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# A HARZBURGITE-BEARING MONCHIQUITE FROM WAWA, ONTARIO

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## ABSTRACT

Composite lamprophyre dykes containing xenoliths of harzburgite and wehrlite occur near Wawa, Ontario. The lamprophyre is an ocellar monchiquite containing phenocrysts and xenocrysts of olivine set in a panidiomorphic groundmass of titanomagnetite, aluminous pyroxene and titanian phlogopite, with a mesostasis of analcite, iron-rich pyroxene and calcite. The chrome-spinel-bearing harzburgite exhibits a coarse granular texture. The olivine is a low-CaO (0.02%) forsterite [with Mg/(Mg+Fe) in the range 0.88 to 0.93]; the orthopyroxene is Al- and Cr-poor enstatite [Mg/(Mg+Fe) from 0.93 to 0.94, $Al_2O_3$ between 0.95 and 1.87%, $Cr_2O_3$ between 0.15 and 0.26%]; the chrome spinel is $TiO_2$-poor magnesian aluminous chromite [Cr/(Cr+Al) in the range 0.45 and 0.67, Mg/(Mg+Fe) between 0.72 and 0.79]. The harzburgites are similar to harzburgite xenoliths found in kimberlites; the specimens are highly depleted samples of mantle material derived from depths of 50 to 90 km. A garnet wehrlite xenolith is considered to be a high-pressure cumulate from the monchiquite magma. In this xenolith, retrograde reactions during transport have led to the breakdown of pyrope to spinel.

*Keywords:* harzburgite, monchiquite, garnet wehrlite, upper mantle, Wawa, Ontario.

## SOMMAIRE

On trouve des xénolithes de harzburgite et de wehrlite dans des dykes composites de lamprophyre près de Wawa (Ontario). La roche intrusive est une monchiquite ocellaire qui contient phénocristaux et xénocristaux d'olivine dans une pâte panidiomorphe de titanomagnétite, pyroxène alumineux et phlogopite titanifère, avec mésostase d'analcime, pyroxène enrichi en fer et calcite. La harzburgite à spinelle chromifère montre une texture grenue à gros grain. L'olivine est une forstérite [Mg/(Mg+Fe) entre 0.88 et 0.93] pauvre en Ca (0.02% CaO); l'orthopyroxène est une enstatite pauvre en Al et Cr [Mg/(Mg+Fe) de 0.93 à 0.94, $Al_2O_3$ entre 0.95 et 1.87%, $Cr_2O_3$ entre 0.15 et 0.26%]; le spinelle est une chromite alumineuse magnésienne [Cr/(Cr+Al) entre 0.45 et 0.67, Mg/(Mg+Fe) entre 0.72 et 0.79]. Ces xénolithes de harzburgite ressemblent à ceux des kimberlites et, comme ceux-ci, seraient dérivés d'un matériau stérile du manteau à des profondeurs de 50 à 90 km. Un xénolithe de wehrlite à grenat représenterait un cumulat issu à haute pression du magma monchiquitique. Le transport de ce xénolithe a occasionné la rétrogression du pyrope au spinelle.

(Traduit par la Rédaction)

*Mots-clés:* harzburgite, monchiquite, wehrlite à grenat, manteau supérieur, Wawa, Ontario.

## INTRODUCTION

Composite lamprophyre dykes are exposed along Highway 17 in a roadcut 8 km south of the town of Wawa (Grid Reference 635088, NTS Sheet 41/N15). There are three parallel dykes; two are 1 metre in width, the other is 3 metres in width. The vertically dipping dykes, which intrude a small stock of granodiorite, strike 060°. They are fine-grained greenish melanocratic rocks in which phenocrysts of olivine and mica are visible. The widest dyke is the result of a multiple intrusion, with the different phases being enriched in olivine or mica. The olivine-rich variety contains small (1–10 cm) rounded harzburgite xenoliths. This occurrence of ultramafic xenoliths has been briefly described by Janse (1977). New compositional data for the minerals of the lamprophyre and xenoliths are presented here and used to assess the origins of the harzburgites. Minerals were analyzed using a fully automated MAC 500 microprobe (wavelength-dispersion mode) using the Bence–Albee alpha-factor method.

