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Spinel Compositional Variation in the Crustal and Mantle Lithologies of the Othris Ophiolite

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Abstract. Spinels from cumulus and non-cumulus members of the Othris ophiolite display a considerable variation in composition. Cumulus picrites and gabbros contain either a primary chromite and/or a reaction spinel formed by reaction with co-existing silicates (Cr—Al variation) or intercumulus liquid (Cr—Fe variation). Non-cumulus peridotites contain spinels which vary along a Cr—Al trend. Harzburgites contain a Cr-spinel and lherzolites a more aluminous spinel. The occurence of gabbroic segregations within the host lherzolite appears to affect the spinel chemistry. Spinels adjacent to these plagioclase—diopside veinlets are richer in aluminium than the spinels scattered within the depleted lherzolite surrounding the veinlet. [Protoclastic harzburgites contain a highly aluminous spinel phase either as an exsolution phase within pyroxenes or as a groundmass spinel.] The Cr—Al variation of the peridotites is believed to have resulted from interaction with interstitial aluminous liquid—in situ basaltic melt from a fused peridotite?

Introduction

The Othris ophiolite, situated in Central Greece, contains a diversity of ophiolitic lithologies within an east-west section. This Mesozoic ophiolite is believed to have formed at the inception of rifting of continental crust, and thus represents a section of early spreading oceanic crust and upper mantle (Hynes *et al.*, 1972; Menzies and Allen, 1974). Crustal lithologies include basalts, dolerites and gabbros, while the mantle section is dominated by foliated harzburgite-dunite and minor lherzolite.

Spinels occur throughout the mantle peridotites, but are limited to occasional gabbros and scattered picritic basalts within the crustal lithologies. Hynes (1972) completed preliminary studies of the spinels within the ultramafic rocks and he concluded that the plagioclase peridotites contained a more aluminous spinel than the plagioclase free peridotites, a conclusion partially supported by this study. Nisbet (pers. comm.) analysed spinels from the picrites and commented on their highly chromiferous nature.

Analytical Method

Representative spinels from each sample were analysed using energy dispersive analysis. Approximately twenty individual spinel grains were analysed on each section. The beam was carefully positioned such as to avoid magnetite rims and checks were made for possible zonation. The equipment used consisted of the Harwell Highspec pulse analyser system 3073 which is interfaced to a DGC Nova 1220 mini computer. Two separate programmes, PEST 1 and PESTSTRIP were used for spectra accumulation and input, and for peak area determination and ZAF correction. Elemental and oxide percentages are output directly and ionic percentages calculated using the FERRIC programme devised and written by Peter Statham. Many of the compositional variations were observed during routine analytical work using the Cambridge Instruments Geoscan electron probe microanalyser.

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Analytical Data

This study indicates that not only is there a difference in spinel composition between different rock types but also a range in spinel composition within the one section. A considerable range in spinel composition exists within one peridotite unit—the harzburgites. Such a variation is compatible with data on other peridotite masses, e.g. Mount Albert (Mac Gregor and Basu, pers. comm.).

Crustal basalts and gabbros—The picritic basalts occur in close association with highly serpentinised peridotite, dikes and basaltic flows or as exotic blocks elsewhere in Othris. Euhedral precipitates of olivine and pyroxene in partially devitrified glass enclose small euhedra of spinel. Skeletal and euhedral spinels occur within the glass and tend to cluster around the margins of euhedral olivines. These groundmass spinels are richer in Fe^{3+} (Fig. 1a) than the spinels occuring within silicate phases. All the enclosed spinels are consistently Cr rich and show less of a compositional spread. The content of Al^{3+} is also more restricted than in the groundmass spinel phase and the compositional difference between the two groups (a and b in Fig. 1a) appears to lie along a Cr—Fe tie line at constant alumina content.

Spinel bearing gabbros contain mainly cumulus plagioclase and interstitial olivine, which enclose spinel euhedra, and minor space filling pyroxene. The spinel phase exists as clusters within plagioclase crystals or as disseminated grains throughout the gabbro. These spinels exhibit a more restricted range in composition when compared with the picrites and they also tend to be much enriched in Al^{3+} (Fig. 1a, b). If the Cr-spinel occuring within the olivines of the cumulus picrite is representative of the primary spinel phase to crystallise from a basaltic melt, then the spinels occuring within the cumulus gabbro are perhaps formed by reaction along a Cr—Al line.

