

**The petrography, mineral chemistry and isotope geochemistry of
a mantle xenolith suite from the Letlhakane DK 1 and DK 2
kimberlite pipes, Botswana.**

THESIS

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Declaration

I hereby declare that all the work presented in this thesis is my own, except where otherwise stated.

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ABSTRACT

This thesis involves a petrographic, mineralogical and isotopic study of a representative mantle suite found in the Letlhakane DK 1 and DK 2 kimberlites, located approximately 40km southeast of Orapa, Botswana. The nodule types include: peridotites, pyroxenites, eclogites, megacrysts and associated intergrowths, MARID and glimmerite xenoliths, as well as metasomatized peridotites and pyroxenites. This thesis represents the first detailed description of the mantle suite at this locality and the first detailed study of the peridotite suite from the mantle below Botswana.

The various peridotites and pyroxenites can be distinguished on the basis of primary mineral composition, in particular garnet chemistry, the forsterite content in olivine, and CaO, Cr_2O_3 , Na_2O and Al_2O_3 in clinopyroxene. Rock textures vary from coarse to mosaic-porphyroclastic. The Botswana geotherm, determined using mineral thermobarometry, is similar in shape to those determined from the Kaapvaal craton and other diamond-bearing localities and is indicative of a deep, cool, cratonic root.

The sequence garnet peridotite (GP), garnet phlogopite peridotite (GPP), and phlogopite peridotite (PP), is present, as at Kimberley, although no evidence of a phlogopite K-richterite peridotite (PKP) suite was found at Letlhakane. Clinopyroxene in phlogopite-bearing (metasomatized) peridotites can be distinguished from clinopyroxene in phlogopite-free (non-metasomatized) peridotites by higher Cr_2O_3 and Na_2O . Evidence for a possible relationship between intergrain variation of Cr_2O_3 in clinopyroxene and textural disequilibrium is also present.

Three main metasomatic events can be distinguished on the basis of petrography and mineral chemistry in the peridotites and pyroxenites. Deep metasomatism is represented by TiO_2 and Na_2O zonation in garnet from two peridotites and a TiO_2 -rich group of peridotitic garnets, all in the absence of phlogopite. A shallower metasomatic episode is represented by the primary metasomatic mineral suite consisting of low- TiO_2 , low- Cr_2O_3 phlogopite, high- Cr_2O_3 , high- Na_2O clinopyroxene, ilmenite, rutile, sulphides and Cr-spinel. A few pyroxenites are thought to have been metasomatized at even shallower levels, as evidenced by the presence of edenitic hornblende and the absence of primary metasomatic phlogopite. A relationship was found between depth and intensity of primary metasomatism. Sm, Nd and Sr concentrations in clinopyroxene increase as temperatures and pressures of equilibration decrease. The secondary metasomatic mineral suite is represented by high- TiO_2 phlogopite, calcite, serpentine, clinopyroxene, Al-spinel andargasitic hornblende and resulted from the effects of the kimberlite emplacement.

The Letlhakane peridotites exhibit a wide range of Sr- and Nd-isotopic ratios, similar to values reported from Kimberley and Jagersfontein. Archaean Nd model ages were obtained for garnet from a subcalcic garnet harzburgite and a GPP, and for clinopyroxene from a spinel-bearing xenolith. Sr- and Nd-isotopic compositions can be accounted for by complex mixing processes of EM₁-EM₂-DMM mantle components.

A wide variety of accessory minerals are found in the eclogites. These include: diamond, graphite, rutile, ilmenite, spinel and primary metasomatic amphibole and phlogopite. Two groups of eclogites can be identified, based on the Na₂O-content in garnet. The eclogite suite equilibrated in a temperature range of 750-1340°C (assuming P = 45kb). Group I eclogites crystallized at slightly higher temperatures than Group II eclogites. C-isotope studies on a graphite-bearing garnet websterite and eclogites are indicative of mantle origin ($\delta^{13}\text{C} = -5.37$ to -12.50 ‰). Three different sources of carbon may have existed.

The following megacrysts are found at Letlhakane (listed in order of decreasing abundance): garnet, clinopyroxene, ilmenite and orthopyroxene. Two Cr-rich Granny Smith clinopyroxene megacrysts are also described. Clinopyroxene-ilmenite intergrowths comprise the bulk of the samples exhibiting intergrowth textures. Other intergrown phases include clinopyroxene-garnet and orthopyroxene-ilmenite. It is speculated that some of the orthopyroxene-ilmenite intergrowths may be related to the metasomatized peridotite suite.

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- Plate 19b: An identical view of JSL 511 to Plate 19a, but photographed under crossed nicols. Note the irregular olivine grain boundaries and the fact that the orthopyroxene inclusions are not restricted to any particular part of the olivine and are not in optical continuity with each other. Field of view = 3.5mm wide. Crossed nicols.
- Plate 20: A large plate of primary metasomatic edenitic hornblende (amph) in a garnet clinopyroxenite (JSL 180). Other phases include garnet (gt) and clinopyroxene (cpx). Field of view = 4mm wide. Plane polarised light.
- Plate 21: Brown, pleochroic secondary metasomatic pargasitic hornblende (amph) wedged between two clinopyroxene grains (cpx) and an orthopyroxene grain (opx) in a garnet websterite (JSL 75). Note the smaller size and different colour, in comparison with the amphibole in Plate 20. Field of view = 0.9mm wide. Plane polarised light.
- Plate 22: A garnet websterite (JSL 75) illustrating the change in texture from coarse (left) to granuloblastic (right). Nicols are partially crossed and the field of view is approximately 19mm wide. Birefringent minerals include orthopyroxene and clinopyroxene and the dark patches represent altered material and/or minor sulphides. Rutile is present in the granuloblastic-textured area, but difficult to observe in this plate.
- Plate 23: A garnet-spinel-bearing metasomatized pyroxenite (JSL 252) showing brown Al-spinel (sp) surrounded by colourless garnet (gt). Field of view = 3.5mm wide. Plane polarised light.
- Plate 24: A typical example of pristine garnet (gt) unaffected by primary metasomatism with minor brown secondary metasomatic phlogopite. The garnets are typically large and rounded and associated with equally coarse olivine (ol). The standard deviation of Cr_2O_3 in clinopyroxene from these samples is typically <0.1 . Field of view = 4mm wide. Plane polarised light.

- Plate 25: The breakdown of garnet has commenced, resulting in the formation of plates of brown primary metasomatic phlogopite (phlog) intergrown with green primary metasomatic clinopyroxene (cpx) in JSL-/177. Note the reduced size of the garnet (gt) compared to the previous stage. Field of view = 6.8mm wide. Plane polarised light.
- Plate 26: An extensively metasomatized garnet, also from JSL-/177. Note the irregular fragment of remaining garnet (gt) and the rounded intergrowth of primary metasomatic phlogopite (phlog) and clinopyroxene (cpx). The small grain size of clinopyroxene compared to the size of the surrounding olivine (ol) is quite obvious. The standard deviation of Cr_2O_3 in clinopyroxene from JSL-/177 is high (0.36). Field of view = 6.8mm wide. Plane polarised light.
- Plate 27: The garnet in this sample (JSL-/93) has been totally destroyed with resultant primary metasomatic phlogopite (phlog), clinopyroxene (cpx) and Cr-spinel (sp) as products. The standard deviation of Cr_2O_3 in clinopyroxene from this sample is 0.38. Field of view = 6.8mm wide. Plane polarised light.
- Plate 28: Bright green clinopyroxene (cpx), brown phlogopite (phlog) and Cr-spinel (sp) surrounded by olivine (ol). No garnet is present in this sample, but note the similarity of the spinel texture to some of the spinels illustrated in Plate 27, suggesting that garnet may have been present in this sample. Although difficult to infer from these plates, the grain size of clinopyroxene and spinel is increasing. This becomes more obvious when the thin sections are viewed with the unaided eye. Field of view = 3.5mm wide. Plane polarised light.
- Plate 29: A metasomatized phlogopite peridotite (JSL 547) in the later stages of equilibrium. Note the larger clinopyroxene (cpx) and Cr-spinel grain size (sp) and more regular grain boundaries, suggesting a more evolved state of equilibrium compared to for example, JSL-/177 in Plate 26. The colourless phase is olivine (ol). The standard deviation of Cr_2O_3 in clinopyroxene from this sample is 0.07. Field of view = 3.5mm wide. Plane polarised light.
- Plate 30: A texture typical of the Group I eclogites from Letlhakane. Note the large, anhedral garnets (gt) and the anhedral clinopyroxene matrix (cpx). Field of view = 3.5mm wide. Plane polarised light.
- Plate 31: A texture typical of Group II eclogites from Letlhakane. Note the more angular garnets (gt) and clinopyroxene (cpx), as well as the general interlocking grain texture, compared to the Group I eclogite in Plate 30. Primary metasomatic phlogopite (phlog) may be present in the Group II eclogites, as shown here. Field of view = 3.5mm wide. Plane polarised light.
- Plate 32: Possible garnet (gt) exsolution from clinopyroxene (cpx) in a Group II biminerallitic eclogite (JSL 77). Field of view = 3.5mm wide. Crossed nicols.
- Plate 33: The general texture and appearance of JSL 200, a graphite- and diamond-bearing Group I eclogite. Note the tabular graphite (graph) flake, with embayments towards the bottom right. Interstitial clinopyroxene (cpx) is situated between anhedral garnets (gt). Field of view = 4mm wide. Plane polarised light.

- Plate 34: A scanning electron micrograph of the diamond, a sharp-edged macle, found in JSL 200. A scalebar is included in the plate. Note the smooth, unpitted and unetched appearance of the diamond.
- Plate 35: A typical rutile grain (rut) in sample JSL 203, a Group I eclogite from Letlhakane. The rutile is partly enclosed by brown pleochroic amphibole (amph) plates. The amphibole plate below the rutile also contains a brown phlogopite inclusion (phlog). Note the highly altered state of the surrounding clinopyroxene (cpx). Field of view = 3.5mm wide. Plane polarised light.
- Plate 36: An ilmenite-bearing eclogite (JSL 254) containing pale brown, secondary metasomatic phlogopite (phlog), brown amphibole (amph) and greenish chloritic(?) material associated with the ilmenite (ilm). Note the embayed ilmenite boundaries. The above phases are surrounded by altered clinopyroxene (cpx). Field of view = 3.5mm wide. Plane polarised light.
- Plate 37: A single plate of primary metasomatic, edenitic hornblende (amph) in a Group II eclogite (JSL 59). Primary clinopyroxene (cpx) is also visible. Field of view = 3.5mm wide. Plane polarised light.
- Plate 38: Primary metasomatic, edenitic hornblende (amph) in another Group II eclogite (JSL 98), surrounded by garnet (gt) and clinopyroxene (cpx). Note the difference in colour, size and habit of the amphibole in Plate 35, compared to the amphibole in Plates 37 & 38. Field of view = 3.5mm wide. Plane polarised light.
- Plate 39: A large thin section of JSL 600, illustrating the various subzones in this composite xenolith from borehole LFD, Letlhakane DK 1. See text for a description of the various subzones. Field of view = 7.2cm wide.
- Plate 40: Recrystallization in a Granny Smith clinopyroxene megacryst. Field of view = 3.5mm wide. Crossed nicols.
- Plate 41: Orthopyroxene megacryst (JSL 2) containing material similar to a spinel lherzolite (see text for explanation). Dominant phases are brown spinel (sp) and colourless olivine (ol), embedded in orthopyroxene (opx). Field of view = 3.5mm wide. Plane polarised light.
- Plate 42: A rounded, orange-coloured garnet (gt) intergrown with clinopyroxene (cpx) (JSL 28). Field of view = 3.5mm wide. Plane polarised light.
- Plate 43: Exsolved garnet (gt) in clinopyroxene (cpx) (JSL 29). The clinopyroxene exhibits signs of recrystallization. Note the difference in habit of the garnet when compared to the garnet in Plate 42. Field of view = 3.5mm wide. Crossed nicols.
- Plate 44: "Quench"-textured orthopyroxene (colourless lath-shaped grains - opx), intergrown with ilmenite (ilm) and phlogopite (phlog) from JSL 160. Note the anhedral grain of pale green clinopyroxene (cpx) and the ilmenite inclusions in a phlogopite plate (top right). Field of view = 3.5mm wide. Plane polarised light.
- Plate 45: Phlogopite plate (phlog) included in ilmenite (ilm) from a MARID xenolith (JSL 51). Note the embayed phlogopite contacts and the two green clinopyroxene (cpx) inclusions in phlogopite. Field of view = 3.5mm wide. Plane polarised light.

CHAPTER 1

INTRODUCTION

1.1 Objectives of the current study

The study was undertaken on a mantle xenolith suite collected from the DK 1 and DK 2 kimberlites in Botswana with the following objectives in view:

- 1) To characterize the petrography and mineralogy of the peridotite-pyroxenite, eclogite, megacryst and silicate intergrowth suites. Shee (1978) analysed the mineral phases of seven peridotites collected at DK 1, which he included in a study on the Orapa eclogites. Apart from the above study, no detailed work has ever been undertaken at Letlhakane.
- 2) To carry out a geothermobarometric study aimed at reconstructing a geotherm for the subcontinental lithosphere at this locality.
- 3) To compare the results obtained with those from the Orapa mantle xenolith suite and occurrences elsewhere.
- 4) To search for evidence of mantle metasomatism and its related features and to compare the findings with metasomatic features noted at Kimberley.
- 5) To perform radiogenic Rb/Sr and Sm/Nd isotope studies on selected peridotites and a composite pyroxenite xenolith to determine whether or not the Letlhakane samples exhibit significant isotopic differences when compared with other, well-known localities.

Owing to the fact that DK 1 and DK 2 have never been studied in detail, apart from a small petrographic and mineral chemistry study of a few nodules by Shee (1978), this work is deliberately broad, since it is intended as a reference guide for any future study of these pipes. All rock types from the mantle

have therefore been included. Unique and important xenoliths, e.g. JSL 143, 500, 511, 516 and 600 have, however, been studied in greater detail (see Chapters 3 & 4).

The xenolith-megacryst assemblage at Letlhakane provides a unique opportunity for the study of the Zimbabwe craton because of the large variety of xenoliths present in this locality and it is the author's hope that this work will be of some assistance to those continuing the study of the mantle beneath Botswana.

1.2 An overview of the major geological and tectonic features of Botswana

A brief overview is provided of the major geological and tectonic features of Botswana, based on published geological, gravimetric and geomagnetic observations. The reader is referred to Hutton et al. (1974) for a stratigraphic table for Botswana, as a detailed description of lithologies is not relevant here. Interpretation of the tectonic development of Botswana is hampered by the extensive covering of young Karoo sedimentary rocks and basalts and Kalahari deposits (Fig. 1.1). A major step forward was made when regional aeromagnetic and gravity surveys of most of the "Kalahari Beds" facilitated a greatly improved interpretation (Reeves, 1978) of the sub-Kalahari geology in Botswana. This was closely followed by the Kalahari Drilling Project, during which a number of magnetic and gravity anomalies were drilled and interpreted (Meixner and Peart, 1983). Data and interpretations from the above studies are summarised in Figs. 1.2-1.4 which illustrate the major tectonic divisions in Botswana. These features are discussed below.

Baldock et al. (1976) divided Botswana into cratonic regions, mobile belts and platform regions. The cratonic regions, represented by the Kaapvaal and Zimbabwe cratons (Figs. 1.2-1.4), are comprised of parts of ancient and stable Archaean gneisses and tonalites varying in age from 3.6-2.5 Ga (Barton and Key, 1983; Hawkesworth et al., 1979). The Zoetfontein Lineament (Fig. 1.3) is considered by Stowe et al. (1984) to represent the northern boundary of the Kaapvaal craton, but Corner (pers. comm., 1993) suggested that the Kaapvaal craton may in fact extend as far north as the Okwa Valley (Fig. 1.2). Corner's premise is based on interpretations of recent high intensity aeromagnetic data from Botswana. (Images of aeromagnetic and gravity data for the Kaapvaal craton were provided by Geodass (Pty) Ltd). The Kaapvaal and Zimbabwe cratons are separated by the 3800-2600 Ma old Archaean Limpopo Mobile Belt (Figs. 1.2-1.4), but definition is obscured to the west by younger deposits (Key and Hutton, 1974). Conflicting opinions exist as to the exact extent of the Limpopo Mobile Belt under these younger deposits. Key and Hutton (1976) proposed that the Limpopo Mobile Belt dies out under the Karoo cover and does not extend into central

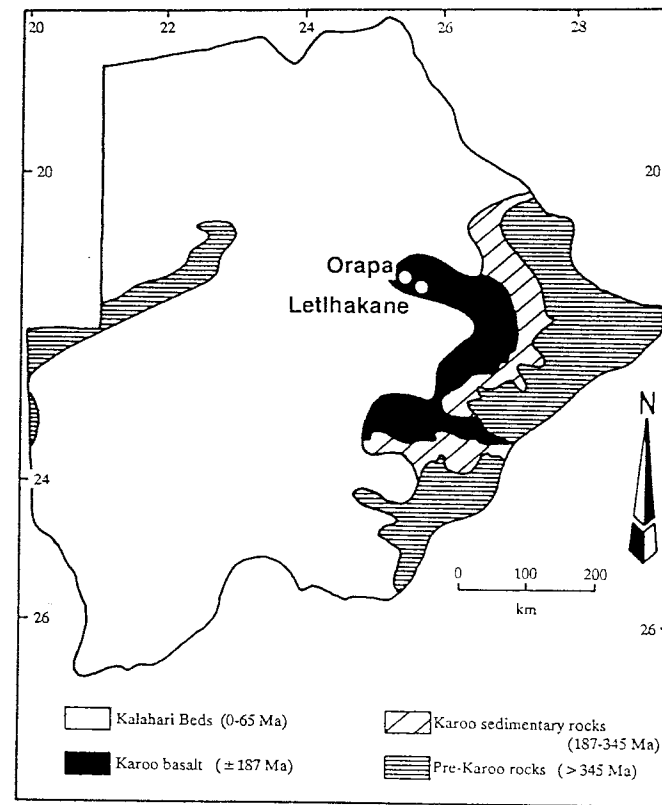


Fig. 1.1 An illustration of the extensive covering of Mesozoic and Cainozoic deposits in Botswana. Data from Key and Rundle (1981) and Eales et al. (1984).

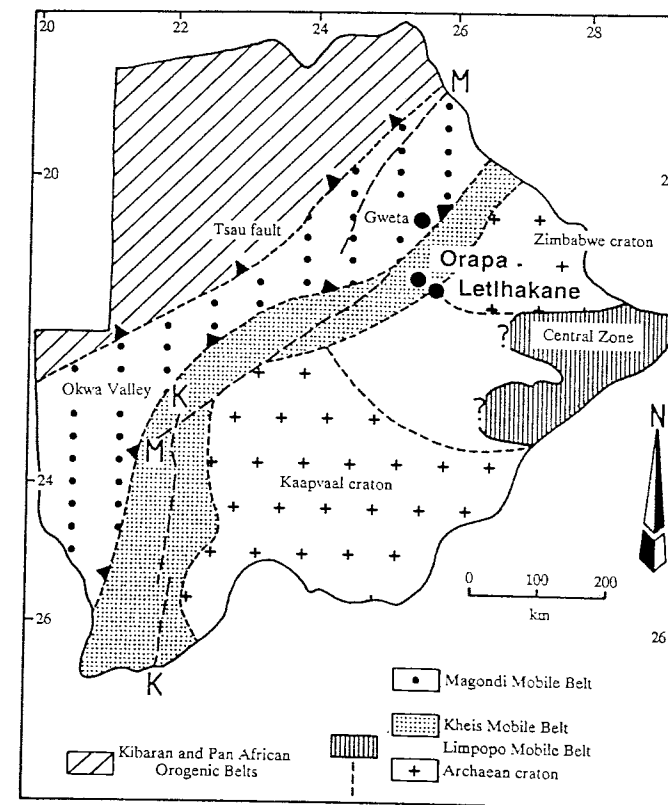


Fig. 1.2 The distribution of major crustal units in Botswana, as interpreted by Carney and Dowsett (1991) from borehole data near Gweta. They envisaged the deformation and tectonic juxtaposition of crustal terranes onto the edge of the Kalahari craton. Long dashed lines represent aeromagnetic and gravity lineaments as identified by Reeves (1978) and Meixner and Peart (1983). Short dashed lines represent inferred boundaries. M-M: Makgadikgadi Lineament, K-K: Kalahari Lineament. Only the Central Zone of the Limpopo Mobile Belt is shown and the extent of outcrop was taken from Coward (1983).

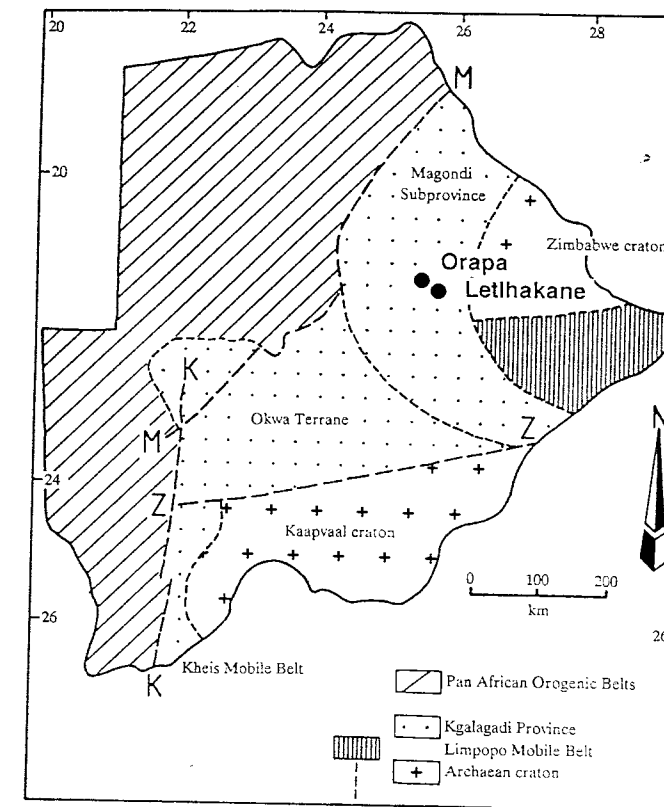


Fig. 1.3 The distribution of major Archaean, Eburnian and Kibaran crustal units in Botswana as interpreted by Stowe et al. (1984). Note the difference in interpretation with respect to the Limpopo and Kheis Mobile Belts when compared to Fig. 1.2. Definition of the various dashed lines are as in Fig. 1.2. M-M: Makgadikgadi Lineament, K-K: Kalahari Lineament and Z-Z: Zoetfontein fault.

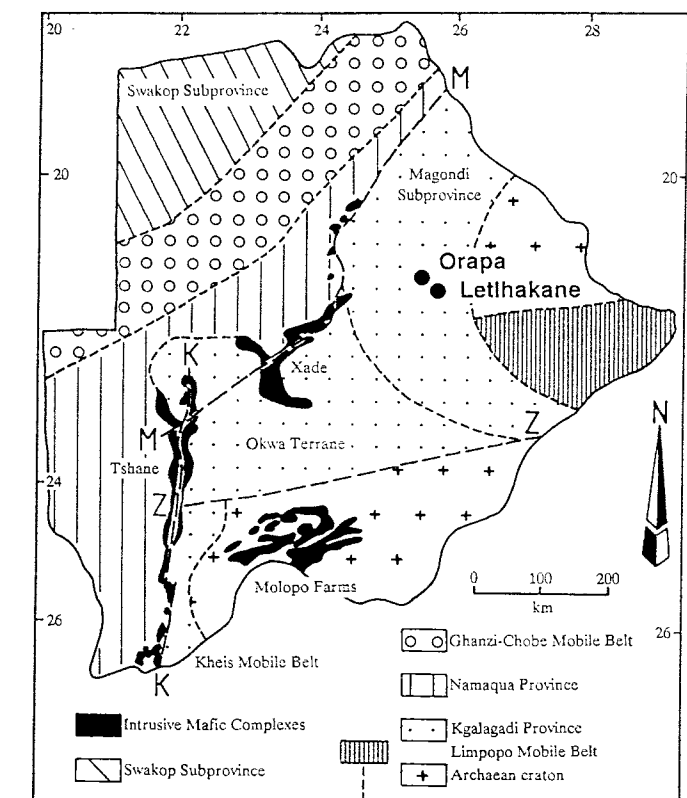


Fig. 1.4 The major tectonostratigraphic units in Botswana, illustrating the full sequence of Archaean, Eburnian, Kibaran and Pan-African Orogenic Cycles. Prominent mafic intrusive complexes are also shown. Symbols and abbreviations are defined in the caption to Fig. 1.3. The Ghanzi-Chobe Mobile Belt is shown as a separate unit for greater clarity, but it should be stressed that Stowe et al. (1984) included the Ghanzi-Chobe Mobile Belt in both the Namaqua and Damara Provinces, due to an overlap in deformation ages between these provinces. Data sources include Stowe et al. (1984) and Meixner and Peart (1983).

and western Botswana (e.g. Fig. 1.3). Other interpretations include the continuation of the Limpopo Mobile Belt to the western edge of the Kaapvaal and Zimbabwe cratons (Barton and Key, 1981), along the Zoetfontein fault, or a northwestward curve around the Zimbabwe craton (Carney and Dowsett, 1991) (Fig. 1.2). Recent high intensity aeromagnetic studies of southern Africa suggest that the Limpopo Mobile Belt does indeed curve around the Zimbabwe craton to the northwest (Corner, pers. comm., 1993). Other Mobile Belts in Botswana include the Early Proterozoic Magondi (2200-2050 Ma) and Kheis (1800-1740 Ma) Belts (Figs. 1.2, 1.4), and the Late Proterozoic Ghanzi-Chobe (820 Ma) and Damara (530 Ma) Belts (Fig. 1.4). These deformation ages were taken from Stowe et al. (1984). Interpretations by Stowe et al. (1984) and drill core examinations by Carney and Dowsett (1991) in the Gweta area (Fig. 1.2) suggest that the Gweta basement represents part of an early Proterozoic terrane, rather than being an extension of the Zimbabwe craton. This implies that the Makgadikgadi Lineament (Fig. 1.2) appears to divide Proterozoic crust and not Archaean domains, as was suggested by Reeves (1978).

The Limpopo Mobile Belt is a linear zone of highly metamorphosed and multiply-deformed rocks and is commonly divided into 3 E-NE trending structural zones: a Central Zone and Northern and Southern Marginal Zones (Barton, 1983, and references therein). The Central Zone consists of high-grade epicratonic supracrustal rocks (granitic, mafic and basic orthogneisses, and supracrustal gneisses), while the Marginal Zones consist of reworked, high-grade equivalents of granite-greenstone successions from the Kaapvaal and Zimbabwe cratons (collectively known as the Kalahari craton). Steep, southerly-dipping shear zones separate the various structural zones. Rocks in the structural zones were subjected to granulite facies metamorphism, but retrograde metamorphism to amphibolite facies occurred in many areas. Mafic dykes of gabbroic composition are common (Barton, 1983).

The Magondi Mobile Belt is a SE-vergent fold and thrust belt (Hartnady et al., 1985) and is composed of volcanics, orthoquartzites and carbonate sequences. Stowe et al. (1984) interpreted the Magondi Belt as part of the Eburnian Orogenic Cycle and classified it as part of the Kgalagadi tectonic province (Fig. 1.3). A more detailed discussion and stratigraphy of this unit in Zimbabwe are presented by Treloar (1988). Whereas Stowe et al. (1984) interpreted the Magondi Belt as curving southeastwards into the Mahalapye area of Botswana (Fig. 1.3), Carney and Dowsett (1991) are of the opinion that it continues southwestward into the Okwa area, since the overall structure and metamorphism in the Mahalapye area appears to be similar to that of the Southern Marginal Zone of the Limpopo Mobile Belt (Fig. 1.2). Treloar (1988) stated that, since the NW margin of the Magondi Belt has not yet been identified, interpretations such as those made by Stowe et al. (1984) as shown in Fig. 1.3 must be regarded as tentative. Aeromagnetic data, however, support the interpretations of Stowe et al. (1984) (Corner, pers. comm., 1993).

The Kheis Mobile Belt was interpreted by Hartnady et al. (1985) as representing an E-verging, thin-skinned fold and thrust belt, composed of quartzites, phyllites and metabasites. Reeves (1978) reported the

presence of an unfaulted block of granitic rocks in the Okwa Valley, but the geological correlation of these rocks is not clear. Key and Rundle (1981) included the Okwa Block (1810-1971 Ma) as a terrane-forming part of the Kheis Belt (1800-1740 Ma) (not shown), while Carney and Dowsett (1991) favour a correlation with the Magondi Mobile Belt (Fig. 1.2). Stowe et al. (1984) interpreted both the Kheis Belt and the Okwa Terrane as part of the Kibaran Orogenic Cycle, but included them, along with the Magondi Belt, as components of the Kgalagadi Province (Figs. 1.3, 1.4).

The Late Proterozoic Ghanzi Group, forming part of the Ghanzi-Chobe Belt, is composed of arkoses, siltstones, limestones and quartzites. The Ghanzi-Chobe Mobile Belt itself is a folded and faulted volcano-sedimentary unit interpreted by Stowe et al. (1984) as part of the Pan-African Orogenic Cycle. Because of its apparent chalcophile mineral potential, parts of the Ghanzi Group have in the past been prospected for sedimentary stratabound deposits (Meixner and Peart, 1983). The reader is also referred to Key and Rundle (1981) for additional information on this belt.

The Damara Province is a high-grade Pan-African Orogenic Belt which covers most of Namibia and consists of 2 branches: one subparallel to the present coast of Namibia, and the other (intracratonic) branch trending NE-SW into Botswana (Miller, 1983). These branches can be subdivided further into tectonostratigraphic zones. The Damara Province was subdivided by (Hartnady et al., 1985, and references therein) into the Swakop and Khomas Belts, the latter of which extends into Botswana as the Otavi and Swakop Groups. The Otavi Group represents a very stable carbonate depositional environment, as is evident from its stromatolite marker beds. The Swakop Group represents a spreading environment and contains turbidites in the grabens and carbonate-pelite-quartzite units in the shallower marginal areas (Miller, 1983). Rare outcrops of these units in the northwest of Botswana reveal tectonites formed by marbles and argillites with a NE-SW orientation (Key and Rundle, 1981, and references therein).

Several intrusive complexes, of which the Tshane, Xade and Molopo Farms Complexes are the largest, are also shown in Fig. 1.4. Most of these are characterized by distinct magnetic anomalies. The Tshane Complex is a layered pre-Karoo, magnetite-bearing cumulate gabbro/gabbro-norite body which has been interpreted by Reeves (1978) as representing oceanic lithosphere obducted onto the cratonic margin. The large extent of this body is clearly visible in Fig. 1.4. The Xade Complex consists of a vertically extensive magnetite-bearing, gabbroic dolerite body which is lithologically analogous to the Tshane Complex. Lateral variation in mineral content and magnetic susceptibility, and a close relation to major lineaments are apparent in both complexes, as is their great thickness ($> 7\text{km}$) (Meixner and Peart, 1983). In contrast to the above, the Molopo Farms Complex, in the south of Botswana, is geologically more complex and minor sulphide mineralization is present. The Molopo Farms Complex (2050 Ma, i.e. of similar age to the

Bushveld Igneous Complex in South Africa) is divided into three parts: the Ultrabasic Series (1.85 km of layered orthopyroxene and olivine cumulates), the Layered Basic Series (> 1.7 km of orthopyroxene-plagioclase cumulates, minor orthopyroxene gabbros/pyroxenites and melanorites) and the Minor Intrusive Suite (dykes and sills of basic to intermediate composition) (Gould et al., 1987).

Note that in both the illustrated interpretations of the tectonic units (Figs. 1.2, 1.3) younger material has been thrust over, or deposited onto, the western edge of the Zimbabwe craton, effectively covering the real boundary. The presence of a craton can be confirmed by mantle xenoliths (this study) in diamond-bearing kimberlite at Letlhakane, apparently within a Proterozoic Mobile Belt. Thermobarometric analyses (Chapter 6) of these xenoliths reveal a deep, cool lithospheric root (i.e. craton) in this locality.

1.3 The geology of the Letlhakane DK 1 and DK 2 kimberlite pipes

Most of the following information regarding the Letlhakane Diamond Mine has been taken from reports by Gibson (1983) and McClenaghan (1989). The Letlhakane Diamond Mine is located 190 kms west of Francistown and approximately 40km south-east of the Orapa Diamond Mine in central eastern Botswana (Fig. 1.1).

There are two kimberlite pipes at Letlhakane, locally known as DK 1 and DK 2, which were discovered in 1968. DK 1 and DK 2 have surface areas of 11.6 and 3.6 hectares respectively and both are rooted in rocks of the Zimbabwe craton. DK 2 was mined for a short period between June 1985 and May 1986. DK 1 is an opencast mine and is still in production.

The DK 1 and DK 2 pipes contain Group 1 (after the definition of Smith, 1983a, and references therein) tuffisitic kimberlite breccias at present erosional levels. Both pipes contain xenoliths of Karoo rocks and are overlain by a 4-10 m thick cover of Kalahari sand and calcrete. Thus the kimberlites are clearly post-Karoo and pre-Kalahari in age. The age of the pipes is thought to be approximately 90 Ma. Unfortunately, McClenaghan (1989) does not state the basis for this age determination. After emplacement, very little erosion occurred before the deposition of the Kalahari formation. This is evident from the preservation of a small amount of sedimentary crater facies material in the upper part of the diatreme. However, the erosion level is deeper than at Orapa which has a well-preserved crater facies (McClenaghan, 1989).

Fig. 1.5 illustrates the roughly circular outcrop pattern of DK 1 and DK 2, respectively. DK 1 is the more complex intrusion of the two, and three different intrusive events can be recognized. The kimberlite in these intrusions is an ilmenite- and spinel-rich monticellite kimberlite and the different intrusive events are represented by the following facies of this kimberlite type:

1. the southern kimberlite basalt breccia;
2. the Letlhakane Mine 1 tuffisitic kimberlite breccia (LM 1 TKB)
3. the Letlhakane Mine 2 tuffisitic kimberlite breccia (LM 2 TKB);

The southern kimberlite basalt breccia

The basalt breccia can be divided into an upper and a lower unit. The upper unit consists of brown, moderately-weathered breccia with varying clast to matrix ratio. This overlies the lower, hard, grey breccia which has a lower matrix content. The contact between the two units varies from sharp to gradational with a 30° dip towards the centre of the kimberlite body (i.e. centripetal dip). McClenaghan (1989) considered the upper unit to be an epiclastic kimberlite, but noted that the evidence for an epiclastic origin was "somewhat ambiguous". He also documented a "general structural trend" within the upper unit, which dips at approximately 35° towards the centre of the pipe. This is attributed to poorly-developed "bedding". The lower unit is an *in situ* explosive breccia with a matrix of injected kimberlite. The matrix content is highly variable. The brecciated basalt which occurs in the west is distinguished from the southern kimberlite basalt breccia by the absence of kimberlite matrix and represents a large xenolith of Karoo basalt.

The LM 1 TKB

Compared to the LM 2 TKB, this breccia is remarkably homogeneous with little variation in the basalt xenolith content (less than 20%, McClenaghan, 1989). Uniform weathering and calcite/talc-chlorite veins can be observed, resulting in a soft kimberlite that can be dug by hand shovel down to 50m below surface in places. The contact with the LM 2 TKB in the south-west is characterized by kimberlite with a higher basalt xenolith content and is referred to as blocky TKB (Fig. 1.5). Towards the south-east, the LM 1/LM 2 contact becomes vague and gradational over a distance of approximately 20m (McClenaghan, 1989).

The LM 2 TKB

The LM 2 TKB is a competent blue-grey rock, although badly weathered in places with extensive carbonate vein development at the surface and talc-chlorite at depth. The basalt breccia is truncated with a near vertical contact, indicating the post-basalt breccia age of the LM 2 TKB. The LM 2 TKB is further subdivided into four units according to the highly variable basalt xenolith concentration. The basalt xenoliths are generally of cobble size, although large metre-sized boulders do occur. The cobbles present in the LM 2 TKB are rounded, in contrast to the angular clasts in the southern kimberlite basalt breccia. McClenaghan (1989) suggested that this was the result of abrasion of the clasts within the pipe during the intrusion.

Although weathering characteristics and xenolith content provide a practical means of distinguishing between the two tuffisitic breccias, petrographic identification of the two is difficult. However, the LM 1 TKB has a higher mica content and the LM 2 TKB yields up to three times as much ilmenite per kilogram as the LM 1 TKB. Other heavy mineral abundances are similar.

1.4 Mantle xenoliths in kimberlites: a review

1.4.1 Xenolith types

Mantle xenoliths are commonly divided into five groups (Dawson, 1980):

- * the peridotite-pyroxenite suite;
- * metasomatized peridotites;
- * eclogites;
- * the glimmerite- and MARID-suites;
- * the discrete nodule or megacryst suite

Many earlier definitions and interpretations mentioned in this section have been taken from Dawson (1980, and references therein).

Mazzone and Haggerty (1989) recently reported three new varieties of aluminous assemblages from the Jagersfontein kimberlite in South Africa. The assemblages are garnet + spinel (alkremite), corundum + garnet (corganite) and corundum + garnet + spinel (corgaspinite). These are probably related to the eclogite suite.

The peridotite-pyroxenite suite

The classification of peridotites and pyroxenites, as recommended by the International Union of Geological Sciences (IUGS), is illustrated in Fig. 1.6. This classification is based on the volume percentage of minerals present. The definition incorporated into Fig. 1.6 has been modified regarding the identification of lherzolite. A convention among mantle petrologists is followed whereby the presence of only a single grain of clinopyroxene is sufficient for rock to be defined as lherzolite and not >5% as is recommended by IUGS (Dawson, 1980). Very olivine-rich rocks, e.g. dunites, are rare owing to the ease with which olivine serpentizes. The peridotite-pyroxenite suite consists of the following mineralogical components: magnesian olivine, Cr-pyroxene garnet, Cr-spinel, orthopyroxene (enstatite), green chromiferous diopside,

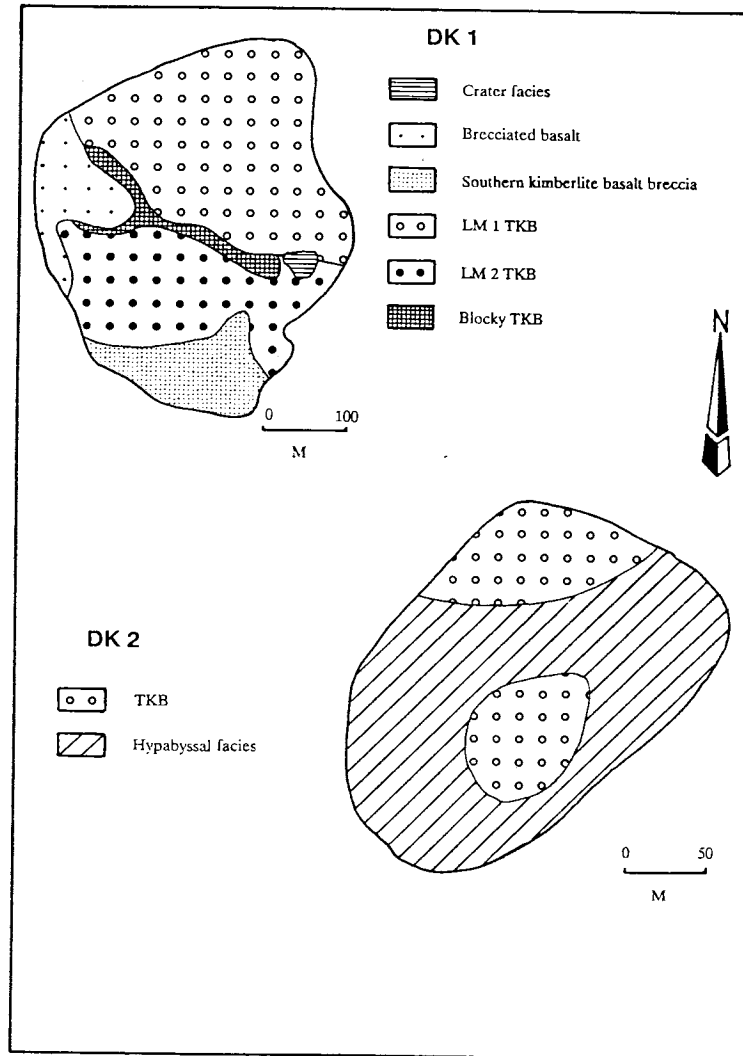


Fig. 1.5 The surface outcrop pattern of DK 1 and DK 2. Data from M.Field (pers. comm., 1990).

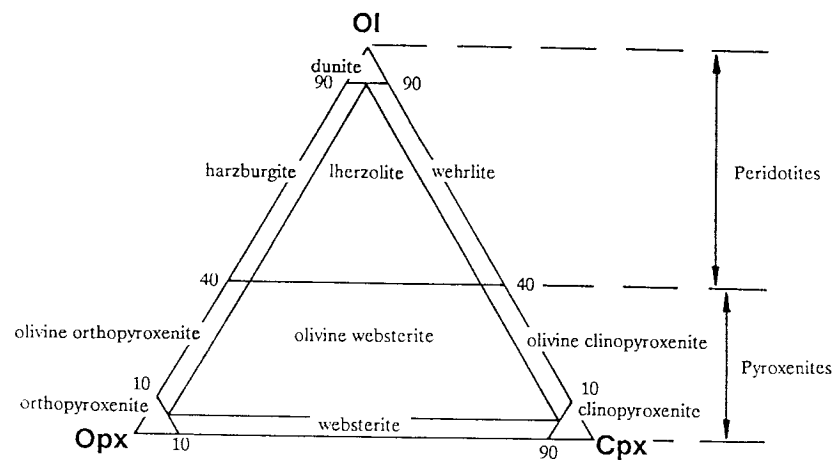
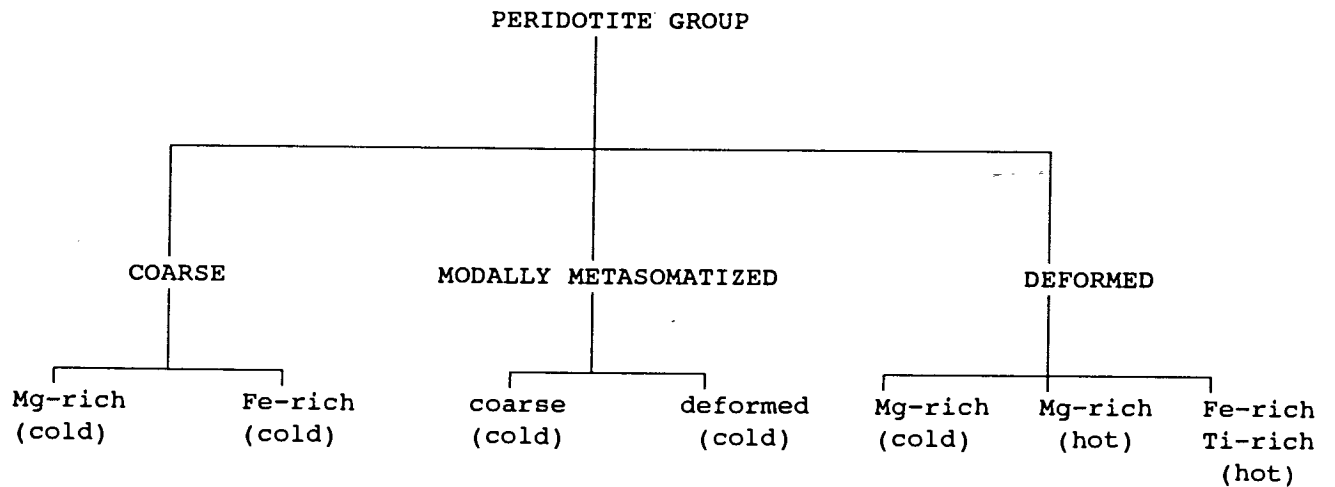


Fig. 1.6 Classification of peridotites and pyroxenites as recommended by the IUGS.

phlogopite and rare pargasitic amphibole. Rocks in which olivine is the dominant phase are most common by far in the suite. Olivine and orthopyroxene comprise the major proportion (>90%, seldom <80%) of phases in these xenoliths (Harte, 1983). Olivine-poor rocks (olivine-garnet websterites, garnet websterites and garnet clinopyroxenites) are rare according to Dawson (1980). Rare accessory minerals include diamond (Shee et al., 1982), graphite, rutile, ilmenite, zircon (Dawson, 1980) and various sulphides (Tsai et al., 1979). With the exception of graphite and diamond, all the above-mentioned are possibly of metasomatic origin (Harte et al., 1975).

Harte (1983) proposed a classification of peridotites based on a combination of mineral chemistry and petrographic features (Table 1.1). The most common peridotites are coarse-grained, Mg-rich and "cold", whereas the less common, though widespread deformed peridotites are Fe-, Ti-rich and "hot". Equilibration temperatures determined from mineral geothermometers form the basis for distinction between "cold" (low T) and "hot" (high T) peridotites. "Coarse" peridotites are rocks characterized by mineral grains 2-10 mm in size with equant to tabular shapes. Slight internal strain may be present as well as garnet, spinel and pyroxene exsolution lamellae within pyroxene. The "coarse" and "deformed" subdivisions in Table 1.1 are based on the textural features noted by Harte (1977) (Table 1.2). Harte's (1983) "deformed" group includes the porphyroclastic and mosaic-porphyroclastic categories identified by him earlier (Harte, 1977). Nixon and Boyd (1973a) drew attention to the "fertile" (higher Fe, Ti and Na) nature of the deformed peridotites at Thaba Putsoa, when compared with the coarse, undeformed peridotites. A fertile peridotite would be capable of yielding a basaltic melt fraction. Depleted peridotites are characterized by low Ca, Na, Al and Fe values, resulting in high Mg/Fe and Cr/Al ratios. Rb/Sr, light rare earth elements (LREE) and large ion lithophile (LIL) concentrations decrease sympathetically. With time, such rocks develop low $^{87}\text{Sr}/^{86}\text{Sr}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ ratios. There is a good correlation between these chemical features and the textural classification, in that coarse peridotites tend to be depleted, while deformed rocks are fertile. Boyd and Nixon (1972) and Nixon and Boyd (1973a) noted that the Cr_2O_3 -content of clinopyroxene is a useful discriminant in distinguishing clinopyroxene from coarse and deformed peridotites. Clinopyroxene in the former is characterized by a higher Cr_2O_3 -content. However, no mention was made by Boyd and Nixon (1972) and Nixon and Boyd (1973a) with regards to any compositional differences between clinopyroxenes from metasomatized and non-metasomatized coarse, undeformed peridotites.

Lawless et al. (1979) described xenoliths known as polymict peridotites from the Bultfontein and De Beers kimberlites. These rocks are composed of a variety of peridotitic, eclogitic and megacrystic fragments cemented by ilmenite, phlogopite, rutile and sulphide minerals. Polymict peridotites have been interpreted as remnant conduit filling left behind after kimberlitic fluid migration. Carswell et al. (1984) proposed that spinel peridotites are present as a continuous layer along the upper boundary of the cratonic lithosphere and overlie garnet peridotite in depth. This led Boyd (1989) to illustrate that it is possible to distinguish between different processes of craton development by studying the compositional relations of the spinel

Table 1.1: Classification of mantle peridotites (after Harte, 1983).**Table 1.2:** Textural classification of peridotites-pyroxenites (modified after Harte, 1977).

Rock type	Porphyroclasts	Grain size and boundaries	Subtypes
Coarse	Absent	Avg. size > 2mm. Boundaries often straight or smoothly curving	1) Equant 2) Tabular
Porphyroclastic	Present. >10% of olivine as porphyroclasts	Porphyroclast (1-2mm) and neoblast (<0.5mm) populations. Irregular porphyroclast boundaries - smooth neoblast boundaries Tabular and equant neoblasts	1) Disrupted 2) Fluidal 3) Laminated and disrupted 4) None of the above
Mosaic-porphyroclastic	Present. <10% of olivine as porphyroclasts	Porphyroclast and neoblast populations	1) Fluidal 2) Laminated and disrupted 3) None of the above
Granuloblastic	Absent or rare	Avg. size < 2mm. Straight or smoothly curving grains of polygonal tabular shape	1) Equant 2) Tabular

peridotites that form the upper portion of the craton lithosphere. Boyd (op. cit.) described the Kaapvaal spinel peridotites as being of unusually coarse grain size (1-2 cm) with most orthopyroxene (enstatite) containing exsolution lamellae of possible clinopyroxene. The spinel is characterized by symplectites.