## MINERALOGY OF THE LAMPROPHYRE

Petrographically the lamprophyre dyke-rock is a monchiquite that has a panidiomorphic texture. Olivine phenocrysts are euhedral to subhedral and may be slightly or completely altered to a pale yellow serpentine. The olivine grains are zoned to an iron-rich margin (Table 1). Olivine can also be found as aggregates of

TABLE 1. REPRESENTATIVE ANALYSES OF MINERALS FROM THE MONCHIQUITE DYKES

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 39.96 | 39.08 | 35.83 | 36.06 | 49.00 | 49.27 | 49.28 | 48.14 | 56.92 | 0.0 | 0.0 | 0.46 |
| $TiO_2$ | 0.04 | 0.07 | 4.44 | 4.47 | 2.33 | 2.36 | 1.64 | 3.30 | 0.0 | 5.91 | 14.58 | 50.42 |
| $Al_2O_3$ | 0.11 | 0.08 | 15.19 | 15.33 | 3.54 | 4.52 | 2.53 | 2.73 | 23.79 | 7.04 | 3.73 | 0.05 |
| $Cr_2O_3$ | 0.04 | 0.0 | 0.07 | 0.03 | 0.04 | 0.13 | 0.07 | 0.09 | 0.0 | 34.32 | 0.0 | 0.02 |
| FeO* | 13.92 | 18.29 | 9.86 | 10.36 | 6.40 | 6.37 | 12.64 | 15.15 | 0.0 | 40.34 | 70.72 | 41.15 |
| MnO | 0.13 | 0.21 | 0.14 | 0.20 | 0.12 | 0.11 | 0.66 | 0.63 | 0.0 | 0.21 | 1.11 | 2.24 |
| MgO | 45.71 | 43.41 | 18.85 | 18.40 | 14.12 | 14.27 | 9.05 | 8.06 | 0.0 | 9.36 | 5.15 | 2.83 |
| CaO | 0.18 | 0.20 | 0.34 | 0.13 | 23.14 | 22.92 | 22.13 | 20.55 | 0.0 | 0.0 | 0.0 | 0.43 |
| $Na_2O$ | 0.0 | 0.0 | 0.50 | 0.58 | 0.34 | 0.48 | 2.22 | 2.74 | 10.61 | 0.0 | 0.0 | 0.0 |
| $K_2O$ | 0.0 | 0.0 | 8.26 | 8.50 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| NiO | 0.27 | 0.20 | 0.0 | 0.05 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | 100.38 | 101.53 | 93.77 | 94.09 | 99.05 | 100.43 | 100.33 | 101.60 | 92.27 | 97.18 | 95.29 | 97.61 |

1-2 core and rim euhedral olivine; 3-4 core and rim zoned mica microphenocryst; 5-6 euhedral pyroxene microphenocrysts; 7-8 acicular pyroxenes; 9 analcite; 10 titaniferous aluminous magnesian chromite (FeO=23.5%; $Fe_2O_3$=19.2%); 11 aluminous magnesian ulvöspinel-magnetite (FeO=36.9%; $Fe_2O_3$=38.65%); 12 ilmenite

