. The Othris plutonics formed either within small pockets of mafic liquid, or within feeders. Applying the Verhoogen model, the thickness of harzburgite expected on Othris would be considerably less than Troodos by almost a factor of three. This limited develop-

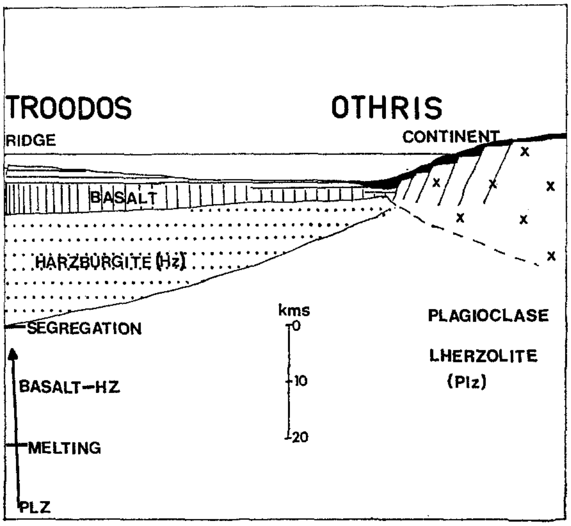

Fig. 5. Diagrammatic representation of the evolutionary environments of the Troodos and Othris complexes. The vertical scale is accurate and the horizontal distance compressed to facilitate representation. No time correlation or formation from the same oceanic asthenosphere is inferred. The thickness of residual mantle, harzburgite, is related to the thickness of overlying oceanic crust by the relationships outlined by Verhoogen (1973). Upwelling masses of primary mantle or plagioclase lherzolite intersect the melting level thus generating basaltic extract and residual harzburgite. On reaching the segregation level the two components separate and produce an accumulation of residual mantle. The coalesced pockets of basaltic extract rise and replenish magma sources below an active ridge. For fuller explanation of the location of Othris and Troodos see text

ment of depleted mantle and the presence of large amounts of plagioclase lherzolite, unlike Troodos, indicates a radically different evolutionary environment.

In Othris, regional mapping shows that the ophiolite forms the highest part of a tectonite stack (Hynes *et al.*, 1972). The systematic facies changes in contemporaneous sediments lower in the stack indicate continental margin deposition. The autochton is a continent. This data suggests that the ophiolites in Othris probably represent ocean floor that formed close to a continent. By contrast, the width of the sheeted complex on Troodos and the absence of continental derived sediments shows that at least part of it must have formed at some distance from the continental margin. This is in agreement with the proposed amount of residual harzburgite below the complex. Conversely, because the Othris oceanic crust formed near to a continent we suggest that at the inception of spreading the pre-existing ocean basin was underlain by undepleted plagioclase lherzolite upper mantle (Fig. 6) (Nicolas and Jackson, 1972). Early formed volcanics would display a continental affinity, and the later basalts a ocean floor affinity, as is possibly the case in Othris (E. Nisbet, pers. comm.). Further development of ocean floor by depletion of underlying plagioclase lherzolite to produce harzburgite would lead to thickening of oceanic crust and build up of magma cells below the spreading ridge. This would be underlain by harzburgite,

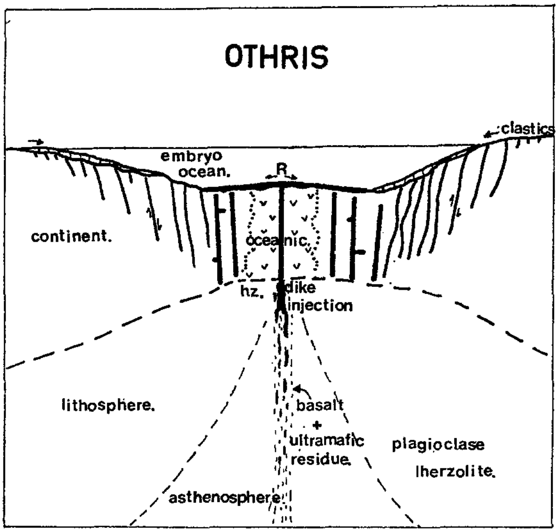

Fig. 6. The evolution of Othris during early rifting of a continent overlying primary mantle plagioclase lherzolite. Upwelling pockets of basaltic extract generate transitional and eventually oceanic crust, via dike injection. Gradually residual ultramafic accumulates below the newly generated crust, hz. on the diagram. Information on ridge (*R*) and continental sediments after I (Price pers. comm.)

and at greater depth by aluminous peridotite (Fig. 5). The steady state disposition of isotherms under continental material is roughly predictable from continental geothermal gradients. At the inception of crustal rifting the basalt generating isotherm of 1100° C would rise from an initial depth of 50–60 km to a shallower level. Any ophiolite formed during the period of rising isotherms in plagioclase lherzolite would possess on only partially modified tectonite mantle complex of the lherzolite sub-type. However, a basement of lherzolite would not be expected in an ophiolite where the 1100° C basalt generating isotherm had achieved a steady state position at the petrological moho. Troodos, with its harzburgite basement, would be expected in this situation. We conclude that Othris formed at the inception of rifting while isotherms were at some depth and rising, while Troodos formed further away from the continental margin at a later stage in oceanic floor evolution.

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