Sobolev et al. (1969, 1973) reported the presence of subcalcic garnets in depleted garnet harzburgite xenoliths which are markedly deficient in CaO when compared to garnets that equilibrated with diopside. The garnet compositions are similar to those found as inclusions in diamond (Gurney and Switzer, 1973). These subcalcic harzburgites are similar to coarse, low-temperature harzburgites (Boyd and Nixon, 1988). Recently however, Boyd et al. (1993) proposed that garnets in subcalcic harzburgite xenoliths differ from those included in diamonds, the latter being more Cr and Mg-rich and Ca-poor. This statement by Boyd et al. (1993) is controversial (Viljoen, pers. comm., 1993) since subcalcic harzburgites from several localities, including Letlhakane, plot within the Cr and Ca compositional field of garnets included in diamond, thereby contradicting their statement. Several theories for the origin of subcalcic garnets have been proposed, including high-pressure metamorphism of subducted meta-serpentinites (Schulze, 1986) and metasomatism by carbon-bearing volatiles (Haggerty, 1986; Nixon et al., 1987). The basis for the latter proposal is the presence of graphite and diamonds in some harzburgites. Ringwood (1975, and references therein) and O'Hara et al. (1975) suggested that harzburgite might be created as a product of lherzolite melting and melt extraction, often in more than one cycle.

Metasomatized peridotites

Metasomatism is defined by Bates and Jackson (1984) as "a process of practically simultaneous capillary solution and deposition by which a new mineral may grow in the body of an old mineral". Erlank et al. (1987) pointed out that a metasomatic mineral need not necessarily be an addition to the primary mineral suite. The same mineral may be present in both pre-metasomatic and metasomatic form. Unfortunately, early definitions of metasomatism were not rigorous. The term should only be applied where unequivocal evidence of unaltered rock exists (Bailey, 1987).

Metasomatized rocks are characteristically veined, with evidence of metasomatic reactions along fissures and grain boundaries. Elements are redistributed rather than replaced. Superimposed on the metasomatic features are the effects of kimberlite emplacement (e.g. kelyphite formation), melt segregations and low-temperature alteration (e.g. serpentinization). Radiometric dating can be employed to determine if metasomatic features are related to the kimberlite intrusion, or to a much older mantle metasomatic event, but is not always successful. Erlank et al. (1987) pointed out that if nodules were not veined and if textural

equilibration had taken place, it would be difficult to prove that metasomatism had occurred. Chemical evidence will only indicate that some enrichment process (either igneous or metasomatic) has taken place. This problem is also discussed in Chapter 3, Section 3.4.3.

Gurney and Harte (1980) distinguished two types of metasomatism: infiltration and diffusion metasomatism. Infiltration metasomatic effects point to the presence and migration of fluids within the upper mantle. These fluids are capable of forming minerals that are enriched in Fe, K, Ti, H_2O , S, Nb, Zr, Hf, Sr, Cu, Rb, Ba, Na and CO_2 . New minerals may be formed by the introduction of elements or pre-existing phases may be modified. Minerals commonly formed by infiltration metasomatism include the following: phlogopite, ilmenite, rutile and, more rarely, richterite and carbonate. Polymict peridotites (Lawless et al., 1979) and "fertile" peridotites from Lesotho (Nixon and Boyd, 1973a) are examples of peridotites modified by infiltration metasomatism.

Diffusion metasomatism implies that diffusive transfer has taken place across grain boundaries, modifying the earlier mineral composition. Diffusive processes are vital in achieving local chemical equilibrium in a rock. The most common example of diffusive metasomatism is caused by host-rock (i.e. kimberlite) interaction with the mantle rocks. Diffusion metasomatism has also been noted in xenoliths with strong chemical gradients between layers of distinct composition, e.g. Hatton (1978).

These two types of metasomatism distinguished by Gurney and Harte (1980) are similar to the "patent" and "cryptic" metasomatism proposed by Dawson (1982). "Patent metasomatism" (synonymous with the "primary metasomatism" of Harte et al., 1975) involves the obvious introduction of minerals, while "cryptic metasomatism" can only be observed in geochemical and isotope studies.

Dawson (1972) first demonstrated the mantle-derived origin of phlogopite on the basis of texture. Carswell (1975) and Delaney et al. (1980) subsequently employed chemical criteria to confirm the observation. Primary phlogopite is recognized texturally as occurring in the form of large tabular plates in textural equilibrium with other phases, and on the basis of chemical composition by its low Cr and Ti content. Secondary phlogopite typically occurs as smaller, undeformed, irregular grains with high Ti and Cr content and is commonly associated with kelyphite rims of garnets. However, Delaney et al. (1980) and Erlank et al. (1987) pointed out the existence of phlogopite grains with intermediate compositions and textures.

Erlank et al. (1987) proposed that the following sequence of peridotites may be viewed as the result of progressive metasomatism: garnet peridotites (GP) < garnet phlogopite peridotites (GPP) < phlogopite peridotites (PP) < phlogopite K-richterite peridotites (PKP). The key factor of the above sequence concerns the removal of garnet to allow crystallization of K-richterite, since K-richterite is not stable when

the chemical potential of Al is high relative to that of K (Kushiro and Erlank, 1970). Waters (1987a) and Waters and Erlank (1988) found that the type of metasomatic mineral assemblage is influenced by depth (i.e. PP is deeper than PKP). PKP's also contain rare and exotic titanate minerals, e.g. lindsleyite and mathiasite (Haggerty et al., 1983). Mathiasite has been identified as discrete macrocrysts at Kolankwanen and Jagersfontein by Haggerty et al. (1983) and in China (Jianxiong et al., 1984). The interested reader is referred to Haggerty (1987) for a review on the metasomatic mineral titanates in upper mantle xenoliths.

Eclogites

Haüy (1882) first applied the term "eclogite" to a metamorphic rock composed of green omphacite and pink pyrope from the Fichtelgebirge in Bavaria. Eclogites are defined by Dawson (1980) as coarse-grained rocks composed principally of garnet and clinopyroxene. Accessory minerals include diamond, graphite, phlogopite, amphibole, corundum, kyanite, chromite, rutile, orthopyroxene, coesite and ilmenite. Grospydite is a peraluminous eclogite defined by Sobolev et al. (1968) as a type of eclogite with accessory kyanite and in which the garnet contains more than 50% grossularite component. The word "grospydite" is derived from the assemblage grossularite-pyroxene-disthene (the old name for kyanite) and was first identified in Russia by Bobrievich et al. (1959). Other eclogite variants may be formed if an additional primary mineral is present in more than accessory quantity, i.e. > 1 modal % (Dawson, 1980).

In xenolith suites from kimberlites, eclogites are less common than peridotites, but may nonetheless comprise a substantial proportion of the xenolith population in some kimberlite pipes, e.g. Roberts Victor, South Africa (Hatton, 1978) and Orapa, Botswana (Shee, 1978). Eclogites occur as discoidal nodules with long axes up to 50 cm at Roberts Victor. The outer surface is commonly well polished. Modal variation of garnet and clinopyroxene often results in a well defined layering. Shee (1978), however, did not observe any such layering in eclogites from Orapa and attributed this to the small size of the xenoliths (1.5-5 cm, long axis).

Dawson and Stephens (1975) formulated a statistical classification of garnets which is widely used today. Using the variation in MgO, FeO, CaO, TiO₂ and Cr₂O₃, they were able to identify 12 cluster groups. Groups 3-6 and 8 are derived from eclogites. A similar classification scheme has been attempted for clinopyroxene (Stephens and Dawson, 1977), which identifies ten clinopyroxene groups. Eclogitic clinopyroxenes mainly fall into groups 8-10.

Eclogites may be divided into two groups based on textural (MacGregor and Carter, 1970) and chemical differences (McCandless and Gurney, 1989). MacGregor and Carter (1970) originally proposed the textural classification for the Roberts Victor eclogites. Group I eclogites are characterized by subhedral

to rounded grains of garnet set in anhedral to interstitial pyroxene. Large pyroxenes may surround the garnets poikilitically. Group II eclogites are composed of anhedral, irregular grains with a tightly interlocking fabric. The classification of McCandless and Gurney (1989) has the advantage of being independent of often ambiguous textures. They have shown that the Roberts Victor eclogites fall into two groups, based on the Na_2O -content of garnet and the K_2O -content of clinopyroxene. Group I eclogites are characterised by K_2O (clinopyroxene) $> 0.08\text{wt}\%$ and Na_2O (garnet) $> 0.09\text{wt}\%$, while levels below these indicate a Group II origin. The chemical classification corresponds closely to the classification of McGregor and Carter (1970).

Some apparently eclogitic garnets may exhibit high levels of Cr_2O_3 , but this is rare. It is thought that such garnets form part of disaggregated peridotite xenoliths and are therefore not of real eclogitic origin. Such eclogites can be recognized by their purple garnets and bright green clinopyroxene, when compared with the red/orange garnets and pale green clinopyroxene of "genuine" eclogites. These disaggregated peridotite fragments should not be confused with ultradeep eclogites (Haggerty and Sautter, 1990), which also contain purple garnets (Chapter 4, Section 4.5.5).

The glimmerite- and MARID-suites

Nodules in which phlogopite forms the dominant mineral are loosely termed "glimmerites" (Dawson, 1980). However, amphibole, clinopyroxene, ilmenite, rutile, apatite and olivine may also be present. Dawson and Smith (1977) were the first to introduce the acronym "MARID" for such xenoliths, referring to the presence in the rock of the minerals mica, amphibole, rutile, ilmenite and diopside. Bayley et al. (1979) considered orthopyroxene and zircon also to be part of the MARID-suite.

Dawson (1980) reported that MARID nodules vary from rounded to discoidal in shape and may be up to 15cm in diameter. Foliation and/or lineation can also be observed, since most MARIDS are deformed. Waters (1987a) stated that it is not essential that all five diagnostic MARID minerals be present. MARID xenoliths can be distinguished from glimmerites by the less deformed nature of the phlogopite and the presence of K-richsterite and rutile in the former. Glimmerites are characterized by a more Al- and Mg-rich phlogopite composition.

Dawson and Smith (1977) concluded that MARID rocks crystallize under highly oxidizing conditions. The presence of amphibole restricts the depth of formation of the magma to < 100 km. Kramers et al. (1983) concluded from trace element and isotopic data that the MARID-suite and material in the metasomatized peridotites could be related, except that the higher Cr_2O_3 and Al_2O_3 concentrations in MARID xenoliths are typical of phases replacing lherzolitic garnet and pyroxene (Dawson, 1987). Dawson

(1987) further proposed that "the injection, crystallization, shearing and metasomatism, together with similar features in polymict peridotites, took place at the margins of an ascending upper-mantle diapir". Kramers et al. (1983) proposed an age of < 200 Ma for the metasomatism and generation of MARID nodules.

Controversy surrounds the parent magma chemistry of the MARID-suite. Waters (1987b) concluded that MARID nodules have major element concentrations very similar to the ultrabasic olivine lamproites of Western Australia, while Dawson and Smith (1977) postulated a magma chemically similar to a kimberlite. Although a superficial similarity exists between the PKP and MARID suites, isotope studies have indicated that no simple relationship exists between these rocks (Waters, 1987a). This contradicts the conclusions of Kramers et al. (1983).

The discrete nodule or megacryst suite

Single crystals (often > 2 cm in diameter) commonly occur as xenocrysts in kimberlites. These crystals are referred to as megacrysts (Boyd and Dawson, 1972) or as discrete nodules (Nixon and Boyd, 1973b). The term "discrete nodule" also includes polygranular, monomineralic nodules with a mosaic texture (Schulze, 1987). Megacryst minerals include orthopyroxene, clinopyroxene, olivine, garnet, ilmenite, phlogopite, zircon and possibly rutile (Schulze, 1990).

Megacrysts may be subdivided into a Cr-poor and a Cr-rich suite (Eggler et al., 1979; Harte, 1983). The Cr-rich suite is rare and restricted to kimberlite pipes in Colorado and Wyoming (U.S.A.) and Orapa (Botswana). Olivine, garnet, clinopyroxene and orthopyroxene may belong to either the Cr-rich or the Cr-poor suite, while ilmenite and zircon megacrysts are members of the Cr-poor suite. Ilmenite is also capable of forming spectacular intergrowths with clinopyroxene and, more rarely, with orthopyroxene (Harte, 1983). A non-equilibrated, quenched orthopyroxene-ilmenite intergrowth from the Weltevreden Mine in South Africa was described by Rawlinson and Dawson (1979). Other megacryst types include exsolved pyroxenes and "Granny Smith" nodules. "Granny Smith" nodules are yellowish-green, Cr-rich diopsides that range in size from 1-15 cm and were first observed by Boyd et al. (1984a). These nodules are commonly deformed and intergrown with ilmenite, rutile and phlogopite and also have a composition similar to diopsides from the MARID and glimmerite suites (Boyd et al., 1984a). Lamellar exsolutions of orthopyroxene, clinopyroxene and garnet within pyroxene hosts have been reported from several localities (Eggler et al., 1979; Gurney et al., 1979b; Boctor et al., 1983). Accessory ilmenite, rutile and chromite may also be present. The silicate composition in these exsolutions does not compare with either the Cr-poor or the Cr-rich suite. Meyer and McAllister (1984) concluded that some of these intergrowths represent Cr-poor megacrysts that may have equilibrated at lower temperatures over long periods of time.

Although the compositional trends of megacrysts vary between different locations, Schulze (1987) concluded that these trends are consistent with an origin through differentiation of a magma related to the host. Schulze (1985) observed polymineralic inclusions in garnet and diopside megacrysts from a kimberlite in eastern Kentucky, U.S.A., which may represent included liquids of the same composition as the liquid from which the megacrysts crystallized. The same author also observed similar inclusions in ilmenite, Cr-poor garnet, Cr-rich garnet and diopsides from the Sloan 2 kimberlite in Colorado. Schulze (1985) thus concluded that the original liquid must have been similar to magnesian calcite and phlogopite-bearing kimberlite.

1.4.2 Geothermobarometry

Nixon and Boyd (1973a) and Boyd (1973) were the first to observe that mantle xenoliths from Cretaceous kimberlites in northern Lesotho can be grouped in order of increasing temperature and depth of origin and proposed that the pressure-temperature array defined by these xenoliths was the fossil Cretaceous geotherm for Lesotho. Various workers have since used this approach to define geotherms employing mantle xenoliths from other kimberlites in southern Africa, the Yakutia Province in Siberia, the western United States and northern Canada.

Boyd (1973) was able to show the presence of a distinct "kink", or inflection to a higher dT/dP at a depth of approximately 170 km in the Lesotho geotherm. Furthermore, the high temperature part of the geotherm is characterized by deformed peridotites, as opposed to undeformed peridotites along the low-temperature segment. Nixon and Boyd (1973a) pointed out that the deformed nodules of Thaba Putsoa are enriched in Fe, Ti and Na (i.e. "fertile") as opposed to the coarse, undeformed peridotites. This feature has also been reported from the Jagersfontein kimberlite (Hops et al., 1989).

However, disagreement exists regarding the "perturbed" geotherm. Most of this disagreement arises from the different methods of estimating the pressure and temperature for high-temperature mantle xenoliths using different geothermometer and geobarometer combinations. Uninflected mantle geotherms have been reported by Adams and Bishop (1986), Ganguly and Bhattacharya (1987) and Carswell and Gibb (1987b). Finnerty and Boyd (1984, 1987) and Finnerty (1989) have illustrated that the kinked geotherm remains present, irrespective of the thermometer used. The presence or absence of a kinked geotherm appears, therefore, to depend on the particular barometer used for pressure determination (Finnerty, 1989). However, all commonly used barometers depend on the solubility of Al in enstatite co-existing with garnet (MacGregor, 1974). The solubility of Ca in olivine co-existing with two pyroxenes is also pressure-dependent (Finnerty and Boyd, 1978; Adams and Bishop, 1986) and, even though crudely calibrated, provides similar results to those obtained using the barometer of MacGregor (1974).

Finnerty (1989) identified extrapolation as being the major obstacle in the accuracy of temperature and pressure determinations. This includes the extrapolation of laboratory temperatures and pressures, as well as synthetic compositions to complex mantle conditions. Luth et al. (1990) caution against the use of Fe/Mg geothermometers and geobarometers on mantle samples if significant quantities of Fe^{3+} are present in the garnets, as large inaccuracies in temperature may result.

1.5 Sample collection and preparation procedures

For logistical and bureaucratic reasons, initial sample collection was undertaken by Matthew Field (Anglo American Research Laboratories). Four sample bags of peridotites, pyroxenites, eclogites and megacrysts totalling 182 nodules were collected on 10/01/90 on the tailings dumps at Orapa where the final concentrate from Letlhakane is dumped. The samples are a mixture from the DK 1 and DK 2 kimberlites, but have been separately treated from the Orapa kimberlite so that there is no possibility that material from Orapa could have been included in this sample suite. The samples are small in size, varying from 1.56 - 5 cm in length (long axis). Another large bag of samples (also collected by M. Field) arrived at the Anglo American Research Laboratories during early July 1990 and was sorted by the author. The combined collection totalled approximately 935 ultramafic nodules and 130 were selected for study purposes. The various rock types collected from Letlhakane are listed in Tables 2.1, 3.1, 4.1 and 5.1. A further 64 eclogites were selected for analysis as grain mounts.

The author and his supervisor were eventually allowed to visit Letlhakane during mid-November 1991 and access to the open pits at both Orapa and Letlhakane was permitted, as well as the acquisition of drill cores from three boreholes drilled into the basement at Letlhakane. A large number of crustal xenoliths were collected at Orapa, while collection at Letlhakane was aimed at discovering more metasomatized mantle xenoliths. The majority of the metasomatized samples discussed and analysed in Chapter 3 were collected during this visit.

During collection, certain criteria were applied in selecting the xenoliths. These were 1) the absence of alteration and 2) the presence of garnet. The latter condition was applied to ensure that an adequate selection of material was available for thermobarometric studies. Application of these criteria resulted in a bias in the samples away from material likely to have been extensively metasomatized. This was, however, compensated for during the last collecting trip.

Xenoliths were washed in water and sorted into various subdivisions according to their mineralogy. Eclogites were further subdivided into Cr-poor and Cr-rich groups by using the colour of garnet and clinopyroxene. Cr-poor and Cr-rich clinopyroxene megacrysts were also sorted on a colour basis. The samples were then studied under a stereomicroscope and any notable textures, accessory minerals and possible metasomatic effects were recorded. Sample selection for preparation of polished sections for mineral analysis by electron microprobe followed. Wherever possible, half of the original sample was preserved for possible further study. Large metasomatized xenoliths were initially sawn in half to determine the presence of any notable petrographic features. A total of over 220 mantle xenoliths of all types were eventually studied.

Probe sections were cut with a Buehler ISOMET (trade mark) low speed saw which has a thinner blade and slower cutting speed than the average saw. This was done to achieve a better quality cut and to minimize the destruction of potentially important minor phases by the blade. The thin sections were polished using successively finer grades of diamond abrasive (15, 5, 1, .25 micron). Large thin sections (7.5 x 11 cm) and polished slabs of selected samples were also prepared. This facilitated the study of textural relationships and banding/veining, especially in coarse-grained samples.

CHAPTER 2

PERIDOTITES AND PYROXENITES

2.1 Introduction

In this chapter an attempt will be made to show that petrographic and mineralogical differences exist between the various peridotite and pyroxenite types found at Letlhakane. Little emphasis has been placed on modal analyses, because, since many of the individual samples are so small, they are unlikely to render representative results. This can be justified on the basis that mineral phases are seldom homogeneously distributed throughout a xenolith - in fact, several members of the peridotite-pyroxenite and metasomatized peridotite-pyroxenite suites had to be reclassified, since classification based on modal proportions is sometimes inconsistent with classification of the rock based on garnet composition. Wherever the two classifications disagree, the latter, based on garnet composition, is used in preference (e.g. JSL 114 which appears to be a garnet clinopyroxenite, but is in fact a garnet wehrlite according to its garnet chemistry) (Table 2.1).

Petrographic descriptions of each rock group, as represented in this chapter, may at first appear superfluous and unnecessary, but the extent of textural variation possible in these rocks, particularly where metasomatism has occurred (Chapter 3), warrants this detail. The large number of plates provided will hopefully emphasize this point.

The samples had been subjected to first-stage crushing procedures at Orapa and are without exception ovoid in shape, pitted and no longer than 5 cm in length (long axis). Most samples are unaltered. No banding or layering can be observed, possibly because of the small size of the samples, despite the fact that banding on a small scale is not uncommon, e.g. in xenoliths from the Obnazhennaya kimberlite pipe in Siberia (Sobolev and Sobolev, 1964), Matsuko (Harte et al., 1975) and Bultfontein (Dawson, 1980). Banding is, however, present in a large phlogopite peridotite (JSL 516), and in a composite pyroxenite xenolith (JSL 600), both of which will be discussed in the following chapters.

At the risk of oversimplifying metasomatic processes in the mantle, it was decided to classify all primary metasomatic phlogopite and amphibole-bearing samples (after the definition of Carswell, 1975, and Delaney et al., 1980; see also Section 1.4.1) as being metasomatized (see also Chapter 3, Section 3.1). This is

Table 2.1: Petrographic and textural summary of the Letlhakane peridotite-pyroxenite suite. The star symbol denotes the presence of primary phases (eg. GT, OLV, OPX and CPX), while those of possible secondary metasomatic origin (eg. PHL) are indicated as (S). The superscript (x) denotes phases observed in thin section only and which were not analysed.

Sample no.	Rock type	Texture	GT	OLV	OPX	CPX	SP	PHL	GRA
JSL 107	Web.	G			*	*			
JSL 108	Gt. lherz.	C/P	*	*	*	*		S ^x	
JSL 112	Gt. lherz.	MP	*	*	*	*		S ^x	
JSL 113	Gt. harz.	C	*	*	*		*, S	S ^x	
JSL 114 ¹	Gt. wehrl.	C	*		*	*		S ^x	
JSL 116	Gt. lherz.	C	*	*	*	*		S ^x	
JSL 118	Web.	C			*	*		S ^x	
JSL 119	Gt. lherz.	MP	*	*	*	*		S ^x	
JSL 124	Sp. lherz.	C		*	*	*	*		
JSL 126	Gt. lherz.	P	*	*	*	*		S ^x	
JSL 134	Gt. lherz.	C	*	*	*	*		S ^x	
JSL 140	Gt. lherz.	G/P	*	*	*	*		S ^x	
JSL 153	Sp. lherz.	G		*	*	*	*		
JSL 154	Sp. lherz.	C		*	*	*	*		
JSL 156	Sp. lherz.	G		*	*	*	*		
JSL 157	Sp. lherz.	G		*	*	*	*		
JSL 158	Sp. lherz.	C/G		*	*	*	*		
JSL 166	Dunite	C		*	*				
JSL 170	Gt. harz.	C	*	*	*		*	S ^x	
JSL 171	Gt. web.	C	*		*	*			
JSL-193	Gt. lherz.	C	*	*	*	*		S ^x	
JSL 202	Gt. web.	C	*		*	*			*
JSL 209	Gt. web.	C	*		*	*			
JSL 250	Alkremite	C	*				*		
JSL 261	Gt. lherz.	C	*	*	*	*		S ^x	
JSL 262	Gt. harz.	C	*	*	*	S ^x		S ^x	
JSL 263	Gt. harz.	P	*	*	*				
JSL 266	Gt. harz.	C	*	*	*			S ^x	
JSL 267	Gt. harz.	C	*	*	*			S ^x	
JSL 268	Gt. harz.	C	*	*	*	S ^x		S ^x	
JSL 279	Gt. lherz.	P	*	*	*	*		S ^x	
JSL 280	Gt. lherz.	P	*	*	*	*		S ^x	
JSL 296	Gt. web.	C	*		*	*		S ^x	
JSL 306	Lherz.	C		*	*	*			

Abbreviations used in this table:

Minerals

GT - garnet
 OLV - olivine
 OPX - orthopyroxene
 CPX - clinopyroxene
 SP - spinel
 PHL - phlogopite
 GRA - graphite

Rock types

Gt. harz. - garnet harzburgite
 Gt. lherz. - garnet lherzolite
 Gt. web. - garnet websterite
 Web. - websterite
 Sp. lherz. - spinel lherzolite
 Lherz. - lherzolite
 Gt. wehrl. - garnet wehrlite

Textures

C - coarse
 G - granuloblastic
 P - porphyroclastic
 MP - mosaic porphyroclastic

1: Garnet chemistry indicates a peridotitic composition

in keeping with the terminology of Waters (1987a) and Erlank et al. (1987) and provides some form of consistency with other literature. This is obviously somewhat subjective and it is entirely possible for a sample to have been metasomatized through diffusive processes and not contain phlogopite and/or amphibole. Ilmenite and rutile are also considered to be of metasomatic origin (Harte et al., 1975) and rutile/ilmenite-bearing samples have therefore been included as such (Chapter 3), even though phlogopite/amphibole may be absent.

2.2 Petrography

2.2.1 Garnet peridotites

2.2.1.1 Garnet lherzolites

Major phases include olivine, clinopyroxene, orthopyroxene and garnet, while secondary metasomatic phlogopite is the most common accessory mineral and is associated with kelyphite resulting from garnet breakdown. Textures, based on the classification of Harte (1977), vary from coarse to mosaic porphyroclastic (Plates 1 & 2. See also Table 2.1). As far as could be ascertained, deformed peridotites described herein are the first to be reported from this locality. Approximately equal numbers of coarse- and porphyroclastic-textured garnet lherzolites are present, but this is not representative as a result of sample bias. None of the porphyroclastic-textured lherzolites exhibit any fluidal textures. Mineral grains in the coarse-textured garnet lherzolites generally exhibit gently curving grain boundaries associated with triple junctions. These features indicate that equilibrium conditions prevailed at the time of crystallization.

The size, shape and colour of the garnets vary with textural type. Porphyroclastic and mosaic porphyroclastic lherzolites display smaller, (<0.5-2mm) more rounded or discoid-shaped garnets than the coarse-textured lherzolites (Plates 1 & 2). Garnets in the former vary from dark orange (JSL 112, 280) to reddish purple (JSL 263). Kelyphite rims are well developed and in extreme cases kelyphite pseudomorphs are present. Small euhedral brown and green spinels, secondary metasomatic phlogopite platelets, and euhedral to subhedral, colourless clinopyroxene and orthopyroxene grains may be present in the kelyphite rims. Coarse-textured peridotites contain larger (up to 5mm), more rounded, purple garnets. Kelyphite rims are generally not as well developed as in the porphyroclastic peridotites. All the lherzolitic garnets display cracks.

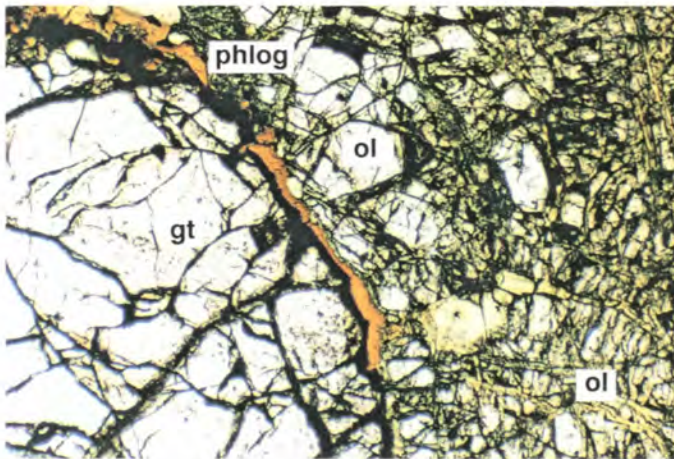


Plate 1: A typical coarse-textured lherzolite (JSL 142), showing a large garnet (gt) surrounded by partly serpentinized olivine (ol). Note the brown secondary phlogopite (phlog) surrounding the garnet. Field of view = 4mm wide. Plane polarised light.

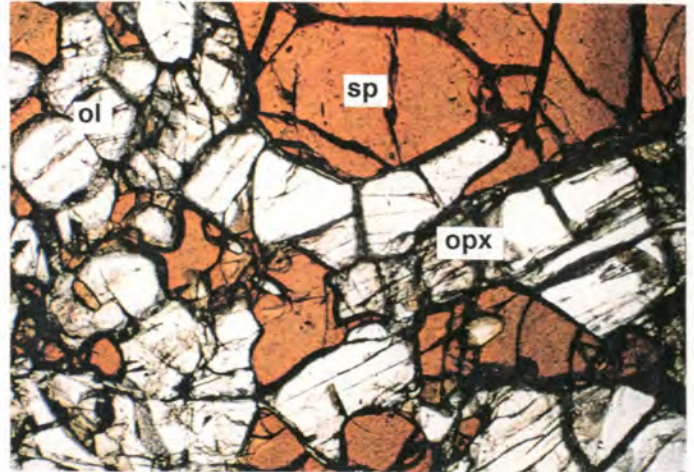


Plate 4: An Al-spinel (picotite)-bearing spinel lherzolite (JSL 157). Note the colour difference between this spinel (sp) and the spinel shown in Plate 3. The other dominant phases in this plate are orthopyroxene (opx) and olivine (ol). Field of view = 3.5mm wide. Plane polarised light.

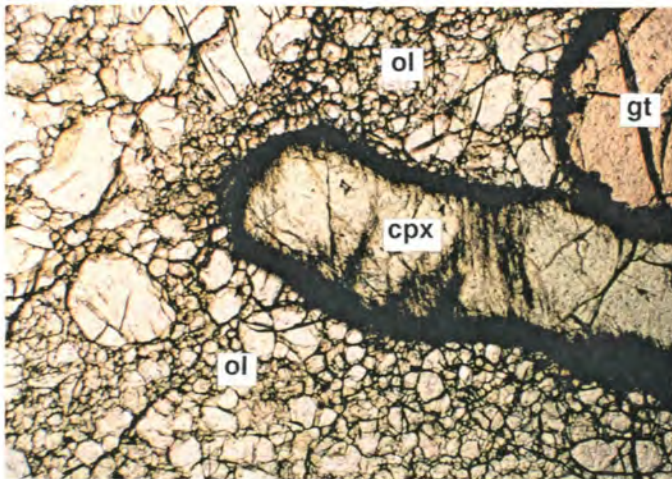


Plate 2: A deformed garnet lherzolite (JSL 280) showing the finely recrystallized, 'spongy' rim around a clinopyroxene porphyroclast (cpx). Major phases include garnet (gt) and olivine (ol). Field of view = 3.5mm wide. Plane polarised light.

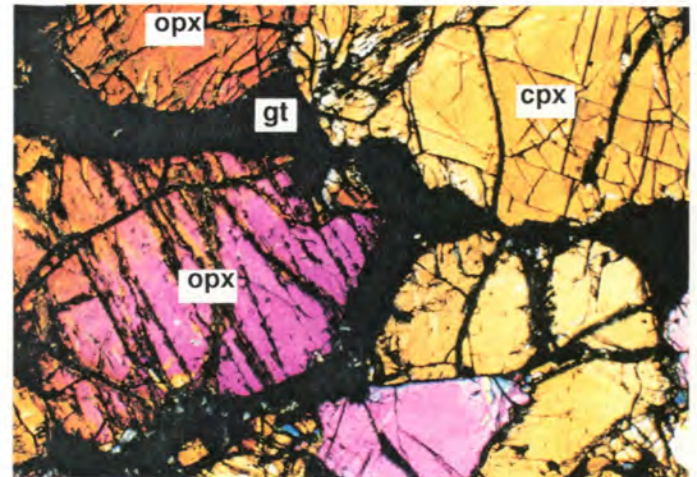


Plate 5: A graphite-bearing garnet websterite (JSL 202) showing a 'necklace' of exsolved garnet (gt) around orthopyroxene (opx). A clinopyroxene grain (cpx) is also shown. Field of view = 3.5mm wide. Crossed nicols.

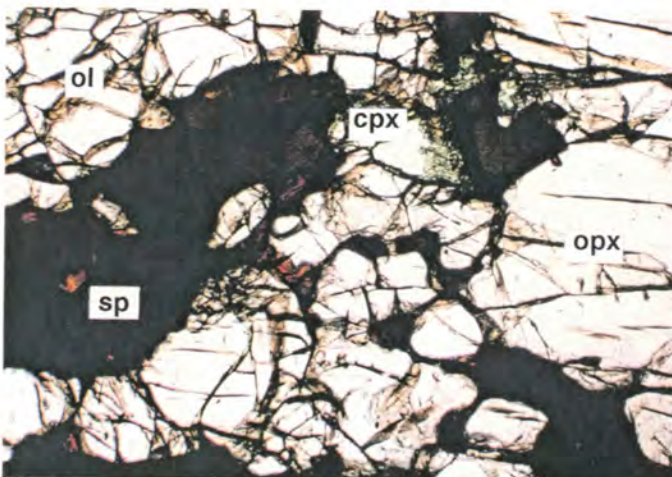


Plate 3: A spinel lherzolite (JSL 154) containing abundant dark brown Cr-Al spinel (sp). Other phases include pale green clinopyroxene (cpx), orthopyroxene (opx) and olivine (ol). Field of view = 3.5mm wide. Plane polarised light.

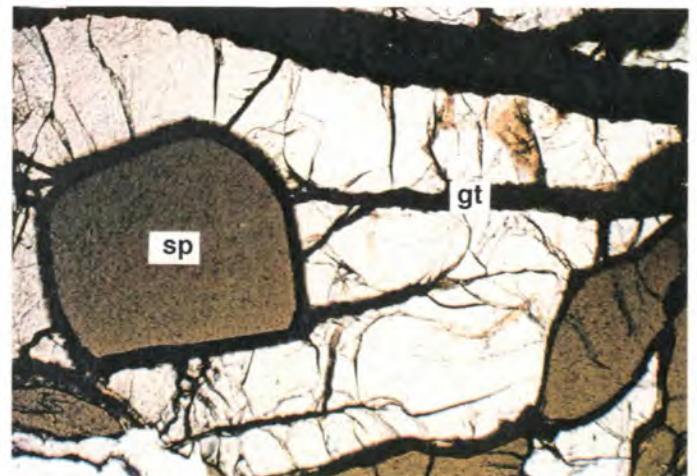


Plate 6: Primary garnet (gt) and spinel (sp) from alkremite JSL 250. No other phases are present in this rock. Note that the colour (i.e. the composition) of the spinel is different from spinel in Plates 3 & 4. Field of view = 3.5mm wide. Plane polarised light.

JSL 114 contains a garnet with a train of anhedral, rounded sulphide inclusions. Closer inspection revealed that these sulphides have crystallized along a healed fracture. The sulphides in this grain have been identified as pentlandite, millerite, pyrrhotite and chalcopyrite intergrown with pentlandite. Exact compositions have not been determined, but peridotitic sulphides, reported by Tsai et al. (1979), fall within the system Cu-Fe-Ni-S and form part of a solid solution.

Olivine neoblasts vary from 0.1 - 2mm in size, whereas porphyroclasts may be up to 8mm long (long axis). The shape of the olivine grains varies from anhedral with smoothly curving grain boundaries, to irregular in the case of the porphyroclastic xenoliths. The smoothly curving grain boundaries are associated with triple junctions and are common in the coarse-textured lherzolites, e.g. JSL 116. These grain boundaries are indicative of an equilibrated environment. Irregular olivine grains are restricted to porphyroclastic-textured lherzolites (JSL 112, 119, 126) and exhibit undulose extinction and deformation lamellae. The irregular boundaries may point to unattained equilibrium. Serpentine veinlets are always present, especially in olivine from coarse-textured nodules.

Primary clinopyroxene is represented as anhedral, bright green to colourless grains, varying from 1-8mm in size, with curving grain boundaries. Undulose extinction may occur, especially in the porphyroclastic-textured peridotites. Primary clinopyroxene grains often exhibit rims of finely recrystallized, "spongy" material. Similar material was observed by Ehrenberg (1982) in lherzolites from the Thumb in the U.S.A. This phenomenon is best observed in the porphyroclastic-textured lherzolites, e.g. JSL 112, 280 (Plate 2). Colourless, euhedral clinopyroxene grains (<1mm in size) have also been observed in the kelyphite rims of a few garnets.

Orthopyroxene grains are colourless, anhedral and vary in size from 1-6mm. Undulose extinction and irregular grain boundaries of orthopyroxene porphyroclasts are common in the porphyroclastic-textured lherzolites. A very thin recrystallized orthopyroxene rim may be present around these grains. Colourless, subhedral to euhedral orthopyroxene grains are present in the kelyphite rims of a few garnets.

2.2.1.2 Garnet harzburgites

Seven garnet harzburgites have been studied (Table 2.1). Five of these, JSL 113, 262, 266, 267 and 268, are subcalcic garnet harzburgites, while JSL 263 is porphyroclastic-textured and JSL 170 coarse-textured and calcic. All samples, except JSL 263, exhibit coarse equant textures. Their mineral chemistry will be discussed in a later section. Accessory minerals are mostly limited to secondary metasomatic phlogopite.

The garnets vary from a rounded to anhedral elongate shape, ranging in size from 2.5 to 6mm with an average of approximately 3.5mm. Colours vary from light pink (lherzolites) to deep purple (subcalcic harzburgites). No clustering of garnet can be observed. Apart from the colour difference in garnet, no other obvious distinctions between the normal and subcalcic harzburgites have been detected. Kelyphite rims are well developed in most cases with secondary phlogopite and brown euhedral spinels as the major alteration products.

The olivine grains are colourless and anhedral with straight to gently curving grain boundaries, indicating that the samples have equilibrated. Grain sizes vary from 1 to 10mm (average approximately 4mm). Undulose extinction is a common feature, as are serpentine-filled cracks and veinlets.

JSL 262 contains small (<0.3mm), colourless to brown subhedral clinopyroxenes. They are associated with serpentine and located in areas of alteration. The above features of the clinopyroxene are indicative of a secondary metasomatic origin.

The orthopyroxene grains are colourless and anhedral with a grain size ranging between 1.2 and 4.5mm (average approximately 3mm). Grain boundaries are once again straight to slightly curved, indicating that equilibrium conditions prevailed during crystallization. Undulose extinction is present, but varies in intensity. JSL 268 contains an orthopyroxene with undulating grain boundaries which may point to a small, localized area of disequilibrium.

JSL 170 contains discrete, anhedral Cr-spinel grains, varying from 0.3-0.6 mm in size. No evidence of metasomatism (i.e. phlogopite, rutile, ilmenite or clinopyroxene) is present and it is therefore uncertain whether the spinels are derived from the breakdown of garnet. A single discrete Cr-spinel grain is also present in JSL 113.

2.2.2 Lherzolites

Only one garnet- and phlogopite-free lherzolite, JSL 306, has been studied and its modal mineralogy is presented in Table 2.1. Owing to its general petrographic similarity to the garnet peridotites, a separate description is not warranted, and the reader is referred to Section 2.2.1.1. It should, however, be noted that some distinct petrographic differences with respect to orthopyroxene exist in this sample.

The orthopyroxene grains exhibit severe textural disequilibrium in the form of embayed and irregular boundaries, and they are associated with an intergrowth of fine-grained (<0.5 mm) olivine and clinopyroxene. The maximum grain size for olivine and orthopyroxene in this sample (≤ 7.5 mm) gives some indication of the small grain size of these intergrowths. Note that no phases indicative of metasomatism (i.e. phlogopite, ilmenite, rutile, etc.) are present, but that similar intergrowths of fine olivine and clinopyroxene have been observed in metasomatized peridotites (Chapter 3) from Letlhakane.

2.2.3 Spinel lherzolites

Six spinel lherzolites have been studied. Four samples (JSL 124, 153, 154 and 156) contain Cr-spinels, while JSL 157 and 158 contain an aluminous variety of spinel (picotite). The spinels display an irregular, anhedral shape and grain sizes vary from <0.6 - 3.5mm and textural relations point to a possible late origin for the spinels. These rocks are finer-grained (approximately 1mm) than other peridotites. The Cr-spinels display a deep red-brown colour in thin section, whereas picotite exhibits a nut-brown colour as shown in Plates 3 and 4. Primary metasomatic phlogopite and other secondary minerals are notably absent. The modal proportions of phases in these rocks differ, but all phlogopite-free, spinel-bearing rocks have been included in this section, because these rocks may have been formed by similar processes.

Textures vary from coarse to granuloblastic (Table 2.1). All the spinel lherzolites contain a few porphyroclasts. These porphyroclasts (<8 mm in size, approximately 3mm average) are composed of olivine, clinopyroxene and orthopyroxene. Most exhibit uneven grain boundaries and all show undulose extinction. Orthopyroxene porphyroclasts contain exsolution lamellae of clinopyroxene and vice versa, especially those in JSL 154, 157 and 158. JSL 157 contains a late-stage cross-cutting veinlet of serpentine, secondary metasomatic clinopyroxene and minor phlogopite. The spinels in contact with this veinlet have dark, altered rims of unknown composition.

The textures in the spinel lherzolites from Letlhakane differ considerably from those described by Boyd (1989) from the Kaapvaal craton (See Chapter 1, Section 1.4.1) from the Kaapvaal craton. The Letlhakane spinel lherzolites are considerably finer grained and the spinel occurs as discrete, anhedral grains, and not as symplectites. The modal proportion of spinel is also larger in the Letlhakane samples. The exsolution of clinopyroxene in orthopyroxene is, however, present in both cases. Possible origins of the spinel lherzolites, based on additional radiogenic isotope data, are discussed in Chapter 7, Section 7.4.5.

2.2.4 Dunites

Two dunites, JSL 166 and 167, have been studied. Both are coarse-grained, but JSL 167 contains primary metasomatic phlogopite (Table 3.1) and is therefore included in Chapter 3, Section 3.2.2, as a phlogopite peridotite. Olivine and orthopyroxene are the only primary minerals present in these xenoliths and undulose extinction and deformation lamellae are common features in minerals from both samples.

2.2.5 Pyroxenites

A total of 12 pyroxenites was studied, two of which (JSL 107 and 118) contain no garnet, while another 6 are metasomatized (Chapter 3, Section 3.2.4). All 6 non-metasomatized pyroxenites can be classified as garnet websterites and most of these are coarse-textured, only JSL 107 exhibiting a granuloblastic texture. JSL 118 contains a few mineral grains with undulating boundaries, indicating local disequilibrium.

There is a notable colour difference between garnets of the peridotites and websterites. Websteritic garnets vary from pale pink to colourless and from 1 to 7mm in size. Both rounded and irregular grains are observed. Kelyphite rims are well developed, but vary from sample to sample. The garnets in JSL 171 contain a rim of small recrystallized pyroxenes and subhedral to euhedral spinels. Secondary metasomatic phlogopite is also present.

Colourless to pale green clinopyroxene is present in all the websterites. The grains are anhedral to irregular and are commonly less than 5mm in size (< 1.5mm in the granuloblastic-textured sample). Crystallographically oriented, acicular inclusions of rutile(?) are common. Irregular grain boundaries are present in sample JSL 118, suggesting local disequilibrium. The clinopyroxene in JSL 171 exhibits undulose extinction and deformation lamellae.

Colourless, anhedral orthopyroxene (<6mm in size) showing straight to slightly curving grain boundaries is visible in all samples. Orthopyroxenes in JSL 118 also show undulating boundaries and deformational features.

JSL 202 is unique in that it is the only graphite-bearing garnet websterite present in the suite. The overall texture of the rock is coarse, bordering on porphyroclastic. Minor neoblast development is present around a few ortho- and clinopyroxene porphyroclasts (exhibiting undulose extinction). Grain boundaries of

all minerals are generally curved and embayed, indicating that equilibrium was not quite attained in this nodule. Orthopyroxene contains exsolution lamellae of clinopyroxene(?), while clinopyroxene contains oriented inclusions of rutile(?). Garnet is present in two textural forms. Exsolved garnet forms "necklaces" around several clinopyroxene and orthopyroxene grains (Plate 5), but no garnet lamellae within pyroxene could be detected. Garnet is also present as three coarse (3-5mm) grains. A single face of one of the garnets displays embayed contacts, suggesting local disequilibrium. The coarse garnets display small rutile(?) inclusions, oriented along crystallographic planes. These rutile inclusions are absent in the exsolved garnet. Graphite is present as rounded to tabular flakes, 0.4-3.5mm in size. A few of the tabular flakes are kinked. Garnet is always in close contact with the graphite, touching on at least one side. Two graphite flakes are embedded in ortho- and clinopyroxene respectively.

2.2.6 Alkremite

This rock type is represented by a single example (JSL 250). The rock is composed exclusively of colourless garnet and greenish-brown, primary spinel (Plate 6). No alteration products are present.

2.3 Mineral chemistry

Minerals were analysed using an electron probe microanalyzer. Analytical details are given in Appendix 1 and analyses are given in Appendix 3. All analyses represent the core of a mineral grain, unless stated otherwise. Samples containing zoned minerals are listed in Tables 2.2, 2.3 and 2.4 of this chapter, with selected core and rim analyses illustrating the zoning. Core-rim variations were frequently sought, but seldom found, indicating that most of the samples are homogeneous and equilibrated. Analytical uncertainty is mostly less than the symbol sizes used in the graphs, but where relevant, these uncertainties are noted. The methods of calculating detection limits and lower limits of determination can be found in Appendix 1. Compositional differences resulting in distinctions between and within different rock types in the plots are all larger than analytical uncertainty and thus considered to be real. The analytical value of a phase quoted in the text and illustrated on the plots represents an average of several analyses from each phase in the sample. This was done to avoid complete cluttering of the plots by single analyses. A key to the symbols used in the plots can be found in the back folder.

2.3.1 Olivine

The olivines are forsteritic with Mg-number ($100 \cdot \text{Mg}/(\text{Mg} + \text{Fe})$) varying from 89 (JSL 112) to 94 (JSL 266). It is shown in Chapters 2 & 3 that all three major peridotite types (i.e. coarse, deformed and modally metasomatized) as proposed by Harte (1983), are present at Letlhakane. With the aid of the olivine compositions, the coarse and deformed rock types may now be further subdivided. Harte (op. cit.) placed the boundary between Mg and Fe-rich peridotites at a Mg-number of 91. The coarse peridotites from Letlhakane all have olivine with Mg-numbers >91 and are therefore Mg-rich (Fig. 2.1). Conversely, the deformed peridotites are all Fe-rich with the exception of a deformed garnet harzburgite (Fig. 2.1). Fig. 2.2 compares the Mg-numbers of olivine from coarse and deformed lherzolites from Premier, northern-Lesotho, Frank Smith and Kimberley (Danchin, 1979) with those of Letlhakane in Fig. 2.1. The Letlhakane olivines exhibit a narrow Mg-number range, compared to other localities, except Kimberley. Mg-numbers of olivines in coarse-textured lherzolites are similar (90-94), irrespective of locality.

Olivines in the deformed lherzolite suites from some of the above localities (notably northern Lesotho and Frank Smith) exhibit variations of up to 6% forsterite between different samples, mostly towards Fe-rich compositions. The Fe-rich nature of some olivines is considered to be the result of diffusive metasomatic effects, with fluids possibly derived from metasomatism of the Cr-poor megacryst suite (Harte and Gurney, 1981; Hops et al., 1989), and is thus an example of cryptic/diffusive metasomatism. This also serves to illustrate the highly variable nature of metasomatic fluids between various parts of the asthenosphere at different localities. Olivines from coarse lherzolites, harzburgites and spinel peridotites are the most forsteritic (i.e. primitive) with a Mg-number varying between 91 and 94, followed by the deformed lherzolites, indicating the progressively more fertile nature of this rock. The dunite contains olivine exhibiting a Mg-number of 91.7.

NiO-contents of olivine vary between 0.26 wt% (JSL 140) and 0.44 wt% (JSL 126). CaO values range between the detection limit of approximately 0.01 wt% (JSL 170) and 0.04 wt% (JSL 112). Shee (1978) reported that wehrlitic olivines at Orapa contain higher MnO-values than lherzolitic olivines. This study indicates that MnO also correlates with textures. Deformed peridotites from Letlhakane contain slightly higher MnO-values (generally >0.10 wt.%) than undeformed rocks.