*Total iron calculated as FeO

anhedral grains. These olivine grains are more magnesian than the phenocrystal olivine and represent xenocrysts derived by the disaggregation of harzburgite xenoliths. The bulk of the "groundmass" in which the olivine is set consists of small euhedral prisms of colorless to pale brown pleochroic pyroxene, together with laths and poikilitic plates of colorless to orange brown pleochroic mica. The proportions of pyroxene to mica vary widely within and between dykes. The pyroxene is a titaniferous aluminous augite, the mica, a titaniferous phlogopite (Table 1). Some of the mica grains are zoned, with margins that are darker and richer in iron than their cores. The mesostasis, in which the above minerals are set, consists of analcite (Table 1), calcite and an unresolvable dark amorphous Mg-rich material (MgO 27.5%, FeO 5.2%, $SiO_2$ 59.5%). Commonly this mesostasis forms ocelli, which are zoned from analcite–carbonate cores *via* regions of minute green acicular pyroxene, analcite and carbonate to phlogopite-rich rims. The acicular prisms of pyroxene are common thoughout the rock, having nucleated in spray-like aggregates upon earlier pyroxenes or micas. This late-stage pyroxene, presumably a "quench" phase, is richer in iron and sodium than the earlier pyroxene (Table 1). Spinels occur abundantly as euhedral opaque grains. They are, essentially, titaniferous aluminous magnesian chromite and aluminous magnesian ulvöspinel - magnetite (Table 1). Commonly, these Ti-rich spinels have nucleated upon cores of Ti-poor aluminous chromite, identical to the spinel found in the harzburgites; such cores are presumed to be xenocrysts. Ilmenite occurs as rare groundmass laths; it is a manganoan magnesian variety (Table 1). The order of the beginning of crystallization of the essential phases in this monchiquite is olivine, spinel, aluminous clinopyroxene and mica, mica, iron-rich pyroxene, analcite and carbonate.

## HARZBURGITE XENOLITHS

The harzburgite xenoliths, composed of olivine, orthopyroxene and chrome spinel, are typically fresh, with only minor serpentinization of the silicates. The texture is best described as coarse granular, using the nomenclature of Harte (1977). The silicates are essentially strain-free but, in some examples, undulose extinction and kink bands are present in olivine. In addition, such grains exhibit recrystallized margins of anhedral neoblasts. Orthopyroxene commonly occurs as elongate lobate crystals surrounded and embayed by anhedral olivine. The chrome spinel, as deep red to opaque rounded grains, occurs interstitially between the silicates. Symplectite intergrowths with orthopyroxene appear to be absent, indicating that the spinels (a) probably have not formed by garnet breakdown or (b) if they have, they have subsequently undergone a prolonged period of re-equilibration (Carswell 1980).

Representative compositions of the olivine, orthopyroxene and chrome spinel in typical xenoliths are given in Table 2. The xenoliths are classed as chrome spinel harzburgites using Carswell's (1980) classification. The olivine grains, of uniform composition, are forsterite [Mg/(Mg+Fe) from 0.88 to 0.93] low in CaO (0.02%). The orthopyroxene contains moderate Al and is Cr-poor enstatite [Mg/(Mg+Fe) from 0.93 to 0.94, $Al_2O_3$ from 0.95 to 1.87%, $Cr_2O_3$ from 0.15 to 0.26%]. Individual grains within a single xenolith are uniform in composition, but each xenolith contains a distinct orthopyroxene. The chrome spinel is a $TiO_2$-poor