Within the crustal cumulus basaltic rocks the spinel composition appears to vary along either a Cr—Fe or a Cr—Al trend if one assumes that prior to emplacement the studied assemblages were co-magmatic.

Mantle peridotites—The dominant lithological types are dunites, harzburgites and lherzolites, the latter containing gabbroic segregations and occasional plagioclase schlieren. All the analysed peridotites have a marked foliation while the previous group of crustal rocks exhibit cumulus textures indicative of an origin from within a basaltic magma. Menzies and Allen (1974) outlined the chemistry and field relations of these peridotites and postulated a possible origin via partial fusion of mantle lherzolite. Because of this previous interpretation of the peridotites, spinel compositional variation will be interpreted in the light of this model, but it will become apparent that an alternative hypothesis, based on spinel chemistry is also valid. This origin would involve generation and deformation of mantle cumulates containing variable amounts of intercumulus liquid.

Harzburgites analysed by Hynes (1972) contain a Cr-spinel, and a more Al-rich spinel exists in plagioclase lherzolites and lherzolites containing gabbroic and feldspar segregations. Spinels within depleted (plagioclase free) lherzolite or harzburgite surrounding these segregations are poorer in Al^{3+} than the spinels adjacent to the veinlets. This compositional difference may be related to the bulk chemical gradient which exists, from an essentially refractory environment of

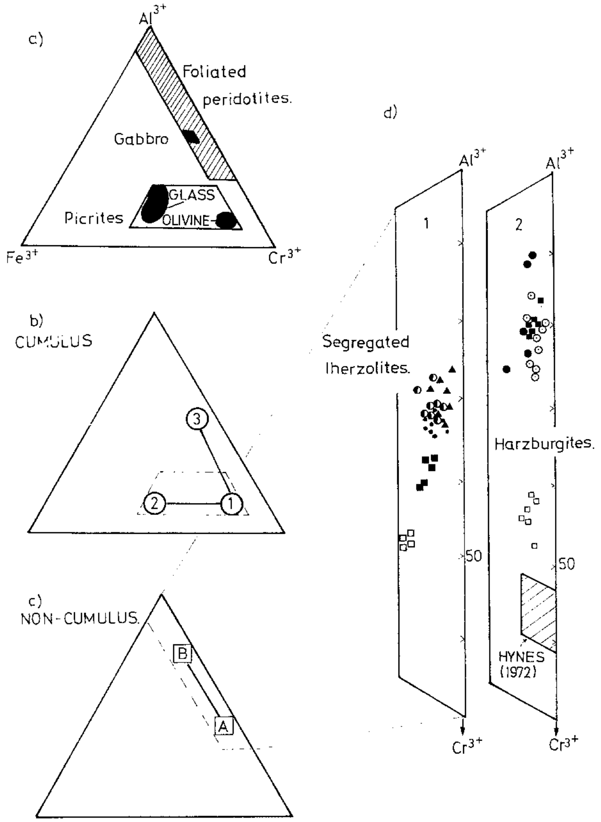

Fig. 1a—d. Compositional variation of Al, Cr and Fe^3 in spinel from cumulus and non-cumulus members of the Othris ophiolite. (a) Compositional fields for the foliated peridotites and the magmatic rocks, (gabbro and picrite). Spinels from within the picrites occur as groundmass euhedra (glass) or in olivine and pyroxene phenocrysts, (olivine). (b) Al and Fe trends within the cumulus members. The initial cumulus chromite (*1*) is believed to have reacted with intercumulus liquid and associated silicates to form the spinels (*2*) and (*3*) respectively. (c) Al trend in foliated peridotites, where (*A*) represents the Cr-spinel occuring in peridotite which has not reacted with aluminous liquid, and (*B*) represents spinel formed by possible reaction. (d) Enlarged area of (c). *1* The Al^3 content of spinels in segregated lherzolites increases towards plagioclase rich veins and gabbroic schlieren, ▲; whereas plagioclase poor lherzolites contain less aluminous spinels, ■. *2* The aluminous spinels in the protoclastic harzburgites are related to exsolution phenomena within pyroxenes, but the more Cr rich spinels represent isolated spinel phases which did not react with aluminous liquid. [Hynes (1972) analysed a series of serpentinised harzburgites]

olivine and orthopyroxene, to a plagioclase and diopside enriched veinlet (Fig. 1c, d). Small compositional differences exist within individual samples of lherzolite and harzburgite (Fig. 1d) but in the protoclastic harzburgites there are considerable differences in the composition of co-existing spinels. These harzburgites contain a groundmass spinel and a spinel phase which is exsolving from deformed and bent pyroxenes. Platelets and worm-like spinels are visible within the pyroxenes and aggregates of spinel occur around heavily deformed pyroxenes, and along internal fracture surfaces. The groundmass spinel is enriched in Al^{3+} (Fig. 1 d) relative to the exsolution phase within or around the pyroxene megacrysts.