2.3.2 Orthopyroxene

Mg-numbers of orthopyroxene vary between 82.6 (JSL 107) and 95 (JSL 266). Al_2O_3 -contents are commonly <1 wt%, except in the case of a websterite (JSL 118, 3.6-4.0 wt%) and a spinel lherzolite (JSL 124, 1.9-2.7 wt%). TiO_2 -contents are elevated from a general value of <0.1 wt% to 0.14-0.18 wt% in

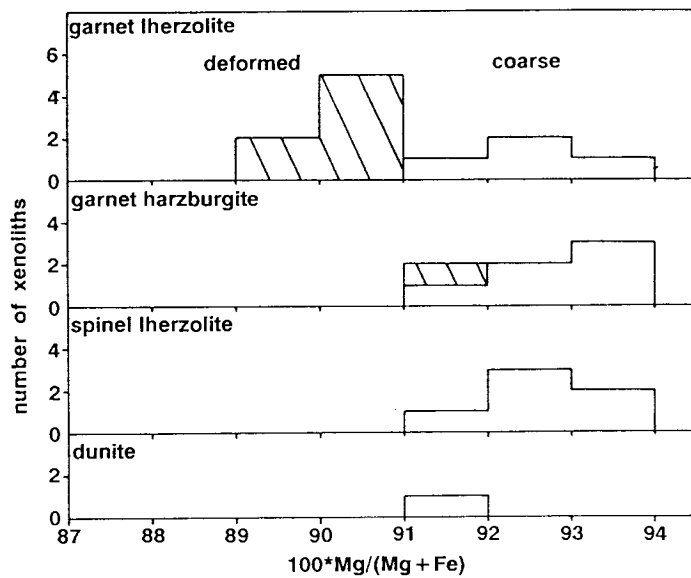


Fig. 2.1 Histograms of the Mg-number of olivine in garnet lherzolite, garnet harzburgite, spinel lherzolite and dunite: all from Letlhakane.

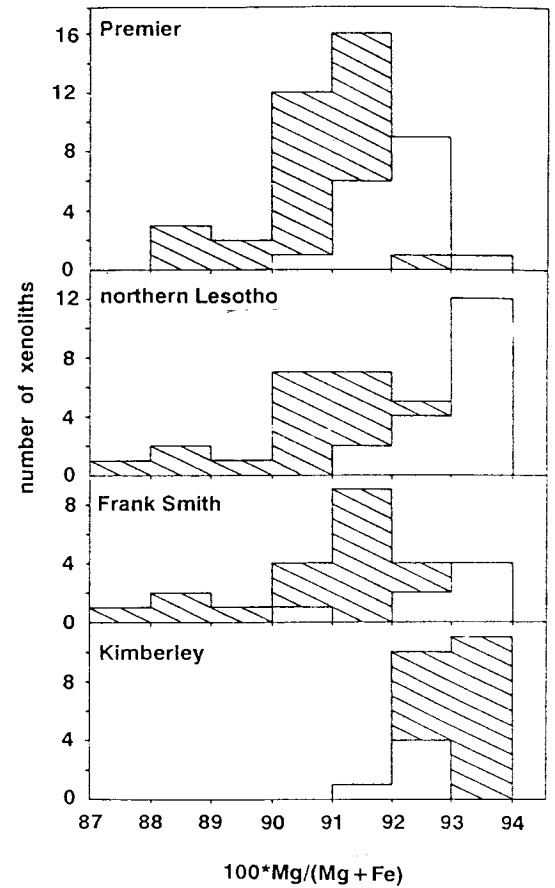


Fig. 2.2 Histograms of the Mg-number of olivines from coarse-textured and deformed lherzolite from Premier, northern Lesotho, Frank Smith and Kimberley (modified from Danchin, 1979). Shading as in Fig. 2.1.

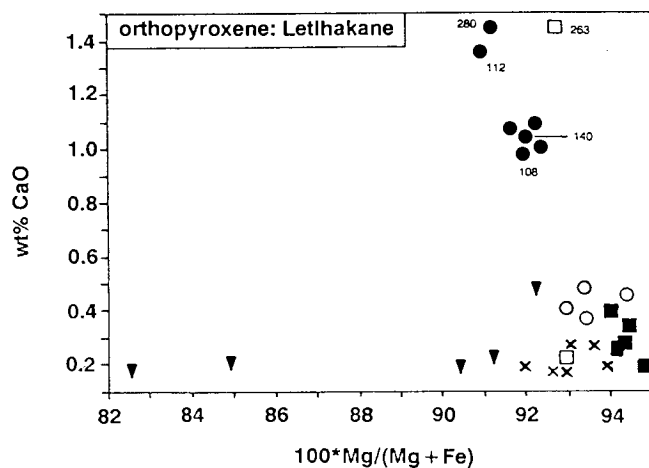


Fig. 2.3 Wt% CaO vs. Mg-number of orthopyroxenes from peridotites and websterites. Note the two groups of orthopyroxene in the deformed lherzolites and the wide range of Mg-number among the websterites.

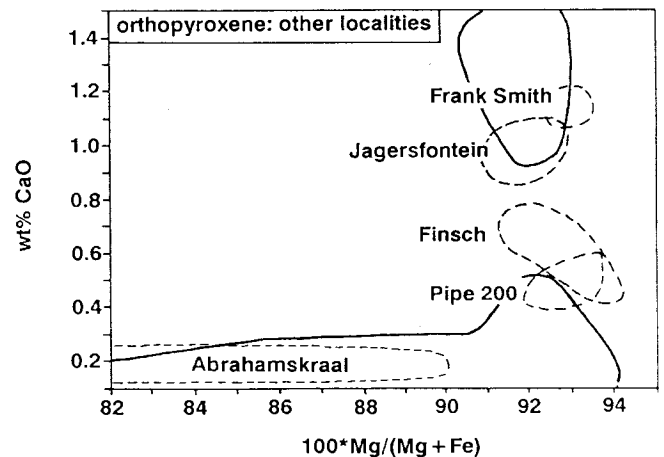


Fig. 2.4 Wt% CaO vs. Mg-number of orthopyroxene from the Letlhakane deformed peridotites (top) and websterites (bottom) in comparison with data from other localities. Data from other localities taken from Boyd (1974), Hops et al. (1989), Skinner (1989), Carswell et al. (1979) and Nowicky (1990).

orthopyroxene from some of the deformed peridotites. Cr_2O_3 -contents vary between a detection limit of 0.04 (JSL 266) and 0.5 wt% (JSL 113). The Ca-number ($100 \cdot \text{Ca}/(\text{Ca} + \text{Mg})$) shows little change. CaO-contents of orthopyroxene in coarse peridotites (approximately 0.35 wt%) differ from those of deformed peridotites (> 1 wt%) (Fig. 2.3). Na_2O follows a similar trend, although the differences are smaller.

Orthopyroxenes in deformed peridotites from Letlhakane may be divided into two groups, based on their CaO-content (Fig. 2.3). Orthopyroxenes from the majority of deformed peridotites exhibit CaO-values ranging from 1-1.1 wt%. The second group, with more than 1.35 wt% CaO in orthopyroxene, consists of two garnet lherzolites (JSL 112 and JSL 280) and a garnet harzburgite. These elevated CaO-levels are found in the orthopyroxene porphyroclasts and not in the neoblasts, as is the case in some Jagersfontein samples (Hops et al., 1989). The Mg-number decreases with an increase in CaO in the orthopyroxene of both coarse and deformed lherzolites (Fig. 2.3), albeit slightly. Al_2O_3 in orthopyroxene increases sympathetically with the CaO (not shown). The two groups of deformed peridotites, identified on the basis of CaO, also exhibit variation in Al_2O_3 (1.04 wt% vs. 0.57-0.89 wt%).

A comparison of orthopyroxene compositions in the Letlhakane mantle suite with those from other localities on the Kaapvaal craton indicates that orthopyroxene from coarse and deformed lherzolites is of largely similar composition. Minor inter-pipe differences do, however, occur. Deformed lherzolites from the Frank Smith and Jagersfontein kimberlites correspond to the low-Ca group from Letlhakane (Fig. 2.4). The orthopyroxenes in the Abrahamskraal garnet websterites show a considerable range in Mg-number (down to 78) (Fig. 2.4).

Orthopyroxenes are unzoned, with the exception of the following samples: JSL 108, 113, 116, 262 and 266, three of which are subcalcic garnet harzburgites. Representative core and rim analyses of each are shown in Table 2.2. Table 2.2 also illustrates that FeO and MgO are the most variable oxides in these samples. The change in concentration of MgO and FeO is unrelated, i.e. there is no systematic increase of FeO with decreasing MgO. An orthopyroxene grain in a subcalcic harzburgite (JSL 266) is substantially zoned in TiO_2 , Na_2O , FeO, MgO and CaO, while orthopyroxenes from JSL 113 and 262 exhibit slight zonation in their Cr_2O_3 -content.

2.3.3 Clinopyroxene

The Mg-numbers of clinopyroxene range between 90 (JSL 112) and 95 (JSL 118, 124). Ca-numbers ($100 \cdot \text{Ca}/(\text{Ca} + \text{Mg})$) vary from 34 (JSL 280) to 52 (JSL 118). The classification of Harte (1983) indicates that the deformed Letlhakane peridotites are all "hot", i.e. $100 \cdot \text{Ca}/(\text{Ca} + \text{Mg}) < 43$. Na_2O -contents of clinopyroxene from the peridotites and pyroxenites vary between 0.5-4.5 wt%.

Table 2.2: Zoning in orthopyroxene

Sample	JSL 108		JSL 113		JSL 116		JSL 262		JSL266	
	core	rim	core	rim	core	rim	core	rim	core	rim
SiO ₂	58.27	57.38	58.05	58.01	58.36	57.27	57.82	57.75	57.59	56.93
TiO ₂	0.16	0.17	0.01	0.03	0.00	0.00	0.01	0.02	0.00	0.34
Al ₂ O ₃	0.75	0.72	0.66	0.75	0.53	0.58	0.50	0.57	0.59	0.79
Cr ₂ O ₃	0.39	0.37	0.45	0.50	0.24	0.25	0.32	0.37	0.37	0.39
FeO	5.06	5.32	4.04	4.16	4.59	4.74	4.03	3.85	3.57	5.46
MnO	0.06	0.11	0.10	0.09	0.11	0.12	0.14	0.13	0.06	0.11
NiO	0.12	0.11	0.13	0.10	0.12	0.11	0.08	0.05	0.08	0.07
MgO	33.85	34.18	36.03	36.01	36.34	35.31	36.95	36.75	37.23	35.03
CaO	1.10	1.09	0.27	0.37	0.49	0.51	0.37	0.39	0.17	0.82
Na ₂ O	0.29	0.29	0.20	0.22	0.10	0.14	0.13	0.12	0.03	0.19
Total	100.04	99.73	99.93	100.23	100.88	99.03	100.34	100.00	99.70	100.13

Table 2.3: Zoning in clinopyroxene

Sample	JSL 108		JSL 112		JSL 116		JSL 124	
	core	rim	core	rim	core	rim	core	rim
SiO ₂	54.45	53.73	55.11	53.49	52.97	53.88	53.07	53.28
TiO ₂	0.29	0.49	0.21	0.46	0.61	0.48	0.34	0.36
Al ₂ O ₃	1.99	2.04	2.14	2.33	2.54	0.83	6.03	5.89
Cr ₂ O ₃	1.48	1.57	0.60	0.82	1.39	2.10	1.79	1.57
FeO	3.41	3.30	4.02	3.50	3.52	2.99	1.59	1.41
MnO	0.13	0.12	0.05	0.07	0.16	0.17	0.05	0.03
NiO	0.03	0.05	0.09	0.00	0.03	0.01	0.00	0.03
MgO	19.36	18.49	20.51	18.12	17.23	18.11	14.20	14.02
CaO	17.04	19.18	15.46	19.36	19.92	20.39	19.94	20.20
Na ₂ O	1.85	1.43	1.50	1.27	1.33	1.37	2.93	2.93
Total	100.03	100.38	99.69	99.42	99.70	100.33	99.97	99.72

Zoning in clinopyroxene (continued)

Sample	JSL 126		JSL 156		JSL 171	
	core	rim	core	rim	core	rim
SiO ₂	54.86	50.60	54.17	54.00	54.48	53.88
TiO ₂	0.07	1.27	0.06	0.08	0.17	0.18
Al ₂ O ₃	0.98	3.97	4.55	3.33	2.61	2.57
Cr ₂ O ₃	0.52	0.66	2.28	2.10	0.46	0.47
FeO	2.82	3.15	1.42	1.90	2.05	2.08
MnO	0.14	0.04	0.05	0.06	0.04	0.09
NiO	0.03	0.02	0.08	0.04	0.03	0.01
MgO	19.85	15.76	14.02	14.87	16.32	16.51
CaO	20.45	23.96	19.46	20.29	22.84	22.75
Na ₂ O	0.76	0.67	3.34	2.65	1.52	1.48
Total	100.46	100.10	99.43	99.32	100.54	100.04

Table 2.4: Zoning in garnet

Sample	JSL 108		JSL 112		JSL 113		JSL 262		JSL 266	
	core	rim	core	rim	core	rim	core	rim	core	rim
SiO ₂	41.88	41.69	42.43	42.45	41.62	41.27	41.28	41.05	41.34	41.39
TiO ₂	0.93	0.97	0.71	0.81	0.00	0.11	0.03	0.05	0.03	0.00
Al ₂ O ₃	19.14	18.47	20.54	20.46	17.11	16.85	18.65	18.51	15.90	16.33
Cr ₂ O ₃	4.37	4.71	2.60	2.44	9.37	9.02	6.82	7.06	10.99	9.96
FeO	7.14	7.10	7.24	7.24	5.91	5.83	6.78	6.65	5.34	5.46
MnO	0.33	0.27	0.32	0.27	0.30	0.25	0.41	0.38	0.32	0.30
NiO	0.01	0.00	0.00	0.02	0.03	0.02	0.00	0.00	0.04	0.00
MgO	21.71	21.56	22.42	22.27	23.33	22.55	21.44	20.93	23.51	24.07
CaO	4.98	5.08	4.48	4.36	2.24	3.54	4.28	4.94	2.42	2.27
Na ₂ O	0.08	0.09	0.08	0.09	0.04	0.07	0.03	0.04	0.01	0.01
Total	100.56	99.96	100.82	100.42	99.95	99.50	99.73	99.60	99.90	99.79

Clinopyroxene compositions from Letlhakane are summarized in Figs. 2.5 and 2.7-2.10. The two groups of deformed peridotite defined on the basis of CaO in orthopyroxene - see previous section and Fig. 2.3 - are less noticeable, but still evident in Fig. 2.5. Note that samples containing high-CaO orthopyroxene now contain low-CaO clinopyroxene (Compare Figs. 2.3 and 2.5). JSL 263 is not shown in Fig. 2.5 since it does not contain any clinopyroxene. Coarse peridotitic clinopyroxenes from Pipe 200 (Carswell et al., 1979) are enriched in Cr_2O_3 (Fig. 2.6) when compared to similar clinopyroxene from Finsch and Letlhakane. This is most likely to be owing to the inclusion of metasomatized peridotites by Carswell et al. (1979). They discussed textures similar to those observed in metasomatised peridotites from Letlhakane (Chapter 3). The deformed lherzolites from Letlhakane exhibit a regular increase in Na_2O (not shown), TiO_2 (Fig. 2.8), FeO (Fig. 2.7) and Al_2O_3 (not shown), against decreasing $100 \cdot \text{Ca}/(\text{Ca} + \text{Mg})$. These trends are less apparent in coarse lherzolites, while spinel peridotites and websterites exhibit a large range of variation with regard to some of these oxides at almost similar $100 \cdot \text{Ca}/(\text{Ca} + \text{Mg})$ (e.g. TiO_2 , Fig. 2.8).

Zoned clinopyroxene is present in a few of the samples, especially with respect to TiO_2 , Al_2O_3 , CaO , MgO and, to a lesser extent, Na_2O . Samples exhibiting zoning in one or all of the above elements include: JSL 108, 112, 116, 124, 126, 156 and 171. Selected core-rim analyses are shown in Table 2.3. CaO and MgO zonation exhibit a consistent relationship of increasing CaO with decreasing MgO in some of the zoned clinopyroxenes, (e.g. samples JSL 108, 112 and 126), but in others CaO-MgO changes are again variable. Zonation of clinopyroxene is not restricted to any rock type in particular, but zoning in clinopyroxene may be more pronounced than in orthopyroxene.

In addition to the distinction between clinopyroxene from coarse and deformed peridotite, it is also possible to distinguish clinopyroxene from peridotite as opposed to pyroxenite groups (Figs. 2.9 & 2.10). Primary clinopyroxenes from the peridotite suite (including coarse and deformed lherzolites, but excluding the spinel lherzolites) are characterized by a wide range in Cr_2O_3 (Figs. 2.5, 2.9 and 2.10) and low Al_2O_3 (Fig. 2.9), in comparison with the websteritic clinopyroxene. Websteritic clinopyroxenes are characterized by lower Cr_2O_3 -contents when compared to peridotitic clinopyroxenes, but have highly variable Al_2O_3 -contents, up to 6.5 wt% Al_2O_3 . Clinopyroxenes from spinel lherzolites may be distinguished from those in other peridotites by a higher proportion of Al_2O_3 (3-6.5 wt% - Fig. 2.9). The peridotite suite as a whole (coarse, deformed and spinel peridotites) exhibits a positive correlation of Na_2O vs. Cr_2O_3 (Fig. 2.10), when compared to the almost constant Cr_2O_3 in the websteritic clinopyroxenes. The use of Cr_2O_3 in clinopyroxene as a discriminant between various rock types will be discussed in detail in Chapter 3, Section 3.4.2.

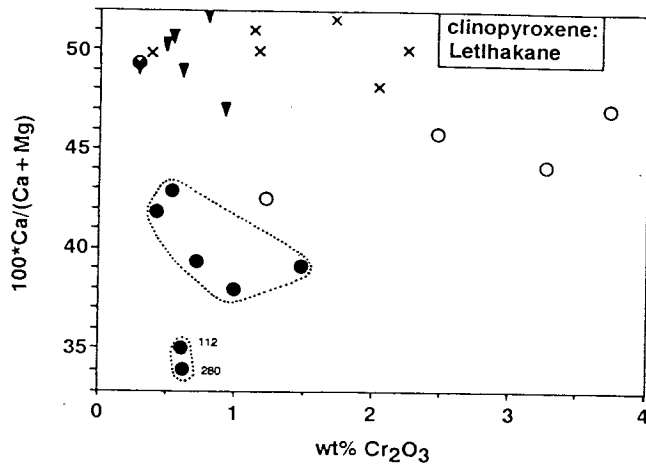


Fig. 2.5 $100 \cdot \text{Ca}/(\text{Ca} + \text{Mg})$ vs. $\text{wt}\% \text{Cr}_2\text{O}_3$ in clinopyroxene from peridotites and websterites. Dotted line encloses two groups of deformed Iherzolite, defined on the basis of CaO in orthopyroxene. Those with high-CaO orthopyroxene (JSL 112 and JSL 280) contain low-CaO clinopyroxene.

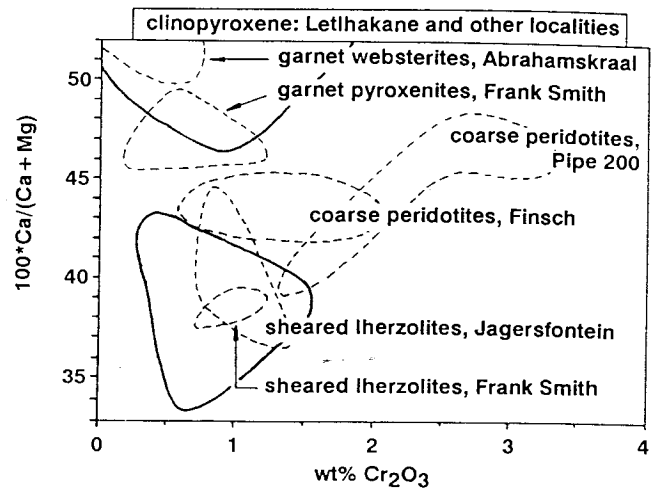


Fig. 2.6 $100 \cdot \text{Ca}/(\text{Ca} + \text{Mg})$ vs. $\text{wt}\% \text{Cr}_2\text{O}_3$ showing peridotitic and websteritic clinopyroxene. Bold lines represent compositional fields of Letlhakane websterites (top) and deformed Iherzolites (bottom). Other data taken from Nowicky (1990), Boyd (1974), Skinner (1989), Hops et al. (1989) and Carswell et al. (1979).

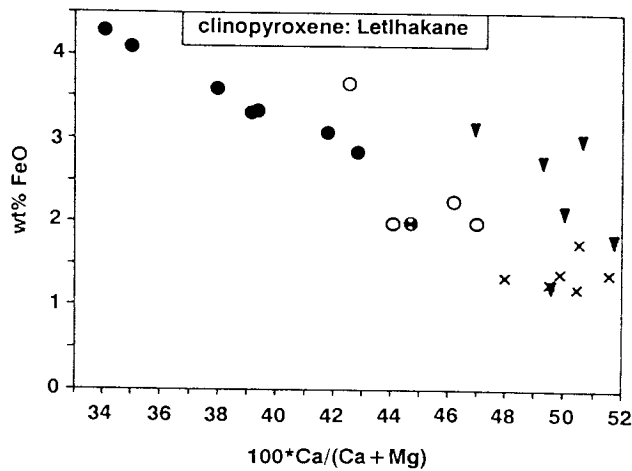


Fig. 2.7 $\text{wt}\% \text{FeO}$ vs. $100 \cdot \text{Ca}/(\text{Ca} + \text{Mg})$ in clinopyroxene. Note the well-developed negative correlation for the deformed Iherzolites in comparison with other rock types.

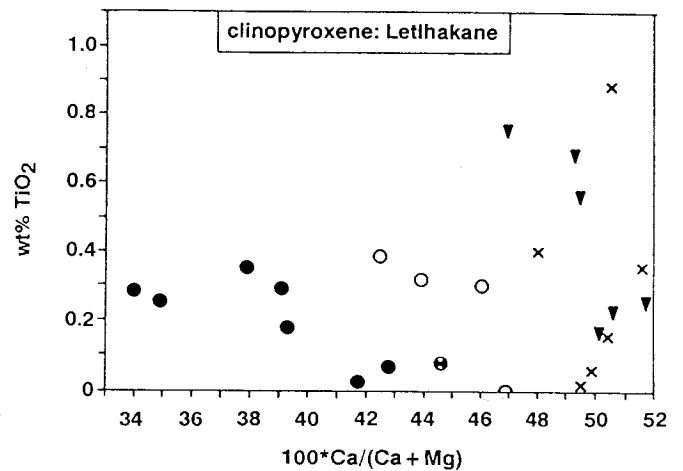


Fig. 2.8 $\text{wt}\% \text{TiO}_2$ vs. $100 \cdot \text{Ca}/(\text{Ca} + \text{Mg})$ for clinopyroxene in peridotites and websterites. Note the large variation in $100 \cdot \text{Ca}/(\text{Ca} + \text{Mg})$ of clinopyroxenes in Iherzolites, when compared to those in websterites and spinel peridotites.

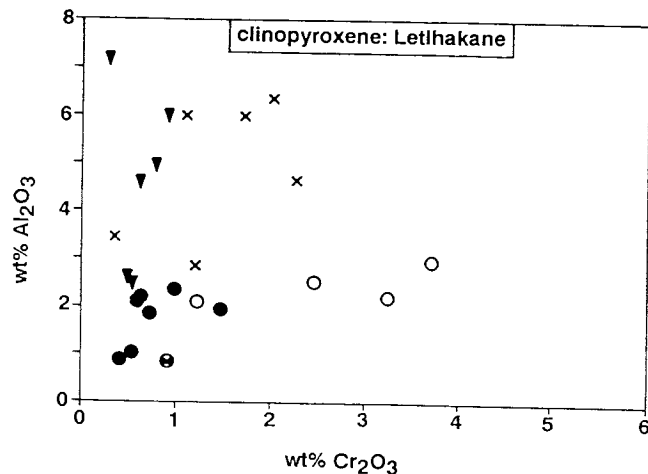


Fig. 2.9 $\text{wt}\% \text{Al}_2\text{O}_3$ vs. $\text{wt}\% \text{Cr}_2\text{O}_3$ in clinopyroxene. Clinopyroxene in websterites and spinel peridotites is distinguished from that in Iherzolites by the higher Al_2O_3 -content of clinopyroxene in the former.

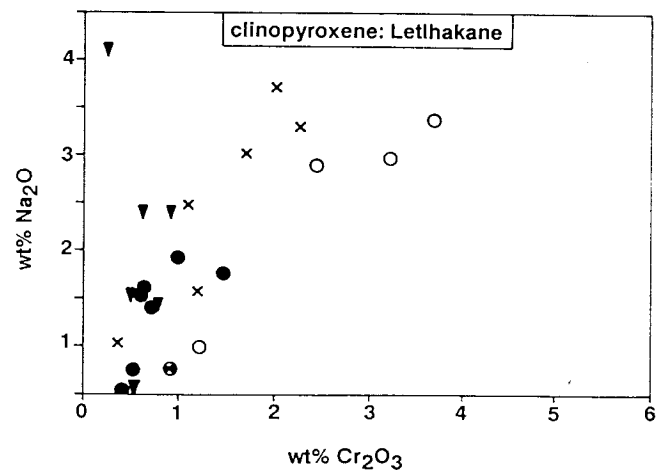


Fig. 2.10 $\text{wt}\% \text{Na}_2\text{O}$ vs. $\text{wt}\% \text{Cr}_2\text{O}_3$ in clinopyroxene. Note the positive correlation in the peridotites and the more constant Cr_2O_3 -levels in the websterites.

2.3.4 Garnet

Four major garnet types have been identified in the Letlhakane peridotite-pyroxenite suite. The common Cr-pyrope is most abundant and is recognized by its high Cr_2O_3 (>4 wt%) and MgO (>20 wt%) and low TiO_2 (<0.1 wt%) content. The Cr-pyrope garnets in JSL 170 contain higher MnO-values (approximately 0.48 wt%). Ti-pyrope garnets represent the second largest group of garnets. They are recognized by their much higher TiO_2 -content (> 0.80 wt%). The Ti-pyropes are restricted to the deformed peridotites. The third group is the low-Ca Cr-pyropes, a small but important group, which is restricted to the subcalcic harzburgites. They are identified by high Cr_2O_3 (5-11 wt%) and low CaO contents. The last group is composed of almandine pyropes, characterized by a slightly higher FeO-content of between 9 and 11 wt%. This group is restricted to the websterites.

Fig. 2.11 represents a plot of wt% Cr_2O_3 vs. wt% CaO, employed by Gurney (1984) as a means of distinguishing garnets from subcalcic garnet harzburgites, other peridotites and eclogites. He used a Cr_2O_3 -content of 2 wt% as an arbitrary division between peridotitic garnets (>2 wt% Cr_2O_3) and eclogitic garnets (<2 wt% Cr_2O_3). Fig. 2.11 illustrates an inclined 85% line with a positive slope, and another horizontal 85% line at 4 wt% Cr_2O_3 , defining a high- Cr_2O_3 , low-CaO field. Gurney (1984) placed these lines so that 85% of the high-Cr garnets included in diamonds from Finsch (Shee et al., 1982) plotted within this field, separate from the lherzolite trend. The lines were therefore chosen in such a way that peridotitic and eclogitic garnets from non-diamondiferous kimberlites were excluded from this field. The lherzolite trend was identified by Sobolev (1977) and represents Ca-saturated garnets (i.e. garnets which have crystallized in the presence of clinopyroxene) plotting to the right of, and along, the inclined 85% line. Ca-oversaturated and Ca-undersaturated garnets are equivalent to the G9 and G10 garnets respectively in the classification scheme of Dawson and Stephens (1975).

Pyroxenitic garnets from Letlhakane are characterized by low Cr_2O_3 -contents (<1.5 wt%), while lherzolitic garnets occupy intermediate Cr_2O_3 -levels as shown in Fig. 2.11. The single alkemite contains garnet with approximately 1 wt% Cr_2O_3 . The CaO-contents of the harzburgitic garnets are highly variable (approximately 2-6 wt%, Fig. 2.11), more so than the other peridotites. Fig. 2.12 shows that most garnets of the Letlhakane peridotite-pyroxenite suite contain similar low amounts of TiO_2 , except for some of the deformed lherzolites. Four deformed lherzolites contain garnets with up to 1 wt% TiO_2 (Fig. 2.12). All garnets in the high-Ti deformed lherzolites exhibit Ti-rich cores. These differences are therefore real and are not the result of the accidental analysis of a Ti-rich garnet rim.

Garnets are mostly unzoned but, as in the case of orthopyroxene, a few exceptions occur. These include garnets in JSL 108, 112, 113, 262 and 266. Representative core-rim analyses are included in Table 2.4. JSL 112 and 113 exhibit core-to-rim increases in TiO_2 and Na_2O . Garnets from JSL 108 and 266 exhibit

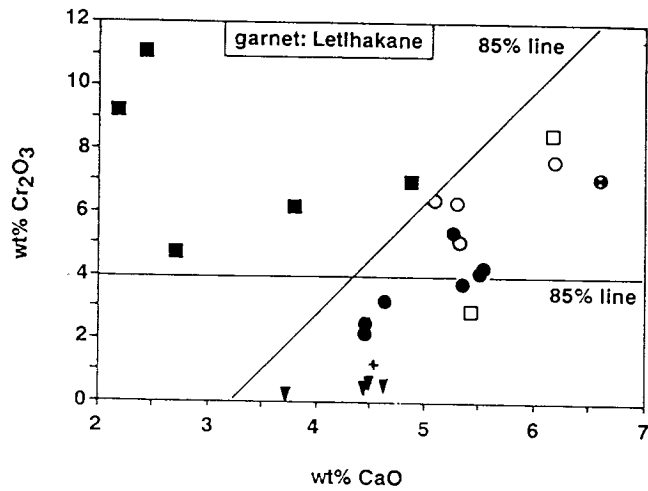


Fig. 2.11 Wt% Cr_2O_3 vs. wt% CaO in garnet. Note the small variation in Cr_2O_3 -content of garnets from the websterites, when compared to, for example, the harzburgites. The purpose of the 85% lines is explained in Section 2.3.4.

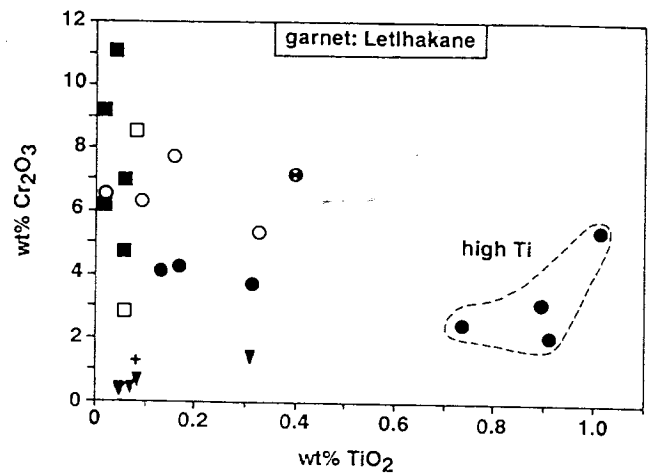


Fig. 2.12 Wt% Cr_2O_3 vs. wt% TiO_2 in garnet. On the basis of composition, the deformed lherzolites may be divided into high- and low-Ti groups.

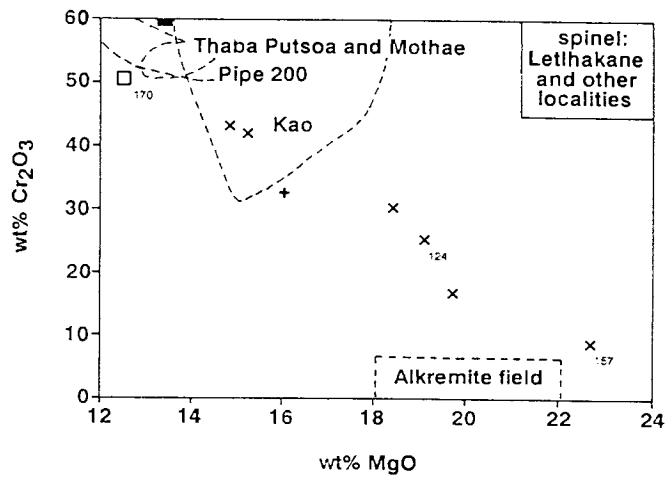


Fig. 2.13 Wt% Cr_2O_3 vs. wt% MgO in spinels. Note the pronounced negative correlation for the spinels. The single alkremite contains considerably more Cr_2O_3 than those shown from other localities (taken from Nixon et al., 1978). Note the composition of the spinel in the harzburgite (JSL 170) when compared to that of the spinel lherzolites. Variations in the composition of chromite from other lherzolites are also shown. Data were taken from Nixon and Boyd (1973b), Carswell et al. (1979) and MacGregor (1979).

systematic zonation in Cr_2O_3 and Al_2O_3 . Garnets in JSL 108, 113, 262 and 266 also exhibit variance with respect to CaO and MgO. This is most probably because a complete solid solution exists between the Ca (grossular) and Mg (pyrope) garnet endmembers. Both elements are present in the form of divalent cations, thereby facilitating substitution. Note that the orthopyroxenes in JSL 108, 113, 262 and 266 also exhibit zoning, as discussed previously in Section 2.3.2.

2.3.5 Spinel

The spinels from the six spinel lherzolites may be divided into two groups on the basis of spinel petrography (see Section 2.2.3). The chemical compositions confirm this subdivision. The deep red-brown spinels are Cr-Al-spinels. Cr_2O_3 varies between 30 and 43 wt% and Al_2O_3 ranges from 25 to 39 wt%. There is considerable variability between samples (see Fig. 2.13). The spinel may contain significant TiO_2 (0.10-0.15 wt%). JSL 157 contains highly aluminous Cr-bearing spinel (picotite) in which Al_2O_3 -contents vary from 57-60 wt% and Cr_2O_3 ranges between 9 and 17 wt%. It appears that samples with a low modal proportion of olivine (e.g. JSL 124 and JSL 157) contain the smallest amount of Cr_2O_3 in their spinels, although overlap exists.

Fig. 2.13 indicates that spinel with the highest Cr_2O_3 -content is found in a subcalcic garnet harzburgite, closely followed by spinel in a calcic harzburgite (JSL 170). Spinel from JSL 250, a garnet-spinel xenolith, is also shown in Fig. 2.13. This sample is thought to be an alkremite, although the spinel composition in this rock is substantially more Cr-rich than in the alkremites found at Orapa (see Fig. 2.13). Peridotitic spinel compositions from Pipe 200 (Carswell et al., 1979), Kao (MacGregor, 1979) and Thaba Putsoa and Mothae (Nixon and Boyd, 1973a) are included in Fig. 2.13 for comparison. The high Cr_2O_3 -content of these spinels is notable.

2.4 Discussion

The Letlhakane kimberlite pipes have produced samples of a wide selection of peridotitic material, ranging from fertile garnet lherzolite to depleted dunite. This is in contrast to the Orapa kimberlite pipe, barely 40 km to the northwest, where only eclogites have been discovered thus far (Shee, 1978, and M. Field, pers. comm., 1993). The presence of peridotitic material at Orapa was inferred by Shee (1978) from a study of garnet grains found in the concentrate, but actual xenoliths have not been found. All primary mineral phases at Letlhakane, (i.e. olivine, clinopyroxene, orthopyroxene and garnet) reveal distinct chemical

differences depending on whether they are from coarse lherzolites, deformed lherzolites or pyroxenites. The author will attempt to interpret the results of the petrographic observations and mineral chemistry in the following sections of the discussion.

2.4.1 High-Ti garnets

The presence of Ti-rich garnets in deformed lherzolites (Fig. 2.12, Section 2.3.4) is thought to result from metasomatic activity. This interpretation has been offered to explain Ti-rich garnets from other localities on the Kaapvaal craton, e.g. Jagersfontein (Hops et al., 1989), Lesotho (Boyd and Nixon, 1975, and Cox et al., 1973), Premier (Danchin, 1979), as well as in other continents, e.g. the Thumb, U.S.A. (Ehrenberg, 1982). This feature, therefore, appears to occur worldwide and not to be restricted to any single craton. The higher TiO_2 in garnet is associated with higher Na_2O and FeO (less obvious) and is also observed in the coexisting orthopyroxene and clinopyroxene. Gurney and Harte (1980) postulated that fluids responsible for this type of metasomatism are derived during formation of the Cr-poor megacryst suite (Cr-poor megacrysts from Letlhakane are described in Chapter 5, Section 5.2). A type of diffusive metasomatism, similar to that proposed by Dawson (1980), is envisaged to explain the higher TiO_2 -values in the TiO_2 -rich garnet group mentioned above.

2.4.2 CaO-rich orthopyroxenes

Two deformed peridotites (JSL 112 and 280) and a deformed harzburgite (JSL 263) contain orthopyroxene with elevated CaO-levels (> 1.3 wt%), while the remainder contain 0.95-1.1 wt% CaO (Fig. 2.3, Section 2.3.2). This feature appears to be unrelated to the processes causing TiO_2 -enrichment in garnets, since only half the samples containing high- TiO_2 garnet exhibit higher CaO in their co-existing orthopyroxenes (Fig. 2.3).

Attempts were made to determine whether the high-Ca orthopyroxenes are in equilibrium with the clinopyroxenes in each respective sample, by using the 2-pyroxene geothermometer of Lindsley (1983). However, this thermometer proved to be unsuitable owing to: 1) the great depth at which these rocks were formed, 2) a limited calibration range, and 3) the effect of non-quadrilateral components on temperature estimation. Geothermobarometric studies (Chapter 6, Table 6.1 and Fig. 6.1), have shown that these xenoliths, especially JSL 112 and 280, plot above the continental geotherm, irrespective of the thermometer/barometer combination. It is proposed that the high CaO content in these orthopyroxenes,

compared to orthopyroxenes from other deformed lherzolites, may partly be owing to the lack of equilibration. The high-CaO orthopyroxenes may also represent one end-member of a continuous range in orthopyroxene composition.

2.4.3 Websterites

Garnet websterites from Letlhakane are mineralogically distinct from lherzolites and harzburgites, but show some overlap with spinel peridotite compositions. The clinopyroxenes in the websterites exhibit the highest Ca-numbers and TiO_2 -contents of all the clinopyroxenes in the peridotite-pyroxenite suite. Low CaO-contents and variable $\text{Mg}/(\text{Mg} + \text{Fe})$ is a characteristic feature of orthopyroxenes in the websterites.

The orthopyroxenes in JSL 202 and 107 contain more than twice the amount of FeO found in orthopyroxene in the rest of the suite. However, this high FeO is not associated with covariance of any of the other elements in orthopyroxene, nor in the composition of other primary mineral phases. Modal metasomatism is considered an unlikely cause, since no phlogopite or any other evidence of metasomatism could be found in these samples. No convincing explanation of this enrichment can be offered.

2.4.4 Mineral zoning

Nixon and Boyd (1973 a,b) were among the first to report zoned minerals, especially garnet, in deformed lherzolites from the kimberlites in northern Lesotho. Several further studies (Smith and Ehrenberg, 1984; Smith and Boyd, 1987,1989) illustrated that zoning is a common feature in deformed peridotites, but is less common in coarse peridotites.

Zoning is present in a few samples from Letlhakane, but is not confined to any particular rock type. As noted earlier, olivine, orthopyroxene and garnet are, with rare exceptions, unzoned. The compositional homogeneity of orthopyroxene and olivine was previously noted by Smith and Boyd (1987, 1989) and Ehrenberg (1982), and is therefore not unique to Letlhakane. Several authors (Ehrenberg, 1982; Smith and Ehrenberg 1984; Smith and Boyd 1987, 1989) have linked the increase of TiO_2 , Na_2O and FeO in garnet rims to metasomatism, rather than to temperature and pressure changes. Bishop et al. (1978) found that Na is preferentially partitioned into clinopyroxene over garnet at lower temperatures. The garnet rims in JSL 113 (Table 2.4, Section 2.3.4) should therefore exhibit lower and not higher levels of Na_2O if the zoning feature was of primary origin. No significant zoning of FeO is present in the garnet. JSL 108, 112, 113, 170, 262 and 266 exhibit zoning in all or most of their primary minerals (Tables 2.2, 2.3 and 2.4) and it is therefore suggested that these xenoliths have either not fully equilibrated, or have undergone metasomatism. The group includes two deformed peridotites and one harzburgite, as well as three subcalcic harzburgites.

It is not possible to identify any single process responsible for the zonation in the unequilibrated samples mentioned above. The author believes that at least one diffusive(?) metasomatic event was involved in order to account for TiO_2 and Na_2O zonation in garnet from JSL 112 and 113, but it is uncertain if the CaO , MgO and FeO zonation resulted from local disequilibrium during formation of the rocks, or from later diffusive effects. It is also uncertain whether the postulated metasomatic event is related to the formation of the Ti-rich garnets discussed in Section 2.4.1. Schulze and Helmstaedt (1988) proposed that zonation observed in garnet from subcalcic garnet harzburgites (e.g. JSL 113), may have been the result of re-equilibration of the depleted harzburgite to the lherzolitic composition of the upper mantle.

The apparent selective zoning of clinopyroxene and not orthopyroxene, olivine or garnet in some of the Letlhakane samples is problematic. Conflicting reports exist on cation diffusion rates in pyroxene and garnet (Freer et al., 1982, and Smith and Ehrenberg, 1984). The latter authors concluded that the rates of diffusion of elements seem to decrease in the order $\text{Fe} > \text{Ti} > \text{Cr}$, all being more mobile in pyroxene than in garnet. This is consistent with observations made in xenolith suites at a variety of localities, i.e. that orthopyroxene and clinopyroxene are often less zoned than garnet (Smith and Boyd, 1987; Smith and Ehrenberg, 1984; Smith and Boyd, 1989). Metasomatism may have been the cause of zoning in clinopyroxene, but then it would be expected that garnet would also show evidence of this. The absence of zonation in olivine and orthopyroxene may also be explained by the possibility that TiO_2 , Cr_2O_3 , Al_2O_3 and Na_2O are preferentially distributed into clinopyroxene and garnet at lower temperatures. The trace concentrations of these elements and their constant values in orthopyroxene when compared to clinopyroxene and garnet, is an indication that their entry into the former is restricted. Orthopyroxene and olivine become saturated at a much faster rate, because only a small amount of highly charged R^{3+} and R^{4+} cations are present in these minerals.

The absence of optical discontinuities in the Letlhakane clinopyroxene, argues against the possibility that their zonation could be explained by overgrowths, crystallized from a fluid which was introduced after deformation. "Spongy" recrystallized rims around the clinopyroxenes are, however, common in many of the peridotites. These rims are in optical continuity with the cores, but display abrupt changes into the unaltered mineral. Ehrenberg (1982) noted a similar feature at the Thumb, U.S.A. He proposed that the variation in Al_2O_3 , Cr_2O_3 and Na_2O of these rims resulted from a breakdown of the clinopyroxene in the xenoliths as a result of a decrease in pressure as the kimberlite ascended. It is suggested that a similar process was responsible for the zonation of the clinopyroxenes in the Letlhakane peridotite suite. However, it is not possible to distinguish between the above process and any zoning that may have resulted from possible metasomatic activity. The "spongy" rims observed in the clinopyroxene are present in all the deformed lherzolites and most of the coarse-textured lherzolites, but are almost totally absent in the websterites. It would therefore appear that the zoning in the websteritic clinopyroxene is the result of a

different process than that in the peridotite suite. The websterites formed at shallower depth (Section 6.3) and their clinopyroxene could therefore have escaped severe pressure-related modification. The large core-to-rim changes in elements that normally undergo rapid equilibration (Mg, Ca, Fe), suggest that the zonation may have been caused by sudden cooling and that the websterites were erupted in an unequilibrated state.

2.5 Summary

To summarize, the following important facts and interpretations in this chapter may be noted:

- 1) The various peridotites and pyroxenites from Letlhakane can be distinguished successfully on the basis of primary mineral compositions. Garnet compositions, the forsterite content of olivine and CaO, Cr₂O₃, Na₂O and Al₂O₃ concentrations in clinopyroxene are useful in this regard. The websterites at Letlhakane are characterized by their olivine-poor nature. The compositions of minerals of the peridotite-pyroxenite suite from Letlhakane correspond closely to those of similar rocks from other kimberlite occurrences on the Kaapvaal craton. Petrographic study of the spinel peridotites indicates, however, that these rocks are considerably different in texture and modal mineralogy from those reported by Boyd (1989) from the Kaapvaal craton.
- 2) Lherzolitic garnets can be divided into Ti-poor and Ti-rich varieties. The Ti-rich group is thought to have resulted from diffusive metasomatic activity. Orthopyroxene and clinopyroxene in samples from the high-Ti group also exhibit higher TiO₂, but on a lesser scale. In addition, a sample from the Ti-rich group (JSL 112) and a subcalcic garnet harzburgite (JSL 113) exhibit core-to-rim zonation of TiO₂ and Na₂O in garnet, possibly indicating another metasomatic event by infiltration, but possibly at great depth, hence the absence of phlogopite.
- 3) Olivine, orthopyroxene and garnet are homogeneous in composition (with rare exception). However, clinopyroxene may be zoned, especially in Al₂O₃, Na₂O, Cr₂O₃, CaO and MgO. It is suggested that the zonation in the peridotitic clinopyroxenes is different in nature from that of the pyroxenitic clinopyroxenes. Zoning in the former resulted from decompression during ascent of the kimberlite host and/or deep metasomatism. Zoning in the pyroxenitic clinopyroxene is of uncertain origin, possibly due to disequilibrium at the time of emplacement.

CHAPTER 3

METASOMATIZED PERIDOTITES AND PYROXENITES

3.1 Introduction

Prior to 1970, little was known about mantle metasomatism. The pioneering studies of Erlank and Finger (1970) and Kushiro and Erlank (1970) on the discovery and stability of K-richterite in the mantle resulted in a surge of interest in this new field of study. A metasomatic origin for primary phlogopite was also advocated shortly thereafter (Erlank, 1973; Carswell, 1973), particularly after Erlank (1973) and Erlank and Rickard (1977) reported the presence of K-richterite in phlogopite-bearing peridotites. A multitude of studies followed, mostly of the Kimberley peridotites (Erlank et al., 1987 and references therein), but also in other localities, e.g. Jagersfontein (Haggerty et al., 1983; Winterburn et al., 1990). A brief summary of terminology and recent publications can be found in Chapter 1, Section 1.4.

The current study adopts the criteria suggested by Erlank et al. (1987) with regard to the recognition of metasomatism, i.e. any peridotite containing primary metasomatic phlogopite and/or K-richterite is considered to be metasomatized. Ilmenite and rutile-bearing samples are also included (Chapter 2, Section 2.1). Diffusive or cryptic metasomatism (see Section 1.4) obviously complicates this simple classification, since both require chemical analytical techniques to be detected. Evidence for such diffusive metasomatism may be present as Ti-rich garnets from sheared peridotites (Chapter 2, Sections 2.3.4 and 2.4.1) However, in the interests of simplicity and to avoid undue confusion, the metasomatized peridotites and pyroxenites have been identified in the current investigation by the following modal criteria:

- (1) The presence of phlogopite, ilmenite, rutile, spinel and amphibole, either alone or in combination. Clinopyroxene is also a member of the metasomatic suite and can be distinguished from primary clinopyroxene by its composition, texture, and association with known metasomatic minerals. Secondary metasomatic phlogopite, amphibole and spinel in kelyphite rims and any other late-stage, kimberlite-associated minerals (e.g. serpentine) are obviously excluded here.
- (2) The presence of veins of the above minerals.
- (3) Any intergrowth, reaction or replacement texture involving the above minerals.

3.2 Petrography

In this section similar rock types have been grouped together and, to avoid unnecessary repetition, summary descriptions of each group are given. These groups are: garnet phlogopite peridotites (GPP), phlogopite peridotites (PP), veined or banded peridotites, and pyroxenites. Where samples contain important and unique features or textures (e.g. JSL 143, 500, 511 and 516), a description of the entire sample is given. Three of the above samples have been studied in great detail, involving the preparation of several polished thin sections, large thin sections and polished slabs.

3.2.1 Garnet phlogopite peridotites (GPP)

This suite is represented by ten xenoliths, all of which are coarse-grained (after the textural definition of Harte, 1977). Most of these xenoliths are garnet lherzolites, with the exception of JSL 143 which will be discussed separately in this section due to its unique nature. Note that two xenoliths (JSL 111 and 151 - Plate 7) have been included in this group on the basis of the composition of their garnets, despite the absence of olivine. A summary of the samples as well as an analysis of their texture and modal mineralogy can be found in Table 3.1.