TABLE 2. REPRESENTATIVE ANALYSES OF MINERALS IN WAWA SPINEL HARZBURGITES

| | W23/2 | | | W23/3 | | | W23/4 | | | W23/5 | | | W23/9 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | OPX | OL | SPINEL | OPX | OL | SPINEL | OPX | OL | SPINEL | OPX | OL | SPINEL | OPX | OL | SPINEL |
| $SiO_2$ | 57.06 | 41.37 | - | 57.28 | 41.60 | - | 57.41 | 39.94 | - | 57.46 | 41.72 | - | 56.94 | 40.96 | - |
| $TiO_2$ | 0.03 | 0.0 | 0.71 | 0.01 | 0.0 | 0.01 | 0.01 | 0.03 | 0.37 | 0.13 | 0.0 | 0.13 | 0.01 | 0.0 | 0.05 |
| $Al_2O_3$ | 1.87 | 0.01 | 21.57 | 1.93 | 0.0 | 29.90 | 0.95 | 0.05 | 16.39 | 1.46 | 0.0 | 20.06 | 1.33 | 0.04 | 20.36 |
| $Cr_2O_3$ | 0.33 | 0.0 | 42.95 | 0.40 | 0.04 | 36.96 | 0.26 | 0.05 | 50.73 | 0.45 | 0.05 | 48.56 | 0.34 | 0.0 | 47.77 |
| FeO | 4.93 | 8.15 | 19.16 | 4.60 | 7.21 | 15.01 | 3.93 | 11.70 | 17.15 | 4.36 | 6.79 | 13.96 | 4.39 | 7.04 | 15.43 |
| MnO | 0.13 | 0.11 | 0.26 | 0.12 | 0.11 | 0.23 | 0.13 | 0.10 | 0.26 | 0.12 | 0.11 | 0.22 | 0.09 | 0.03 | 0.24 |
| MgO | 35.15 | 50.20 | 15.28 | 35.76 | 51.28 | 16.83 | 37.44 | 49.01 | 14.82 | 35.42 | 51.95 | 16.63 | 36.37 | 52.75 | 15.57 |
| CaO | 0.22 | 0.02 | - | 0.36 | 0.02 | - | 0.27 | 0.16 | - | 0.84 | 0.02 | - | 0.39 | 0.02 | - |
| $Na_2O$ | 0.11 | - | - | 0.05 | 0.01 | - | 0.07 | 0.05 | - | 0.10 | 0.0 | - | 0.13 | 0.01 | - |
| $K_2O$ | - | - | - | 0.0 | 0.0 | - | - | - | - | - | - | - | - | - | - |
| NiO | 0.03 | 0.37 | - | 0.04 | 0.36 | - | 0.06 | 0.20 | - | 0.06 | 0.36 | - | 0.06 | 0.32 | - |
| | 99.86 | 100.23 | 99.93 | 100.55 | 100.63 | 98.94 | 100.47 | 101.29 | 99.72 | 100.40 | 101.00 | 99.56 | 99.99 | 101.17 | 99.42 |
| T°C¹ | 1079 | | | 1007 | | | 1329 | | | 1127 | | | 1030 | | |
| T°C² | 1073 | | | 1047 | | | 1566 | | | 1196 | | | 1034 | | |

Equilibration temperatures are from 1, Fabriès (1979) and 2. Roedder et al. (1979).

magnesian aluminous chromite [Cr/(Cr+Al) from 0.45 to 0.67, Mg/(Mg+Fe) from 0.72 to 0.79]. Individual xenoliths are characterized by a particular spinel composition.

## GARNET–SPINEL WEHRLITE

One example of a garnet-bearing xenolith was found. This consists essentially of olivine and clinopyroxene, which occur as a fine-grained mosaic of strain-free polygonal crystals in which are set larger strained porphyroclasts of olivine and clinopyroxene. The texture is best described as mosaic porphyroclastic (Harte 1977). The occurrence of recrystallized clinopyroxene in deformed ultramafic xenoliths is unusual because of the greater degree of resistance of pyroxene to deformation than olivine. Anhedral colorless garnet occurs throughout the mosaic and typically exhibits a reaction corona of pale green spinel. Isolated patches of spinel indicate completely replaced garnet crystals. The rock was originally a garnet wehrlite. Retrograde reactions during transport have led to replacement of garnet by spinel.

Representative compositions of the minerals are given in Table 3. The olivine grains are uniform, with no differences in composition being evident between the neoblasts and porphyroclasts. They are forsteritic [Mg/(Mg+Fe) 0.88], of low CaO content (<0.1%) and relatively high NiO content (0.6%). The pyroxenes are magnesian [Mg/(Mg+Fe) 0.89] and aluminous. The composition between grains is not uniform; increased $Al_2O_3$ is accompanied by increased $Na_2O$, reflecting the presence of a significant jadeite component (5–14 mol.% Jd). Chrome contents are low. The spinel is pleonaste of uniform composition [Mg/(Mg+Fe) 0.91, Cr/(Cr+Al) 0.1]. The garnet is pyrope that contains negligible $TiO_2$ and $Cr_2O_3$.