Spinel compositional variation within these "alpine peridotites" associated with the ophiolite occurs along a Cr—Al trend with very little change in Fe^3.

Discussion and Conclusion

Interpretation of spinel compositional data from alpine type peridotites and basement ultramafics to ophiolites is based on either a magmatic or fusion hypothesis. Thayer (1946, 1964, 1969, 1970) has advocated a cumulus origin for alpine peridotites and consequently spinel variation would be the result of magmatic processes or reactions. Recently Dickey and Yoder (1972), using experimental data on an Fe-free system, postulated that the chemical variation observed in the spinel phase of peridotites could be the result of interaction of the spinel with generated basaltic liquid. This in situ melt occurs as an interstitial phase within the fused peridotite. Interaction would produce the required range in Cr—Al in an environment similar to that of the melting of chromian diopside to a liquid and spinel (Dickey *et al.*, 1970). The Cr and Al content of the spinel would then become a function of the bulk composition and small variations in temperature and pressure. Fused spinel bearing peridotites, which may be considered as suitable candidates for a study of such affects on spinel composition, occur as basement (ophiolites) and alpine ultramafics.

Although other possibilities exist, the Cr and Al variation within the spinel phase of foliated peridotite masses may be the result of:

a) Magmatic processes involving genesis and deformation of mantle cumulates. The spinels within this secondary tectonite will have initially inherited their compositional variation from reactions within a magmatic environment.

b) Fusion processes involving melting of mantle lherzolite (primary tectonite), genesis of an in situ basaltic melt and production of a harzburgite residue. Migration of the basaltic liquid facilitates reaction with the spinel phase.

c) A complicated process which may involve migrating basaltic liquid and primary or secondary tectonites.

Spinel variation within the Othris peridotites could conceivably be ascribed to any one of these processes. Previous work on the chemistry and mineralogy of these peridotites (Menzies, 1973, 1974; Menzies and Allen, 1974) indicates that a fusion mechanism could have produced the intimate association of foliated peridotite (harzburgite—lherzolite) and gabbro. Consequently the spinel variation within the Othris peridotites is believed to have been caused by interaction with migrating basaltic melt. Ample evidence exists within these peridotites of a percolating aluminous liquid, or a leakage of a plagioclase—diopside component into nearby gabbroic veinlets or plagioclase schlieren. Similar observations were made in the Lanzo complex, Italy (Boudier, 1972; Boudier and Nicolas, 1972) where a variation in spinel composition could be related to a fusion episode.

Within a fused peridotite, spinels, which are open to reaction with migrating basaltic liquid would presumably be different in composition to spinels immediately isolated in refractory harzburgite by total removal of all interstitial liquid. As observed within the Othris peridotites, spinels in the vicinity of segregated basaltic liquid are compositionally different from those isolated in the nearby peridotite. The highly chromiferous spinels within the harzburgites are compatible with this model, in that they were isolated in a refractory environment. During genesis of basaltic liquid is it not possible that cumulate phases may be dropped by the ascending basaltic liquid? This has been proposed for the origin of dunitic patches within harzburgite (e.g. Menzies and Allen, 1974) and may also lead to the existence of "cumulus" spinels in a primary tectonite environment. Despite these possible complications which cannot be entered into in this paper, the spinel variation is believed to have been caused by migrating aluminous liquid, probably basaltic.