Garnet textures vary considerably between samples. JSL 142 contains well-rounded ($\leq 5\text{mm}$), pale purple garnets surrounded by thin kelyphite rims. JSL 572 contains small ($< 1\text{mm}$), highly irregular and partly kelyphitized fragments of garnet associated with extensive secondary alteration products such as phlogopite, carbonate and serpentine (Plate 8). JSL -/177 contains similar, irregular garnet fragments, which are set in rounded intergrowths of bright green clinopyroxene and pale brown phlogopite. Spinel may also be present in these intergrowths, (e.g. JSL -/91). Garnets from all samples in this suite lie between the two textural extremes described above.

The olivine grains are in most cases colourless, anhedral in shape and exhibit straight to gently curving grain boundaries. Grain sizes are generally $< 10\text{mm}$, but may decrease when intergrown with clinopyroxene (e.g. JSL 572, approximately 0.5mm), but this feature is not ubiquitous. Curving serpentine-filled cracks and undulose extinction are common features of olivines in these rocks. Orthopyroxene grains are also colourless, anhedral, and mostly $< 7\text{mm}$ in size. Unlike olivine however, orthopyroxene commonly displays slightly embayed boundaries when in contact with secondary alteration products and bright green, primary clinopyroxene. Once again, these features are not always present in the rock. Undulose extinction of the orthopyroxene may be present.

Table 3.1: Petrographic and textural summary of the metasomatized peridotite-pyroxenite suite. The star symbol denotes the presence of primary (eg. GT, OLV, OPX and CPX) and metasomatic phases. A distinction was made between primary (P) and secondary (S) metasomatic phlogopite and amphibole. The superscript (x) denotes phases observed in thin section only, i.e. not analysed.

Sample no.	Rock type	Texture	GT	OLV	OPX	CPX	SP	PHL	AMP	ILM	RUT
JSL 25	Gt. opx.	C	*		*			S		*	
JSL 75	Gt. web.	C/G	*		*	*		S	S		*
JSL-/91	Gt. lherz.	C	*	*	*	*	*	P			
JSL-/93	Lherz.	C		*	*	*	*	P			
JSL 110	Gt. web.	C	*		*	*			P	*	*
JSL 111 ¹	Gt. lherz.	C	*		*	*	*	P, S			
JSL 142	Gt. lherz.	C	*	*	*	*		P, S			
JSL 143 ²	Gt. harz.	C	*	*	*	*	*	P, S			
JSL 151 ³	Gt. lherz.	C	*		*	*		P, S			
JSL 167	Dunite	C		*	*			P			
JSL-/177	Gt. lherz.	C	*	*	*	*	*	P			
JSL 180	Gt. cpx.	C	*		*	*		P			
JSL 252	Gt-sp. web.	C	*		*	*	*	S	P		**x
JSL 273	Lherz.	C		*	*	*	*	P			
JSL 278	Gt. lherz.	C	*	*	*	*		P ⁶			
JSL 298	Gt. web.	C	*		*	*			P		
JSL 303	Wehrl.	C		*	*	*		P ^x			
JSL 304	Lherz.	C		*	*	*	*	P			
JSL 500 ⁴	Harz?	veined, C		*	*	*		P		*	
JSL 504	Gt. lherz.	C	*	*	*	*		P			
JSL 511	Harz.	C		*	*	*		P		*	
JSL 516 ⁵	Harz?	banded, C		*	*	*		P			
JSL 520	Wehrl.	C		*	*	*		P			
JSL 532	Wehrl.	C		*	*	*		P		*	
JSL 533	Gt. lherz.	C	*	*	*	*	*	P			
JSL 547	Lherz.	C		*	*	*	*	P, S			
JSL 565	Lherz.	C		*	*	*	*	P			
JSL 572	Gt. lherz.	C	*	*	**x	*		S			

Abbreviations used in this table:

Minerals

GT
OLV
OPX
CPX
SP
PHL
AMP
ILM
RUT

- garnet

- olivine

- orthopyroxene

- clinopyroxene

- spinel

- phlogopite

- amphibole

- ilmenite

- rutile

Rock types

Gt. harz.

Gt. lherz.

Gt. web.

Web.

Sp. lherz.

Lherz.

Wehrl.

Gt. cpx

Gt. opx

Gt-sp. web.

Harz.

Textures

C

G

- garnet harzburgite

- garnet lherzolite

- garnet websterite

- websterite

- spinel lherzolite

- lherzolite

- wehrlite

- garnet clinopyroxenite

- garnet orthopyroxenite

- garnet-spinel websterite

- harzburgite

- coarse

- granuloblastic

1,3: Garnet chemistry indicates a peridotitic composition

2 : The garnets are mildly subcalcic in composition

4 : The clinopyroxene may be associated with metasomatic processes responsible for the veining

5 : Textures suggest a metasomatic origin for the clinopyroxene

6 : Only found after mineral separation for isotope geochemistry

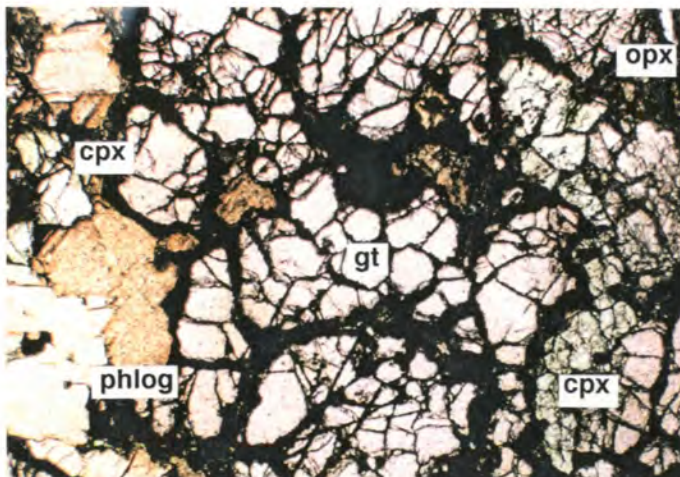


Plate 7: Pale-green, primary metasomatic clinopyroxene (cpx) and brown phlogopite (phlog) in a garnet phlogopite peridotite (GPP) (JSL 111). The clinopyroxene is located in a thin strip to the right, surrounded by garnet (gt) and orthopyroxene (opx). Three clinopyroxene grains are also embedded in the phlogopite on the left. Field of view = 3.5mm wide. Plane polarised light.

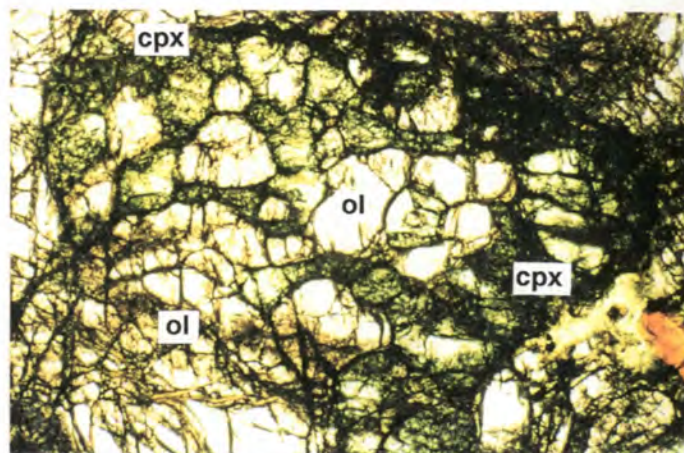


Plate 10: Bright green primary metasomatic clinopyroxene (cpx) intergrown with recrystallized olivine (ol) in JSL 572. No significant zoning is present in either olivine or clinopyroxene, although intergrain variation in the clinopyroxene composition, particularly with respect to Cr_2O_3 , is present. Field of view = 3.5mm wide. Plane polarised light.

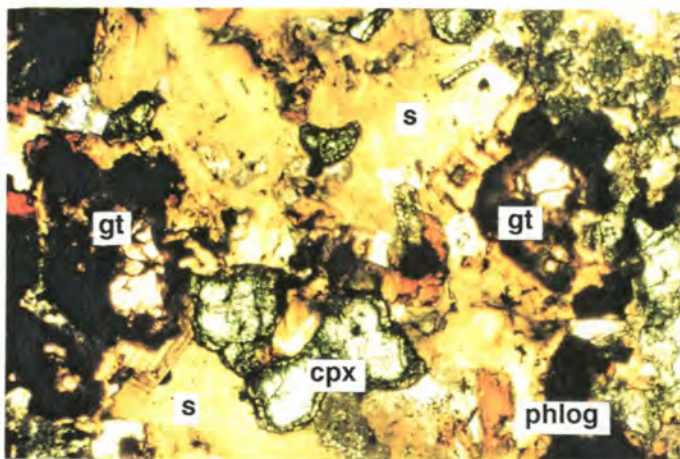


Plate 8: A GPP (JSL 572) exhibiting extremely irregular garnet fragments (gt) and bright green clinopyroxene (cpx) in a pool of pale brown secondary metasomatic serpentine (s) and reddish-brown secondary metasomatic phlogopite (phlog) on the extreme left and middle bottom. This plate illustrates the combined effects of primary and secondary metasomatism. Field of view = 3.5mm wide. Plane polarised light.

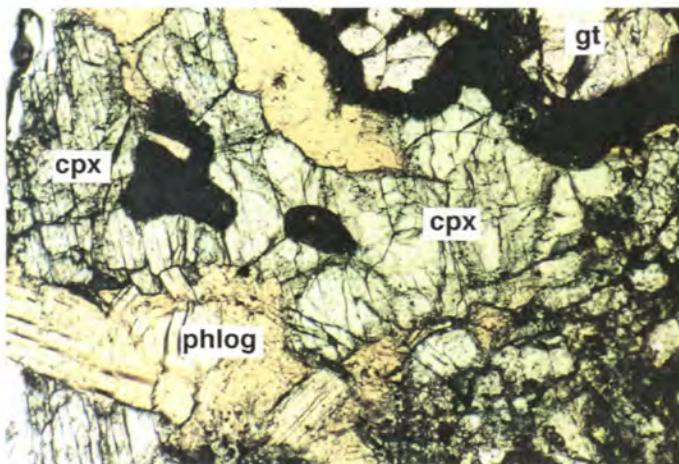


Plate 11: A GPP (JSL 143) containing mildly subcalcic, embayed garnets (gt) and primary metasomatic clinopyroxene (cpx) and phlogopite (phlog). Discrete Cr-spinel is present, although not visible in this plate. Field of view = 1.56mm wide. Plane polarised light.

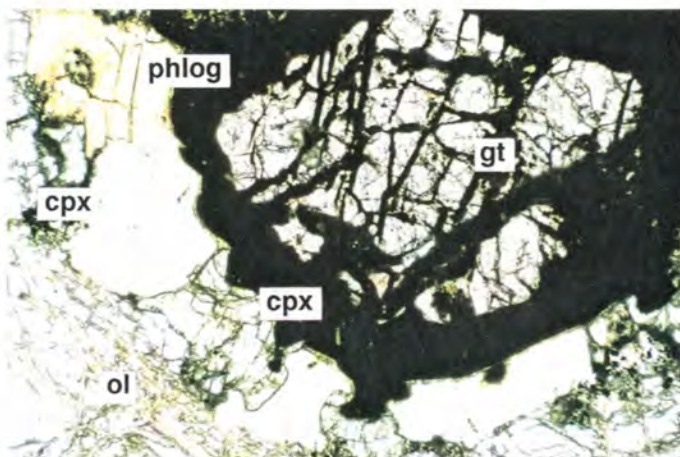


Plate 9: Small primary metasomatic clinopyroxene (cpx) intergrown with pale brown primary metasomatic phlogopite (phlog) and surrounding garnet (gt) in a typical GPP. Other phlogopites are not exhibiting maximum pleochroism in their respective positions, hence the pale colours. The intergrowth is surrounded by olivine (ol). Field of view = 3.5mm wide. Plane polarised light.

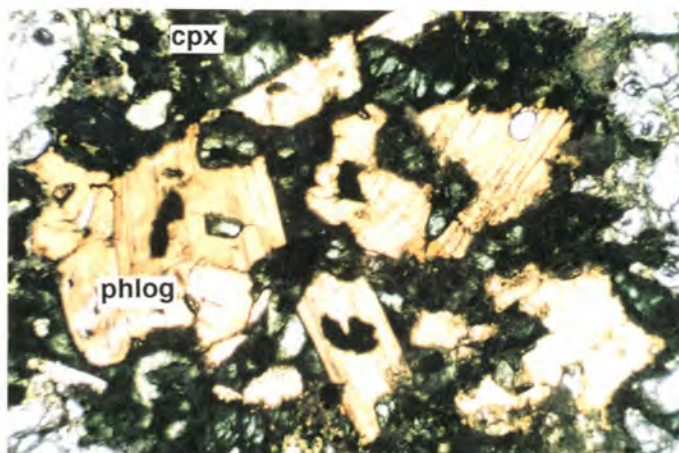


Plate 12: Bright green primary metasomatic clinopyroxene (cpx) intergrown with brown primary metasomatic phlogopite (phlog). This texture is typical of many PP xenoliths. The intergrowth is surrounded by colourless olivine. Note the absence of garnet, compared to the GPP shown in Plate 9. Field of view = 3.5mm wide. Plane polarised light.

Clinopyroxene may exhibit important textural features not observed in the non-metasomatized garnet peridotites (Chapter 2). The clinopyroxene is typically, but not always, finer-grained than the associated olivine and orthopyroxene. The largest clinopyroxene grain observed in this suite is 3.5mm in size (long axis), but average sizes are <2.5mm. There is a notable tendency for clinopyroxene to exhibit a close spatial association with garnet in the form of patchy irregular grains around garnet (e.g. JSL 142), or as rounded grains (commonly <1.5mm in size) intergrown with coarse phlogopite, with or without spinel, e.g. JSL -/177 and -/91 (see also Plate 9). The garnets in these phlogopite-clinopyroxene-spinel intergrowths vary from rounded grains to small, irregular fragments. The clinopyroxene in JSL 572 occurs in two different habits. Small, rounded clinopyroxene grains are associated with the garnet fragments mentioned above (Plate 8). In addition, fine clinopyroxene is also interfingering with small, recrystallized(?) olivine (Plate 10). These olivine-clinopyroxene intergrowths are similar to those observed in a garnet and phlogopite-free lherzolite (Chapter 2, Section 2.2.2). A distinct association of clinopyroxene with coarse, primary metasomatic phlogopite (after the definition of Carswell, 1975) occurs in the GPP suite. The mineralogical differences between clinopyroxene from the garnet peridotite and garnet phlogopite peridotite suites will be discussed in Section 3.3.3.

Primary metasomatic phlogopite ($\leq 2\text{mm}$ in size) is present in all the samples, except JSL 572. This sample is, however, included here due to the presence of other textures which are indicative of metasomatism, e.g. bright green clinopyroxene associated with garnet. It is thought that the primary metasomatic phlogopite has been destroyed and overprinted by a secondary metasomatic event. Kinked and deformed plates of phlogopite are common in the other GPP xenoliths and may contain spinel and clinopyroxene if associated with garnet, as mentioned above. Samples such as JSL -/177 where only small remnants of garnet are left, contain the largest modal proportion of phlogopite, while those with unaltered or slightly irregular garnets, e.g. JSL 142, contain less phlogopite.

Four xenoliths (JSL 111, -/171, -/91 and 533) contain spinel and in all cases these spinels are situated within, or close to, coarse phlogopite associated with garnet. The spinel is commonly present in the form of euhedral to anhedral rounded grains (e.g. JSL 533), or as a dendritic-type intergrowth in phlogopite (e.g. JSL -/91). These habits often occur together.

A brief, separate description of JSL 143 is presented below. This coarse-grained sample is unique in that garnet is mildly subcalcic in composition (Section 3.3.4), but is in association with clinopyroxene, which is rare for this rock type. The dominant phases in this sample are olivine, orthopyroxene and garnet. Grain sizes vary from approximately 7.5mm to <0.2mm. Most phases, except garnet, exhibit some evidence of deformation, e.g. kink bands or undulose extinction. The garnets are cracked and rimmed by brown kelyphite, containing brown, secondary Al-spinel. Minor secondary metasomatic phlogopite is also present. Two analysed garnets exhibit irregular boundaries and embayments, and both contain Cr-spinel inclusions.

Both garnets are also associated with plates of primary metasomatic phlogopite (0.4-1mm in size) intergrown with green clinopyroxene (Plate 11). Patches of kelyphite are visible in these coarse phlogopites, suggesting that these garnets may initially have been of larger size.

3.2.2 Phlogopite peridotites (PP)

This suite is represented by 9 coarse-grained peridotites which are characterized by the complete absence of garnet (Table 3.1). Two of these xenoliths (JSL 520 and 565) have been studied in detail (polished slabs and multiple polished thin sections per sample) to determine the chemical homogeneity of the samples. Xenoliths JSL 500, 511 and 516 are also garnet-free, but have been described separately in the next section due to their veined, banded or unusual textures. The modal mineralogy of the phlogopite peridotites can be found in Table 3.1. All samples are lherzolites, with the exception of JSL 167, which is a dunite, and JSL 303, 520 and 532, which are wehrlites.

Olivines in this rock suite are colourless, anhedral and vary from 0.5 to 9mm in size. The olivine boundaries are typically straight to gently curving, although a few samples, (e.g. JSL 532 and 565) exhibit areas where annealing of olivine grains has taken place, and straight-edged, tabular grains are more common. Generally however, the olivines are extensively cracked and veined by secondary serpentine. Minor strain deformation is visible in many of the grains.

Orthopyroxene grains are also colourless and anhedral, but boundaries are often highly irregular and embayed, e.g. in JSL 304 and -/93. Small remnants of orthopyroxene, optically continuous with the main grain, often extend into the surrounding olivine, indicating that the orthopyroxene was part of a much larger grain, e.g. in JSL -/93. These small remnants of orthopyroxene are often included in olivine, suggesting that orthopyroxene was partly resorbed while the olivine simultaneously recrystallized around the orthopyroxene.

Compared to those in the GPP suite, a larger variation in clinopyroxene habit and grain size is present. The clinopyroxenes vary from anhedral, irregular shaped grains (JSL 565: 0.5-3.5mm in size), through triple-bounded larger grains (JSL 547: ≤ 5 mm), to an almost circular, 3mm diameter grain in JSL 532. Although JSL 520 contains clinopyroxene with apparent sizes of up to 12mm, these grains are not in optical continuity and are therefore recrystallized aggregates rather than single grains. The rounded intergrowths of bright-green clinopyroxene, coarse, brown phlogopite and spinel described in the garnet phlogopite peridotites (Section 3.2.1) are often present, obviously now without garnet (Plate 12), and may reach sizes of up to 10mm in diameter, e.g. in JSL 565.

Coarse, primary-textured phlogopite may reach sizes of up to 3.5mm in diameter and may locally contain white carbonate lamellae, e.g. in JSL 520 and 532 (Plate 13). Whether these lamellae are of mantle or kimberlitic affinity remains open to debate. The close association of phlogopite with bright-green clinopyroxene in this rock suite is a conspicuous feature of these xenoliths.

Spinel is common in this suite, except in samples JSL 167, 303 and 520. A close relationship between spinel, phlogopite, and, more rarely, clinopyroxene (JSL 304 and 565) is apparent in the phlogopite peridotites. The spinel grains may reach a size of 3.5mm (JSL 565) and are present in the form of dendritic or irregular to subhedral grains, similar to those in the GPP suite (Plate 27). Ilmenite is present in a single sample, JSL 532, and occurs as a rounded, anhedral grain in close proximity to clinopyroxene and phlogopite.

3.2.3 Veined and banded peridotites

This suite is represented by one veined (JSL 500), one banded (JSL 516), and one pervasively metasomatized peridotite (JSL 511) which is included here owing to its unusual textures and modal mineralogy. Their many unique textures warrant a detailed description of each xenolith.

JSL 500 was retrieved from the LM 1 intrusion in the open pit at Letlhakane DK 1. The xenolith measured approximately 12x13x8cm before cutting and contains veins of ilmenite and associated phlogopite. Polished and normal thin sections were cut perpendicular to the veins, after which the xenolith was sawn in half. One section of the xenolith was then prepared as a polished slab.

The dominant phases are olivine, orthopyroxene, clinopyroxene, primary metasomatic phlogopite and ilmenite. No garnet is present in this sample. The olivine is coarse-grained (after the definition by Harte, 1977) and exhibits undulose extinction and extensive serpentine vein development. The orthopyroxene grains vary from approximately 2-5mm in size and alteration of this phase appears to increase towards the veined areas with the development of complex symplectites. The veins and lenticles in this sample are composed chiefly of ilmenite, and vary from <1-9mm in width. The veins run continuously for several centimeters across the sample. Associated lenses of phlogopite and bright green clinopyroxene are also present in addition to the phlogopite and clinopyroxene dispersed throughout the sample (Plate 14). The ilmenite veins are generally restricted to one half of the sample, while the phlogopite and clinopyroxene become more dispersed throughout the rock with increasing distance from the veins.

Thin sections were made of an extremely large orthopyroxene grain (23x14mm) along one edge of the xenolith and the associated symplectite, recrystallization and alteration features studied in great detail. Only

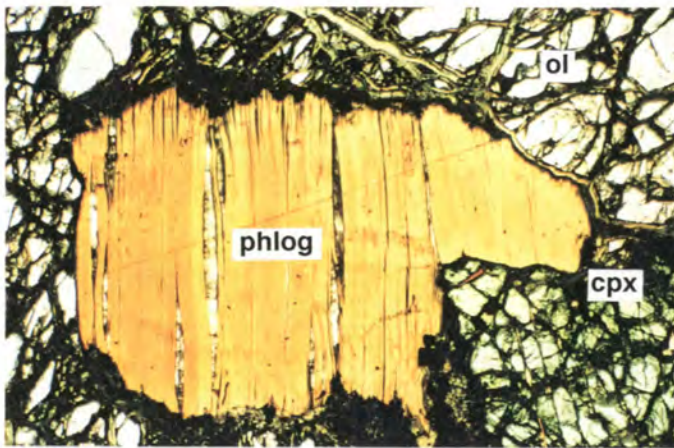


Plate 13: White carbonate lamellae along cleavage planes in a plate of brown primary metasomatic phlogopite (phlog) from sample JSL 520. Other phases include bright green clinopyroxene (bottom right) and ubiquitous colourless olivine (top). Field of view = 3.5mm wide. Plane polarised light.

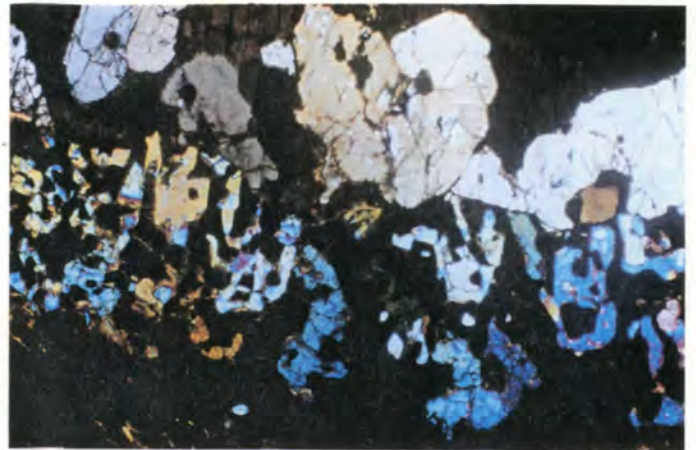


Plate 15b: An identical view of JSL 500 to Plate 15a, but photographed under crossed nicols. Field of view = 6.8mm wide.

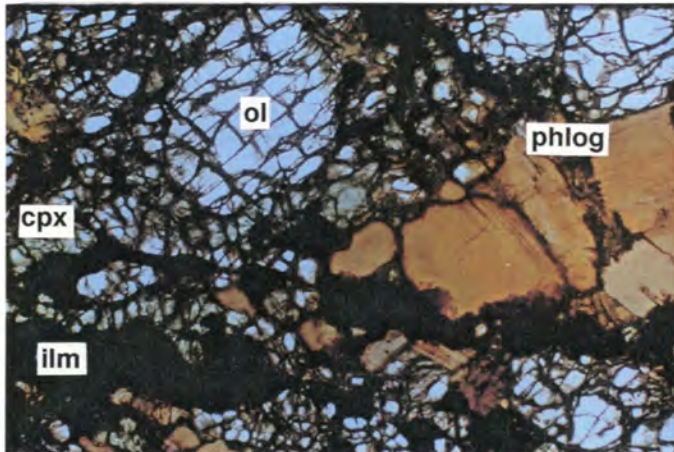


Plate 14: A vein of opaque ilmenite (ilm) and associated primary metasomatic phlogopite (phlog) and green clinopyroxene (cpx) from veined peridotite JSL 500. The colourless host phase is olivine (ol). Field of view = 6.8mm wide. Plane polarised light.

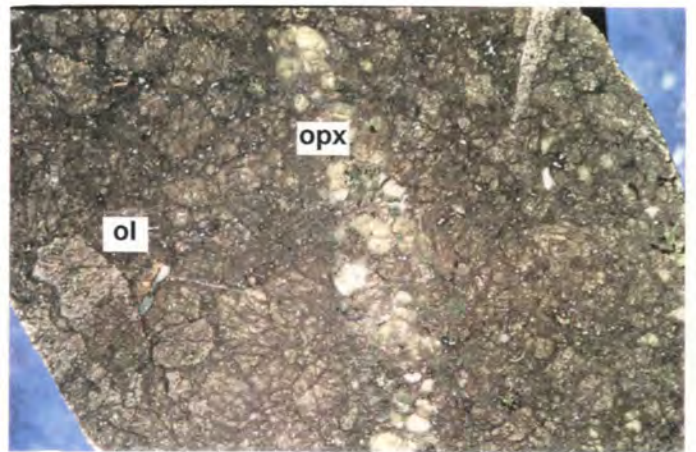


Plate 16: A polished slab of JSL 516, illustrating the orthopyroxene-rich band (opx) and associated bright green clinopyroxene and brown phlogopite (above and below the opx label). Note the difference in olivine grain size to the left and right of this band (ol) and the lack of orthopyroxene to the left of the band. Small orthopyroxene grains are present to the right of the band (bottom right), but are poorly visible in this plate. Field of view is 16cm wide.

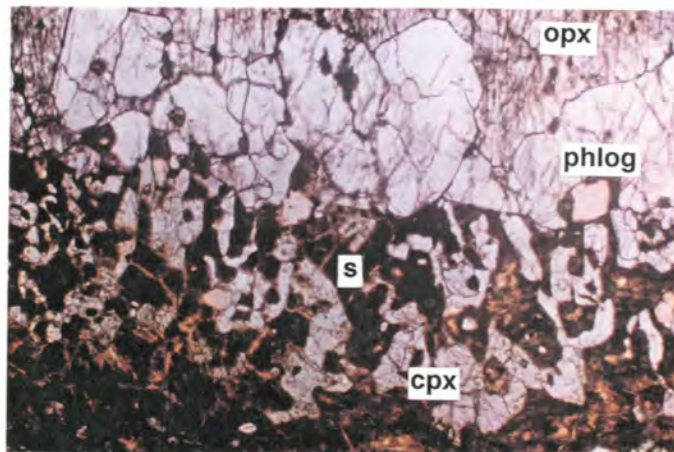


Plate 15a: A clinopyroxene-orthopyroxene-olivine symplectite in JSL 500. The olivine is totally altered to a brown serpentine mass (s). Pale green clinopyroxene (cpx) is intergrown with the serpentine pseudomorphs. The orthopyroxene in contact with the symplectite has recrystallized, but parts of the original crystal (opx) are still visible along the top. Note the small plates of primary metasomatic phlogopite (phlog) in the orthopyroxene neoblasts. Field of view = 6.8mm wide. Plane polarised light.

two such symplectic orthopyroxenes are visible in the slabs, both in close proximity to the veins. The olivine surrounding the orthopyroxenes is totally altered to a brown mass of optically irresolvable material, possibly serpentine(?). Original serpentine veinlets within the altered olivine are still visible. Closer to the margin of the orthopyroxene, this brown alteration material is intergrown with green clinopyroxene and orthopyroxene in the form of a symplectite (Plates 15a&b). The contact between the orthopyroxene and the symplectite is gradational, the latter often extending into the orthopyroxene along cracks and may be associated with primary metasomatic phlogopite. Recrystallization of the orthopyroxene occurred in several areas, leading to the development of large (approximately 1-1.5mm) equant neoblasts. Globules of the brown material and associated phlogopite are commonly present along the neoblast boundaries. The neoblasts themselves are free of alteration, except for occasional phlogopite grains occurring within. The original orthopyroxene is cracked and dusted with a fine, brown material (Plate 15a). The orthopyroxene also contains blebs and stringers of this brown material and phlogopite. It can therefore easily be distinguished from the orthopyroxene neoblasts in thin section, even with the unaided eye. Phlogopite in the orthopyroxene commonly occurs as embayed and dislocated grains which are in optical continuity.

JSL 516 measured approximately 17x15.5x14cm before cutting and was collected from the LM 1 intrusion in the open pit at Letlhakane DK 1. Exterior examination revealed that this xenolith is a phlogopite peridotite. The xenolith was initially cut in half, at which time a prominent 2cm-wide band, rich in coarse orthopyroxene, was found to bisect the rock (Plate 16). One half of the xenolith was then repeatedly slabbed parallel to the band to determine its lateral extent. One of these slabs was polished, while several polished thin sections and a large thin section (7.5x10.5cm) were made of material above, within, and below the orthopyroxene-rich layer.

The xenolith consists of olivine, orthopyroxene, clinopyroxene and phlogopite, listed in decreasing order of abundance. No garnet or opaque phases are present. The orthopyroxene-rich band separates the rock into two distinct halves. One half of the xenolith consists predominantly of very large, megacrystalline olivine grains, varying from 10-40mm (long axis). The textures indicate that equilibrium was attained, but minor recrystallization of olivine rims is present. No orthopyroxene is present in this part of the xenolith, but rare, bright green clinopyroxene and primary metasomatic phlogopite occurs as small (<0.5mm), rounded patches between the olivine grains. The band of orthopyroxene consists of a concentration of numerous 1-7mm sized orthopyroxene grains (on average >4mm) with minor amounts of olivine. A sudden modal increase in green clinopyroxene and primary metasomatic phlogopite is visible and associated with the orthopyroxene. The orthopyroxene-rich band does not appear to be a very penetrative feature and gradually diminishes from one end of the xenolith to the other.

In the other half of the xenolith, the decrease in grain size of the olivine to <10mm is readily apparent, although it is still the major phase. Scattered, minor orthopyroxene, also of smaller size (<6mm),

occurs in this zone. Clinopyroxene and phlogopite are more abundant in this half of the xenolith compared to that described above. A fine interfingering of clinopyroxene and recrystallized olivine ($<0.5\text{mm}$ in size) is common and is similar to that shown in Plate 10. The orthopyroxenes in this half are strongly embayed and surrounded by intergrown clinopyroxene and recrystallized olivine (Plates 17a&b). This intergrowth of olivine and clinopyroxene occurs only along orthopyroxene grain boundaries. The interfingering of olivine and clinopyroxene is also found in the orthopyroxene-rich band, but it is not as common.

To summarize, the xenolith consists of a megacrystalline, predominantly dunitic segment, separated from a more lherzolitic segment by an orthopyroxene-rich layer.

The mica-rich xenolith, JSL 511, was recovered from the LM 1 kimberlite intrusion at DK 1. The xenolith is ovoid in shape and measured approximately $20\times 8\times 8\text{cm}$ before cutting. After being sawn in half, a polished slab, one large thin section (Plate 18) and two polished thin sections were prepared.

The xenolith consists of phlogopite, olivine, ilmenite and rare orthopyroxene. No clinopyroxene or garnet is present. An estimation of the abundance of the above phases is difficult due to the modal heterogeneity in the xenolith. Certain areas in JSL 511 are composed almost exclusively of phlogopite and ilmenite with no orthopyroxene, whereas other areas contain equal proportions of olivine and phlogopite and lesser amounts of ilmenite. Suffice to say that up to 50% of the rock contains phlogopite, resulting in this being the most mica-rich xenolith found at Letlhakane apart from the MARID and glimmerite xenoliths (Chapter 5, Section 5.4). Despite the large modal proportion of phlogopite and ilmenite, no primary veins of the above phases are visible and it appears as if the entire sample was subjected to pervasive metasomatism. Phlogopite and ilmenite-rich zones generally exhibit a larger grain size and greater grain size variation ($<0.2\text{--}7\text{mm}$) than areas rich in olivine ($<0.1\text{--}1\text{mm}$).

Anhedral to irregular olivine grain boundaries are common (Plate 19a). Olivines with irregular boundaries, partly or wholly enclosed by other olivines are ubiquitous. Rare subhedral to euhedral olivine grains are also present. Grains showing these well-developed crystal-faces are mostly in contact with other olivine grains, but straight olivine-ilmenite contacts are also present. Olivine is bordered by, but not included within, phlogopite. Rare inclusions of olivine and phlogopite within ilmenite do, however, exist.

Phlogopite is ubiquitous in this sample and varies from reddish brown to pale brown in colour. Its grain size is highly variable ($<7\text{mm}$) and large phlogopite plates in particular, exhibit evidence of deformation. Ilmenite is commonly included within phlogopite and exhibits a variety of shapes. Rare, acicular inclusions of an unidentified opaque phase are also present.

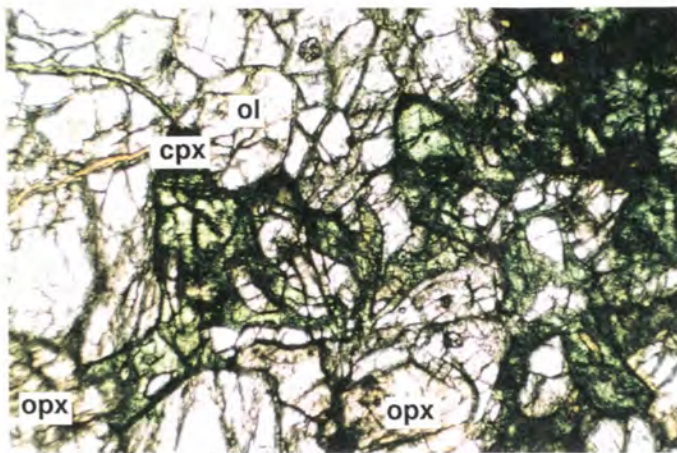


Plate 17a: Severely embayed orthopyroxene (opx) surrounded by bright green primary metasomatic clinopyroxene (cpx) which, in turn, is interfingered with olivine (ol). The total size of the orthopyroxene grain (including parts outside the field of view) is 7mm (long axis). This example is taken from a thin section of another peridotite, JSL 579, but shown here to illustrate the extent to which the destruction of orthopyroxene can occur. Examples also exist where the orthopyroxene is totally destroyed. Similar textural embayments are visible in orthopyroxene from JSL 516, though not as well developed as the example shown here. Field of view = 3.5mm wide. Plane polarised light.

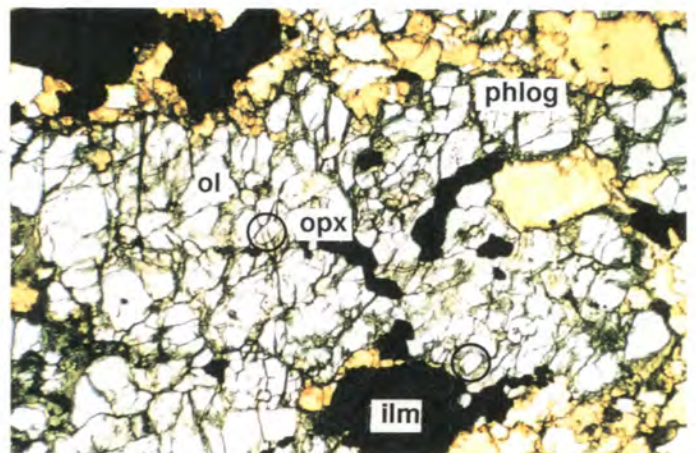


Plate 19a: An olivine-rich area (ol) in JSL 511, illustrating the irregular nature of the olivine and the rounded, anhedral inclusions of orthopyroxene (opx). Two of these inclusions are ringed for easy identification, but several more are visible in the immediate vicinity. Larger and smaller recrystallized plates of primary metasomatic phlogopite (phlog) and opaque ilmenite grains (ilm) constitute the remainder of the field of view. Field of view = 3.5mm wide. Plane polarised light.

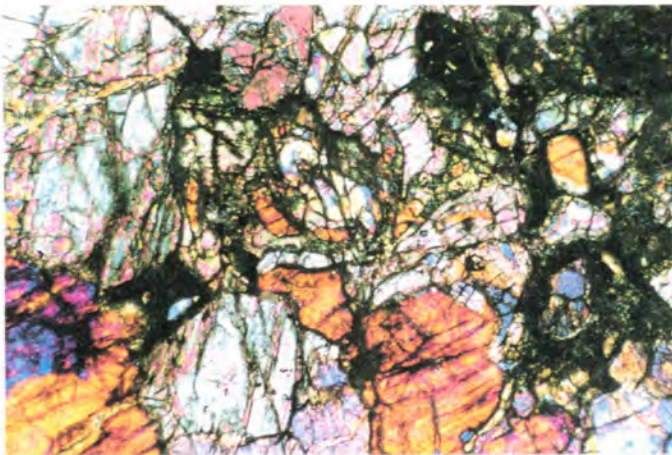


Plate 17b: A similar view of JSL 579, but photographed under crossed nicols to further illustrate the former extent of the orthopyroxene. Note that all the orthopyroxene fragments surrounded or associated with clinopyroxene are in optical continuity with the rest of the grain. This plate has been slightly displaced compared to Plate 17a so as to include more orthopyroxene in the field of view. Field of view as in Plate 17a.

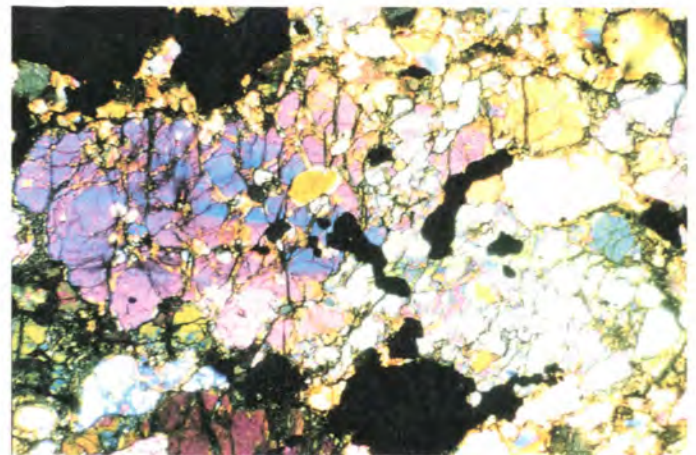


Plate 19b: An identical view of JSL 511 to Plate 19a, but photographed under crossed nicols. Note the irregular olivine grain boundaries and the fact that the orthopyroxene inclusions are not restricted to any particular part of the olivine and are not in optical continuity with each other. Field of view = 3.5mm wide. Crossed nicols.



Plate 18: A large thin section (7.5x10.5cm) of JSL 511, illustrating the general petrography of this unusual peridotite. The various phases include opaque ilmenite, brown primary metasomatic phlogopite and colourless olivine. No clinopyroxene is present. The orthopyroxene inclusions in olivine are not visible on this scale.

The ilmenite exhibits no distinct features other than occurring both as inclusions in olivine and phlogopite, and as large (<5mm) discrete grains. Unlike ilmenite in the MARID (Chapter 5, Section 5.4), no rutile or apatite inclusions are present.

The orthopyroxene in this specimen occurs as small (<0.3mm) rounded and anhedral inclusions in olivine (Plates 19a&b). No large, discrete orthopyroxene grains are present in any of the thin sections, in contrast to typical peridotites (Chapter 2, Section 2.2). The orthopyroxene inclusions exhibit no preferred pattern of distribution in the olivines, i.e. they occur both in rims and/or the cores of their olivine hosts. No orthopyroxene inclusions are found in phlogopite. The orthopyroxene inclusions are not in optical continuity with each other and it is therefore unlikely that they form part of an intergrowth or exsolution. The orthopyroxene commonly contains reddish opaque inclusions, possibly spinel or rutile.

These observations suggest that the sample is a harzburgite that has been highly metasomatized by a potassium- and titanium-bearing fluid. A more detailed interpretation of the observed textures will be given in Section 3.4.6(d).

3.2.4 Pyroxenites

This suite is represented by 6 samples, 3 of which contain primary metasomatic amphibole. JSL 75, 110 and 298 are garnet websterites, while JSL 180 is a garnet clinopyroxenite, and JSL 25 a garnet orthopyroxenite but with mineral chemistry similar to the garnet websterites. All samples in this suite are coarse-textured, with the exception of JSL 75, and no olivine is present in any of the xenoliths (Table 3.1).

Garnets vary from approximately 0.4-8mm in size and are mostly colourless to pale pink in colour, anhedral and rounded with thin kelyphite rims. The garnet in JSL 25 is unaltered, but does contain secondary metasomatic phlogopite along the grain boundaries. The kelyphite rims surrounding garnets in the pyroxenites are less well developed than those surrounding garnet in most of the peridotites. The garnets in JSL 110 are severely cracked and resorbed with well-developed, optically irresolvable brown rims.

The orthopyroxene grains are colourless, <7mm in size and exhibit straight to gently curving grain boundaries. Undulose extinction and kink bands which are commonly present in the peridotitic orthopyroxenes (Chapter 2, Section 2.2) are rarely found. JSL 25 contains several anhedral, irregular blebs of garnet in orthopyroxene and it is possible that the garnet may have exsolved from the orthopyroxene.

Clinopyroxenes are irregular in shape and vary from 0.8-3.7mm in size. No inclusions are present and the mineral is commonly unaltered. Unlike the peridotites, no primary metasomatic phlogopite is present in any of these samples.

Amphibole is best developed in JSL 180, where it is present as several coarse-grained plates (Plate 20). The largest plate is 3x5mm in size, pale brown and slightly pleochroic. The large size of the amphibole grains and the general lack of alteration in this sample suggests a primary metasomatic origin for the mineral. The amphibole in JSL 298 is unfortunately situated on the edge of the thin section and most was lost during its preparation. The small remaining fragment, however, is similar in colour and habit to the amphibole from JSL 180. The amphibole in JSL 110 is pale brown, slightly pleochroic and occurs as several discrete rafts, approximately 0.9-2mm in length. One such raft contains two subhedral rutile grains. A small (<0.5mm) strip of brown amphibole, situated between other silicate phases is present in JSL 75. Due to its small size and different habit compared to the other amphiboles, it is suggested that this may be a secondary metasomatic amphibole (Plate 21).

JSL 110 also contains single, discrete grains of ilmenite in addition to several rutile grains. These phases are mostly situated along the grain boundaries of the major silicates. Ilmenite is present in JSL 25 as a single anhedral grain (0.35 mm in diameter), surrounded by a pocket of secondary alteration material and included in an orthopyroxene host.

Unusual textural relations necessitate a closer look at samples JSL 75 and 252. JSL 75 contains garnet in two textural forms. One end of the thin section is dominated by granuloblastic garnet (approximately 0.5mm average size) with lesser granuloblastic pyroxene. A coarsening in grain size is observed towards the other end of the thin section where garnets are 3-8mm in size (Plate 22). Garnet is also present as exsolution blebs in two large (approximately 3mm) orthopyroxene grains. Rounded, anhedral rutile grains (<0.3mm in size) are commonly present in the granuloblastic-textured area. Interstitial blebs of sulphide minerals (millerite-silicate intergrowths) are restricted to the coarse-grained part of the rock. It is possible that this sample represents incomplete recrystallization of a coarse-grained garnet websterite. This would account for the variable textural features observed. The presence of garnet exsolution indicates that the sample may not have reached equilibrium.

JSL 252 contains both primary spinel (picotite) and garnet. The rock is coarse-grained, but contains a distinct porphyroclastic component. Neoblast development is most prominent around the clinopyroxene. The spinel is rust-brown in colour, anhedral to irregular in shape and the largest bleb is 6mm long. The spinel is always surrounded by granuloblastic-textured garnet, although not as clearly defined rims (Plate 23). Widespread development of kelyphite around these garnets can be observed. Minor oriented inclusions of rutile(?) are again present in the large grains of garnet and clinopyroxene, but not in the smaller grains.

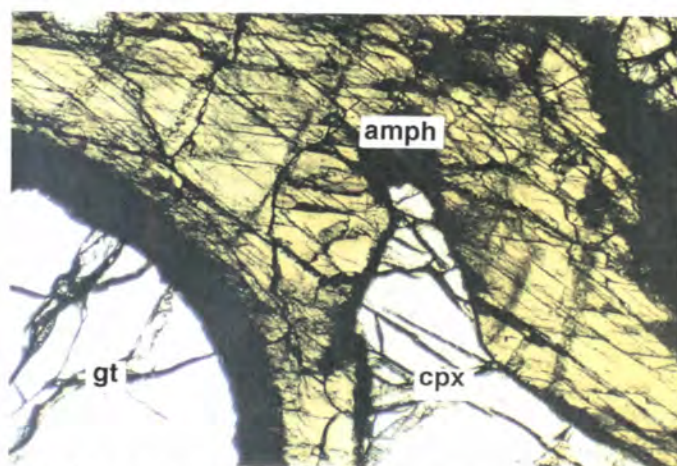


Plate 20: A large plate of primary metasomatic edenitic hornblende (amph) in a garnet clinopyroxenite (JSL 180). Other phases include garnet (gt) and clinopyroxene (cpx). Field of view = 4mm wide. Plane polarised light.

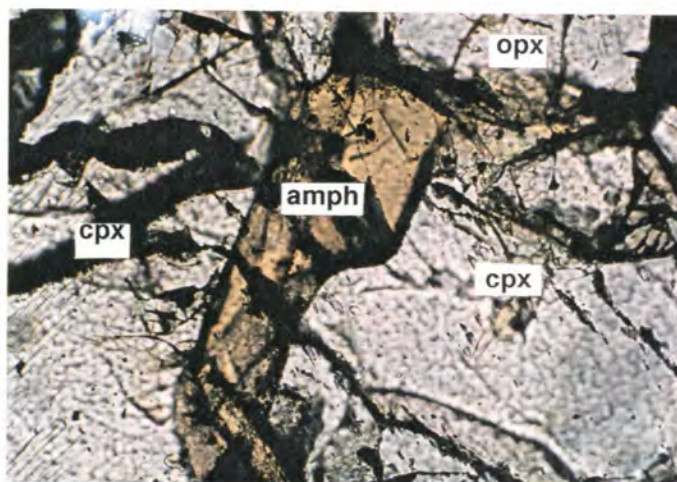


Plate 21: Brown, pleochroic secondary metasomatic pargasitic hornblende (amph) wedged between two clinopyroxene grains (cpx) and an orthopyroxene grain (opx) in a garnet websterite (JSL 75). Note the smaller size and different colour, in comparison with the amphibole in Plate 20. Field of view = 0.9mm wide. Plane polarised light.

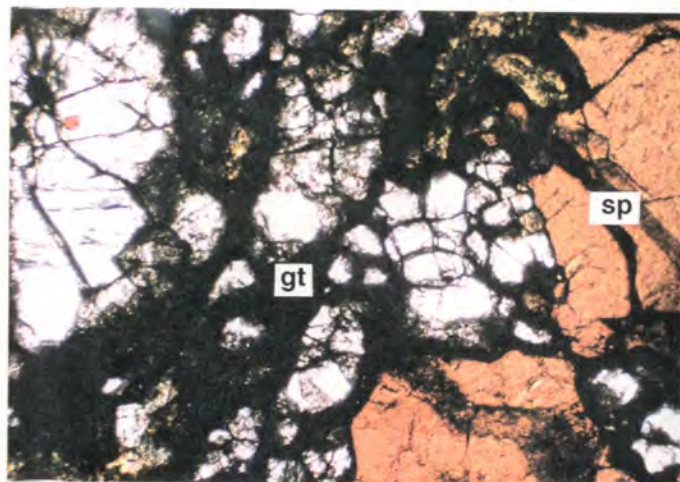


Plate 23: A garnet-spinel-bearing metasomatized pyroxenite (JSL 252) showing brown Al-spinel (sp) surrounded by colourless garnet (gt). Field of view = 3.5mm wide. Plane polarised light.