TABLE 3. REPRESENTATIVE ANALYSES OF MINERALS IN THE GARNET-SPINEL-WEHRLITE

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| $SiO_2$ | 40.38 | 42.23 | 53.68 | 53.39 | 0.0 |
| $TiO_2$ | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| $Al_2O_3$ | 0.0 | 24.01 | 4.76 | 7.38 | 65.62 |
| $Cr_2O_3$ | 0.0 | 0.08 | 0.15 | 0.11 | 0.55 |
| FeO | 11.71 | 10.13 | 2.98 | 3.13 | 12.02 |
| MnO | 0.10 | 0.22 | 0.0 | 0.0 | 0.10 |
| MgO | 47.63 | 19.07 | 16.33 | 14.08 | 21.93 |
| CaO | 0.09 | 5.11 | 22.56 | 20.36 | 0.0 |
| $Na_2O$ | 0.0 | 0.0 | 0.87 | 2.13 | 0.0 |
| NiO | 0.63 | 0.0 | 0.11 | 0.04 | n.d. |
| | 100.54 | 100.85 | 100.76 | 100.58 | 100.22 |

1. olivine; 2. garnet; 3-4 pyroxene; 5. spinel

## GEOTHERMOBAROMETRY

### *Harzburgite*

As the xenoliths lack clinopyroxene, estimates of their equilibration temperatures must be made using the olivine–spinel geothermometer of Irvine (1965). Owing to uncertainties in the thermodynamic data used to calibrate this geothermometer, it is not as reliable as methods based upon coexisting pyroxenes, but does give realistic temperatures as demonstrated by Roeder *et al.* (1979) and Fabriès (1979) in their re-evaluations of this method.

Table 2 presents equilibration temperatures calculated for the xenoliths. It indicates that equilibration occurred at 1007–1127°C (Fabriès 1979) or 1047-1196°C (Roeder *et al.* 1979). Sample 23/4 gives extremely high temperatures and probably represents a nonequilibrium assemblage. The calculations were made using spinel ferric-iron contents determined by Carmichael's (1967) method. The temperature range determined by each method is relatively small and indicates that prolonged subsolidus equilibration at low temperatures has not occurred. Application of the olivine–spinel geothermometer to alpine lherzolites and basic intrusions has demonstrated that, in these environments, prolonged low-temperature re-equilibration does occur. Accordingly, the retention of high equilibration-temperatures in the harzburgite xenoliths indicates rapid cooling and quenching during emplacement of the lamprophyre dykes.

Equilibration pressures are difficult to estimate and can be only obtained indirectly. Assuming that the lamprophyre occurrences are a part of the Helikian regional alkaline rock–carbonatite activity, they may have been derived from subcontinental mantle with a normal shield geotherm of 42–50 $mWm^{-2}$ (Pollack & Chapman 1977). For the calculated temperatures of equilibration, this would imply maximum depths of origin of 90 to 125 km (30 to 40 kbar). Higher geothermal gradients would imply a shallower origin; as we would expect that any magmatism will perturb the local geotherm to a steeper gradient than the average continental geotherm, we would expect derivation from above 90 km. Exact depths cannot be estimated; even though the harzburgite and wehrlite are unlikely to be genetically related, some constraints can be placed on the depth of origin of the harzburgite from the geothermobarometry of the wehrlite xenolith.

### *Garnet-spinel wehrlite*

Two geothermometric methods should be applicable to the garnet-bearing wehrlite, the garnet–clinopyroxene (Ellis & Green 1979) and the olivine–spinel equilibria. Temperatures calculated for the latter method by the equations of either Roeder *et al.* (1979) or Fabriès (1979) are negative, indicating clearly nonequilibrium assemblages. The pyroxenes are not uniform; temperatures calculated using the Ellis & Green approach for 30 kbar, with a stoichiometrically derived ferric-iron correction, range from 817 to 1023°C, again demonstrating lack of equilibrium.

The presence of pyrope garnet, however, indicates that this xenolith probably originated within the garnet stability field for this bulk composition within the upper mantle. Retrograde spinels are aluminous and the garnet-spinel transition for Al-rich systems of this type at 800 to 1000°C would be at about 15 to 18 kbar, according to O'Hara *et al.* (1971). Hence, the xenoliths were probably derived from depths greater than 50 km.

In conclusion, all the xenoliths are clearly mantle-derived and have been transported from depths of 50 to 90 km by the monchiquite magma, which presumably originated at similar depths. This interpretation is in agreement with experimental studies, which indicate a depth of generation of hydrous basanitic (monchiquitic) magmas of 90 to 100 km (Green 1973).