The highly aluminous spinels occuring primarily as an exsolution phase within the protoclastic harzburgites, are problematical. Chemically the groundmass spinel is highly aluminous when compared with the exsolved phase (Fig. 1d). MacGregor (pers. comm.) suggested that an unmixing reaction involving this groundmass spinel and the exsolved spinels, may be arrested at some stage such that chemically different, unequilibrated spinels are formed. The spinel exsolution originates within a highly aluminous pyroxene via the reaction: (MacGregor, 1974)

$$x\mathrm{Mg_2SiO_4} + \mathrm{MgSiO_3} \times \mathrm{Al_2O_3} \rightleftharpoons x\mathrm{MgAl_2O_4} + (1+x)\ \mathrm{MgSiO_3} \quad \text{(similarily for } \mathrm{MgSiO_3}\ x\mathrm{Cr_2O_3}).$$

The apparent lack of highly aluminous pyroxenes within the harzburgites favours the right hand side of this reaction, as does the existence of large exsolution blebs within the pyroxene. Lack of equilibrium between this exsolved phase and the groundmass spinel will account for the highly aluminous nature of the groundmass spinel. Rodgers (1973) reported highly aluminous spinels within a cumulate sequence of peridotites from New Caledonia. These spinels occur within a harzburgite and Rodgers explains their existence via utilisation of aluminous interstitial liquid which crystallizes to form a highly aluminous pyroxene. This then recrystallizes to spinel and pyroxene during upwelling (Green, 1964).

This process could explain the highly aluminous spinels within the tectonite harzburgites of the Othris ophiolite as certain of the harzburgites contain minor amounts of plagioclase, perhaps a remnant aluminous liquid. This further illustrates that it is difficult to distinguish, on a compositional basis, spinels which have formed via reaction with interstitial basaltic melt, as possibly is the case in Othris, and spinels which have formed via reaction with "intercumulus aluminous liquid".

The magmatic cumulus rocks of this ophiolite contain spinels which vary along two possible trends—Cr—Fe and Cr—Al, within the picrites and gabbros respectively. The occurence of Cr-spinel within olivine phenocrysts is a common phenomena in basaltic rocks. These spinels will be considered to be the intial cumulus chromite within the basaltic magma which formed the picrites and/or the cumulus gabbros. The $\mathrm{Fe^{3+}}$ enrichment visible in the groundmass spinels is compatible with a possible reaction involving intercumulus liquid, itself enriched in iron by removal of forsteritic olivine and clinopyroxene. Reactions involving intercumulus liquid and co-existing silicates were postulated by Henderson (1974). These in situ reactions were first outlined by Henderson and Suddaby (1971) within the magmatic rocks of the Rhum (Scotland) layered intrusion. The spinel compositions lie along two distinct trends—an Fe-trend produced over a large T °C range by possible reaction of a primary cumulus chromite and intercumulus liquid, and, an Al-trend produced over a small T °C range by reaction of the chromite with olivine and plagioclase or an aluminous liquid. Both trends appear to exist within the Othris cumulus rocks, Fe-trend in the picrites and an Al-trend within the gabbro (Fig. 1b). The spinel gabbro has an obvious cumulus texture and during crystal accumulation, in this case plagioclase, most of the interstitial liquid seems to have been removed. Since this gabbro has presumably formed from a basaltic melt, one can infer that the initial cumulus chromite was similar in composition to that crystallizing from the picrite, and preserved within the olivine euhedra. It is tentatively suggested that this chromite was trapped in an aluminous environment of plagioclase crystals where reaction occured thus producing an aluminous spinel (Fig. 1b). The lack of inter-cumulus phases indicates that most, if not all, of the interstitial liquid phase was removed, thus removing the potential source of iron and any chance of iron enrichment in these spinels. This type of reaction would have been further inhibited as most of the spinels are enclosed within plagioclase crystals.

The major interest in spinel compositional variation is whether or not spinels exhibit a restrictive range in chemistry for different genetic environments. This would then permit the use of spinel composition as an accurate indicator of genetic environment. However considerable overlap exists between stratiform, alpine peridotites and ophiolitic complexes (cumulus and non-cumulus members) and ultimately this affects the interpretation of the spinel data. Because of this problem and the existence of Fe and Al enrichment reactions in magmatic and tectonite rocks, accurate correlation of spinel composition and genesis is further complicated.

One of the most interesting problems concerning foliated peridotites is whether the Cr/Al variation involves reaction with in situ melt or intercumulus liquid. As yet no geochemical technique exists which will unequivocally distinguish primary mantle tectonites and secondary mantle tectonites (metacumulates). Consequently the interpretation of spinel variation is decided, in the case of Othris, by previous work which outlined a possible fusion mechanism for the peridotite assemblage.

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