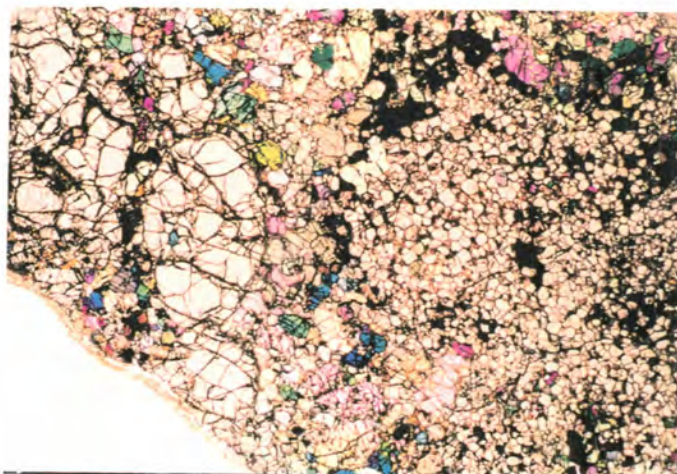


Plate 22: A garnet websterite (JSL 75) illustrating the change in texture from coarse (left) to granuloblastic (right). Nicols are partially crossed and the field of view is approximately 19mm wide. Birefringent minerals include orthopyroxene and clinopyroxene and the dark patches represent altered material and/or minor sulphides. Rutile is present in the granuloblastic-textured area, but difficult to observe in this plate.

Most orthopyroxenes exhibit undulose extinction, whereas a single orthopyroxene grain shows evidence of being replaced by kinked, secondary metasomatic phlogopite. Metasomatic phlogopite laths are in abundance and oriented, acicular inclusions of an unidentified mineral (calcite?) occur in several of these phlogopite plates. Rare, discrete rutile grains (<0.3mm) are associated with the metasomatized areas. It is suggested that JSL 252 underwent a period of either: 1) increase in pressure or, 2) a decrease in temperature, to account for the disequilibrium texture of spinel surrounded by garnet.

3.3 Mineral chemistry

Analyses were performed on the JEOL 733 microprobe at Rhodes University, the analytical details of which can be found in Appendix 1. Repeat analyses of olivine and orthopyroxene in some xenoliths were also performed on a Cameca SX-50 microprobe at the Anglo American Research Laboratories and compared to results of the same phases analysed at Rhodes. The comparisons are listed in Appendix 1. All analyses represent mineral cores, unless stated otherwise. Each point in the various plots and histograms represents an average of several mineral analyses, e.g. clinopyroxene, from a particular xenolith. The average values plotted in this chapter and the standard deviation about the mean can be found in Appendix 3. Single analyses of all phases are available on the diskette in the back folder.

In xenoliths which have been studied in great detail, e.g. JSL 500, evidence for chemical zonation within individual grains was specifically sought, but seldom found to be significant. Zoning is most commonly present in phases such as phlogopite, spinel or ilmenite, and commonly only in the rims, suggesting a secondary origin. Intergrain variations are more common, as indicated by the standard deviation of Cr_2O_3 in clinopyroxene (Section 3.4.3). In diagrams summarising the compositional data, analytical uncertainty is indicated by error bars where necessary and a key to symbols used in the plots is available in the back folder.

Constant comparison will be made throughout this section with the mineral compositions of phases in phlogopite-free garnet peridotites as described in Chapter 2. The term "phlogopite-bearing peridotite" used in this section will include garnet phlogopite peridotites (GPP), phlogopite peridotites (PP) and veined peridotites. "Phlogopite-free peridotites" will refer to the garnet peridotites (GP) described in the previous chapter. This includes garnet lherzolites and garnet harzburgites. The spinel peridotite suite is regarded as being totally separate from the garnet peridotites and is treated as a distinct rock suite (Chapter 2). The garnet-free lherzolite (JSL 306, see Table 2.1 and Chapter 2, Section 2.2.2) is excluded from the phlogopite-free peridotite group, due to the fact that it may have been affected by metasomatism.

3.3.1 Olivine

All olivines from metasomatized (i.e. phlogopite-bearing) peridotites are forsteritic (Mg-number = 88-94, Fig. 3.1). There is a greater range in the Mg-number of olivines from phlogopite-bearing peridotites, caused by the PP suite, when compared to the olivines in the phlogopite-free peridotites (Fig. 3.2). Olivines in a GPP, JSL 143, and a banded PP, JSL 516 (Sections 3.2.1 and 3.2.3), exhibit Mg-numbers of 93.

The NiO- and MnO-contents of olivine in GPP and PP xenoliths vary from 0.26-0.44 wt% and 0.07-0.19 wt% respectively. CaO-values are mostly close to detection limits and can therefore not be interpreted reliably.

Olivine in the metasomatized peridotites from Kimberley exhibits broadly similar compositional features. However, the total number of samples containing primitive (Mg-number ≥ 93) olivine is smaller than at Letlhakane. This may, in part, be owing to the exclusion of garnet harzburgites from the xenoliths studied by Waters (1987a) and Erlank et al. (1987).

3.3.2 Orthopyroxene

Orthopyroxenes from GPP and PP xenoliths exhibit a restricted range in Mg-number (90-94), which is similar to orthopyroxene from phlogopite-free peridotites, including the deformed peridotites (Chapter 2, Section 2.3.2 and Fig. 3.3). Orthopyroxene from the metasomatized harzburgite, JSL 143, is characterized by a Mg-number of 94, similar to orthopyroxene from other harzburgites. The veined (JSL 500) and extensively metasomatized (JSL 511) peridotites contain orthopyroxene with Mg-numbers of ± 90.5 , i.e. more Fe-rich than those in the coarse-grained GPP and PP xenoliths. This correlates with their Fe-rich olivine composition (Section 3.3.1 and Fig. 3.2). Orthopyroxenes and their recrystallized neoblasts in JSL 500 are all homogeneous. CaO concentrations extend from 0-0.6 wt% and are broadly similar to those of the phlogopite-free peridotites. The composition of orthopyroxenes in the Letlhakane peridotites is similar to those from the Kimberley xenoliths (Table I in Erlank et al., 1987). Fig. 3.4 illustrates a general increase in TiO_2 -content of orthopyroxene from the garnet harzburgites through other coarse-grained peridotites to the deformed peridotites. Orthopyroxene from phlogopite-bearing peridotites, however, spans the entire range from 0 to 0.17 wt% TiO_2 . The Cr_2O_3 -content of orthopyroxene varies from 0 to 0.5 wt% (see Fig. 3.5) and shows an overlap in composition with orthopyroxene from non-metasomatized peridotites. The Al_2O_3 -content of orthopyroxene in metasomatized peridotites is < 1 wt% and therefore distinct from that in the spinel peridotites (1-3 wt% Al_2O_3), but similar to orthopyroxene from other peridotites. From the above, it is clear that no significant differences exist in the TiO_2 , CaO, Na_2O , Al_2O_3 or Cr_2O_3 contents of orthopyroxenes from metasomatized and non-metasomatized peridotites.

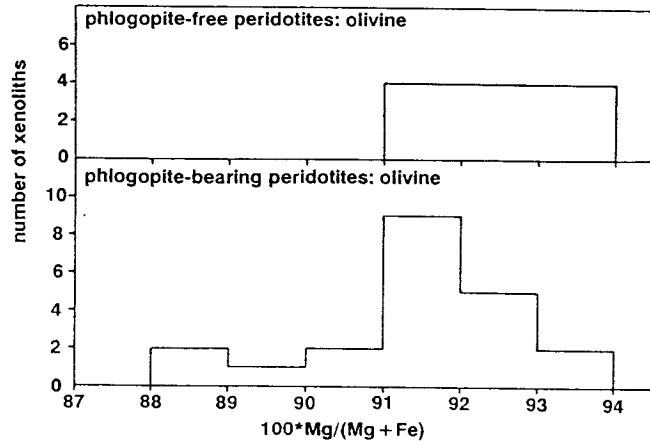


Fig. 3.1 Histograms of the Mg-number of olivine in phlogopite-free and phlogopite-bearing peridotites from Letlhakane.

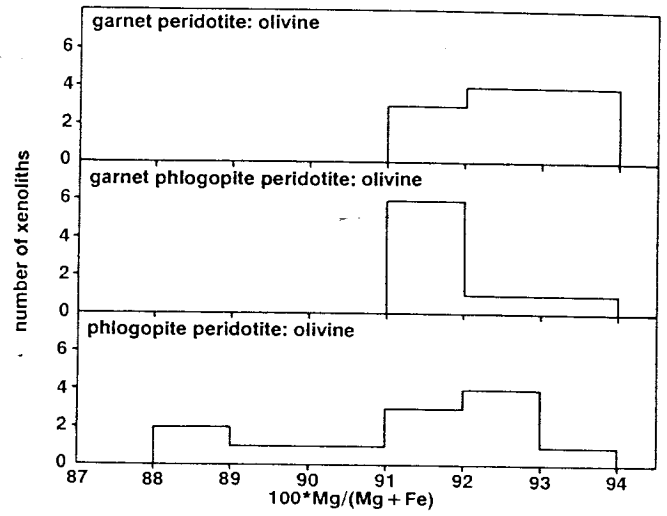


Fig. 3.2 Histograms of the Mg-number of olivine in GP, GPP and PP xenoliths from Letlhakane.

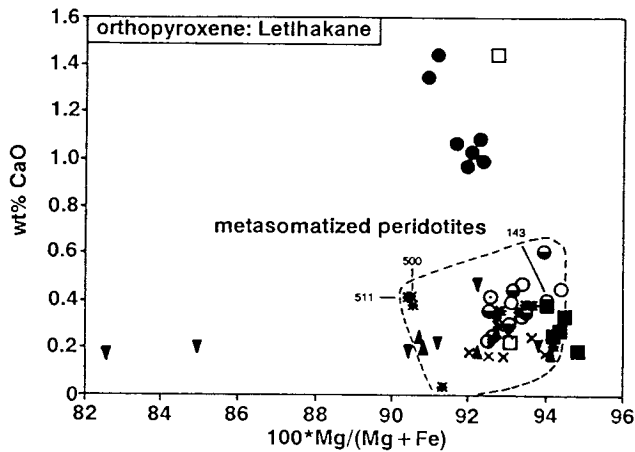


Fig. 3.3 Wt% CaO vs. Mg-number of orthopyroxenes from phlogopite-free and metasomatized (dashed field) peridotites and pyroxenites. Note the similarity of orthopyroxene compositions from both the metasomatized and non-metasomatized xenoliths.

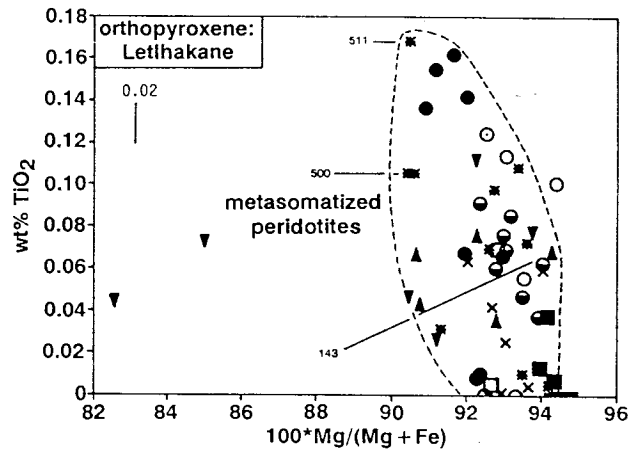


Fig. 3.4 Wt% TiO₂ vs. Mg-number of orthopyroxenes from phlogopite-free and metasomatized (dashed field) peridotites and pyroxenites. The 2σ error = 0.02wt% TiO₂.

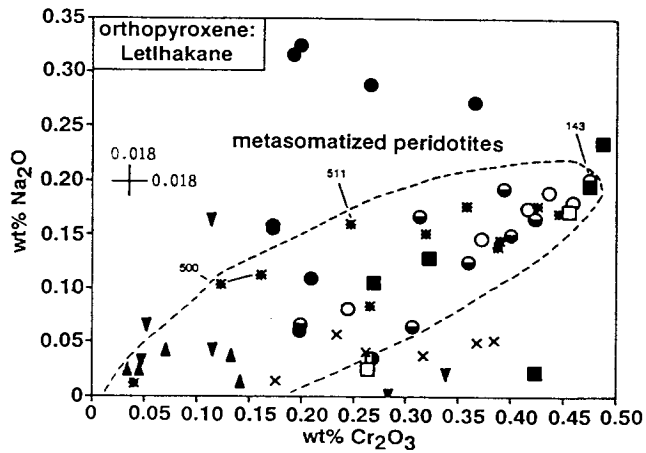


Fig. 3.5 Wt% Na_2O vs. wt% Cr_2O_3 for orthopyroxene from phlogopite-free and metasomatized (dashed field) peridotites and pyroxenites. Note that the orthopyroxene neoblasts in JSL 500 exhibit slightly elevated Cr_2O_3 and Na_2O , compared to the original orthopyroxene, but this is of little significance when compared to the 2σ error of Na_2O and Cr_2O_3 (both 0.018wt%).

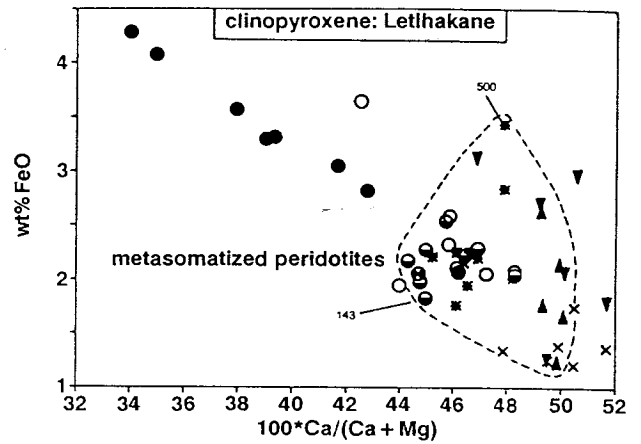


Fig. 3.6 Wt% FeO vs. $100 \cdot \text{Ca}/(\text{Ca} + \text{Mg})$ of clinopyroxene from phlogopite-free and metasomatized (dashed field) peridotites and pyroxenites. Note the clustering of coarse-textured peridotites between Ca-numbers of 44 and 48 (with a single exception). No significant differences between clinopyroxenes from phlogopite-free and phlogopite-bearing peridotites exist.

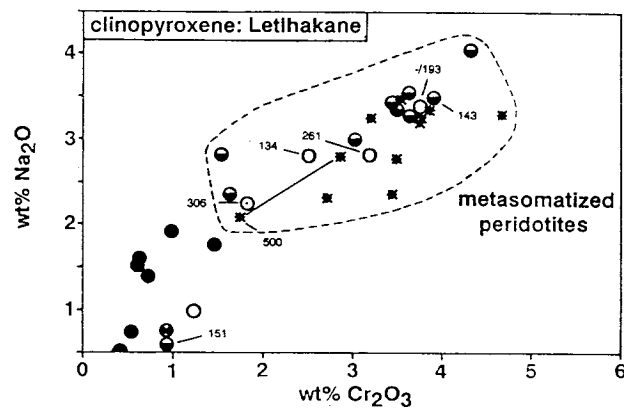


Fig. 3.7 Wt% Na_2O vs. wt% Cr_2O_3 in clinopyroxene from phlogopite-free and phlogopite-bearing peridotites. The spinel peridotites and pyroxenites have been excluded to avoid cluttering the diagram. These rocktypes are plotted in Fig. 2.10. Note that, with a few exceptions, clinopyroxene from metasomatized peridotites is restricted to higher Cr_2O_3 and Na_2O compositions as indicated by the dashed field.

3.3.3 Clinopyroxene

Fig. 3.6 illustrates the large variation in the Ca-number ($100 \cdot \text{Ca}/(\text{Ca} + \text{Mg})$) of clinopyroxenes from the peridotite-pyroxenite suite (34-52). Note that clinopyroxene from most of the coarse-grained peridotites is similar in composition with respect to FeO and Ca-number, but as a group is distinctly different in composition from clinopyroxene in the deformed peridotites. Clinopyroxenes in deformed peridotites are more Fe-rich and exhibit lower Ca-numbers than clinopyroxenes in metasomatized peridotites. The TiO_2 - and Al_2O_3 -contents of clinopyroxene in the phlogopite-bearing peridotites vary between 0 and 0.4 wt% and 1 and 4 wt% respectively (not shown). The lower Al_2O_3 -content of peridotitic clinopyroxene distinguishes it from that of the spinel peridotites and pyroxenites (see Chapter 2, Fig. 2.9). Zonation of Al_2O_3 and Cr_2O_3 in clinopyroxene from the websterites is highly variable (Table 3.2) in comparison with the zoning of clinopyroxene in the peridotites, and the absence of any covariance precludes explanation of these changes by pure Cr^{3+} - Al^{3+} substitution. Na_2O in websteritic clinopyroxene mostly decreases towards the rim, but with some exceptions.

A plot of wt% Cr_2O_3 vs. wt% Na_2O in clinopyroxene (Fig. 3.7) is able to differentiate between clinopyroxene from phlogopite-free (i.e. GP) and phlogopite-bearing peridotites (GPP and PP). Also of note is the large difference in composition between the symplectic and anhedral clinopyroxenes of veined peridotite JSL 500, described in Section 3.2.3, particularly with respect to Cr_2O_3 , Na_2O , CaO and MgO . The Ca- and Mg-numbers of these two clinopyroxene types are similar, however. The presence of high- Cr_2O_3 , high- Na_2O clinopyroxene in JSL 143, a mildly subcalcic harzburgite, is also significant. Clinopyroxene is the only mineral common to both phlogopite-free and phlogopite-bearing peridotites whose composition affords reasonable distinction between these rock suites. Spinel peridotites, pyroxenites and deformed peridotites have been excluded from Fig. 3.7 for greater clarity, but data from these xenoliths are shown in Chapter 2, Fig. 2.10. It can be inferred from Fig. 3.7 that primary metasomatic phlogopite (Section 3.3.7) is mostly associated with a high- Cr_2O_3 , high- Na_2O clinopyroxene. There are, however, a few samples containing high- Cr_2O_3 clinopyroxene, but no phlogopite, e.g. JSL 134,-/193, 261 and 306. A possible explanation for this feature will be provided in Section 3.4.2.

The presence of Fe^{3+} in clinopyroxene also affords reasonable distinction between the metasomatized and non-metasomatized peridotite suites. The method of calculating Fe^{3+} in clinopyroxene is presented as a flow diagram in Fig. 3.8. This method is based on the assumption that any extra Na remaining after the formation of the $\text{NaTi}(\text{Si},\text{Al})\text{O}_6$, $\text{NaCrSi}_2\text{O}_6$ and $\text{NaAlSi}_2\text{O}_6$ molecules, will bond with Fe^{3+} to form $\text{NaFe}^{3+}\text{Si}_2\text{O}_6$ molecules. Fig. 3.9 represents a ternary plot of the calculated minor end-member components of acmite ($\text{NaFe}^{3+}\text{Si}_2\text{O}_6$), jadeite ($\text{NaAlSi}_2\text{O}_6$) and ureyite ($\text{NaCrSi}_2\text{O}_6$). Also note the higher Cr-content shown by these clinopyroxenes in Fig. 3.7, represented here as a higher ureyite

Table 3.2: Zoning in metasomatic clinopyroxene

Sample	JSL 111		JSL 180		JSL 252	
	core	rim	core	rim	core	rim
SiO ₂	54.75	54.83	53.84	54.08	53.47	53.89
TiO ₂	0.30	0.35	0.09	0.10	0.44	0.44
Al ₂ O ₃	2.81	3.27	1.88	2.12	4.37	3.43
Cr ₂ O ₃	3.69	3.64	0.25	0.22	0.50	0.40
FeO	2.54	2.48	2.74	2.90	1.11	1.00
MnO	0.06	0.05	0.05	0.04	0.00	0.01
NiO	0.03	0.02	0.08	0.04	0.03	0.02
MgO	15.58	15.04	16.96	16.67	16.00	16.37
CaO	17.73	17.09	23.05	22.73	21.90	22.10
Na ₂ O	3.20	3.61	1.14	1.27	1.66	1.43
Total	100.70	100.39	100.09	100.17	99.49	99.09

Table 3.3: Zoning in Cr-spinel

Sample	JSL 143		JSL 532		JSL 533		JSL 547		JSL 565	
	core	rim	core	rim	core	rim	core	rim	core	rim
TiO ₂	1.74	1.76	0.94	1.93	1.44	1.47	2.22	2.20	2.65	2.22
Al ₂ O ₃	7.51	7.61	1.12	2.20	8.42	8.73	6.18	6.12	5.99	5.43
Cr ₂ O ₃	58.29	58.35	63.95	61.21	56.89	57.18	60.75	60.26	55.60	57.26
FeO (P)	18.21	18.78	24.00	23.18	20.02	18.96	16.77	17.22	23.68	22.51
FeO (C)	13.81	14.36	19.22	18.17	16.09	15.17	14.11	14.66	18.13	17.46
Fe ₂ O ₃	4.89	4.92	5.31	5.51	4.37	4.22	2.95	2.85	6.17	5.61
MnO	0.27	0.29	0.43	0.33	0.28	0.27	0.29	0.28	0.31	0.26
NiO	0.15	0.14	0.08	0.12	0.09	0.16	0.16	0.14	0.13	0.10
MgO	13.44	13.20	8.62	10.01	11.74	12.42	13.38	12.89	10.93	11.00
Total:P	99.61	100.14	99.14	98.99	98.88	99.19	99.75	99.12	99.30	98.78
Total:C	100.10	100.63	99.67	99.55	99.32	99.62	100.05	99.41	99.91	99.35

content. Most phlogopite-free peridotites contain almost no detectable acmite component. However, a few phlogopite-free peridotites, e.g. JSL 134, 261 and 306, contain clinopyroxene displaying higher levels of Fe^{3+} , in addition to higher Cr_2O_3 and Na_2O (Fig. 3.7). This feature will be discussed in Section 3.4.2.

The presence of Fe^{3+} in clinopyroxenes from the metasomatized peridotites can also be inferred from Fig. 3.10 through the use of atomic Na and (Al + Cr). This plot is based on the same principle as Fig. 3.9, i.e. Na^+ substitution in clinopyroxene requires an additional trivalent cation, probably Fe^{3+} , to maintain the charge balance. Note that the clinopyroxene from most of the phlogopite-bearing peridotites plot on, or to the left of the 1:1 line, suggesting the presence of Fe^{3+} .

3.3.4 Garnet

The major types of garnet present in the peridotite-pyroxenite suite are described in Chapter 2, Section 2.3.4. Garnets in the GPP suite belong to the common Cr-pyrope group, with the exception of sample JSL 572, which contains Ti-pyrope, common in the deformed peridotites, despite its coarse grain size.

Fig. 3.11 illustrates the CaO- and Cr_2O_3 -contents of GPP garnets compared to garnets in the phlogopite-free rocks. Note that garnet in JSL 143 plots to the left of the 85% (hercynite) line. The plot reveals that the composition of garnet from phlogopite-bearing and phlogopite-free peridotites is indistinguishable on the basis of CaO and Cr_2O_3 concentrations. Fig. 3.12 illustrates a similar feature for TiO_2 and also indicates the high-Ti nature of garnet in JSL 572. Garnets in this sample exhibit considerable compositional heterogeneity and they also exhibit unusual angular fragmented textural features (Section 3.2.1 and Plate 8). The small size and altered nature of these fragments precluded detailed examination of possible compositional zonation in the grains. The large amounts of serpentine and high-Ti phlogopite in this sample indicate that secondary metasomatic processes were active at some stage. The possibility that the high TiO_2 concentrations in garnet were derived from secondary processes can therefore not be excluded.

Garnets from the amphibole-bearing pyroxenites contain low Cr_2O_3 , TiO_2 (Figs. 3.11 and 3.12) and Na_2O (not shown). However, these features are typical of all pyroxenitic garnets and cannot be used to discriminate metasomatized from non-metasomatized samples.

End-member calculation for clinopyroxenes

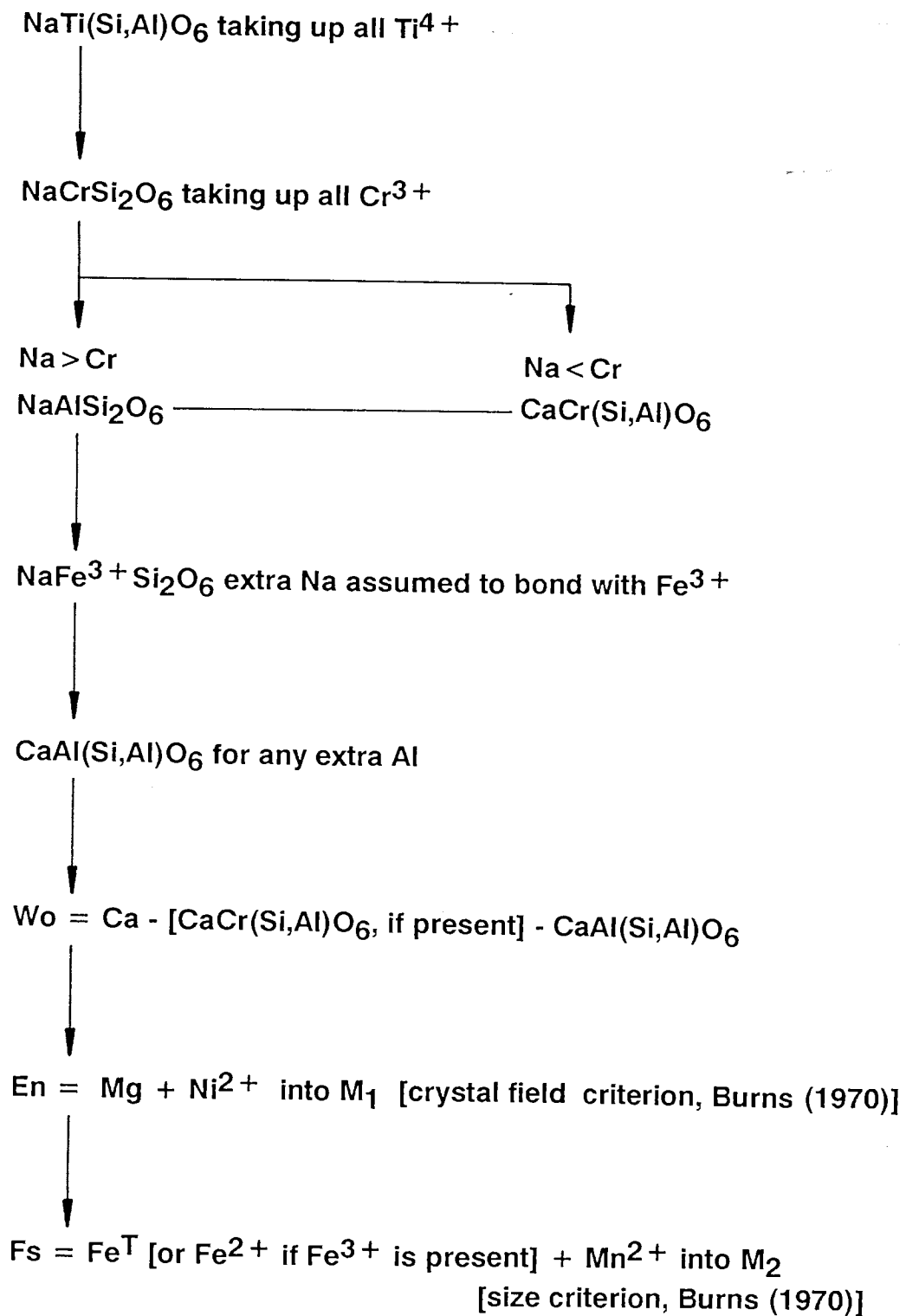


Fig. 3.8 A flow diagram illustrating the method of end-member calculation for peridotitic and pyroxenitic clinopyroxene.

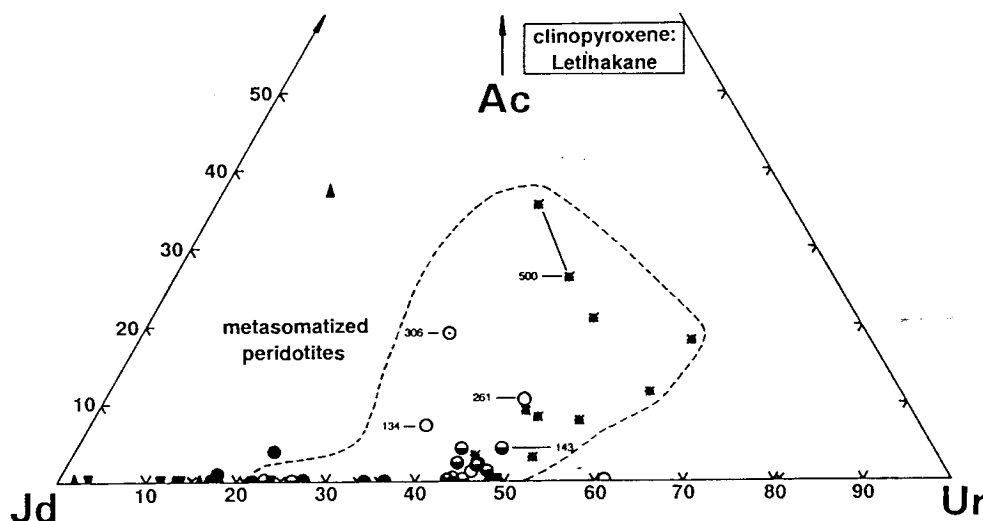


Fig. 3.9 A ternary plot of mole% acmite, jadeite and ureyite, illustrating the higher Fe^{3+} -content of clinopyroxene in metasomatized peridotites.

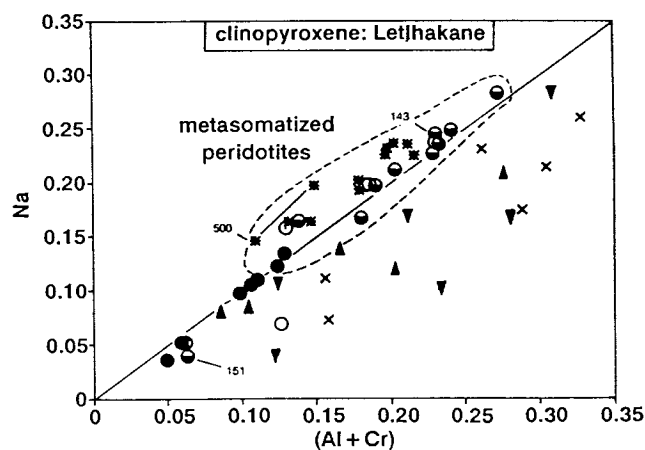


Fig. 3.10 Atomic Na vs. (Al+Cr) in clinopyroxene from phlogopite-free and phlogopite-bearing (metasomatized) peridotites. Clinopyroxenes plotting to the left of the 1:1 line may contain some Fe^{3+} .

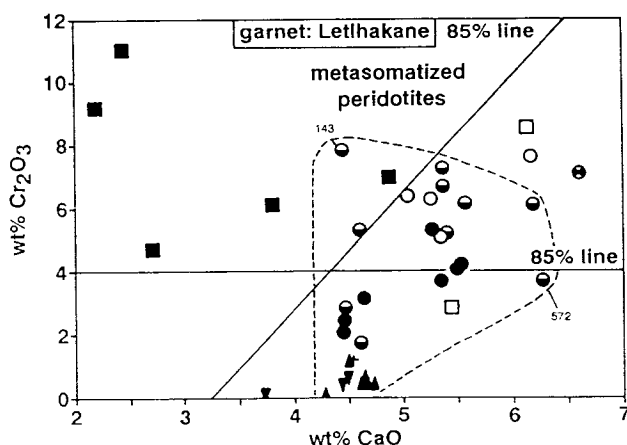


Fig. 3.11 Wt% Cr_2O_3 vs. wt% CaO in garnet. The 85% line is discussed in Chapter 2, Section 2.3.4. Note the composition of garnet in the phlogopite-bearing sample, JSL 143. The dashed field encloses garnets from metasomatized peridotites and pyroxenites.

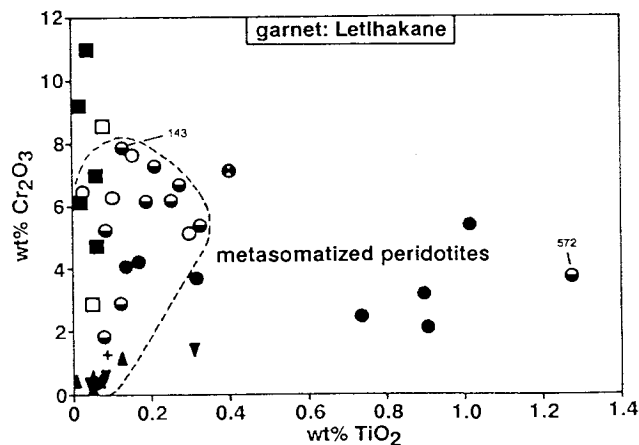


Fig. 3.12 Wt% Cr_2O_3 vs. wt% TiO_2 in garnet. No clear distinction between phlogopite-free and phlogopite-bearing peridotites or pyroxenites can be drawn. Note the high TiO_2 -content of garnet in JSL 572. The dashed field encloses garnets from metasomatized peridotites and pyroxenites.

3.3.5 Spinel

Spinel is a ubiquitous phase in many phlogopite-bearing peridotites. The characteristic features of true spinel lherzolites, as opposed to these phlogopite-bearing varieties, are discussed in Chapter 2, Section 2.2.3. There are numerous petrographic differences between the spinel in the spinel lherzolites (*sensu stricto*) and that in the phlogopite-bearing peridotites, most notably with respect to colour, habit and mode of occurrence of the spinel (Chapter 2, Section 2.2.3 and Section 3.2.2). Differences in composition would therefore also be expected.

Fig. 3.13 illustrates that the majority of spinel from the GPP and PP xenoliths contain >45 wt% Cr_2O_3 and <15 wt% MgO. Spinel from JSL 143 and 113, both subcalcic harzburgites, contains 58.3 and 59.9 wt% Cr_2O_3 respectively. Note the difference in composition between the primary spinel and that from the garnet kelyphite rims in JSL 113 (Fig. 3.13 and 3.14). Three types of spinel have been found in JSL 111. The average Cr_2O_3 -content of these three types are 48, 36 and 20 wt% respectively, with standard deviations about the mean of each type being 2.68, 1.59 and 4.71 wt% Cr_2O_3 respectively (Fig. 3.13). The intergrain variation in Cr_2O_3 between these spinel types is therefore quite large. All three types occur as discrete grains, although the latter appears to be associated with secondary metasomatic processes. Secondary metasomatic spinels from Letlhakane are characterized by lower Cr_2O_3 , higher MgO and higher Fe_2O_3 .

Considerable differences exist between the different spinel types with respect to calculated Fe_2O_3 -contents, as shown in Fig. 3.14. Secondary metasomatic spinel, associated with kelyphite development in garnet, contains Cr_2O_3 -values overlapping those of spinels in the spinel lherzolites, but considerably higher Fe_2O_3 . Coarse, primary metasomatic spinels contain the highest Cr_2O_3 -levels, as well as high MnO (not shown) and TiO_2 concentrations (Fig. 3.15), which partially overlap with those of the secondary metasomatic spinels. Zoning trends in selected spinels are shown in Table 3.3. The zoning is extremely irregular with TiO_2 and Cr_2O_3 both increasing and decreasing towards the rims.

3.3.6 Ilmenite and rutile

In contrast to spinel, ilmenite is a rare phase in the GPP and PP xenoliths and the amphibole-bearing pyroxenites. However, it is common in the veined peridotites, e.g. JSL 500, where it occurs in great abundance.

Ilmenite from both the veined (JSL 500) and mica-rich (JSL 511) xenoliths is characterized by elevated Cr_2O_3 -contents, as shown in Fig. 3.16., and heterogeneous compositions, especially at the rims, as shown by the zoning traverse in Table 3.4. Table 3.5 illustrates zoning trends in discrete ilmenite grains from

JSL 500 and JSL 511. Calculated Fe_2O_3 appears to increase consistently towards the rims. Trends with respect to other oxides are irregular. The results of rim analyses should be treated with caution, owing to the possibility of overprinting by any secondary processes that may have occurred.

A single amphibole-bearing garnet websterite (JSL 110) contains discrete grains of ilmenite and rutile. The Cr_2O_3 -content of the ilmenite is approximately 4.5 wt% and similar to that of peridotitic ilmenite from Kao (MacGregor, 1979), as shown in Fig. 3.16. The rutiles (not shown) also contain significant amounts of Cr_2O_3 (1.7-2.3 wt%). The FeO-content of rutile is highly variable, ranging between 0.12 and 2.24 wt%. Due to the small size of the grains and the common exsolution features, especially in rutile, a study of possible zoning features was not attempted.

3.3.7 Phlogopite

The TiO_2 -contents of primary metasomatic phlogopite range between the detection limit of approximately 0.10 up to 0.97 wt% and MgO varies from 25.1 to 26.6 wt%. Secondary metasomatic phlogopite may contain up to 4.5 wt% TiO_2 and up to 16 wt% Al_2O_3 . The distinction between primary and secondary metasomatic phlogopite from Letlhakane can be inferred from the Cr_2O_3 and TiO_2 concentrations of the phlogopite in these two suites (Fig. 3.17). Note that primary metasomatic phlogopite is characterized by low Cr_2O_3 and TiO_2 concentrations, compared to secondary metasomatic phlogopite. Figs. 3.17 and 3.18 also illustrate the variable composition of secondary metasomatic phlogopite in terms of Cr_2O_3 , Al_2O_3 and TiO_2 , in comparison with primary metasomatic phlogopite. Fig. 3.17 shows that primary metasomatic phlogopite from Letlhakane is similar in composition to that from other xenolith samples in southern Africa (Delaney et al., 1980).

Primary metasomatic phlogopite in JSL 143 exhibits surprisingly little zonation. Only the extreme outer edges of the grains exhibit a slight increase in Na_2O and, less noticeably, TiO_2 . JSL 111 and 142, however, contain some clearly zoned primary metasomatic phlogopite. In these phlogopites TiO_2 , Al_2O_3 and Cr_2O_3 increase notably at the rims. Zoning is most severe where the phlogopite is in contact with altered material in the rock, but markedly less when in contact with a primary mineral phase, e.g. in JSL 142 (Table 3.6). The observation that these compositional changes are restricted to the rims of the grains only and associated with secondary material, leads to the conclusion that the zonation was caused by secondary metasomatic effects.

Phlogopite is a ubiquitous phase in the metasomatized peridotites and this warrants some discussion. The distinction between primary and secondary metasomatic phlogopite has long been the subject of investigation (Carswell, 1975; Delaney et al., 1980; Erlank et al., 1987). Carswell (1975) noted that the

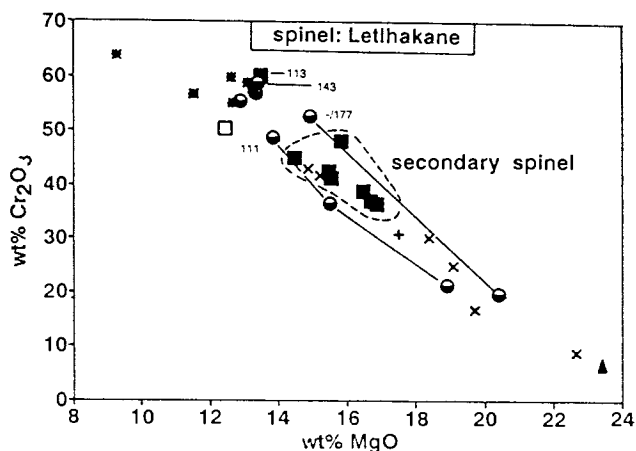


Fig. 3.13 Wt% Cr_2O_3 vs. wt% MgO in spinel. Spinel in spinel herzolites (Chapter 2) is compared to spinel from phlogopite-bearing peridotites and secondary, kelyphitic spinels from JSL 113 (dashed field). Tielines join co-existing primary and secondary spinels from JSL-177 and three types of spinel from JSL 111. Note that spinel from PP xenoliths contains the highest Cr_2O_3 and lowest MgO values.

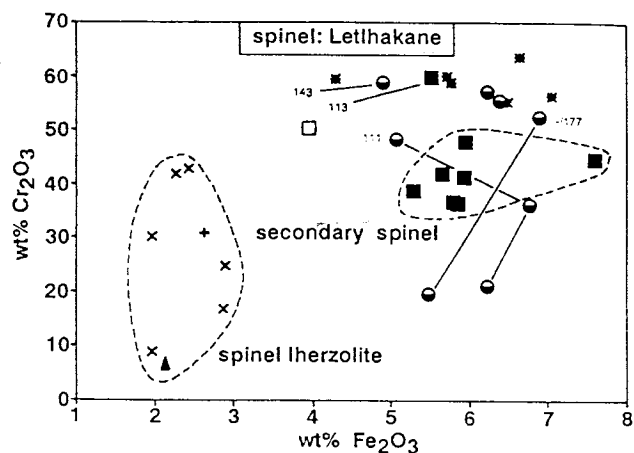


Fig. 3.14 Wt% Cr_2O_3 vs. wt% Fe_2O_3 in spinel. Note the difference in Fe_2O_3 -content of spinels from spinel herzolites when compared to spinel from the phlogopite-bearing peridotites.

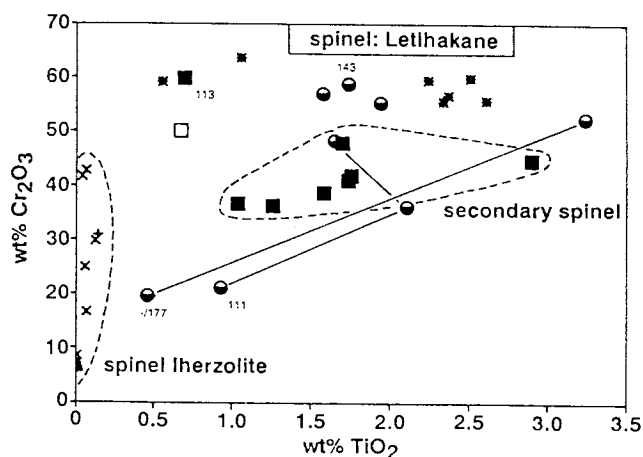


Fig. 3.15 Wt% Cr_2O_3 vs. wt% TiO_2 in spinel. Note the low TiO_2 in spinels from spinel herzolites (Chapter 2) compared to those of the phlogopite-bearing peridotites.

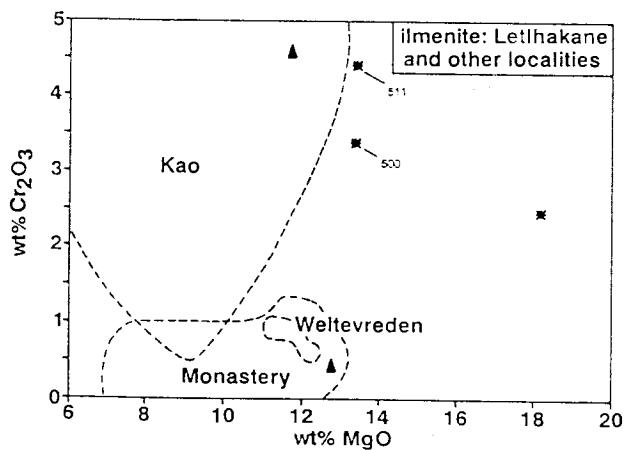


Fig. 3.16 Wt% Cr_2O_3 vs. wt% MgO in ilmenite from metasomatized peridotites and a pyroxenite. Letlhakane data are compared to ilmenite megacrysts (Monastery), orthopyroxene-ilmenite intergrowths (Weltevreden) and peridotitic ilmenites (Kao). Data sources include MacGregor (1979), Gurney et al. (1979) and Rawlinson and Dawson (1979).

Table 3.4: Traverse across an ilmenite vein in JSL 500B. Ilmenite at 1 and 5 is in contact with olivine and secondary serpentine respectively.

Sample	JSL 500B				
	1	2	3	4	5
TiO ₂	54.21	54.23	54.09	53.93	56.98
Al ₂ O ₃	0.26	0.24	0.18	0.21	1.17
Cr ₂ O ₃	2.99	2.93	2.93	2.97	2.44
FeO (P)	28.39	28.83	28.95	29.18	20.62
FeO (C)	25.19	25.46	25.54	25.49	17.66
Fe ₂ O ₃	3.56	3.74	3.79	4.10	3.30
MnO	0.23	0.21	0.21	0.27	0.25
NiO	0.18	0.21	0.15	0.18	0.13
MgO	13.00	12.84	12.77	12.66	18.63
Total:P	99.26	99.48	99.26	99.39	100.22
Total:C	99.61	99.86	99.64	99.80	100.55

Table 3.5: Zoning in discrete ilmenite grains

Sample	JSL 500B		JSL 511A		JSL 511A	
	core	rim	core	rim	core	rim
TiO ₂	54.03	54.35	54.00	54.19	55.02	54.44
Al ₂ O ₃	0.18	0.16	0.20	0.15	0.45	0.26
Cr ₂ O ₃	4.44	4.28	4.51	3.98	3.19	3.05
FeO (P)	27.11	27.41	25.91	25.87	26.37	28.02
FeO (C)	23.93	23.91	23.11	22.48	24.49	24.92
Fe ₂ O ₃	3.54	3.88	3.11	3.77	2.09	3.44
MnO	0.20	0.21	0.24	0.22	0.17	0.16
NiO	0.19	0.19	0.24	0.21	0.15	0.17
MgO	13.62	13.78	14.01	14.49	13.84	13.30
Total:P	99.76	100.39	99.11	99.12	99.19	99.39
Total:C	100.12	100.78	99.42	99.49	99.40	99.74

primary metasomatic plates are large and show apparent equilibrium towards other primary phases. Delaney et al. (1980) pointed out that zoning is absent in primary metasomatic phlogopite. In terms of composition, primary metasomatic phlogopite has lower TiO_2 , Cr_2O_3 , Al_2O_3 , $\text{Fe}^{2+}/\text{Mg}^{2+}$ and Na^+/K^+ ratios, but a higher SiO_2 -content than secondary phlogopite (Chapter 1, Section 1.4.1).

Previous studies also suggest that phlogopites associated with kelyphite rims around garnet are of secondary origin. Primary metasomatic phlogopite does, however, occur in contact with garnet (Delaney et al., 1980, and this study), but can be distinguished by its larger grain size and composition. Secondary phlogopite may also be found as rims around clinopyroxene, in veinlets associated with serpentine, and as rims around primary micas (Carswell, 1975).

3.3.8 Amphibole

Amphibole occurs in only four samples, all of which are garnet websterites. In any one xenolith amphibole compositions are uniform, but in JSL 110 the amphibole exhibits slight compositional variation, e.g. TiO_2 ranges from 0.83 to 0.90 wt% and FeO varies between 3.58 and 4.17 wt%. Fig. 3.19 illustrates the compositional differences between the two amphibole groups as described in Section 3.2.4 and shown in Plates 20 and 21. The large amphibole plates (edenitic hornblendes) plot in a tight cluster at 10.7 wt% CaO and 11 wt% Al_2O_3 , while the smaller, intergrain strip of amphibole in JSL 75 plots at a higher Al_2O_3 value and is classified (after Leake, 1978) as a pargasitic hornblende. The edenitic hornblendes plot within the compositional field of amphibole from the Jagersfontein lherzolites (Fig. 3.19). No consistent zoning can be observed in individual grains. The irregular nature of the grains also prevented exact location of the core.

Raase (1974) and Hynes (1982) showed that the Al and Ti contents in amphibole are influenced by temperature and pressure, and that low-pressure amphiboles contain significantly more Ti than high-pressure amphiboles. This was indeed found to be the case in the Letlhakane amphiboles. The secondary metasomatic pargasitic hornblende in JSL 75 (Section 3.2.4) contains 2.4 wt% TiO_2 , compared to 0.45-0.90 wt% TiO_2 in the primary metasomatic edenitic hornblende. Employing the WE77/FB84 geothermobarometer combination (Chapter 6, Section 6.3), it appears that the pyroxenites containing the edenitic hornblendes equilibrated at <25 kb (approximately 65 km). This is consistent with the stability fields for phlogopite and various amphibole types shown in Fig. 3.20.