## DISCUSSION

### *Origins of the xenoliths*

The garnet wehrlite is probably a high-pressure cumulate from the monchiquitic magma, as the olivine and pyroxene grains are similar in composition to those of the lamprophyre. Shearing and recrystallization have led to the retrograde reactions observed. The harzburgite xenoliths are unlikely to be cumulates as they lack aluminous clinopyroxene; it cannot be expected that orthopyroxene would ever crystallize from an undersaturated monchiquitic magma at any pressure.

Spinel lherzolite and harzburgite xenoliths are common in alkali basalt and kimberlite but appear to be relatively rare in lamprophyric rocks. Examples have been described from the Fen complex, Norway (Griffin 1973), a monchiquite dyke in Inverness-shire, Scotland (Praegel 1981) and from the Ile-Bizard diatreme, Quebec (Marchand 1970). All of these xenoliths differ from the Wawa harzburgite in being richer in $Al_2O_3$. Orthopyroxene in the spinel lherzolite from Fen, Inverness-shire, and Ile-Bizard, for example, contains 4.2–5.0%, 3.8–4.7% and 2–3% $Al_2O_3$, respectively. Spinel compositions similarly are more aluminous and poorer in chromium. All of the above described xenoliths in lamprophyric rocks are considered to be fragments of the upper mantle. The geothermobarometry of the Wawa harzburgite xenoliths also indicates an upper-mantle origin. However, the mantle sampled by this magma is of a type depleted in fertile components.

The xenoliths might be considered to be fragments of alpine-type harzburgite or of harzburgite of the type found as xenoliths in basalts or kimberlites. The xenoliths cannot represent xenoliths of alpine-type harzburgite or peridotite, as these rocks are less depleted in fertile components than the Wawa harzburgite xenoliths. For example, the composition of orthopyroxene in alpine harzburgite typically is less magnesian [Mg/(Mg+Fe) from 0.88 to 0.92] and richer in CaO (0.3–2.0%) and $Al_2O_3$ (2–6%), and the spinels are usually more aluminous (Green 1964, Obata 1980). Similarly, ultramafic xenoliths in basic volcanic rocks are typically characterized by aluminous orthopyroxene and spinel (Donaldson 1978, Frey & Green 1974, Frey & Prinz 1978).

Orthopyroxene of similar composition to that of the Wawa xenoliths is, however, found in spinel and garnet lherzolites and harzburgite xenoliths in kimberlite, and falls into the class of "barren" harzburgites defined by Hervig *et al.* (1980). This type of harzburgite is considered to represent the refractory residue of partial melting of more primitive or fertile mantle (Hervig *et al.* 1980).

## CONCLUSIONS

The mantle-derived monchiquite dykes carry fragments of the upper mantle derived from depths of the order of 50 to 90 km. This mantle is a depleted harzburgite akin to depleted mantle material that occurs as xenoliths in kimberlites in Colorado and on Somerset Island (McCallum *et al.* 1975, Mitchell 1977). The samples are only the third occurrence of material derived from the upper mantle beneath the Canadian Shield. The other occurrences are at Somerset Island and Ile-Bizard (Mitchell 1977, Marchand 1970). Evidence is now accumulating to indicate that the mantle beneath the North American craton is depleted in the components of "basaltic" magma; however, it is not as depleted as the mantle beneath the Kapvaal craton (Carswell 1980), *i.e.*, chromite harzburgite xenoliths containing spinel with a ratio $Cr/(Cr+Al) \gg 65$ have not yet been described from North America.

The Wawa monchiquite dykes are located in a region of widespread alkaline complex–carbonatite magmatism associated with the Kapuskasing fault system and a gravity high. The presence of mantle-derived harzburgite indicates that this fracture system probably taps the upper mantle and controls the emplacement of mantle-derived magmas. Other lamprophyre dykes within this region should be examined for the occurrence of mantle xenoliths.

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## REFERENCES

CARMICHAEL, I.S.E. (1967): The iron titanium oxides of salic volcanic rocks and their associated ferromagnesian silicates. *Contr. Mineral. Petrology* **14**, 36-64.

CARSWELL, D.A. (1980): Mantle-derived lherzolite nodules associated with kimberlite, carbonatite and basalt magmatism: a review. *Lithos* **13**, 121-138.