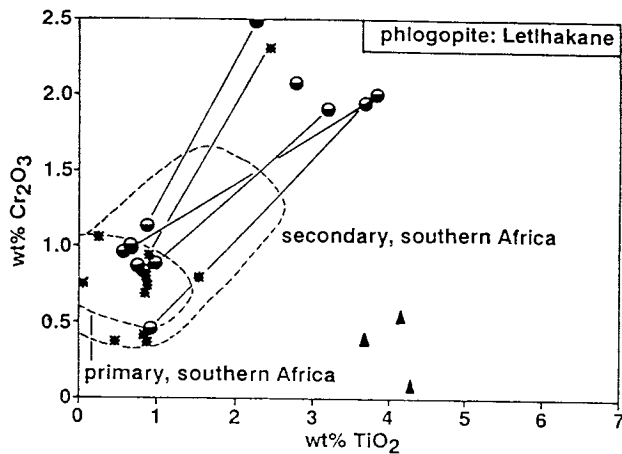


Fig. 3.17 Wt% Cr_2O_3 vs. wt% TiO_2 in phlogopite. Large, texturally equilibrated grains are depleted in TiO_2 and considered to be of primary metasomatic origin. Smaller grains are more variable in composition and contain higher TiO_2 . Note the difference in Cr_2O_3 content of secondary phlogopite in peridotites and pyroxenites. Tielines join co-existing primary and secondary metasomatic phlogopite. Other data from Delaney et al. (1980).

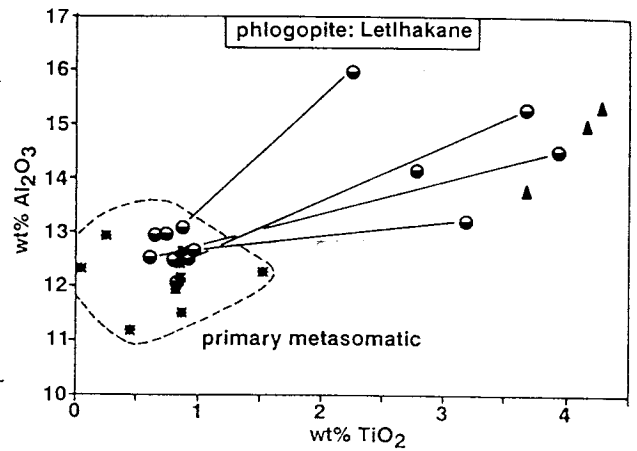


Fig. 3.18 Wt% Al_2O_3 vs. wt% TiO_2 in phlogopite. Secondary, high- TiO_2 phlogopite is also characterized by a higher Al_2O_3 content. Tielines join co-existing phases.

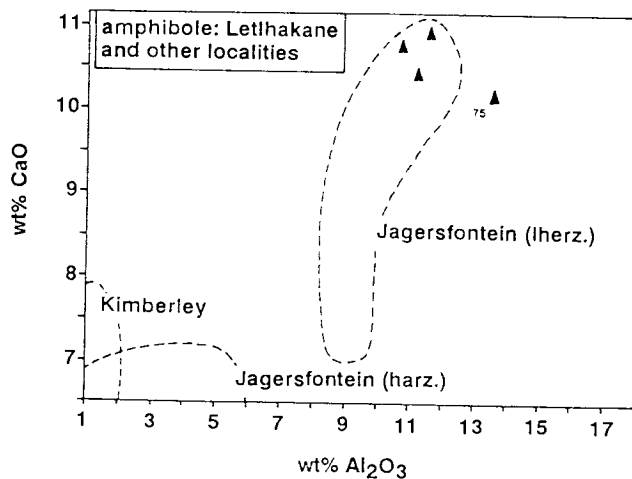


Fig. 3.19 Wt% CaO vs. wt% Al_2O_3 in amphiboles from websterites. Most of these amphiboles plot within the field of amphibole from the Jagersfontein lherzolites (Field et al., 1989). The single amphibole (JSL 75) plotting outside this field exhibits differences in colour, texture and grain size. See also Plates 20 & 21. Amphiboles found in lherzolites from the Kimberley (Jones et al., 1982) and Jagersfontein harzburgites (Field et al., 1989) differ considerably in composition from amphiboles in the Jagersfontein lherzolites and Letlhakane websterites.

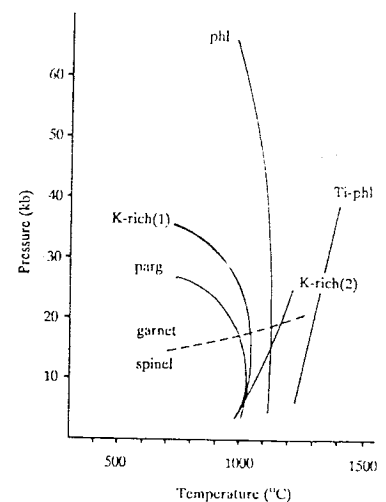


Fig. 3.20 Stability fields of amphibole and phlogopite, as well as the spinel-garnet boundary (modified from Arai, 1986). Data from Hariya (1976), Gilbert and Briggs (1974) and Gilbert et al. (1982).

Table 3.6: Zoning in metasomatic phlogopite

Sample	JSL 111		JSL 142		JSL 142		JSL 142		JSL 143	
	primary		primary		primary		secondary		primary	
	core	rim	core	rim	core	rim	core	rim	core	rim
SiO ₂	41.58	37.50	42.47	42.17	42.73	41.95	39.93	39.35	42.55	41.70
TiO ₂	0.96	2.71	0.99	1.04	0.90	1.81	4.33	3.80	0.84	0.84
Al ₂ O ₃	12.84	15.42	12.79	12.68	12.31	13.24	15.04	15.34	12.91	13.01
Cr ₂ O ₃	0.87	1.61	0.47	0.50	0.41	0.53	1.81	1.43	1.08	1.08
FeO	3.24	4.36	2.93	3.21	2.75	3.48	4.84	4.75	2.61	2.73
MnO	0.02	0.05	0.01	0.04	0.01	0.02	0.05	0.05	0.04	0.03
MgO	26.18	22.74	26.30	26.53	27.25	25.21	22.18	22.35	26.23	25.70
CaO	0.00	0.02	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Na ₂ O	0.15	0.57	0.21	0.42	0.21	0.35	0.51	0.45	0.24	0.31
K ₂ O	10.13	8.16	9.79	9.34	9.73	9.82	9.05	9.11	10.30	9.94
Total	95.99	93.14	95.97	95.94	96.30	96.42	97.78	96.61	96.79	95.33

3.4 Discussion

3.4.1 The sequence garnet peridotite-garnet phlogopite peridotite-phlogopite peridotite-phlogopite-K-richterite peridotite

Erlank and Rickard (1977), Erlank et al. (1982, 1987), and Waters (1987a) proposed that the sequence garnet peridotite (GP), garnet phlogopite peridotite (GPP), phlogopite peridotite (PP) and phlogopite-K-richterite peridotite (PKP) is one of progressive metasomatism. A very brief summary of their findings will be set out below, since it is relevant to the processes that occurred at Letlhakane, and because Kimberley remains one of the few localities (if not the only one) where the complete sequence has been identified. The interested reader is referred to the above references for a more detailed discussion.

Erlank et al. (1982, 1987) have dealt in detail with the textural, mineralogical, chemical and isotopic characteristics of the various rocks comprising the metasomatic suite of peridotites. They proposed that not all PKP rocks need have formed from GP precursors, but that the PKP suite does represent the most highly metasomatized peridotites. The metasomatic medium is considered to be a H₂O-rich fluid containing high concentrations of K and incompatible elements. The most important indicator of metasomatism is the introduction of primary phlogopite, the petrographic features of which have been discussed in Sections 3.2.1 and 3.2.2 of this chapter. Garnet replacement by phlogopite, clinopyroxene and Cr-spinel is common. The peak of metasomatism is represented by the growth of LIMA, Ba-titanates and K-richterite. The PKP suite also exhibits the highest concentration of Na, K, Rb, Ba, Sr, LREE, Fe, Ti, Zr and Nb. Although a superficial similarity exists between the PKP and MARID suites and although they are known to occur in contact (Waters et al., 1989), isotope studies (Waters, 1987a,b) have indicated that no simple relationship exists between MARID and PKP xenoliths and Group I and II kimberlites. The relationship between metasomatic processes and kimberlite formation is complex (Waters, 1987a) and remains controversial. However, Kinny and Dawson (1992) have shown that metasomatism and kimberlite emplacement are synchronous at the Bultfontein kimberlite (± 85 Ma).

Metasomatic amphibole has been the subject of several studies in the past (e.g. Aoki, 1974; Kushiro and Erlank, 1970; Arai, 1986; Erlank et al., 1987 and Winterburn et al., 1990). Amphibole in metasomatized peridotites from the Kimberley cluster is dominantly K-richterite, with only minor edenitic amphibole (Erlank et al., 1987; Waters and Erlank, 1988), while amphiboles from the Jagersfontein kimberlite are mostly edenites and edenitic hornblendes (Winterburn et al., 1990). This illustrates the heterogeneous nature and variable depth of metasomatism in the mantle.

The sequence GP, GPP, PP is present at Letlhakane and these xenoliths exhibit mineral compositions which are very similar to those from the Kimberley xenolith suite (Section 3.3). However, no PKP xenoliths have been found at Letlhakane. No peridotites have been found containing any primary-textured amphibole, although rare pyroxenites containing primary metasomatic edenitic hornblende have been described (Section 3.2.4). It must therefore be concluded that the advanced stage of metasomatism is either absent at Letlhakane, as with so many other localities (Erlank, pers. comm., 1992), or has manifested itself in some other, as yet undiscovered, way, or that the Letlhakane suite is not a complete sample of the mantle. Metasomatism at Letlhakane may also have been too deep for known amphibole stability, e.g. Schneider and Eggler (1986).

3.4.2 The distinctions between metasomatized and non-metasomatized peridotites

The problems of distinguishing metasomatized from non-metasomatized peridotites received detailed attention from Erlank et al. (1987) and Waters (1987a). The present study confirms the results of the above studies with regard to the metasomatic nature of phlogopite, ilmenite, spinel and amphibole (hornblendes) in the peridotites and pyroxenites and that the presence of these minerals indicates one or more metasomatic episode(s).

This study also attempted to distinguish metasomatized and non-metasomatized peridotites on the basis of mineral chemistry (Section 3.3). Overall, this proved to be difficult - in most cases owing to the considerable overlap in mineral compositions, e.g. in olivine, orthopyroxene and garnet. However, using clinopyroxene compositions, it is possible to discriminate between these two suites. The most useful parameters proved to be wt% Cr_2O_3 , wt% Na_2O and calculated atomic Fe^{3+} . Although other parameters such as the Ca-number, wt% FeO and wt% TiO_2 in clinopyroxene can distinguish between the various rock types, e.g. spinel peridotites, deformed peridotites and websterites, none of these can distinguish metasomatized (i.e. phlogopite-bearing) peridotites from their non-metasomatized counterparts.

Spinel compositions are also useful, in that spinels from metasomatized peridotites (GPP and PP) can be distinguished from those in true spinel lherzolites (Section 2.2.3) by their higher Cr_2O_3 , TiO_2 and Fe_2O_3 contents, as shown in Section 3.3.5, Figs. 3.13-3.15. Secondary metasomatic spinels from kelyphite rims are characterized by their lower Cr_2O_3 , higher Fe_2O_3 and MgO , and variable TiO_2 contents (Figs. 3.13-3.15). The petrographic differences between spinel peridotites and spinel-bearing metasomatized peridotites are also quite distinct and are set out in Chapter 2, Section 2.2.3 and Section 3.2.2 of this chapter. However, after extensive re-equilibration, these petrographic differences may become subtle, or disappear altogether, and more emphasis would have to be placed on mineral composition.

Fig. 3.7 in Section 3.3.3 illustrates that, with rare exceptions (e.g. JSL 151), phlogopite-bearing peridotites contain a high- Cr_2O_3 , high- Na_2O clinopyroxene. Note also that the slope of the high- Cr_2O_3 and low- Cr_2O_3 clinopyroxene trends differ. Fig. 3.7 further illustrates the presence of several high- Cr_2O_3 , high- Na_2O clinopyroxenes from phlogopite-free peridotites, e.g. JSL 134, -/193, 261 and 306. It is thought that these samples represent metasomatized peridotites where phlogopite was possibly missed during thin section preparation, or previously removed from the rock by mantle processes. Clinopyroxene data from the Kimberley peridotites (Waters, 1987a) are plotted in Fig. 3.21 together with the Letlhakane data. Note the strong similarity of the trends (Figs. 3.7 and 3.21), apart from some increased scatter. Also included are clinopyroxenes from the Kimberley PKP and PKP-like PP suites (Waters, op. cit.) as well as 3 clinopyroxenes from metasomatized peridotites retrieved from Pipe 200 in Lesotho (Schandl and Clarke, 1982). A total of 62 peridotites is plotted in Fig. 3.21 and the trends displayed in this figure are interpreted in the following paragraphs.

During a metasomatic event, new clinopyroxene may be formed by three possible processes. Firstly, existing primary clinopyroxene may be modified by diffusive/infiltration metasomatism. Secondly, clinopyroxene may crystallize directly from the metasomatic fluid, and thirdly, clinopyroxene may form as a result of the reaction of primary minerals such as orthopyroxene and garnet with the metasomatic fluid. Owing to the ubiquitous association of phlogopite with clinopyroxene in metasomatized peridotites (Section 3.2), it is not unreasonable to assume that the phlogopite, metasomatic clinopyroxene and K-richterite (PKP suite - Kimberley) compositions will be determined by the partitioning of elements between these phases. It is assumed that phlogopite, metasomatic clinopyroxene and K-richterite are the major hosts of Na at moderate to low mantle pressures. The distribution coefficients (D) used below are from Henderson (1982, and references therein) and are relevant to basaltic systems. Whether the chosen distribution coefficients are relevant in mantle conditions remains doubtful at best. The following is merely an attempt to explain the observed trends in Fig. 3.21 and should not be seen as an exact model of the distribution of these elements.

Unfortunately, important distribution coefficients needed for phlogopite, such as D_{Na} and D_{Cr} , are not available and the author was forced to make use of rough estimates. The estimated values of D_{Na} and D_{Cr} were obtained by dividing averages of bulk rock analyses into average phlogopite compositions for the same sample. Analyses from Erlank et al. (1987) of Kimberley GPP, PP and PKP xenoliths were used, resulting in D_{Na} and D_{Cr} values varying between 0.78-2.94 and 1.18-2.29 respectively. The maximum D_{Na} and D_{Cr} values appear abnormally high, considering that Na_2O and Cr_2O_3 concentrations in primary metasomatic phlogopites from the Letlhakane metasomatized peridotite suite do not exceed 0.6 and 1.2 wt% respectively. The minimum values were therefore used.

Due to the moderate distribution coefficient of Na in phlogopite ($D_{\text{Na}}=0.78$), clinopyroxene ($D_{\text{Na}}=0.27$) will lose some of the available Na to phlogopite during crystallization. The simultaneous

destruction of garnet ($D_{Cr}=0.29$), and possibly orthopyroxene ($D_{Cr}=10$), will lead to an increase in Cr in the system which will be preferentially partitioned into clinopyroxene ($D_{Cr}=8.4$) over phlogopite ($D_{Cr}=1.18$) in the GPP suite (assuming that chromite crystallization has not yet commenced). It is possible that additional Cr_2O_3 from external sources may also be introduced. The net result is therefore a decrease of Na/Cr in clinopyroxene from the metasomatized peridotites. This is reflected in the shallower slope displayed by Na_2O vs. Cr_2O_3 in clinopyroxenes of phlogopite-bearing peridotites, in comparison with the slope shown by clinopyroxene in phlogopite-free peridotites. The presence of chromite (D_{Cr} unknown, but certainly > 1) in many of the PP and PKP xenoliths indicate that considerable amounts of Cr_2O_3 must have been present in the system. Owing to the continued crystallization of phlogopite in the GPP xenoliths, and the commencement of spinel and K-richterite crystallization in the PP and PKP xenoliths, the amount of Na and Cr available for partitioning into clinopyroxene therefore steadily decreases from GPP to the PKP xenoliths, resulting in the observed trends shown in Fig. 3.21.

The effects of temperature and pressure on the partitioning of Na and Cr between phlogopite, clinopyroxene and amphibole has not been considered, because there is very little or no experimental data available. However, Vredevogd and Forbes (1975) reported that the ureyite-content of clinopyroxene decreased with increasing pressure in their experiments on the pressure sensitivity of ureyite in clinopyroxene.

3.4.3 The relationship between textural equilibration and intergrain variation of Cr_2O_3 in clinopyroxene from metasomatized peridotites

Although difficult to quantify, the variation of intergrain Cr_2O_3 in high- Cr_2O_3 , high- Na_2O clinopyroxene of a particular sample appears to be dependant on the degree of textural equilibration, i.e. the greater the degree of textural equilibration, the smaller the intergrain variation of Cr_2O_3 in the clinopyroxene of a particular sample. This was determined as follows: all peridotites (GP, GPP and PP) were divided into three textural classes, with particular attention being paid to the clinopyroxene textures.

- Class I: Well-equilibrated samples exhibiting large clinopyroxene grains with interlocking textures, triple junctions and gently curving faces.
- Class II: Partly equilibrated samples. The clinopyroxene is present as smaller, rounded grains which may or may not be penetrated by other major phases. The clinopyroxene may be associated with garnet and/or phlogopite and/or Cr-spinel.
- Class III: Poorly-equilibrated samples. Small, angular fragments of garnet may be present. The clinopyroxene grains are small in size and interfinger with olivine. Olivine-clinopyroxene symplectites may be present, e.g. in JSL 500.

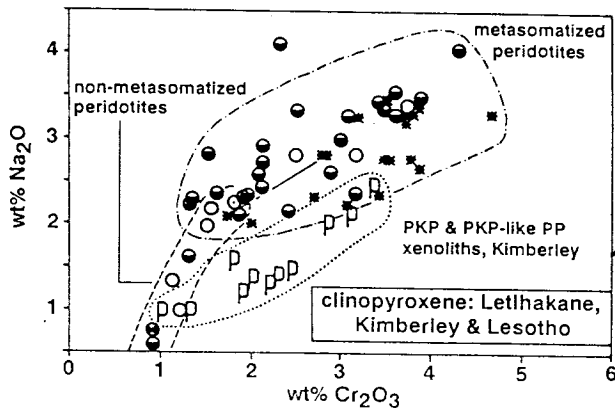


Fig. 3.21 Wt% Na_2O vs. wt% Cr_2O_3 in clinopyroxene from phlogopite-bearing and phlogopite-free peridotites. Data from Letlhakane, Kimberley and Lesotho are shown. "P" symbols represent clinopyroxenes from PKP-like PP xenoliths and PKP xenoliths from Kimberley. See also Fig. 3.7. The trends are interpreted in the text. Data on Kimberley and Lesotho from Waters (1987a) and Schandl and Clarke (1982).

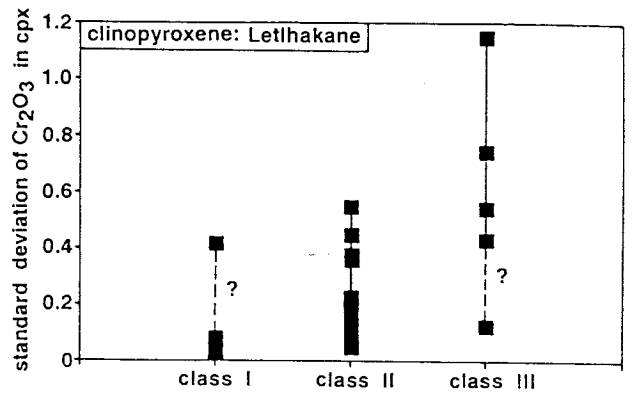


Fig. 3.22 The standard deviation of Cr_2O_3 in clinopyroxene vs. textural group. See text for the definition of the various classes. Samples exhibiting an unusually high (class I) or low (class III) standard deviation of Cr_2O_3 in clinopyroxene in comparison to their texture, are linked by dashed lines.

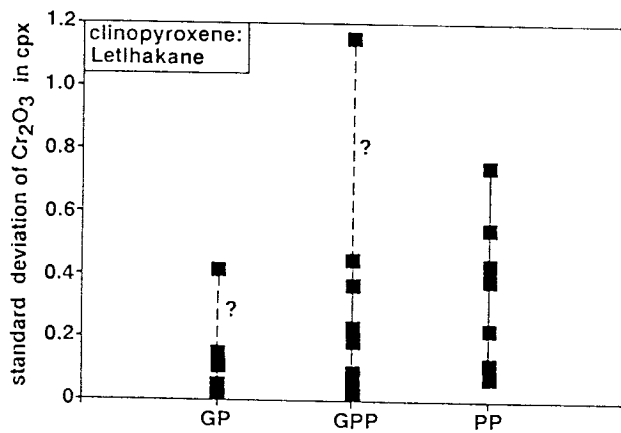


Fig. 3.23 The standard deviation of Cr_2O_3 in clinopyroxene vs. peridotite groups. GP=garnet peridotite, GPP=garnet phlogopite peridotite, PP=phlogopite peridotite. The function of the dashed lines is defined in the caption to Fig. 3.22.

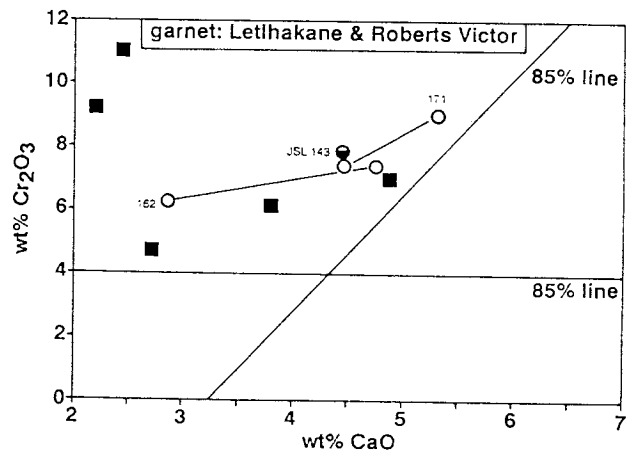


Fig. 3.24 Wt% Cr_2O_3 vs. wt% CaO in garnet. Two subcalcic garnets from Roberts Victor are compared to garnet from JSL 143 and other subcalcic garnets from Letlhakane. Both Roberts Victor harzburgites also contain high- Cr_2O_3 , high- Na_2O clinopyroxene. Data from Viljoen et al. (in press).

The clinopyroxene in JSL 500, a veined peridotite described in Section 3.2.3, serves as a good example of the Group III textural group. The influx of metasomatic fluid resulted in a clinopyroxene-orthopyroxene symplectic intergrowth surrounding the large orthopyroxene grains. The clinopyroxene produced here, possibly as a result of orthopyroxene breakdown in the presence of a fluid, and in the rest of the sample, exhibits large variations in Cr_2O_3 and Na_2O content. The Cr_2O_3 variation in clinopyroxene from these textural groups is displayed in Fig. 3.22. Intergrain variation of Cr_2O_3 in the clinopyroxene is expressed as the standard deviation about the mean of all core analyses of clinopyroxenes from a particular sample. Degree of textural disequilibrium in clinopyroxene increases from left to right in Fig. 3.22. Note the associated increase in the intergrain variation of Cr_2O_3 in clinopyroxene. Intragrain variation (i.e. zoning) in pristine, unaltered clinopyroxene is rare (Section 3.3), except in the outer "spongy" rims, if these are present. This feature has been described and interpreted in Chapter 2, Sections 2.2.1 and 2.4.4.

The assigning of samples to the above groups is obviously somewhat subjective and some readers may disagree with the interpretation of the degree of equilibrium in any particular sample. Nevertheless, the general features of Fig. 3.22 persist even when slightly different groupings of samples are employed. Thus it appears that the intergrain variation of Cr_2O_3 in clinopyroxene within a given sample, which has been noted by other authors (Shimizu and Allegre, 1978; Erlank et al., 1987), is a function of the degree of textural equilibrium. Furthermore, if the peridotite classification as proposed by Waters (1987a) and Erlank et al. (1987) (i.e. GP, GPP, PP) is used instead of the groups suggested in this study, and if the sequence GP-GPP-PP is one of increasing metasomatism (Erlank et al., 1987), the general trend remains very similar, as shown in Fig. 3.23.

This explanation poses the following questions: 1) What would happen if a highly metasomatized rock is allowed to reach textural equilibrium? Will the textural evidence of metasomatism not be wiped out? 2) Is it possible for a metasomatized peridotite to undergo a second phase of metasomatism? Evidence from this study suggests that it is indeed possible for these processes to occur, particularly the first mentioned. It is proposed that extensive re-equilibration of metasomatic clinopyroxene can take place and that many of the distinguishing metasomatic textural features in a phlogopite-bearing peridotite may be destroyed with time (see also Section 3.4.4). The problem lies not so much with phlogopite, which is known to be a metasomatic mineral and can be identified easily, but with the distinction between texturally equilibrated, primary clinopyroxene and equally well equilibrated, petrographically identical, metasomatic clinopyroxene in the absence of phlogopite. It is for this reason that the use of Cr_2O_3 , Na_2O and Fe^{3+} in clinopyroxene as a method of discriminating between metasomatized and non-metasomatized peridotites is important. The presence of phlogopite in the GPP and PP xenoliths is therefore not the only criterion for recognizing metasomatism in these suites.

Thus far it has not been possible to identify samples where multiple episodes of primary metasomatism have occurred. The above tests only indicate that metasomatism has occurred and are not capable of identifying different primary metasomatic events. The variable nature of metasomatic fluids and the possibility of overprinting and re-equilibration suggests that distinction between different primary events is unlikely, perhaps impossible. Overprinting of primary metasomatic processes by secondary metasomatism can however, be recognized, e.g. JSL 572 (Plate 8).

From the above discussion, it is therefore evident that only the textural features of clinopyroxene ($\pm$ phlogopite) and spinel and the compositions of these phases can be used in trying to distinguish metasomatized from non-metasomatized peridotites.

3.4.4 A model for the breakdown reaction of garnet and the subsequent re-equilibration of the products.

Previous workers, e.g. Schandl and Clarke (1982), Erlank et al. (1987) and Waters (1987a), have suggested that Cr-spinel and the associated textures seen in the phlogopite-bearing peridotites result from the breakdown of garnet. Owing to the well-preserved nature of various stages of the breakdown of garnet in the Letlhakane peridotites, some attention was given to this proposal and a model describing these stages is presented here. This model is consistent with observations and deductions made by the above-mentioned workers on material from Lesotho and Kimberley. Two further stages have, however, been added to account for some of the textures observed in the Letlhakane samples. Mass balance calculations on these breakdown products have also been undertaken. Without fail, all clinopyroxenes associated with the breakdown of garnet are high-Cr₂O₃, high-Na₂O in composition.

Stage 1: A metasomatic fluid percolates through the pristine rock (Plate 24) and introduces cations such as Si⁴⁺, Mg²⁺, K⁺, Na⁺, Al³⁺, Fe²⁺, Fe³⁺, and possibly Cr³⁺, as well as OH⁻ or F⁻ anions. Some of these elements may have been extracted from phases through or around which the fluid percolated.

Stage 2: Garnet reacts with the fluid to form low-TiO₂ phlogopite and high-Cr₂O₃, high-Na₂O clinopyroxene (Plate 25). Anhedral, irregular remnants of garnet may still be present. The textures reflect considerable disequilibrium. The metasomatic clinopyroxene has variably high Cr₂O₃ and exhibits an irregular habit and small grain size (Plate 26).

Stage 3: With further reaction, garnet is completely destroyed, producing large amounts of Cr-spinel. The spinel commonly contains between 50 and 60 wt% Cr₂O₃ and may exhibit either equant or dendritic habits. There is no significant difference in the composition of the morphologically different spinel types (Plate 27).

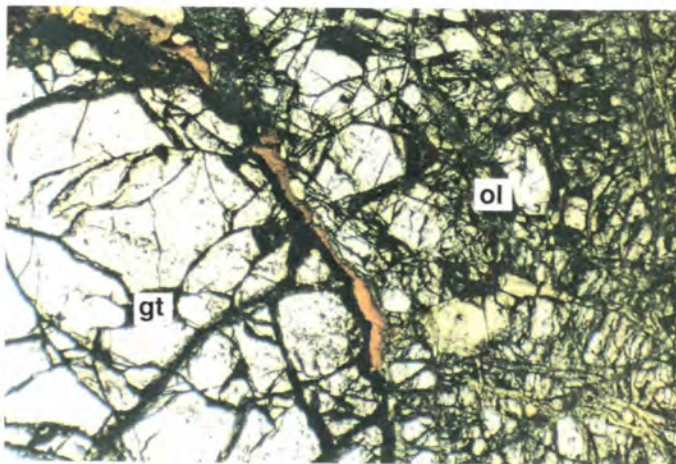


Plate 24: A typical example of pristine garnet (gt) unaffected by primary metasomatism with minor brown secondary metasomatic phlogopite. The garnets are typically large and rounded and associated with equally coarse olivine (ol). The standard deviation of Cr_2O_3 in clinopyroxene from these samples is typically <0.1 . Field of view = 4mm wide. Plane polarised light.

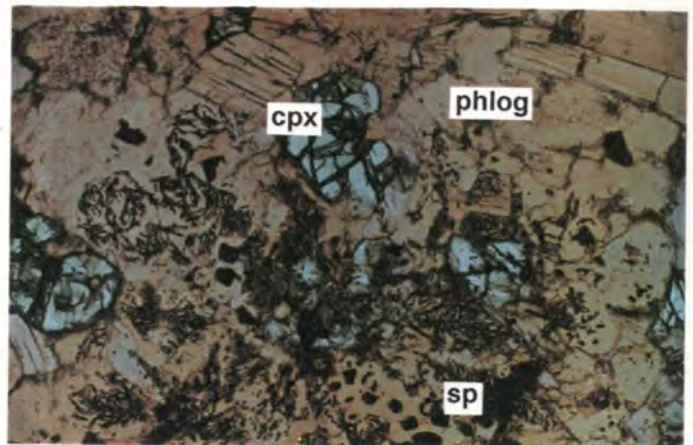


Plate 27: The garnet in this sample (JSL-/93) has been totally destroyed with resultant primary metasomatic phlogopite (phlog), clinopyroxene (cpx) and Cr-spinel (sp) as products. The standard deviation of Cr_2O_3 in clinopyroxene from this sample is 0.38. Field of view = 6.8mm wide. Plane polarised light.

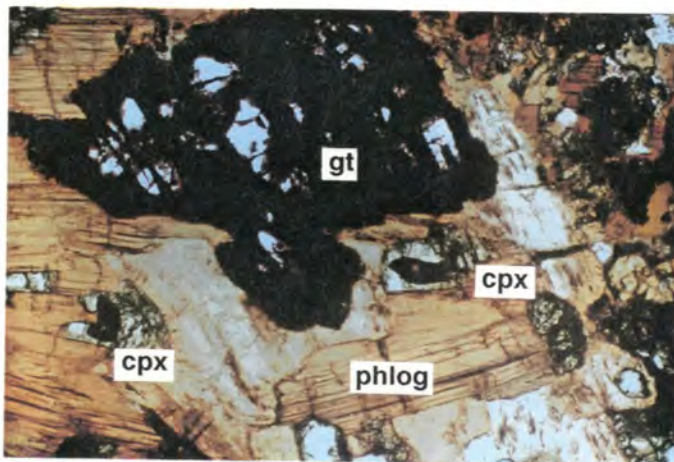


Plate 25: The breakdown of garnet has commenced, resulting in the formation of plates of brown primary metasomatic phlogopite (phlog) intergrown with green primary metasomatic clinopyroxene (cpx) in JSL-/177. Note the reduced size of the garnet (gt) compared to the previous stage. Field of view = 6.8mm wide. Plane polarised light.

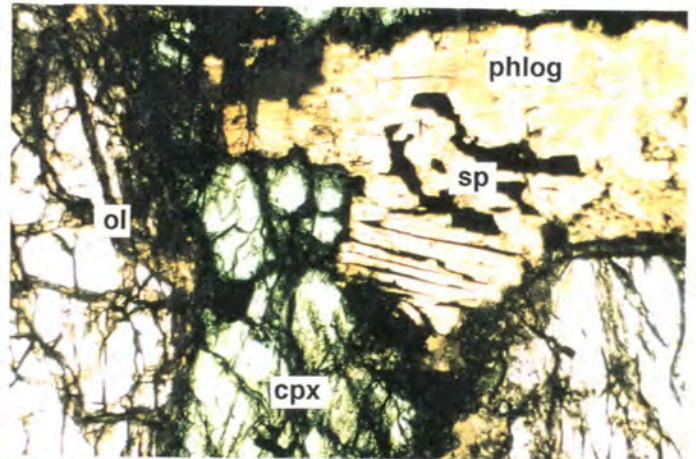


Plate 28: Bright green clinopyroxene (cpx), brown phlogopite (phlog) and Cr-spinel (sp) surrounded by olivine (ol). No garnet is present in this sample, but note the similarity of the spinel texture to some of the spinels illustrated in Plate 27, suggesting that garnet may have been present in this sample. Although difficult to infer from these plates, the grain size of clinopyroxene and spinel is increasing. This becomes more obvious when the thin sections are viewed with the unaided eye. Field of view = 3.5mm wide. Plane polarised light.

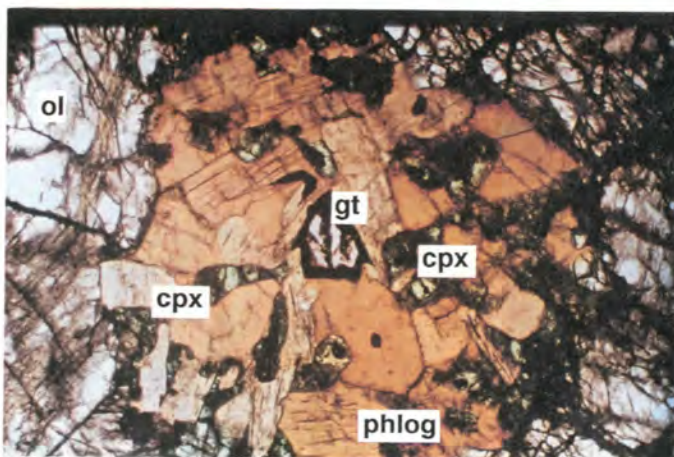


Plate 26: An extensively metasomatized garnet, also from JSL-/177. Note the irregular fragment of remaining garnet (gt) and the rounded intergrowth of primary metasomatic phlogopite (phlog) and clinopyroxene (cpx). The small grain size of clinopyroxene compared to the size of the surrounding olivine (ol) is quite obvious. The standard deviation of Cr_2O_3 in clinopyroxene from JSL-/177 is high (0.36). Field of view = 6.8mm wide. Plane polarised light.

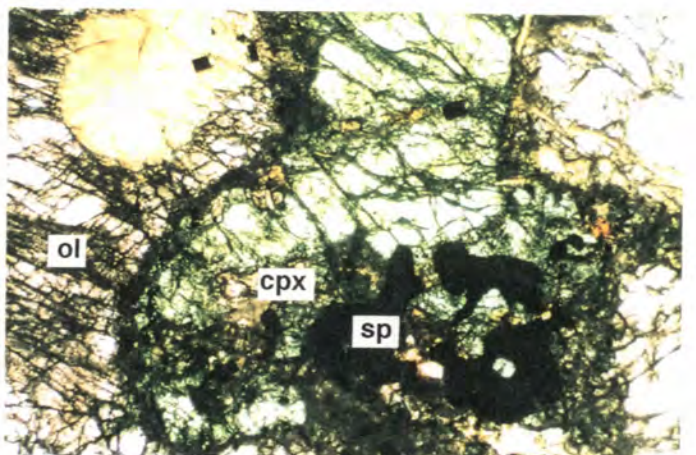


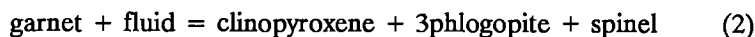
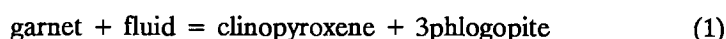
Plate 29: A metasomatized phlogopite peridotite (JSL 547) in the later stages of equilibrium. Note the larger clinopyroxene (cpx) and Cr-spinel grain size (sp) and more regular grain boundaries, suggesting a more evolved state of equilibrium compared to for example, JSL-/177 in Plate 26. The colourless phase is olivine (ol). The standard deviation of Cr_2O_3 in clinopyroxene from this sample is 0.07. Field of view = 3.5mm wide. Plane polarised light.

Stage 4: At the elevated temperatures and pressures of the mantle, and with time, during which the rock may undergo recurring episodes of metasomatism, small clinopyroxene and spinel grains may be broken down and the constituents remobilized (Plate 28).

Stage 5: The variation of Cr_2O_3 in clinopyroxene is now considerably less than in earlier stages of metasomatism. The rock is texturally and compositionally well equilibrated and it is very difficult to distinguish metasomatic from primary clinopyroxene in the absence of phlogopite. However, the presence of high- Cr_2O_3 , high- Na_2O clinopyroxene indicates that the rock has undergone metasomatism in the past (Plate 29).

Kingery et al. (1976) discussed the relationship between grain shape and grain size. Grain boundaries migrate toward their centre of curvature and therefore grains with a small number of faces tend to grow smaller, while those with a large number of faces tend to grow larger. The driving force behind this process is the energy difference between finer-grained material and the larger-sized product, owing to the decrease in grain boundary area and total boundary energy. The radius of curvature of a crystal face is directly proportional to the grain diameter and therefore the rate of grain growth is inversely proportional to grain size (Kingery et al., 1976). This is due to the increasing diffusion distance in larger grains. During the equilibration process, the net result is therefore an increase in grain size and grain boundaries that become straight or gently curving.

Mass balance calculations have also been attempted on the garnet breakdown products. The following reactions are relevant:



A calculated example of each of these equations is set out in Tables 3.7 and 3.8 respectively. No direct textural evidence pointing to the involvement of orthopyroxene in the reaction is present. However, a few samples contain orthopyroxene which displays highly embayed boundaries and associated primary metasomatic clinopyroxene development around the rims. These features do not necessarily occur in orthopyroxene adjacent to garnet, but there is little doubt that this reaction of orthopyroxene occurs during metasomatism. Orthopyroxene may, therefore, indirectly supply elements such as Cr to the breakdown products of garnet. The ratio of clinopyroxene:phlogopite is based on visual estimation of these phases from a single clot in sample JSL -/177. Actual microprobe analyses of clinopyroxene, phlogopite, garnet and spinel have been used in the calculations.

It must be borne in mind that the composition of the fluid or metasomatizing medium is unknown. The "fluid" in the calculation is merely that part of it which has been "fixed" in the rock by the breakdown reaction. The result indicates that the fluid may have been of a peralkaline nature (Table 3.7) and must have been OH⁻ or F⁻-bearing due to the presence of phlogopite as a product. Note that if spinel is added to the products (Table 3.7), i.e. clinopyroxene + phlogopite + spinel, then a large input of Cr is needed to balance the equation (bearing in mind that the spinel contains 50-60 wt% Cr₂O₃) and this creates some problem as to the source of the Cr. It is tentatively proposed that the Cr was obtained from a combination of sources, e.g. the garnet itself, possibly from orthopyroxene and also any primary clinopyroxene that may have reacted with the metasomatic fluid. Table 3.8 illustrates a mass-balance calculation for the same sample (JSL -/177), but with orthopyroxene included as a reactant. Another spinel phase as a source of Cr may also be a possibility, although no evidence for this was found. It remains doubtful whether the above-mentioned silicates would have been able to provide such a large amount of Cr and the problem of the source of Cr remains unsolved.

3.4.5 High-Cr₂O₃, high-Na₂O clinopyroxene in a mildly subcalcic harzburgite: metasomatism in depleted rocks and its implications

Reference was made in Section 3.2.1 to an unusual garnet phlogopite peridotite (JSL 143) in which the garnets are mildly subcalcic (Section 3.3.4), but which also contains high-Cr₂O₃, high-Na₂O clinopyroxene and primary metasomatic phlogopite, similar to that observed in the common metasomatized peridotites (Plate 11). Reports of clinopyroxene-bearing garnet harzburgites are extremely rare in the literature. This can undoubtedly be ascribed to their superficial similarity to a garnet lherzolite in hand specimen. These xenoliths may therefore have been overlooked at many localities. Letlhakane can now be added to the small list of localities, e.g. Colorado-Wyoming (McCallum and Eggler, 1976) and Roberts Victor (Viljoen et al., in press), where these xenoliths have been found.

Clinopyroxene-bearing subcalcic harzburgites are unique in the sense that the low-Ca, high-Cr garnets in these rocks have been interpreted by Sobolev et al. (1969, 1973) as originating in Ca-deficient environments. This has subsequently been confirmed by the recovery of low-Ca, garnet-bearing dunites and harzburgites in southern Africa, Colorado, and Siberia (Danchin and Boyd, 1976; McCallum and Eggler, 1976; Pokhilenko et al., 1977). The clinopyroxenes from both the Letlhakane and the Roberts Victor (Viljoen et al., in press) subcalcic harzburgites are similar in composition, although the latter generally contains higher CaO (Table 3.9). Garnet compositions from the Roberts Victor harzburgites are even more subcalcic than the sample from Letlhakane (Table 3.9 and Fig. 3.24) and approach compositions similar to those of subcalcic garnets from Finsch (Gurney and Switzer, 1973). The clinopyroxenes in all the subcalcic

Table 3.7: Mass-balance calculation of garnet

breakdown. Components in wt%. Dashes indicate
that the component was not analysed.

Reaction: clinopyroxene + 3phlogopite + spinel - garnet = fluid

SiO ₂	53.318	+	3(40.976)	+	-	-	41.023	=	135.223
TiO ₂	0.340	+	3(0.715)	+	1.909	-	0.285	=	4.109
Al ₂ O ₃	2.969	+	3(12.964)	+	8.286	-	19.292	=	30.855
Cr ₂ O ₃	3.308	+	3(0.971)	+	55.389	-	6.629	=	54.981
FeO	2.309	+	3(2.963)	+	14.860	-	7.407	=	18.651
Fe ₂ O ₃	-	+	-	+	5.971	-	-	=	5.971
MnO	0.050	+	3(0.020)	+	0.299	-	0.406	=	0.003
NiO	0.000	+	-	+	0.140	-	0.021	=	0.119
MgO	15.069	+	3(24.947)	+	12.817	-	19.461	=	83.266
CaO	18.536	+	3(0.000)	+	-	-	5.236	=	13.300
Na ₂ O	3.325	+	3(0.296)	+	-	-	0.091	=	4.122
K ₂ O	-	+	3(10.451)	+	-	-	-	=	31.353

Table 3.8: Mass-balance calculation of garnet

breakdown. Components in wt%. Dashes indicate
that the component was not analysed.

Orthopyroxene is included as a reactant.

Reaction: clinopyroxene + 3phlogopite + spinel - garnet - orthopyroxene = fluid

SiO ₂	53.318	+	3(40.976)	+	-	-	41.023	-	57.600	=	77.622
TiO ₂	0.340	+	3(0.715)	+	1.909	-	0.285	-	0.084	=	4.026
Al ₂ O ₃	2.969	+	3(12.964)	+	8.286	-	19.292	-	0.698	=	30.156
Cr ₂ O ₃	3.308	+	3(0.971)	+	55.389	-	6.629	-	0.399	=	54.582
FeO	2.309	+	3(2.963)	+	14.860	-	7.407	-	4.707	=	13.944
Fe ₂ O ₃	-	+	-	+	5.971	-	-	-	-	=	5.971
MnO	0.050	+	3(0.020)	+	0.299	-	0.406	-	0.102	=	-0.099
NiO	0.000	+	-	+	0.140	-	0.021	-	0.122	=	-0.003
MgO	15.069	+	3(24.947)	+	12.817	-	19.461	-	35.785	=	47.481
CaO	18.536	+	3(0.000)	+	-	-	5.236	-	0.377	=	12.924
Na ₂ O	3.325	+	3(0.296)	+	-	-	0.091	-	0.146	=	3.975
K ₂ O	-	+	3(10.451)	+	-	-	-	-	-	=	31.353

Roberts Victor samples are characterized by high- Cr_2O_3 (>1.5 wt%) and high- Na_2O (>2 wt%) concentrations (Table 3.9), similar to clinopyroxenes from metasomatized peridotites from Letlhakane, Kimberley (Erlank et al., 1987; Waters, 1987a) and Pipe 200 (Schandl and Clarke, 1982).

The presence of a Ca-saturated mineral such as clinopyroxene in a Ca-undersaturated rock such as a subcalcic harzburgite suggests that the clinopyroxene was introduced at some later stage. The similarity of the clinopyroxene compositions in the harzburgites, compared to clinopyroxene compositions in rocks which are known to have been metasomatized, supports this suggestion. Therefore it appears possible to metasomatize a subcalcic harzburgite precursor by a Ca-enrichment event in the mantle with the resultant formation of a lherzolite. Such an enrichment event has been proposed by Nixon et al. (1987) to have occurred approximately 1400 Ma ago under the Kaapvaal craton and is consistent with the idea that harzburgite may be concentrated relative to lherzolite at the base of the craton (Boyd and Gurney, 1982; Wyllie et al., 1983). The samples described above may be the remnants of such an event. Additional evidence for the conversion of harzburgite to lherzolite may be found in garnet zoning such as that described by Nixon et al. (1987). They reported a single garnet from a dunite which is zoned from a subcalcic core (<1 wt% CaO) to a calcic rim (5-6 wt% CaO). An important point which needs to be addressed, is whether any diamonds which may have been present in the subcalcic harzburgite would have survived the oxidizing Ca-enrichment event. If this was indeed the case, then metasomatized peridotites may also be a potential source of diamond. Metasomatism by carbon-bearing volatiles, under reducing conditions, has in the past been proposed by Haggerty (1986), Nixon et al. (1987) and Pearson et al. (1990). Clearly, a means for the identification of "harzburgite-derived" lherzolites needs to be developed.

Sobolev et al. (1975) reported four examples of polycrystalline diamond intergrown with high- Cr_2O_3 , high- Na_2O clinopyroxenes (4.41-15.6 wt% Cr_2O_3 and 5.83-10.1 wt% Na_2O) from a Yakutian kimberlite. Two samples also contain co-existing chromites, the compositions of which were unfortunately not reported. Gurney and Boyd (1982) described mineral intergrowths, including clinopyroxene of similar composition to those from Siberia, with polycrystalline diamond from Orapa. Diamond and high- Cr_2O_3 clinopyroxene co-crystallization therefore appears possible. However, diamond-bearing peridotites described in the literature, e.g. from Finsch, Roberts Victor and Argyle (Shee et al., 1982; Viljoen et al., in press; Jaques et al., 1990) appear to be garnet peridotites, i.e. containing low- Cr_2O_3 , low- Na_2O clinopyroxene and no phlogopite. These peridotites are therefore unlikely to be related to the Yakutian and Orapa samples above and it is possible that two separate parageneses are involved.

Table 3.9: Representative garnet and clinopyroxene from the Roberts Victor peridotites (Viljoen et al., in press) and JSL 143. Dashes indicate that the component was not analysed and nd = not detected.

Sample	162			171			JSL 143	
	garnet	garnet	cpx	garnet	garnet	cpx	garnet	cpx
SiO ₂	41.32	41.88	55.53	40.70	41.48	55.76	41.38	54.49
TiO ₂	0.18	0.03	0.21	0.11	0.12	0.05	0.13	0.30
Al ₂ O ₃	18.13	19.58	2.91	16.66	18.63	2.84	17.92	2.93
Cr ₂ O ₃	7.24	6.15	2.92	9.38	7.06	4.93	7.83	3.73
FeO	6.69	6.94	1.97	5.60	5.63	1.50	6.37	1.85
MnO	0.37	0.42	nd	0.30	0.33	nd	0.38	0.06
NiO	-	-	-	-	-	-	0.01	0.06
MgO	21.05	22.66	14.42	20.73	21.86	14.06	22.01	15.53
CaO	4.68	2.81	18.42	5.13	4.43	16.69	4.44	17.49
Na ₂ O	0.06	nd	3.01	0.06	0.04	3.56	0.04	3.36
Total	99.72	100.47	99.39	98.67	99.58	99.39	99.79	100.50

Table 3.10: Mass-balance calculation of the symplectite in JSL 500B. The serpentine analysis is from the De Beers kimberlite (Mitchell, 1986). Dashes indicate that the component was not analysed.

Reaction: clinopyroxene + phlogopite + serpentine - olivine - orthopyroxene = fluid

SiO ₂	54.471	+	42.317	+	39.99	-	39.956	-	57.812	=	39.010
TiO ₂	0.300	+	0.860	+	-	-	-	-	0.104	=	1.056
Al ₂ O ₃	1.344	+	11.307	+	0.95	-	-	-	0.183	=	13.418
Cr ₂ O ₃	1.746	+	0.346	+	-	-	-	-	0.122	=	1.970
FeO	3.463	+	4.091	+	5.33	-	11.367	-	6.595	=	-5.078
MnO	0.077	+	0.035	+	0.11	-	0.165	-	0.153	=	-0.096
NiO	0.035	+	-	+	0.44	-	0.329	-	0.064	=	0.082
MgO	16.063	+	25.693	+	38.11	-	47.908	-	34.808	=	-2.850
CaO	20.600	+	0.013	+	0.63	-	0.024	-	0.401	=	20.818
Na ₂ O	2.076	+	0.252	+	-	-	-	-	0.102	=	2.226
K ₂ O	-	+	10.086	+	-	-	-	-	-	=	10.086

3.4.6 Possible reactions relating to metasomatic activity in the mantle

The controversy over whether the metasomatizing medium in the mantle is a fluid (vapour) or a melt, or both, still continues and recent discussions on this topic can be found in Eggler (1987), Menzies et al. (1987) and Waters (1987a). Aoki (1974), Erlank et al. (1982, 1987) and Menzies et al. (1987) have labelled the metasomatizing agent as a fluid, whereas others, e.g. Schneider and Eggler (1984, 1986), support the theory that melts are the primary metasomatizing agents in the mantle. Menzies et al. (1985) referred to both melts and fluids in the mantle in their discussion on metasomatism. Supporters of the theory that fluids are the major metasomatizing agents have quoted the presence of replacement textures and hydrous minerals in support of their view, whereas Schneider and Eggler (1984, 1986) suggested that fluids are inefficient as metasomatizing media and that large fluid/rock ratios are required for fluid metasomatism to be effective.

From the above discussion it is evident that no clear consensus exists amongst mantle petrologists as to the nature of the metasomatizing medium. The presence of replacement textures, the presence of phlogopite, and the fact that the metasomatic minerals are dispersed throughout most of the xenoliths from the Letlhakane suite, suggests that the metasomatizing agent may have been a fluid. The possibility that metasomatic melts may have been present in the past can, however, not be excluded.

Menzies et al. (1987) suggested that the high-pressure stability of carbonate and its effectiveness as a buffer in the mantle indicates that any free fluid, apart from that required to stabilize phlogopite, will be H₂O-rich. The major metasomatizing agents in the mantle therefore appear to be H₂O-rich fluids (vapours) and silicate melts (Menzies et al., 1987). Many workers, e.g. Taylor and Green (1989) (and references therein) have commented on the relationship between oxygen fugacity and fluid composition in the mantle. H₂O-CH₄ fluids (reducing conditions) and H₂O-CO₂ fluids (oxidizing conditions) appear to be dominant. The lack of graphite in the metasomatized peridotites suggests that oxidizing conditions may have prevailed during metasomatism below Letlhakane. The absence of significant amounts of carbonate minerals in the primary metasomatic mineral suite from Letlhakane suggests that the metasomatizing fluids may have been H₂O-rich and CO₂-poor. H₂O-rich fluid is also capable of transporting a greater variety of elements than CO₂-rich or CO₂+H₂O-rich fluids (Eggler, 1987), possibly explaining the presence of metasomatic ilmenite, rutile, Cr-spinel and sulphide minerals in some of the Letlhakane xenoliths. From results obtained in the mass-balance calculations (Section 3.4.4), it appears that the metasomatic fluids may be peralkaline at high pressure. The composition of these fluids will more than likely change at shallow levels where amphibole is more stable. This is caused by the instability of carbonate at shallow levels and the partitioning of H₂O into silicate melts (Menzies et al., 1987).

The reactions and processes outlined in this section should not be seen as exact. Owing to the nature of metasomatic reactions in the mantle, i.e. open systems, and because fluids are involved, certain relevant components will no doubt have been lost. The phases presently fixed in a metasomite may have little resemblance to the actual fluid composition that once percolated through the rock. It is also not known how many subsequent metasomatic episodes overprinted the rock. Nonetheless, each reaction will be listed and accompanied by a brief discussion of the sample and its related textures in which the reaction is thought to have occurred.

a) The breakdown of garnet in the presence of a metasomatic fluid

These reactions have already been dealt with in detail (see Section 3.4.4) and will not be repeated here. Note however, that this feature is widespread and commonly observed in the mantle.

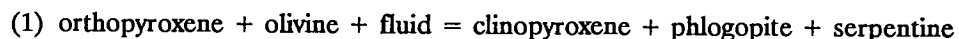
b) Formation of clinopyroxene at the expense of orthopyroxene in the presence of olivine and a Ti-bearing metasomatic fluid

Although not the only metasomatized xenolith recovered from Letlhakane, JSL 500 remains the only sample exhibiting evidence of veining and symplectic intergrowths between ortho- and clinopyroxene (Plates 14-15). Reports of veined peridotite xenoliths are common in the literature, particularly from the well-studied Kimberley pipes (Dawson and Smith, 1977; Jones et al., 1982; Erlank et al., 1987). The anhedral clinopyroxenes in JSL 500, including those associated with the ilmenite and phlogopite veins (Plate 14) are of high- Cr_2O_3 , high- Na_2O composition, similar in composition to the clinopyroxenes associated with garnet breakdown (Section 3.4.4). Clinopyroxene in the symplectite is depleted in Cr_2O_3 and Na_2O and enriched in CaO and MgO , compared to clinopyroxene elsewhere in the sample, but is still similar to clinopyroxene commonly found in the phlogopite-bearing peridotites (Section 3.3.3). It is suggested that the symplectites were formed by the reaction of orthopyroxene with metasomatic fluid. Evidence in support of this is as follows:

- (1) The orthopyroxenes exhibiting these symplectites are located close to or in the path of the metasomatic veins. Orthopyroxene away from the veins exhibits no symplectic intergrowth.
- (2) There is severe alteration of surrounding olivine. The development of clinopyroxene is limited to the outer rim of the orthopyroxene-olivine contact, and does not support an origin by exsolution for the clinopyroxene (Plate 15a).

- (3) Apart from the ubiquitous presence of the usual serpentine veinlets, olivine appears not to have reacted with the metasomatic fluids. Even olivines adjacent to the veins are unaltered. The formation of orthopyroxene symplectites must therefore have been due to the combined presence of olivine and orthopyroxene reacting with the metasomatizing fluid. This is evident by the totally altered nature of the olivine adjacent to the symplectites.

Based on the textures observed in the sample, and the composition of clinopyroxene, it is suggested that JSL 500 was a harzburgite before metasomatism. Metasomatism led to the subsequent introduction of clinopyroxene. The presence of the symplectites in JSL 500 suggests that clinopyroxene may be formed from the breakdown of orthopyroxene in the presence of olivine. The reaction could be represented as follows:



Although ilmenite is not actually present in the symplectite, it is closely associated with veins of phlogopite elsewhere in the sample and probably crystallized from the metasomatizing medium. A mass balance calculation of the symplectite, excluding ilmenite, is presented in Table 3.10. Because of preparation difficulties, it was not possible to analyse the alteration products (serpentine) and a pseudomorphic serpentine analysis from the De Beers kimberlite (Mitchell, 1986) was used in the calculation. Table 3.10 illustrates that MgO, FeO and MnO are overabundant and have to be removed from the system. These oxides may have been incorporated into ilmenite.

The process of Ti-enrichment in peridotites has long been a source of argument. Metasomatic fluids are generally considered to be alkali-rich and Ti-poor (Menzies et al., 1987), yet large amounts of ilmenite are commonly found together with phlogopite in veined and extensively metasomatized peridotites, e.g. JSL 500 and 511 (Section 3.2.3). Schneider and Eggler (1984) suggested that this may be owing to a change in oxygen fugacity during the reaction of H₂O-bearing fluids with mantle assemblages. Menzies et al. (1987) speculated that Ti was not introduced during metasomatism, but is a reflection of Ti-rich, pre-metasomatic peridotite. The author speculates that large amounts of ilmenite need not have crystallized in one event, but could perhaps be the accumulated product of several periods of crystallization over time. Zones of ilmenite enrichment may represent relics of main fracture systems where fluid volumes (and therefore Ti concentrations) were high enough to ensure crystallization of ilmenite.

c) The formation of orthopyroxene from olivine in the presence of a Si-rich metasomatic fluid

The most significant features present in JSL 516 are a band of orthopyroxene-rich material, the absence of orthopyroxene above this band, and the notable change in olivine grain size on either side of it (see Section 3.2.3). The following explanations of these features have been proposed:

- (1) Hatton (pers. comm., 1992) suggested that the harzburgite band may represent the intrusion of a basaltic vein into the peridotite. Cooling resulted in the crystallization of an orthopyroxene cumulate. Microprobe analyses, however, show no detectable differences in orthopyroxene compositions from the band, in comparison with the rest of the sample. Olivine and clinopyroxene compositions above and below this orthopyroxene-rich band are similar. The lack of chemical change may however, be the result of subsolidus re-equilibration and diffusion. A major shortcoming of this proposal is its inability to account for the variation in olivine grain size on either side of the harzburgite band.
- (2) A second possibility is that the xenolith is a layered cumulate produced by magmatic fractionation processes.
- (3) A third possibility, favoured by the author because it may possibly explain the difference in olivine grain size, is that the orthopyroxene may have formed as a result of the dissolution of olivine, in a similar way to the reaction proposed by Schneider and Eggler (1986):



The modal proportion and composition of phlogopite will largely depend on the composition of the fluid. The author is of the opinion that the petrographic evidence (Section 3.2.3) is best explained by such a model. The xenolith therefore contains a frozen fluid front which was producing orthopyroxene at the cost of olivine. Owing to the small amount of fluid available, all the olivine was not destroyed, but merely recrystallized as smaller grains. The megacrystalline olivine in this xenolith represents the original olivine before recrystallization, and therefore contains no orthopyroxene.

It is unlikely that the phlogopite-clinopyroxene patches in JSL 516 crystallized together with the orthopyroxene, because these minerals occur throughout the xenolith, albeit in lesser quantities in the megacrystalline olivine. Petrographic evidence indicates that the orthopyroxene reacted with a fluid. This can be seen from the neoblastic intergrowth of olivine and clinopyroxene

surrounding many orthopyroxenes, particularly below the orthopyroxene-rich band. The orthopyroxene grains here are notably smaller and exhibit variably embayed boundaries. A few optically continuous fragments can be seen poikiloblastically enclosed in neoblastic olivine and clinopyroxene. It is evident that the clinopyroxene and the phlogopite crystallized after the orthopyroxene. No evidence is present to suggest the existence of "older" phlogopite associated with the orthopyroxene. However, it is quite possible that such "old" phlogopite may have been present, but was later remobilized by another metasomatic event.

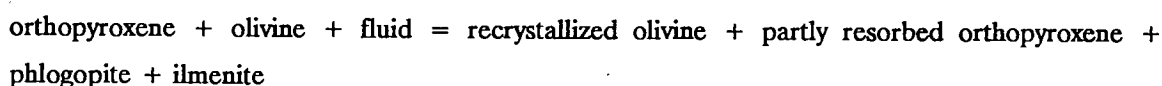
The explanation offered in (3) above may also provide one of several possible answers to the "harzburgite problem", as discussed by Ringwood (1966). It was noted that many mantle samples are too orthopyroxene-rich to be considered as residua of partial melting from a primitive mantle based on the composition of chondrite. Schneider and Eggler (1986) proposed a model whereby the subsolidus lithosphere is subdivided into two regimes: a region of carbonate and phlogopite peridotite, existing at depths below 70 km, and a region of amphibole peridotite at shallower levels. Fluids are H₂O-rich in the former and CO₂-rich in the latter. Whether the phlogopite mentioned by these authors is truly "primary" or of metasomatic origin, is not known. Schneider and Eggler (1986) consider the carbonate subzone as a region of leaching. When an upward-moving, hydrous, silica-rich fluid encounters local phlogopite-enriched zones, large amounts of leaching will occur, if the fluid is solute-undersaturated. Metasomites formed by reaction with hydrous fluids would be phlogopite-, orthopyroxene- and also diopside-enriched (provided CaO is present). Orthopyroxene and clinopyroxene would form as a result of the silicification of olivine. The presence of K₂O-rich metasomatizing agents in the mantle have also been advocated by Aoki (1974), Wendland and Eggler (1980) and McKenzie (1989).

Canil (1992) presented a strong argument against the Si-metasomatism proposal of Schneider and Eggler (1986), on the basis that unrealistically large amounts of Si are needed for such a large scale mantle process. Canil (1992) favours a model whereby the variable orthopyroxene content of mantle peridotites is explained by an "exsolution model". However, it is difficult to envisage the textural features of JSL 516 being produced by exsolution as suggested by Canil (1992). On the other hand, several processes of orthopyroxene-formation are likely to operate in the mantle.

- d) Extensive recrystallization of olivine and the resorption of orthopyroxene in the presence of a metasomatic fluid

JSL 511 is considered to represent an extreme example of metasomatic fluid invasion and crystallization of phlogopite and ilmenite. It is proposed that this fluid reacted with the host harzburgite, resorbed most of the orthopyroxene and recrystallized the olivine extensively, leading to

irregular olivine grain boundaries and olivine inclusions within olivine. Recrystallization of olivine is also supported by the abundant ilmenite inclusions in the olivine. The recrystallization of olivine in the presence of an Fe-rich, Ti-rich fluid, may account for its Fe-rich composition (Section 3.3.1). Owing to the extensive recrystallization of the phases, recognition of the initial texture of the harzburgite is difficult. It is possible that areas of neoblastic olivine may be zones of shearing. The following reaction may be relevant in explaining the observed textures:



Once again, the fluid appears to have been enriched in K_2O , H_2O , Al_2O_3 and TiO_2 . JSL 511 is considered to be of peridotitic rather than MARID origin, owing to the presence of orthopyroxene in the rock. The absence of clinopyroxene is most noteworthy, indicating the absence of CaO in the metasomatizing medium.

3.5 Summary

In summary, the following are important features and interpretations regarding the metasomatized peridotites and pyroxenites:

- (1) Metasomatized peridotites, in the form of garnet phlogopite and phlogopite peridotites, have been identified at Letlhakane and form part of the sequence GP-GPP-PP. No xenoliths of the PKP suite appear to be present.
- (2) Major metasomatic phases include phlogopite, clinopyroxene, ilmenite, spinel and amphibole (pyroxenites only). Owing to the absence of the PKP suite, no exotic REE-titanates were found. Secondary metasomatic phases, derived from late-stage activity include: high-Ti phlogopite, small euhedral clinopyroxene, pargasitic hornblende and Al-spinel.
- (3) It is possible to distinguish between metasomatized and non-metasomatized peridotites on the basis of clinopyroxene compositions. The most useful parameters are wt% Cr_2O_3 , wt% Na_2O and atomic Fe^{3+} . Clinopyroxene in phlogopite-bearing peridotites (GPP, PP) are characterized by a high- Cr_2O_3 (>1.5 wt%) and high- Na_2O (>2 wt%) composition, as well as elevated Fe^{3+} , compared to clinopyroxene from phlogopite-free peridotites (GP).

(4) The intergrain variation of Cr_2O_3 in high- Cr_2O_3 , high- Na_2O clinopyroxenes of a sample appears to be dependent on the degree of textural equilibration, i.e. the greater the degree of textural equilibration, the smaller the variation of Cr_2O_3 in clinopyroxene of a particular sample. Textural disequilibrium appears to increase with metasomatism, although extensive re-equilibration at a later stage often minimizes this.

(5) The probable metasomatic nature of high- Cr_2O_3 , high- Na_2O clinopyroxene is supported by its occurrence in mildly subcalcic garnet harzburgites from Letlhakane and Roberts Victor (Viljoen et al., in press). High-Cr spinels may also be present in these samples. The more variable composition of high- Cr_2O_3 , high- Na_2O clinopyroxene compared to clinopyroxene from garnet peridotites is also consistent with a metasomatic origin. Compositions of metasomatic minerals will vary depending on the different proportions of fluid and host rock in reaction. Based on the large proportion of GPP and PP xenoliths compared to GP rocks in the mantle, it is proposed that the majority of clinopyroxene in the lithosphere is of primary metasomatic origin.

(6) Remobilization of metasomatic phases may occur in response to elevated temperatures and pressures in the mantle, a long time duration, and possible recurring episodes of metasomatism. Distinguishing metasomatic textural features may also be destroyed with time. After re-equilibration, it may not be possible to distinguish mildly metasomatized peridotites from non-metasomatized peridotites in the absence of phlogopite. It is therefore proposed that the Cr_2O_3 , Na_2O and Fe^{3+} contents of clinopyroxene can be taken to indicate a possible metasomatic event.

(7) The following metasomatic reactions are thought to have occurred in the Letlhakane suite, illustrating the variable nature of the products of interaction between a metasomatizing fluid and the host rock:

- 1) garnet + fluid = clinopyroxene + phlogopite $\pm$ spinel
- 2) orthopyroxene + olivine + fluid = clinopyroxene + phlogopite + serpentine
- 3) olivine + fluid = phlogopite + orthopyroxene
- 4) orthopyroxene + olivine + fluid = recrystallized olivine + partly resorbed orthopyroxene + phlogopite + ilmenite

CHAPTER 4

ECLOGITES

4.1 Introduction

Samples of eclogite recovered from Letlhakane are ovoid in shape with a maximum axis of 5cm in length. As in the case of the majority of the peridotites (Chapter 2, Section 2.1), samples exhibit no banding. This may be due to the small sample size. Eclogite is an abundant xenolith type and contains a wide variety of accessory minerals. These include diamond, graphite, rutile, ilmenite and spinel, as well as primary and secondary amphibole and phlogopite. These accessory minerals (except phlogopite) form the basis of a petrographic subdivision of the eclogite xenoliths. It must be stressed that this subdivision is not intended as a rigid classification, since many of the eclogites contain more than one accessory mineral (See Table 4.1). It is merely a convenient and widely used (MacGregor and Carter, 1970; Shee, 1978; Hatton and Gurney, 1987; Hills and Haggerty, 1989, and many others) method of describing these rocks. Geothermometric aspects of the eclogites are included in Chapter 6, Section 6.5.

Texturally, the Letlhakane eclogites may be divided into two groups, based on the classification by MacGregor and Carter (1970). Group I eclogites are characterized by coarse-grained, subhedral to rounded garnets. The garnets are set in an anhedral or interstitial matrix of clinopyroxene (Plate 30). Garnet inclusions may be present in the clinopyroxene and exsolution lamellae of orthopyroxene in clinopyroxene are common. Group II eclogites contain anhedral, more angular garnet and clinopyroxene (Plate 31). The grains may be tightly interlocking, e.g. JSL 86. Garnet and clinopyroxene may alter more readily in Group I than in Group II eclogites.

This study also involves a large number of eclogitic garnet and clinopyroxene grain mounts where textural classification cannot be applied. A different classification using mineral chemistry will therefore be used instead.

Table 4.1: Petrographic and textural summary of the Letlhakane eclogite suite. The star symbol denotes the presence of primary, as well as possible metasomatic phases (eg. SP, ILM and RUT). Where possible, a distinction was made between primary (P) and secondary (S) metasomatic phlogopite and amphibole. The superscript (X) denotes phases observed in thin section only, i.e. they have not been analysed.

Sample no.	Rock type	Texture	GT	CPX	SP	PHL	AMP	ILM	RUT	GRA	DIA
JSL 59	A-ecl.	II	*	*		S ^X	P				
JSL 60	R,S-ecl.	II	*	*	*	S ^X			**X		
JSL 61	R-ecl.	II	*	*	*	S ^X			*		
JSL 62	R,I,A-ecl.	II	*	*		S	S ^X	*	*		
JSL 63	ecl.	II	*	*							
JSL 65	ecl.	II	*	*		P					
JSL 67	R,A-ecl.	I	*	*		S ^X	S		**X		
JSL 69	R-ecl.	II	*	*		S ^X			*		
JSL 77	ecl.	exsol?	*	*							
JSL 83	ecl.	I	*	*		S ^X					
JSL 86	ecl.	II	*	*		P					
JSL 91	ecl.	II	*	*		S ^X					
JSL 95	ecl.	II	*	*		S ^X					
JSL 98	A-ecl.	II	*	*		P, S	P				
JSL 100	ecl.	II	*	*							
JSL 104	A-ecl.	II	*	*		S ^X	S ^X				
JSL 106	R,G-ecl.	I	*	*		S ^X			*	**X	
JSL 200	D,G,A-ecl.	I	*	*			S			**X	**X
JSL 201	G-ecl.	I	*	*						**X	
JSL 203	G,R,A-ecl.	I	*	*		S	S		*	**X	
JSL 204	G,R,A-ecl.	I	*	*			S		*	**X	
JSL 205	G,A-ecl.	I	*	*		S	S			**X	
JSL 206	G,A-ecl.	I	*	*		S ^X	S			**X	
JSL 207	G,R,A-ecl.	I	*	*		S ^X	S ^X		*	**X	
JSL 208	G-ecl.	I	*	*						**X	
JSL 210	ecl.	II	*	*							
JSL 211	ecl.	I	*	*		S					
JSL 212	ecl.	I	*	*		S ^X					
JSL 213	A-ecl.	I	*	*			S ^X				
JSL 214	A-ecl.	I	*	*			S ^X				
JSL 251	A,R-ecl.	II	*	*		S	S		*		
JSL 254	A,I-ecl.	I	*	*		S	S	*			
JSL 600	opx-gt.cpx	II	*	*		P					

Abbreviations used in this table:

Minerals

GT	- garnet	ecl.	- bimineralic eclogite
CPX	- clinopyroxene	A-ecl.	- amphibole eclogite
SP	- spinel	R-ecl.	- rutile eclogite
PHL	- phlogopite	G-ecl.	- graphite eclogite
AMP	- amphibole	D-ecl.	- diamond eclogite
ILM	- ilmenite	S-ecl.	- spinel eclogite
RUT	- rutile	I-ecl.	- ilmenite eclogite
GRA	- graphite	opx-gt.cpx	- orthopyroxenite-
DIA	- diamond		garnet clinopyroxenite

Textures

I	- Group I
II	- Group II
exsol?	- exsolution?

4.2 Petrography

4.2.1 Bimineralic eclogite

The bimineralic eclogites form the largest subdivision of eclogites at Letlhakane. This group does not contain any of the primary accessory minerals mentioned in Section 4.1. Although the textural distinction between the Group I and Group II eclogites can be applied to the bimineralic eclogites, ambiguous cases do occur.

In these eclogites, garnet and clinopyroxene are the dominant minerals. The garnets vary from <1-15mm in size and are anhedral, rounded to irregular in shape and always exhibit cracks. A dark, cloudy alteration may be present in the garnet, especially along cracks. The colour of the garnet varies from light purple to red to orange-yellow and this is a direct reflection of the composition of the garnet (see Section 4.3.1). Inclusions in garnet consist of crystallographically oriented rutile(?) needles (e.g. sample JSL 63) and metasomatic phlogopite (e.g. sample JSL 86).

The clinopyroxene in these eclogites varies from pale to bright green to an almost opaque white colour owing to alteration. The maximum grain size observed is approximately 10mm, while the average is about 5mm. Intricate patterns of optically irresolvable material are possibly derived from the exsolution of Na₂O-rich material (e.g. Plate 30). The clinopyroxene structure cannot accommodate the high levels of Na at lower pressures and it is exsolved as albite. Exsolution of orthopyroxene(?) within clinopyroxene was observed in a few samples (JSL 100, 104 and 212).

Sample JSL 77 contains unique textural features, possibly as a result of exsolution (Plate 32). This is a bimineralic Group II eclogite, with garnet lamellae of variable size (0.3 - 4mm long and 0.15 - 0.75mm wide), the smallest of which have been replaced by kelyphite. The garnet grains vary from tabular elongate to granular in shape. The granular garnets are approximately 2.3mm in diameter. The garnets are cracked, but unaltered, except for minor kelyphite development. The clinopyroxene is pale-green and unaltered. Most clinopyroxenes also exhibit a tabular, elongate habit, up to 7mm in length. Several of the garnets are poikilitically enclosed by an optically homogeneous clinopyroxene crystal. No other minerals or alteration products are present in the sample.

4.2.2 Diamond- and graphite-bearing eclogite

This type of eclogite is represented by a single sample, JSL 200. The xenolith measured approximately 37x25x25mm in hand specimen before cutting. The major phase in this sample is fractured, orange-red

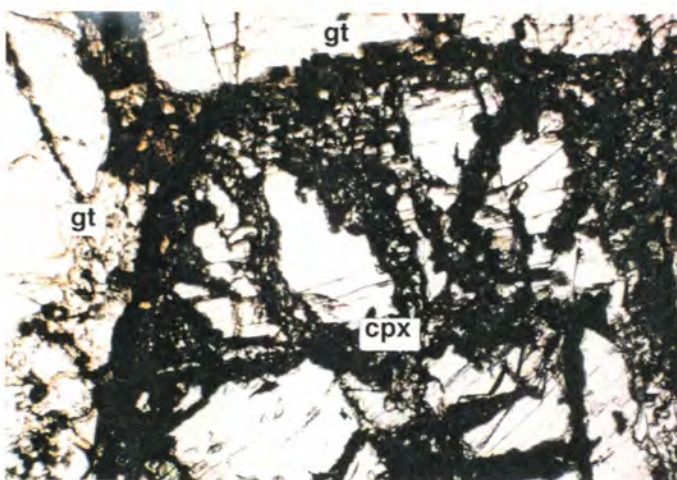


Plate 30: A texture typical of the Group I eclogites from Letlhakane. Note the large, anhedral garnets (gt) and the anhedral clinopyroxene matrix (cpx). Field of view = 3.5mm wide. Plane polarised light.

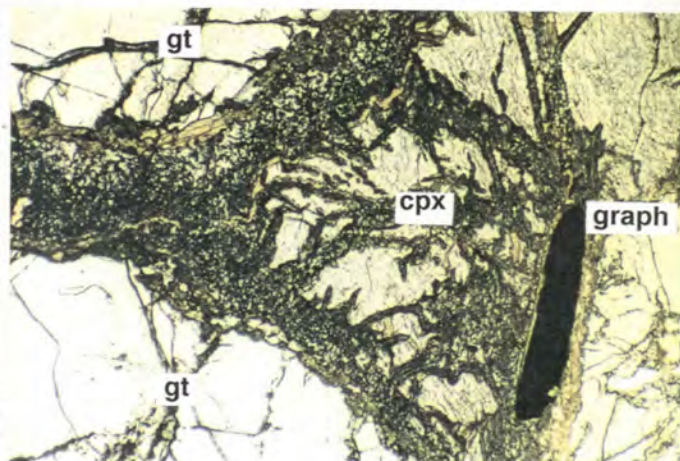


Plate 33: The general texture and appearance of JSL 200, a graphite- and diamond-bearing Group I eclogite. Note the tabular graphite (graph) flake, with embayments towards the bottom right. Interstitial clinopyroxene (cpx) is situated between anhedral garnets (gt). Field of view = 4mm wide. Plane polarised light.

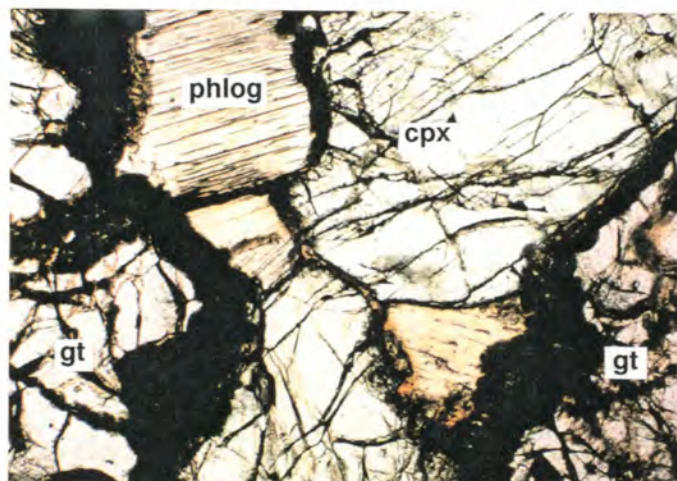


Plate 31: A texture typical of Group II eclogites from Letlhakane. Note the more angular garnets (gt) and clinopyroxene (cpx), as well as the general interlocking grain texture, compared to the Group I eclogite in Plate 30. Primary metasomatic phlogopite (phlog) may be present in the Group II eclogites, as shown here. Field of view = 3.5mm wide. Plane polarised light.



Plate 34: A scanning electron micrograph of the diamond, a sharp-edged macle, found in JSL 200. A scalebar is included in the plate. Note the smooth, unpitted and unetched appearance of the diamond.

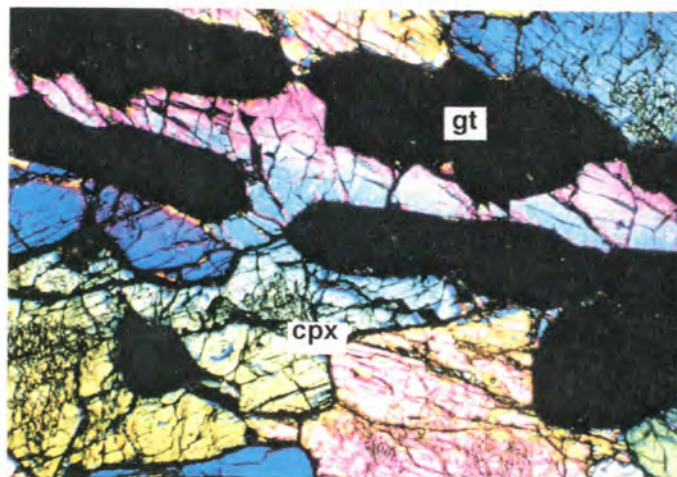


Plate 32: Possible garnet (gt) exsolution from clinopyroxene (cpx) in a Group II biminerallitic eclogite (JSL 77). Field of view = 3.5mm wide. Crossed nicols.

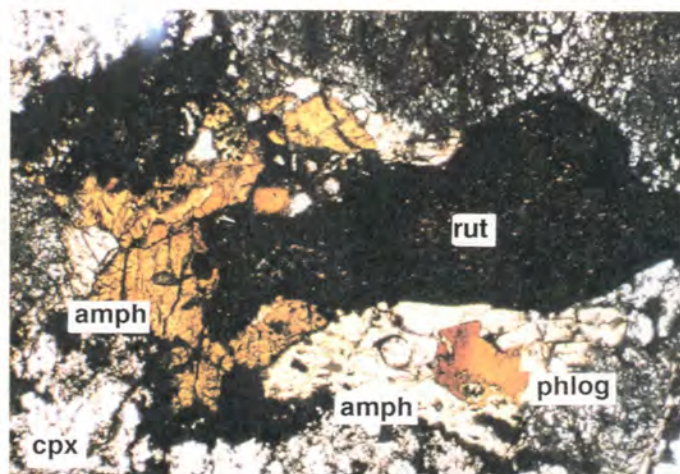


Plate 35: A typical rutile grain (rut) in sample JSL 203, a Group I eclogite from Letlhakane. The rutile is partly enclosed by brown pleochroic amphibole (amph) plates. The amphibole plate below the rutile also contains a brown phlogopite inclusion (phlog). Note the highly altered state of the surrounding clinopyroxene (cpx). Field of view = 3.5mm wide. Plane polarised light.

garnet. In thin section, the garnet is anhedral, rounded and varies in size from 5-15mm. Minor alteration products, e.g. secondary amphibole, euhedral clinopyroxene and green euhedral spinel, are confined to cracks and grain boundaries. The clinopyroxene has an interstitial, anhedral habit and grains vary from 3.5-7mm in size. These garnet and clinopyroxene habits are typical of a Group I eclogite (Plate 33). The clinopyroxene exhibits extensive development of cloudy, optically irresolvable material, often only leaving remnants of the original mineral. A single graphite platelet, approximately 0.3x1.5mm in size, is present in thin section. The graphite is embedded in clinopyroxene, but in contact with garnet (Plate 33).

Accessory minerals include graphite and diamond. Two small platelets of graphite (approximately 3x3mm) were removed for C-isotope analysis (See section 4.4). The graphite does not display any particular crystal shape and is embedded in clinopyroxene, but closely associated with the garnet. No other graphite is visible in hand specimen. The diamond is enclosed in a garnet. It is small (0.5mm), colourless and the exposed triangular face exhibits growth lines. The diamond is a sharp-edged macle (Plate 34), free of etching and pitting. This lack of etching and pitting is characteristic of diamonds derived from xenoliths (Robinson, 1979; Shree et al., 1982).

4.2.3 Graphite-bearing eclogite

Eight other graphite-bearing eclogites have been studied in addition to JSL 200. Table 4.1 summarises the main petrographic details. C-isotope analyses have been carried out on graphite from all samples, except JSL 106, 203 and 205 where the graphite is too small, or too difficult to remove.

Graphite is observed in thin sections from all of the above samples, except JSL 201. The graphite flakes are always embedded in clinopyroxene or along clinopyroxene-garnet grain boundaries (e.g. in JSL 208). Most graphite flakes are tabular (Plate 33), the largest is 2mm in length (JSL 206), and no hexagonal habits have been observed. The edges of the graphite may or may not be embayed. This feature is not restricted to any particular sample and is possibly the result of the effects of late-stage fluids (e.g. JSL 206).

All the graphite-bearing eclogites exhibit textures typical of Group I eclogites. The garnets are reddish-pink in thin section and mostly unaltered, except for samples JSL 106 and 204 which show common development of black kelyphitic material. The anhedral, rounded garnets vary from 0.5-8mm in size. The clinopyroxene is anhedral, interstitial and may be totally altered and recrystallized (e.g. JSL 203). The grain size of clinopyroxene is < 3.5mm. No inclusions other than graphite are present in either clinopyroxene or garnet.

Rutile is a common accessory mineral in JSL 106, 203 and 204. The rutile is anhedral, < 1mm in size, dark red-brown in colour and contains two sets of crystallographically oriented exsolution lamellae. These features will be discussed in the following section. Secondary metasomatic amphibole and phlogopite are common in most of the graphite-bearing eclogites. These minerals are often, but not always, associated with the rutile. The best preserved evidence of metasomatism is observed in JSL 203 where irregular plates of amphibole, 0.5 - 2mm in size, partly enclose rutile (Plate 35). Phlogopite is present, but in lesser amounts. A thin veinlet of fine-grained phlogopite, amphibole and minor calcite is associated with the minerals seen in Plate 35. Phlogopite and amphibole plates also occur along the rims of a few garnets. These features will be discussed in more detail in section 4.2.7, which deals with amphibole-bearing eclogites.

4.2.4 Rutile-bearing eclogite

The garnets in these eclogites are anhedral, rounded to irregular and up to 5mm in size. The colours vary from pale pink (mostly Group II) to orange-red. Features of garnet and clinopyroxene are similar to those discussed in the section dealing with the textures of Group I and Group II eclogites.

Rutile is the third most common accessory mineral in eclogites after amphibole and phlogopite. Ten eclogites contain rutile (Table 4.1), which shows no preference for any particular eclogite type, being equally divided between Group I and Group II eclogites. Rutile is usually associated with amphibole, ilmenite, spinel and, more rarely, graphite.

All rutile grains are brown with a rounded, anhedral shape and sizes vary from 0.7-3.2mm (Plate 35). Two sets of crystallographically oriented exsolution lamellae are present in the rutile. The largest set is identified as ilmenite, while the smaller lamellae at right angles to the former are too small for optical identification, but may be Al-spinel, similar to exsolution observed in eclogitic rutile from the Stockdale kimberlite, U.S.A. (Meyer and Boctor, 1975). Rutile usually occurs as discrete grains, e.g. at Stockdale (Meyer and Boctor, 1975), and not as inclusions in silicate phases. Rutile in four samples (JSL 67, 106, 203 and 204) contains irregular patches of sphene towards the rims. A single rutile grain in JSL 106 has been partly replaced by sphene. A thin rim of ilmenite may or may not surround the rutile grains. The compositions of these minerals have been qualitatively determined using an energy dispersive system attached to an electron microprobe. Note that the sphene is restricted to Group I eclogites, especially those which exhibit evidence of secondary metasomatism.

The garnet and clinopyroxene in JSL 60 contain oriented rutile inclusions. JSL 251, although eclogitic, contains no clinopyroxene. The rutile in JSL 251 is marked by a bright, red-brown colour compared to that of the other eclogites. This type of rutile is associated with primary metasomatism, represented by copious primary metasomatic phlogopite. No amphibole is present, however.

4.2.5 Ilmenite-bearing eclogite

Only two ilmenite-bearing eclogites, JSL 62 and 254, have been found (Table 4.1). JSL 62 is a rutile- and amphibole-bearing Group II eclogite, also containing secondary metasomatic phlogopite associated with the rutile. The general petrography of this sample is included in Section 4.2.4 and therefore not repeated here. The ilmenite occurs as a discrete, anhedral inclusion, approximately 0.35mm in diameter, which is hosted in unaltered clinopyroxene.

JSL 254 is an amphibole-bearing Group I eclogite containing minor secondary metasomatic phlogopite. The anhedral, rounded garnets are pale, orange-red and range from 1-8mm in size. The rims exhibit slight alteration. The clinopyroxene (≤ 8 mm in size) is badly altered and recrystallized with only minor remnants of fresh material left. The ilmenite occurs as anhedral, irregular blebs, 0.3-3.5mm in size, hosted by clinopyroxene (Plate 36). The ilmenite is closely associated with metasomatic alteration products in the form of amphibole, phlogopite and green chloritic(?) material. The boundaries of ilmenite are embayed where in contact with the metasomatic material, suggesting that the assemblage is not in equilibrium (Plate 36).

4.2.6 Spinel-bearing eclogite

This group is represented by a single rutile-bearing Group II eclogite, JSL 60. The general petrography of this rock is therefore included in Section 4.2.4. The spinel is red-brown in colour, and occurs as anhedral, irregular blebs, the largest of which is 0.5mm in size, hosted by garnet. It is similar in colour and habit to the Al-bearing Cr-spinel present in the spinel lherzolites (Chapter 2, Section 2.2.3). The spinel present in JSL 61, also a rutile-bearing Group II eclogite, is small, euhedral and located in kelyphite. The size and habit of this spinel suggest a secondary origin.

4.2.7 Amphibole-bearing eclogite

Amphibole has been detected in 15 eclogites (Table 4.1) and from these eclogites, it was possible to petrographically distinguish two types of amphibole.

The first type of amphibole occurs as vein fillings (JSL 67), irregular plates (JSL 203) and discrete blebs (JSL 214) (Plates 35 and 36). This type of amphibole is dark brown and very common. Compositions are equivalent to pargasites and ferroan pargasites (after the classification of Leake, 1978). These amphiboles exhibit no particular preference for either Group I or Group II eclogites. Grain sizes range

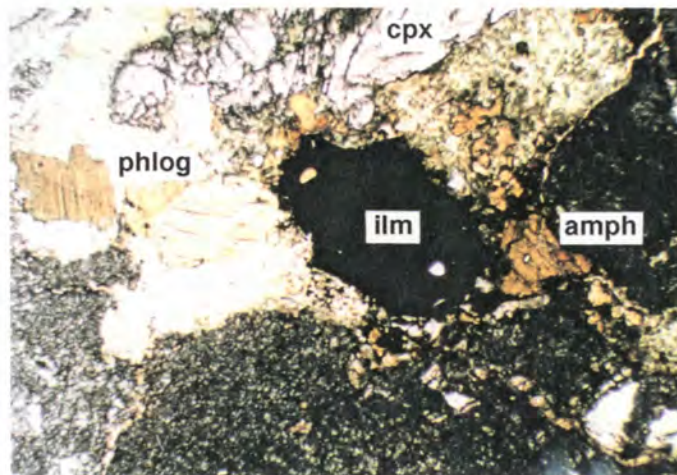


Plate 36: An ilmenite-bearing eclogite (JSL 254) containing pale brown, secondary metasomatic phlogopite (phlog), brown amphibole (amph) and greenish chloritic(?) material associated with the ilmenite (ilm). Note the embayed ilmenite boundaries. The above phases are surrounded by altered clinopyroxene (cpx). Field of view = 3.5mm wide. Plane polarised light.

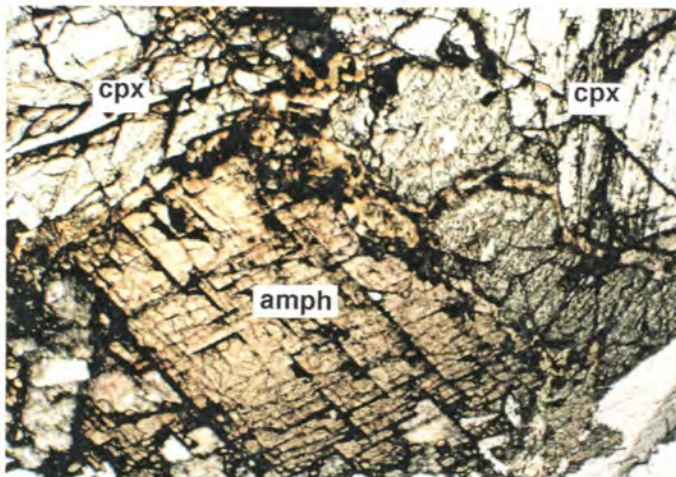


Plate 37: A single plate of primary metasomatic, edenitic hornblende (amph) in a Group II eclogite (JSL 59). Primary clinopyroxene (cpx) is also visible. Field of view = 3.5mm wide. Plane polarised light.

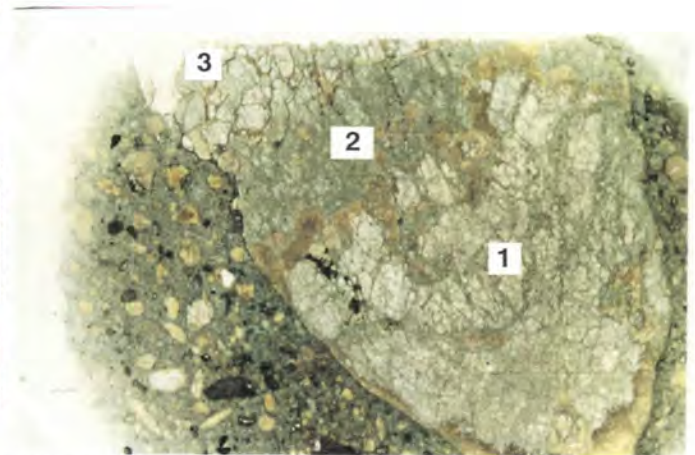


Plate 39: A large thin section of JSL 600, illustrating the various subzones in this composite xenolith from borehole LFD, Letlhakane DK 1. See text for a description of the various subzones. Field of view = 7.2cm wide.

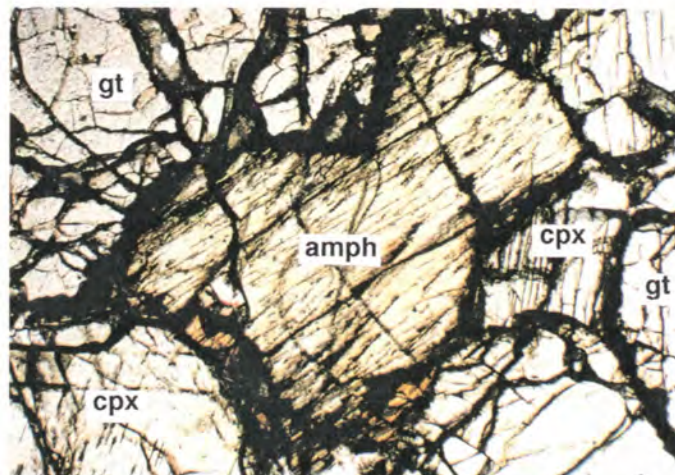


Plate 38: Primary metasomatic, edenitic hornblende (amph) in another Group II eclogite (JSL 98), surrounded by garnet (gt) and clinopyroxene (cpx). Note the difference in colour, size and habit of the amphibole in Plate 35, compared to the amphibole in Plates 37 & 38. Field of view = 3.5mm wide. Plane polarised light.

from 0.3-2mm. Associated minerals include phlogopite, rutile, ilmenite, calcite, secondary clinopyroxene and spinel, serpentine and chlorite(?). Rutile is almost always associated with amphibole and may be totally enclosed in an optically continuous plate of amphibole (JSL 67). Calcite occurs as anhedral, rounded blebs in amphibole (JSL 67). Amphibole is also commonly associated with the kelyphite rims around garnet, but mostly as small, irregular blebs. The habit, size and texture of the amphibole, as well as the associated minerals, suggest a secondary origin.

Two Group II eclogites contain amphibole which differs from that observed in all other eclogites. The amphiboles in these eclogites are pale brown, in contrast to the dark brown types described earlier. They are classified as edenitic hornblendes (after Leake, 1978). Grain sizes range from 2-5mm, i.e. much larger than those of the dark brown amphiboles. The pale brown amphiboles appear to be in better textural equilibrium with straight (JSL 59 - Plate 37) to strongly curving (JSL 98 - Plate 38) grain boundaries. The pale brown amphibole in JSL 98 is associated with primary metasomatic phlogopite (not visible in Plate 38). The above textural features are suggestive of a primary metasomatic origin.

Owing to its probable secondary origin, the first type of amphibole is considered to be of lesser importance than the primary amphibole. It was, however, included to illustrate some of the obvious differences between the two types (Plates 35, 37 and 38). The compositional differences between these two amphibole types will be dealt with in Section 4.3.7.

4.2.8 JSL 600: an orthopyroxenite-garnet clinopyroxenite composite xenolith

The elliptical xenolith (6 x 4.5 cm) was discovered in a section of core from borehole LFD at Letlhakane DK 1. Approximately 1/3 of the sample was lost due to intersection by the drill. The sample appears pristine and the only evidence of alteration is a micaceous material situated in some cracks and along the xenolith-kimberlite contact (Plate 39). The dominant phases are orthopyroxene, clinopyroxene, garnet and phlogopite. No olivine is present in this xenolith. Lesser secondary serpentine, phlogopite, clinopyroxene and carbonate are also present. An unidentified opaque material was also observed. This xenolith can be broadly divided into 3 subzones, illustrating its composite nature.

The first subzone (Plate 39, 1) consists almost entirely of orthopyroxene with rare garnet, exhibiting strongly curved and embayed grain boundaries. All garnets are surrounded by a rim of large, primary-textured phlogopite, intergrown with clinopyroxene. An unidentified opaque phase, possibly ilmenite or spinel, is present in this subzone. Unfortunately, the opaque phase could not be observed in any of the

polished thin sections used for analytical purposes. A single intergrowth of phlogopite and clinopyroxene without garnet is also present. This intergrowth is identical to those with a garnet remnant and it is assumed that all the garnet may have been replaced in this case. Small pockets of clinopyroxene and associated phlogopite are also present in the orthopyroxene.

The second subzone (Plate 39, 2) consists of a band of almost monomineralic greenclinopyroxene, broadening to one side. The orthopyroxene-clinopyroxene contact is highly irregular, embayed and marked by a thin layer of brown irresolvable material, similar to that observed along the orthopyroxene-kimberlite contact. It is probably of secondary origin and almost certainly derived from orthopyroxene breakdown. Rare garnet grains are also present in this subzone, some associated with primary-textured phlogopite. All the clinopyroxene in this subzone, and in fact the entire sample, exhibits "spongy" and recrystallized rims. This feature is discussed and explained in Chapter 2, Section 2.4.4.

The third subzone (Plate 39, 3) is recognized by the sudden modal increase in garnet content. The garnets are red-purple in colour, anhedral to irregular in shape and, together with clinopyroxene, form an interlocking texture. Both primary and secondary metasomatic phlogopite are associated with the garnet. The overall texture of this subzone is remarkably similar to that of the Group II eclogites, described in Section 4.1. The large modal proportion of garnet in this subzone is also more typical of the eclogites than the pyroxenites encountered at Letlhakane. Unfortunately, because the xenolith is incomplete, it is not known whether a 4th subzone may have been present.