DONALDSON, C.H. (1978): Petrology of the uppermost upper mantle deduced from spinel lherzolite and harzburgite nodules at Calton Hill, Derbyshire. *Contr. Mineral. Petrology* **65**, 363-377.

ELLIS, D.J. & GREEN, D.H. (1979): An experimental study of the effect of Ca upon garnet–clinopyroxene Fe–Mg exchange equilibria. *Contr. Mineral. Petrology* **71**, 13-22.

FABRIÈS, J. (1979): Spinel–olivine geothermometry in peridotites from ultramafic complexes. *Contr. Mineral. Petrology* **69**, 329-336.

FREY, F.A. & GREEN, D.H. (1974): The mineralogy, geochemistry and origin of lherzolitic inclusions in Victorian basanites. *Geochim. Cosmochim. Acta* **38**, 1023-1059.

——— & PRINZ, M. (1978): Ultramafic inclusions from San Carlos, Arizona: petrologic and geochemical data bearing on their petrogenesis. *Earth Planet. Sci. Lett.* **38**, 129-176.

GREEN, D.H. (1964): The petrogenesis of the high-temperature peridotite intrusion in the Lizard area, Cornwall. *J. Petrology* **5**, 134-188.

——— (1973): Experimental studies on a model upper mantle composition at high pressure under water-saturated and water-undersaturated conditions. *Earth Planet. Sci. Lett.* **19**, 37-53.

GRIFFIN, W.L. (1973): Lherzolite nodules from the Fen alkaline complex, Norway. *Contr. Mineral. Petrology* **38**, 135-146.

HARTE, B. (1977): Rock nomenclature with particular relation to deformation and recrystallization textures in olivine-bearing xenoliths. *J. Geol.* **85**, 279-288.

HERVIG, R.L., SMITH, J.V., STEELE, I.M. & DAWSON J.B. (1980): Fertile and barren Al–Cr-spinel harzburgites from the upper mantle: ion and electron probe analyses of trace elements in olivine and orthopyroxene: relation to lherzolites. *Earth Planet. Sci. Lett.* **50**, 41-58.

IRVINE, T.N. (1965): Chromian spinel as a petrogenetic indicator. I. Theory. *Can. J. Earth Sci.* **2**, 648-672.

JANSE, A.J.A. (1977): Harzburgite nodules from a lamprophyre near Wawa, Ontario, Canada. *Second Int. Kimberlite Conf. Proc., Santa Fe.* (extended abstr., unpaginated).

MARCHAND, M. (1970): *Ultramafic Nodules from Ile Bizard, Quebec.* M.Sc. thesis, McGill Univ., Montreal, Que.

MCCALLUM, M.E., EGGLER, D.H. & BURNS, L.K. (1975): Kimberlitic diatremes in northern Colorado and southern Wyoming. *Phys. Chem. Earth* **9**, 149-161.

MITCHELL, R.H. (1977): Ultramafic xenoliths from the Elwin Bay kimberlite, the first Canadian paleogeotherm. *Can. J. Earth Sci.* **14**, 1202-1210.

OBATA, M. (1980): The Ronda peridotite: garnet-, spinel-, and plagioclase-lherzolite facies and the P–T trajectories of a high-temperature mantle intrusion. *J. Petrology* **21**, 533-572.

O'HARA, M.J., RICHARDSON, S.E. & WILSON G. (1971): Garnet-peridotite stability and occurrence in crust and mantle. *Contr. Mineral. Petrology* **32**, 48-68.

POLLACK, H.N. & CHAPMAN, D.S. (1977): On the regional variation of heat flow, geotherms and lithospheric thickness. *Tectonophys.* **38**, 279-296.

PRAEGEL, N.O. (1981): Origin of ultramafic inclusions and megacrysts in a monchiquite dike at Streap, Inverness-shire, Scotland. *Lithos* **14**, 305-322.

ROEDER, P.L., CAMPBELL, I.H. & JAMIESON, H.E. (1979): A re-evaluation of the olivine–spinel geothermometer. *Contr. Mineral. Petrology* **68**, 325-334.

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