In summary, the xenolith therefore consists of garnet orthopyroxenite - monomineralic clinopyroxenite - garnet clinopyroxenite / Group II eclogite segments.

4.3 Mineral chemistry

Approximately 62 eclogites have been analysed as grain mounts, i.e. two unaltered grains each of clinopyroxene and garnet were separated from the eclogite, mounted and polished for microprobe analysis. Although this method has obvious disadvantages with regard to the observation of textures and accessory phases, a far larger number of samples can be analysed to provide a better representation of clinopyroxene and garnet composition in the eclogite suite. Garnet and clinopyroxene composition, instead of textures, may then be used to classify the eclogites. Each of the eclogites from which grain mounts were analyzed

were studied under a stereo microscope for obvious accessory phases, e.g. diamond, graphite or rutile. Those containing obvious accessory phases were analysed by thin section instead. Thirty-four polished thin sections of a wide range of eclogite types were prepared. A classification of the various types (thin sections only) is given in Table 4.1. Analyses of the various phases can be found in Appendix 3.

Three polished thin sections of JSL 600 (Section 4.2.8) were prepared. Two sections were cut perpendicular to the orthopyroxene-clinopyroxene contact to determine zoning or disequilibrium features at the contact. Three traverses were undertaken across the length of each of these sections. The third section was cut in the garnet clinopyroxenite subzone to determine whether these mineral compositions are similar to those of the Group II eclogites. Contrary to all expectations, the mineral phases are remarkably homogeneous with respect to major element oxides, particularly garnet, orthopyroxene and primary metasomatic phlogopite.

4.3.1 Garnet

Variations in the major elements are best illustrated on a Ca-Mg-Fe ternary plot as shown in Fig 4.1. The Mg-content is the most variable parameter (approximately 30-80 mole % pyrope). Both Ca and Fe increase with a decrease in Mg. These chemical changes are also responsible for the variable colour of the eclogitic garnets. Garnets close to the pyrope endmember are purple in colour. Increasing Ca and Fe result in a reddish-orange garnet, seen in the diamond and graphite-bearing eclogites. Garnets from these eclogites typically plot towards the center of a Ca-Mg-Fe diagram.

Figure 4.1 also compares the eclogitic garnet compositions from Letlhakane with those of the different eclogite types described by Shee (1978) at Orapa. The Group II garnets from Letlhakane are restricted to the Mg-rich, Ca-poor corner of the plot. Garnet from the composite pyroxenite xenolith, JSL 600 (Section 4.2.8), also plots within this field and close to the websterite field from Orapa, as defined by Shee (1978). Garnets from the composite pyroxenite xenolith exhibit no compositional zoning. Group I garnets exhibit considerably more variation than those of Group II. The majority of the garnets are either Mg-rich, or Ca-Fe rich. A few samples (approximately 10) plot within the Ca-rich field noted at Orapa. No eclogites with garnets of compositions similar to those of the kyanite or corundum eclogites from Orapa have been found. The fields of the Mg-rich, kyanite and corundum eclogites from Koidu, Sierra Leone (Hills and Haggerty, 1989) correspond with those from Orapa. Fig. 4.2 illustrates the composition of garnet from diamond and graphite-bearing eclogites from Letlhakane and various other localities. Most of the graphite-bearing eclogites from Letlhakane have garnet compositions that are similar to those from Orapa.

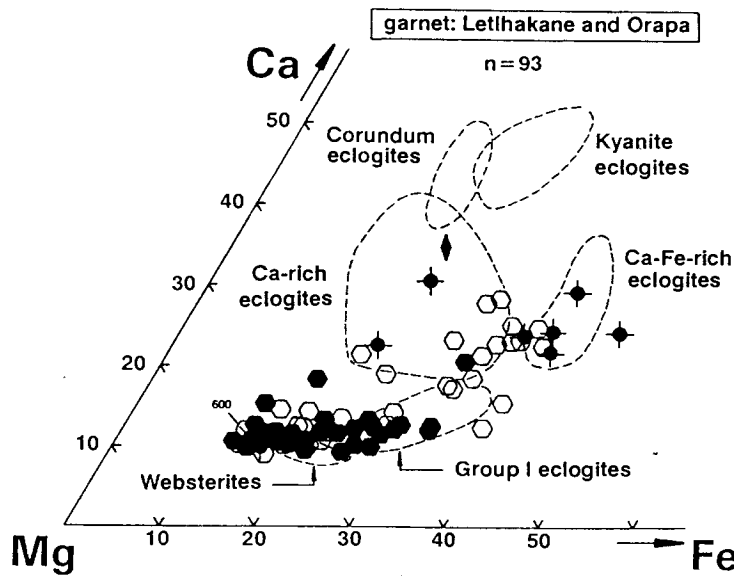


Fig. 4.1 Ternary plot of mole% Pyrope (Mg), Grossular (Ca) and Almandine (Fe), illustrating the Letlhakane Group I and Group II eclogitic garnets. Note the lack of Ca enrichment in the Group II eclogites, in contrast to the Group I eclogites. Dashed fields represent subdivisions of the Orapa eclogites after Shee (1978).

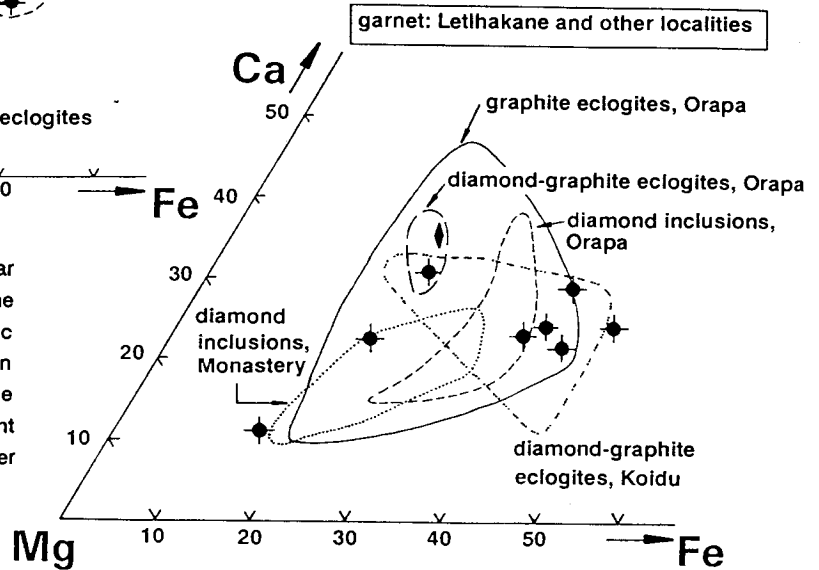


Fig. 4.2 A mole% Mg-Ca-Fe ternary plot, illustrating the composition of graphite- and diamond-graphite eclogitic garnets from Letlhakane in comparison with data from several other localities, taken from Shee (1978), Rickard (unpubl. in Shee, 1978), Hills and Haggerty (1989) and Moore and Gurney (1989). Garnets from the diamond and graphite-bearing eclogites shown are broadly similar in composition, irrespective of locality.

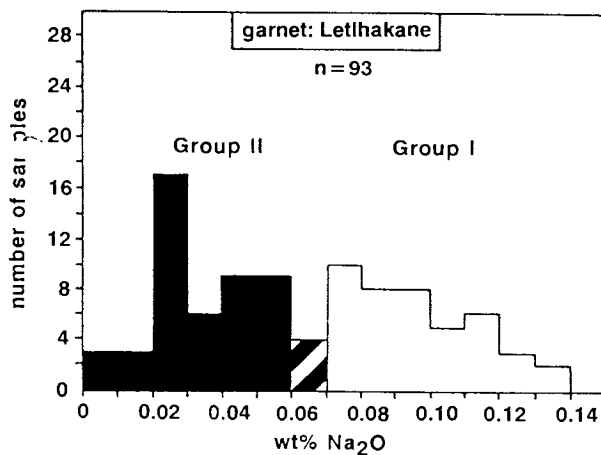


Fig. 4.3 Na_2O -content in eclogitic garnets. 2σ error = 0.02 wt% Na_2O . The division between Group I and Group II is located between 0.06 and 0.07 wt% Na_2O with a slight overlap between the two groups.

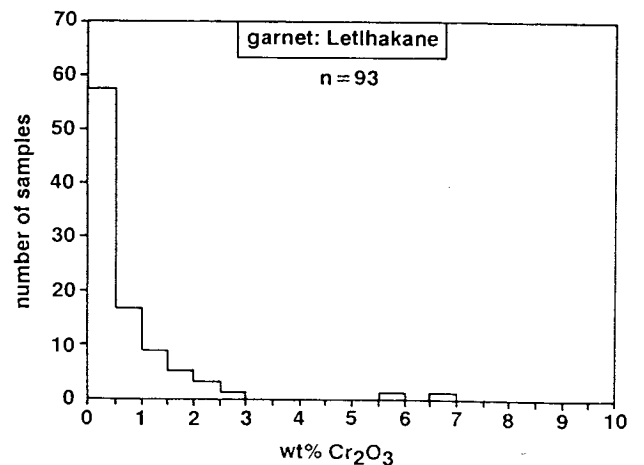


Fig. 4.4 Cr_2O_3 -content in eclogitic garnets. The majority of garnets are characterized by a low Cr_2O_3 -content. Two samples, probably of peridotitic origin, exhibit anomalously high Cr_2O_3 values.

The composition of garnet in the diamond-graphite-bearing eclogite from Letlhakane is in agreement with garnets in similar eclogites from Orapa. Garnet inclusions in diamond from Orapa plot almost entirely within the field of garnets from the Letlhakane graphite-bearing eclogite field (Fig. 4.2).

McCandless and Gurney (1989) showed that the Na_2O -content of garnets can be used to subdivide the Roberts Victor eclogites. They proposed that the Group I eclogites of MacGregor and Carter (1970) have garnets with a Na_2O -content of $>0.09\text{wt}\%$. Conversely, garnets from the Group II eclogites have a Na_2O -content of $<0.09\text{wt}\%$. Group I eclogites have the potential to carry diamonds (McCandless and Gurney, 1989). The histogram in Fig. 4.3 illustrates the Na_2O -content of the Letlhakane eclogitic garnets. Two different groups of garnet exist, one with $\text{Na}_2\text{O} < 0.07\text{ wt}\%$ and the other with $\text{Na}_2\text{O} > 0.07\text{ wt}\%$. The division therefore appears to be at approximately $0.07\text{wt}\%$ Na_2O , but if a 2σ error of $0.02\text{ wt}\%$ is taken into account, the boundary is similar to the one proposed by McCandless and Gurney (1989) for garnets from the Roberts Victor eclogites. According to this classification, garnets from the composite pyroxenite xenolith are of Group II origin.

Fig. 4.4 indicates that the Cr_2O_3 -content of the eclogitic garnet ranges between 0.5 and $3.0\text{ wt}\%$ Cr_2O_3 . The Cr_2O_3 -content of garnets from the composite pyroxenite xenolith, JSL 600, is $1.28\text{ wt}\%$ (from an average of 8 analyses), indicating that these garnets can either belong to Group II, or be of pyroxenitic origin (Chapter 2, Section 2.3.4). Garnets from samples JSL 100 and 102 exhibit anomalously high levels of Cr_2O_3 . Cr_2O_3 and CaO -values of the garnet in these two eclogites compare favourably with those from peridotitic garnets. It is therefore possible that JSL 100 and 102 are not genuine eclogites, but clinopyroxene-garnet fragments derived from disaggregated peridotites.

4.3.2 Clinopyroxene

All clinopyroxenes are optically homogeneous, but those in JSL 202 and 203 exhibit slight chemical inhomogeneity, which may be owing to the extensive recrystallization of the clinopyroxene.

Most clinopyroxenes from the Letlhakane eclogites plot towards the center of Fig. 4.5, a ternary plot of mole % Wo - Jd - Hy . The majority of clinopyroxenes in the MgO -rich Group II eclogites plot towards the Wo - Hy join. Group I eclogites contain clinopyroxene which shows an increasing amount of the Jd -component, with clinopyroxene from the graphite and diamond-bearing eclogites plotting towards the top of the diagram. A single Group I eclogite (JSL 54) contains clinopyroxene which exhibits considerable enrichment in the Hy component (Fig. 4.5). The reason for this is not clear. Fig. 4.5 also illustrates that the clinopyroxene compositions from the composite pyroxenite xenolith (Section 4.2.8) plot within the clinopyroxene field of the Group II eclogites.

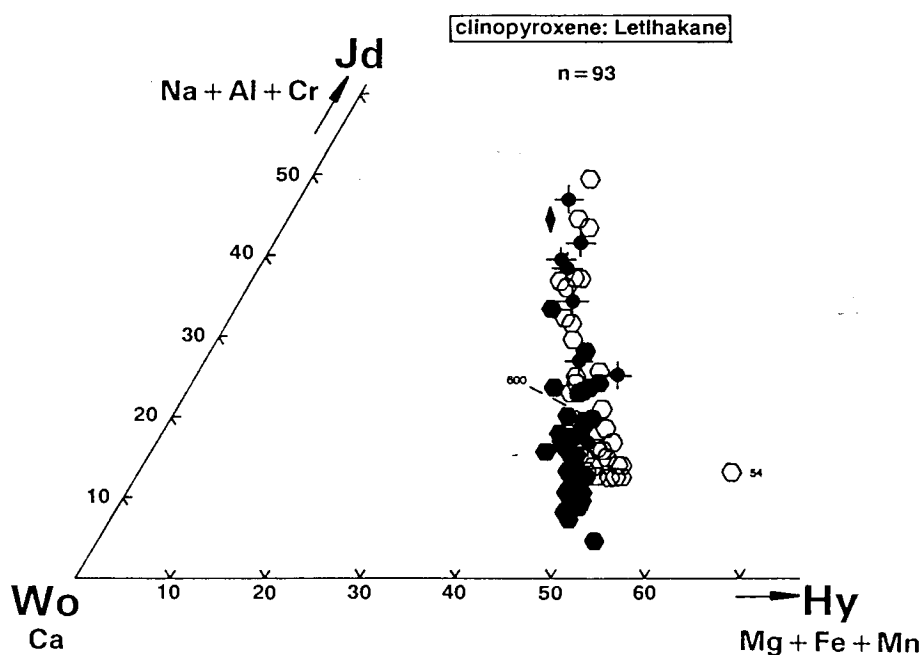


Fig. 4.5 A ternary plot of mole% Wo-Jd-Hy, illustrating the composition of Group I and Group II eclogitic clinopyroxene. A single Group I eclogite (JSL 54) is enriched in the Hy-component and plots considerably outside the Group I field. Note the enrichment in the Jd-component shown by some of the Group I eclogites.

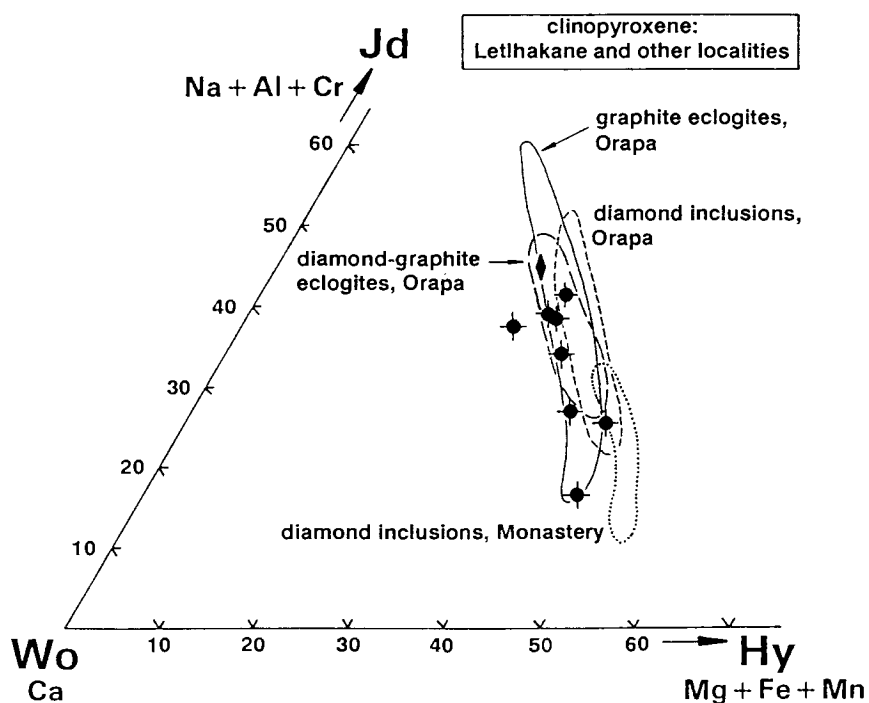


Fig. 4.6 An identical plot to Fig. 4.5, but comparing the graphite- and diamond-graphite-bearing eclogites from Letlhakane to published data taken from Shee (1978), Hills and Haggerty (1989) and Moore and Gurney (1989). Like the garnet in Fig. 4.2, the clinopyroxenes from Orapa, Letlhakane and Monastery are also similar in composition.

General clinopyroxene compositions of the low- and high-MgO eclogites from Koidu (Hills and Haggerty, 1989) and Orapa (Shee, 1978) coincide closely with those of the Group I and Group II eclogites respectively, and are therefore not included. However, clinopyroxene inclusions in diamond and clinopyroxenes from graphite and diamond-bearing eclogites exhibit more variation, as is shown in Fig. 4.6. Clinopyroxenes from graphite-bearing eclogites at Letlhakane exhibit less variation in the Jd-component, but may be slightly more calcic. The compositions of clinopyroxenes included in diamonds from Orapa overlap with those of graphite-bearing eclogitic clinopyroxene from both Orapa and Letlhakane. Diamond-bearing eclogites from Orapa, Letlhakane and Koidu contain clinopyroxenes that are very similar in composition. Clinopyroxene inclusions in diamond from Monastery (Moore and Gurney, 1989) contain less of the Jd-component than similar inclusions from Orapa. Clinopyroxenes included in alluvial diamonds from New South Wales, Australia (Sobolev, 1984) are enriched in Ca (not shown), in comparison with similar inclusions in the Monastery diamonds.

The TiO_2 -contents of the Letlhakane clinopyroxenes are highly variable (0.05-0.91 wt%). Most of the samples containing high-Ti (>0.40 wt%) clinopyroxene have been metasomatized and many of these high-Ti clinopyroxenes occur in Group I eclogites. The Cr_2O_3 -contents of the clinopyroxenes vary from 0.04-2.59 wt%, with clinopyroxene from Group II eclogites exhibiting the highest Cr_2O_3 -values. The K_2O in clinopyroxene was not analysed, since concentrations may be affected by metasomatism and decompression melting (Switzer and Melson, 1969; Reid et al., 1976), as well as crystallographic orientation (McCandless and Collins, 1989). The TiO_2 -, Cr_2O_3 - and Al_2O_3 -contents of clinopyroxene from the composite pyroxenite xenolith (0.24, 1.46, 3.66 wt% respectively for an average of 37 analyses) fall within the ranges exhibited by these oxides for clinopyroxenes in the Group II eclogites, as well as the pyroxenites (Chapter 2). Clinopyroxenes from the various subzones in the composite pyroxenite xenolith (Section 4.2.8) exhibit no significant compositional differences.

4.3.3 Rutile

The petrographic features of rutile have been discussed in Section 4.2.4. Owing to the small size of the exsolution features mentioned, quantitative analyses are not possible. The ilmenite lamellae can be identified using reflected light microscopy. This was confirmed by microprobe analysis of the rutile, during which increases in Fe and Mg were detected as the ilmenite lamellae were traversed. Al is present in the smaller set of exsolution lamellae. Microprobe analyses of sphene were attempted, but are not considered representative, as the Rare Earth Elements (REE) were not included in the analyses.

The primary rutile is reasonably pure, with minor Al_2O_3 , Cr_2O_3 and FeO. The rutile in JSL 251 can be identified by its high (>2wt%) Cr_2O_3 -content. (Fig. 4.7). Websteritic rutiles are included for

comparison. The single rutile in JSL 203 is characterized by high FeO (4.86 wt%), possibly due to accidental analysis of ilmenite exsolution. A rutile grain from Koidu (Hills and Haggerty, 1989) and rutile grains from Stockdale (Meyer and Boctor, 1975) are similar in composition to the Letlhakane eclogitic rutile (Fig. 4.7).

4.3.4 Ilmenite

The eclogitic ilmenite from Letlhakane is characterized by very low Cr_2O_3 -contents (< 0.44 wt%) and variable MgO (Fig. 4.8). Calculated Fe_2O_3 -contents of ilmenites are lower than those of the megacrysts and ilmenite from associated silicate intergrowths. Unfortunately, only two ilmenite grains have been found and they differ considerably in composition (Fig. 4.8). Owing to the small number of grains analysed, it is not known whether these differences signify distinct ilmenite populations in the Group I and Group II eclogites. The ilmenite in JSL 254 (Group II) contains almost double the amount of Fe_2O_3 (6.38 wt%) contained in the ilmenite in JSL 62 (3.7 wt%), suggesting a reduced (and possibly more primitive?) origin for the latter. The ilmenite in JSL 62 contains 6.5 wt% MgO, compared to 14.17 wt% MgO in ilmenite from JSL 254. Ilmenite from JSL 62 is also enriched in NiO (0.37 wt% compared to 0.04 wt% in JSL 254). Ilmenite in the Koidu eclogites exhibits low Cr_2O_3 -contents and MgO-values similar to that of ilmenite in JSL 62.

4.3.5 Spinel

The spinel in JSL 60 is identified as a Cr-bearing Al-spinel. Al_2O_3 -contents vary from 42-43 wt% and Cr_2O_3 from 24.5-26.5 wt%. These spinels differ from the chromites described by Shee (1978) because of their higher Al and lower Cr-values. A typical secondary Al-spinel from JSL 61 is also shown in Fig. 4.9. These small, euhedral spinels are ubiquitous in all samples where breakdown of garnet has occurred and are recognised by their habit, colour and high Al-content. A higher Fe_2O_3 -content is indicative of a more oxidizing environment.

4.3.6 Phlogopite

Two types of phlogopite may be distinguished on the basis of differences in TiO_2 , Cr_2O_3 and MgO. Large grains of phlogopite, in textural equilibrium with adjacent phases (e.g. in JSL 65, 86 and 98), contain < 1.5 wt% TiO_2 , < 0.5 wt% Cr_2O_3 and > 22 wt% MgO (Figs. 4.10 and 4.11). The second type of phlogopite occurs as smaller grains and appears less equilibrated. It is recognized by higher TiO_2 (> 2.5 wt%), variable Cr_2O_3 and lower MgO (< 22 wt%). These two types are of similar composition to the two phlogopite

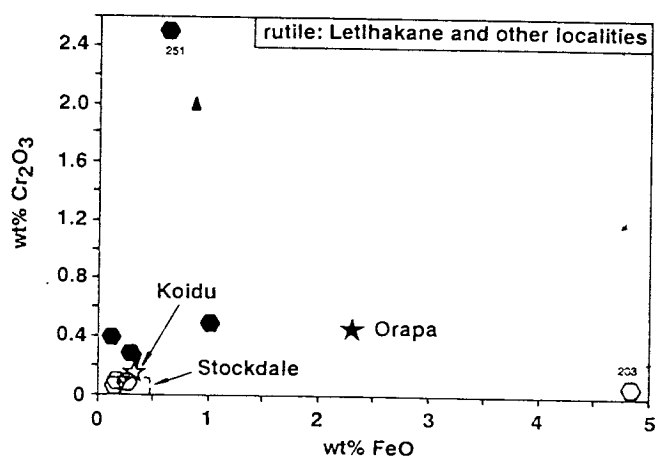


Fig. 4.7 Wt% Cr_2O_3 vs. wt% FeO in rutile. Rutile from a metasomatized pyroxenite is included for comparison. Metasomatic rutile is distinguished on the basis of its high Cr_2O_3 -content. The extreme FeO-enrichment in rutile from a Group I eclogite may be the result of the influence of ilmenite exsolution lamellae. Other data from Hills and Haggerty (1989), Shee (1978) and Meyer and Bector (1975).

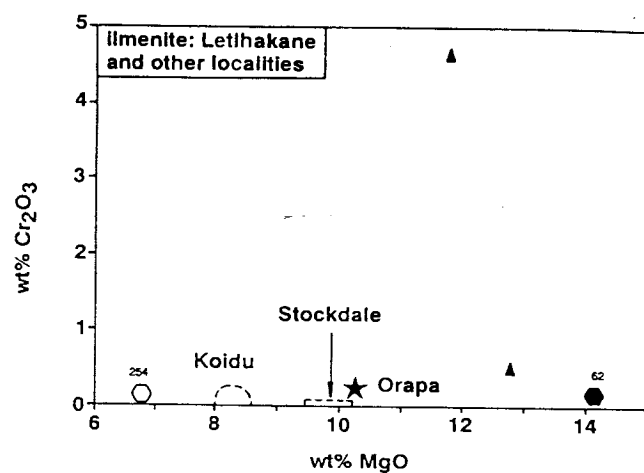


Fig. 4.8 Wt% Cr_2O_3 vs. wt% MgO, illustrating the compositions of ilmenite from eclogites and metasomatized pyroxenites. Note the large difference in MgO-content between the two ilmenites from Letlhakane eclogites. Other data were taken from Hills and Haggerty (1989), Meyer and Bector (1975) and Shee (1978).

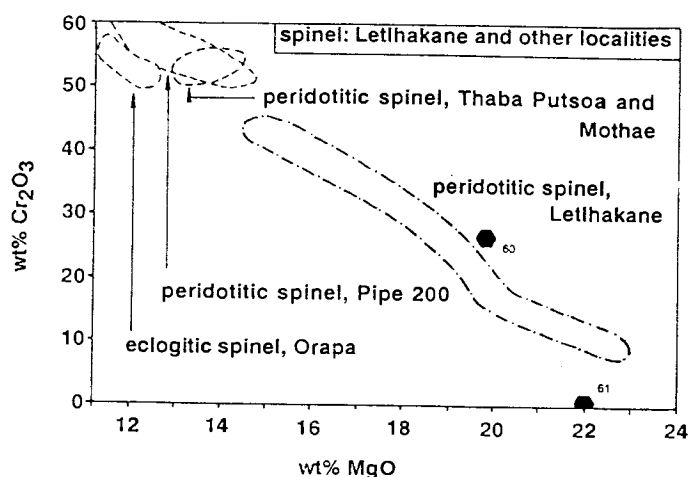


Fig. 4.9 Wt% Cr_2O_3 vs. wt% MgO in spinels from two Letlhakane eclogites. The Cr_2O_3 -poor spinel (JSL 61) represents the composition of a typical secondary aluminous spinel derived from the breakdown of garnet. Other data fields are from Shee (1978), Carswell et al. (1979) and Nixon and Boyd (1973a).

generations identified in the metasomatized peridotite-pyroxenite suite (see Chapter 3, Section 3.3.7). The latter, and phlogopite from a MARID (JSL 51) and a glimmerite (JSL-/181), are included for comparison in Fig. 4.10. Mention must also be made of the fact that no primary metasomatic phlogopite was found in any of the Group I eclogites.

Phlogopite from the composite pyroxenite xenolith (JSL 600) is characterized by a low Cr_2O_3 (<0.65 wt%) and low TiO_2 (<0.60 wt%) composition and plots within the field of primary metasomatic phlogopite compositions in southern Africa. Phlogopite derived from garnet breakdown in the orthopyroxenite is slightly enriched in MgO (by approximately 1.5 wt%) and Na_2O (0.11 wt%), and poorer in Al_2O_3 (1.5 wt%) when compared to phlogopite in the clinopyroxenite. This difference in composition may have been caused by the mineralogical control exerted by the host phase.

4.3.7 Amphibole

The Letlhakane amphiboles may be subdivided into two types based on their TiO_2 , Cr_2O_3 , Al_2O_3 and CaO contents. The first amphibole type is represented by two Group II eclogites (JSL 59 and JSL 98) and is recognized by its larger grain size and pale brown colour (see Section 4.2.7). Compositionally, these amphiboles are characterized by lower Al_2O_3 (approximately 11 wt%) and TiO_2 (0.36-0.47 wt%, not shown) and higher Cr_2O_3 (0.65-0.74 wt%) than the second amphibole type (Figs. 4.12 and 4.13).

The second amphibole type is petrographically recognized by its smaller grain size, variable habit and dark brown colour (see Section 4.2.7). The most notable compositional feature of this amphibole type is its higher and variable FeO- and Al_2O_3 -content (Figs. 4.12 and 4.13), and lower Cr_2O_3 -content (Fig. 4.12). Amphibole from JSL 59 and JSL 98 is similar in composition to possible primary metasomatic amphibole in the metasomatized garnet websterites (Figs. 4.12 and 4.13).

The amphiboles in JSL 59 and 98 (i.e. the first type) are considered to be of primary metasomatic origin on the basis of texture, grain size (see Section 4.2.7) and composition. The second amphibole type is thought to be of secondary metasomatic origin, owing to its smaller grain size, less equilibrated texture and more variable composition.

4.3.8 Orthopyroxene

This section on orthopyroxene compositions is included only because of the presence of orthopyroxene in the composite pyroxenite xenolith (JSL 600, Section 4.2.8). Orthopyroxene compositions

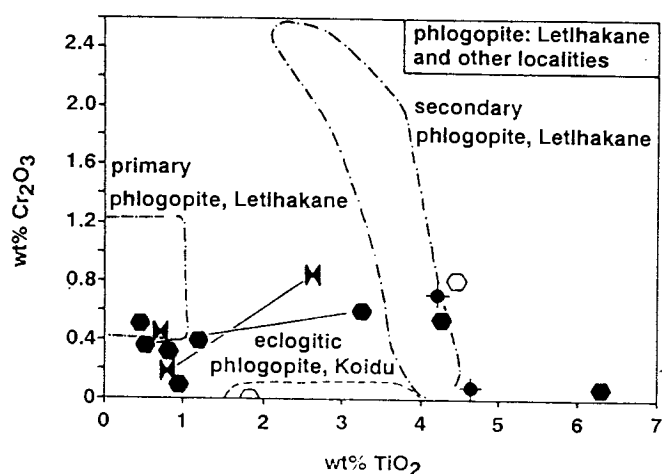


Fig. 4.10 Wt% Cr_2O_3 vs. wt% TiO_2 of phlogopite in eclogites. Primary-textured phlogopites exhibit low TiO_2 values and are all similar in composition. Secondary metasomatic phlogopite compositions are more variable. Also note that no primary metasomatic phlogopite was found in any Group I eclogite. MARID and glimmerite phlogopite from Letlhakane are also shown, as well as primary and secondary metasomatic phlogopite compositions from the Letlhakane peridotites. Data for Koidu was taken from Hills and Haggerty (1989).

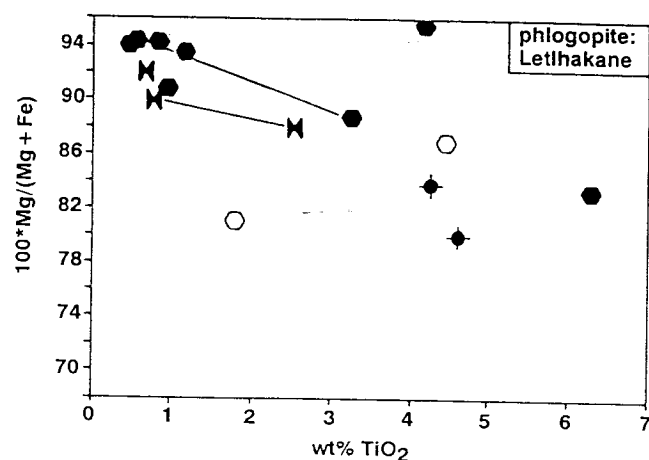


Fig. 4.11 Mg-number vs. wt% TiO_2 of phlogopite from the Letlhakane eclogites. The variable composition of the secondary metasomatic phlogopite is especially noticeable in the Mg-number.

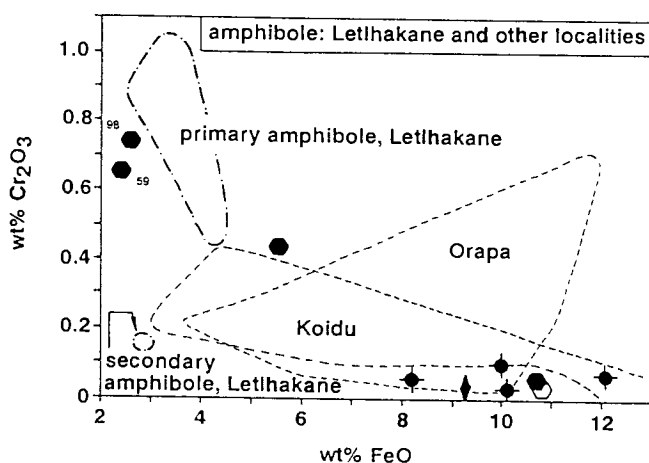


Fig. 4.12 Wt% Cr_2O_3 vs. wt% FeO . Primary metasomatic amphiboles are characterized by their higher Cr_2O_3 and/or lower FeO -content. Other data fields include: primary and secondary metasomatic amphibole from the Letlhakane metasomatized pyroxenites, amphibole from Orapa (Shee, 1978) and from Koidu (Hills and Haggerty, 1989).

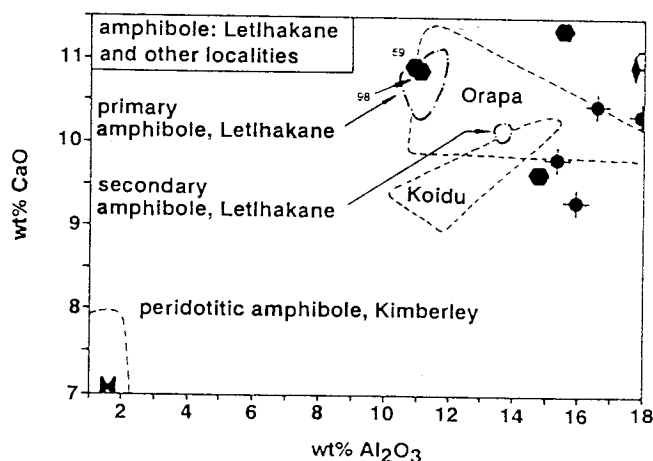


Fig. 4.13 Wt% CaO vs. wt% Al_2O_3 of amphibole from the Letlhakane eclogites. Primary metasomatic amphiboles from eclogites and websterites are similar in composition. Also note the increased scatter in the secondary metasomatic amphibole compositions. Other data fields were taken from Shee (1978), Hills and Haggerty (1989) and Jones et al. (1982). The compositional fields of primary and secondary metasomatic amphiboles from the Letlhakane metasomatized pyroxenites are also shown.

from JSL 600 are compared to those from the websterites (Chapter 2, Section 2.3.2) and metasomatized pyroxenites (Chapter 3, Section 3.3.2). Analytical values reported here for orthopyroxene are derived from an average of 20 analyses.

The orthopyroxene compositions in the composite pyroxenite/eclogite xenolith are extremely homogeneous. The Mg-number of the orthopyroxene is 93, i.e. a typical pyroxenitic value (Fig. 4.14). The TiO_2 - and Cr_2O_3 -contents are both low at 0.075 and 0.113 wt% respectively. However, unlike the orthopyroxenes from other Letlhakane pyroxenites, the Na_2O -content is elevated to 0.125 wt%, compared to general values of <0.07 wt%.

4.4 C-isotope composition of graphite

Despite the recent rise in popularity of the study of mantle carbon and the realization of its importance (Mattey, 1987; Deines et al., 1984, 1987, 1991 and Schulze et al., in press), many questions regarding the source and nature of the carbon are still unanswered: the wide range of $\delta^{13}\text{C}$ values of the mantle, the effect of fractionation on the carbon, and the possibility of carbon recycling, to name but a few. For these reasons, and owing to the fact that no C-isotope studies on graphite have previously been undertaken at Letlhakane, a short section on C-isotope compositions of graphite in eclogites is included here.

Graphite from all the selected eclogites, with the exception of JSL 206, exhibit C-isotope values between -5 and -8 ‰ (Table 4.2). These values are similar to C-isotope compositions shown by MORB (Mattey et al., 1984). The C-isotope values may be divided into three groups. The first is represented by values between -5.37 and -5.98 ‰, the second by JSL 204 (-7.68 ‰) and the third by JSL 206 with a $\delta^{13}\text{C}$ -value of -12.5 ‰. The isotopic differences exhibited by these groups are large and could therefore not have been caused by isotopic fractionation. No Group II graphite-bearing eclogites, similar to samples described by Robinson et al. (1984) have been recovered from Letlhakane. However, a single garnet websterite, JSL 202, was found to contain graphite ($\delta^{13}\text{C} = -5.37$ ‰) within the $\delta^{13}\text{C}$ range for eclogites from Letlhakane.

Based on the isotopic results, it appears that the graphite from some of the eclogites and that contained in the single garnet websterite was derived from a similar source. It is evident from the differences in isotopic values, that more than two, possibly three, sources of carbon existed in the mantle below Letlhakane.

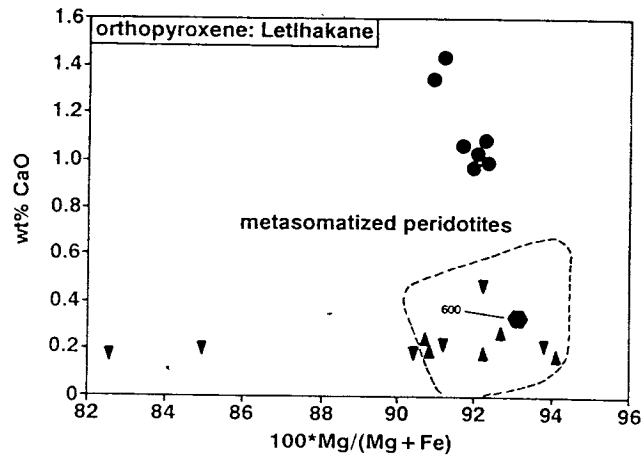


Fig. 4.14 Wt% CaO vs. Mg-number for orthopyroxene. The orthopyroxene composition from JSL 600 is compared to that of orthopyroxene from pyroxenites and deformed peridotites. The dashed field represents the compositions of orthopyroxene from metasomatized peridotites.

Table 4.2: $\delta^{13}\text{C}$ -isotope results (Schulze et al., in press).

Sample no.	Rock type	Diamond	Graphite	$\delta^{13}\text{C}$
JSL 200	Eclogite	*	*	-5.54
JSL 201	Eclogite		*	-5.69
JSL 202	Garnet websterite		*	-5.37
JSL 204	Eclogite		*	-7.68
JSL 206	Eclogite		*	-12.50
JSL 207	Eclogite		*	-5.75, -5.68
JSL 208	Eclogite		*	-5.98

4.5 Discussion

The eclogite suite is well represented at Letlhakane, as it is in other localities on the Kaapvaal craton. Eclogitic garnets and clinopyroxenes from Letlhakane (see Sections 4.3.1 and 4.3.2) are similar in composition to those from Orapa (Shee, 1978), Sierra Leone (Hills and Haggerty, 1989) and Roberts Victor (McCandless and Gurney, 1989). Minor accessory minerals such as ilmenite and rutile (see Sections 4.3.3 and 4.3.4) are also broadly similar in composition according to published data. A single spinel (see Section 4.3.5) was found to be considerably more aluminous than eclogitic spinels reported from Orapa, but owing to the small sample suite, it is not known whether this is of any real significance. Phlogopite and amphibole compositions of the Group II eclogites are similar to those of phlogopite and amphibole from the Letlhakane pyroxenites.

4.5.1 Theories on eclogite evolution

Two theories on eclogite evolution in the upper mantle are currently popular. The first suggests a high-pressure cumulate magmatic origin and the second, subduction of crustal cumulates and ocean basalts (e.g. Smyth et al., 1989; McCandless and Gurney, 1989; MacGregor and Manton, 1986; Schulze and Haelmstaedt, 1988; Gurney, 1990). A principal shortcoming of the high pressure hypothesis is that it fails to account for the wide variations in O-isotopic ratios. These variations require the presence of low-temperature processes (MacGregor and Manton, 1986 and Ongley et al., 1987). It also fails to account for the lack of any Fe-enrichment trend in the grosspydites. The second theory, proposing that some eclogites are subducted remnants of Archaean oceanic crust, also suffers from certain drawbacks. Firstly, it requires a different mode of origin for corundum grosspydites which appear to be genetically related to the eclogite sequence (Smyth et al., 1989). It also does not explain the re-equilibration from near-solidus temperatures at pressures > 30 kb. Pearson et al., (1991, 1993) recently proposed arguments in support of both theories.

Pearson et al. (op. cit.) studied the Nd-, Sr-, Pb-, O- and S-isotopic compositions and REE contents of pyroxenite layers from the Beni Bousera peridotite massif, in northern Morocco. Two garnet pyroxenite layers contain octahedral graphite pseudomorphs after diamond. Unfortunately, no analyses of mineral phases were included by the authors. The $\delta^{18}\text{O}$ values of the host peridotite exhibit considerably less variation (+5.3 to +6.1 ‰) than the pyroxenites (+4.9 to +9.3 ‰). Stable and radiogenic isotope variations suggest that the pyroxenites represent products of subducted, metamorphosed oceanic lithosphere, but the HREE enrichment of the garnet clinopyroxenites supports an origin by high-pressure crystal fractionation. Pearson et al. (1991, 1993) concluded from the tectonic, geophysical and isotopic

evidence in these studies that the pyroxenites formed in a mantle wedge above a subducting slab, but that physical and chemical evidence for high-pressure fractionation precludes a simple origin from subducted oceanic lithosphere.

A recent study on the carbon and oxygen isotope variations of diamond- and graphite-bearing eclogites from Orapa (Deines et al., 1991) revealed that neither subduction, igneous fractionation processes, nor metasomatism, could satisfactorily explain all the observed chemical and isotopic trends. It would therefore appear that the problem of eclogite formation in the mantle is still far from being solved.

4.5.2 Possible processes involved in the formation of Group I and Group II eclogites

The history of the formation of the eclogite suite is best reflected by CaO in garnet and Na₂O in clinopyroxene (Hatton and Gurney, 1987). Fig. 4.15 reveals two different trends for the Group I and Group II eclogites respectively.

Group I eclogites exhibit a scattered, but nonetheless positive trend of increasing CaO in garnet vs. Na₂O in clinopyroxene. Hatton and Gurney (1987) proposed three possible theories to account for such variation: 1) fractional crystallization with orthopyroxene absent in the cumulates, 2) partial melting with no orthopyroxene reaction relationship and no orthopyroxene in the source, and 3) partial melting, but with an orthopyroxene reaction relationship. A similar, positive trend is also displayed by the Group I Roberts Victor eclogites (Hatton and Gurney, 1987). The absence of primary metasomatic phlogopite, the high Na₂O-content of the garnet, and especially the presence of diamond, suggest that the Group I eclogites are of deep-seated origin, possibly the result of some fractional crystallization process in the mantle, during which orthopyroxene was absent. Further evidence in the Group I eclogites of an origin through some igneous crystallization process, is provided by the increase of mole fraction Ca in garnet with decreasing temperature (see Fig. 6.3 in Section 6.5). Group I eclogites also appear to have equilibrated at a higher temperature (see Fig. 6.4 in Section 6.5), a feature which is confirmed by the absence of primary metasomatic phlogopite and amphibole.

Fig. 4.15 shows that the Group II eclogites exhibit a negative slope of decreasing CaO in garnet vs. increasing Na₂O in clinopyroxene. Hatton and Gurney (1987) proposed the following theories for such a trend, also observed in the Roberts Victor eclogites: 1) fractional crystallization with orthopyroxene present in the cumulates and, 2) partial melting with orthopyroxene present in the source, but no reaction relationship. The presence of primary metasomatic phlogopite, the absence of diamond (in samples

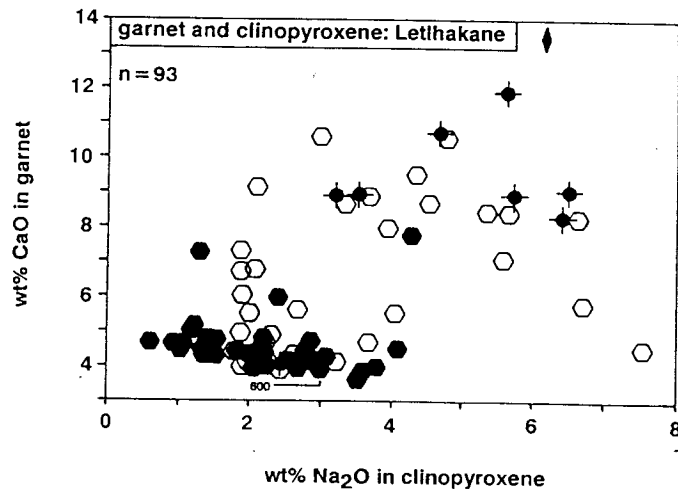


Fig. 4.15 Wt% CaO in garnet vs. wt% Na₂O in clinopyroxene. Note the well-developed negative trend exhibited by the Group II eclogites. Group I eclogites exhibit considerably more scatter, but show a positive trend nonetheless. The significance of these features is explained in the text.

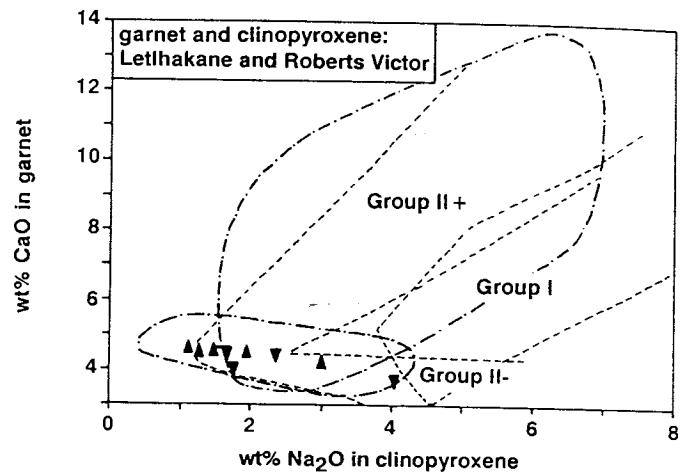


Fig. 4.16 An identical plot to Fig. 4.15, but with the various eclogite groups from Roberts Victor (Hatton and Gurney, 1987) shown for comparison. The bold, dashed lines represent Group I and Group II eclogites from Letlhakane as shown in Fig. 4.15. The pyroxenites from Letlhakane have also been included. Note the trend, similar to that of the Group II eclogites.

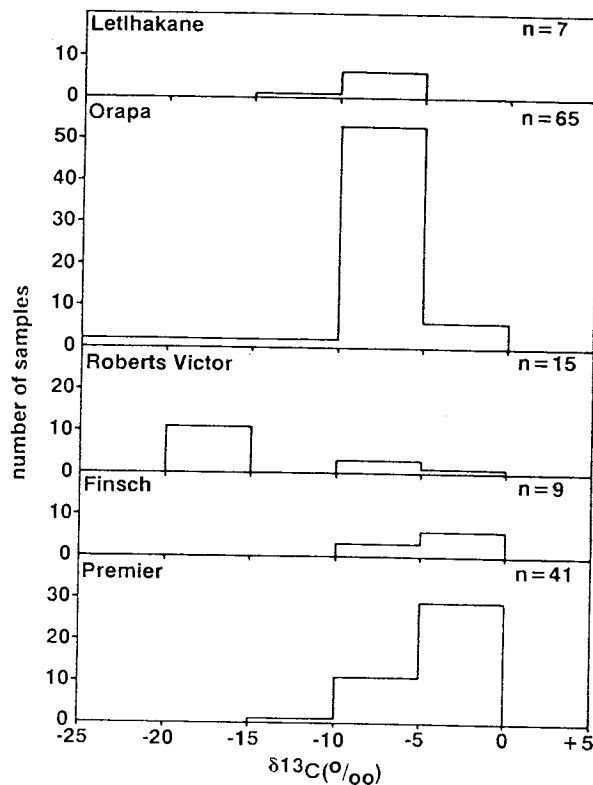


Fig. 4.17 The $\delta^{13}\text{C}$ values of graphite-, diamond- and diamond-graphite-bearing eclogites from Letlhakane (Schulze et al., in press) and several other localities. Data from Deines et al. (1984, 1987, 1991) and Shee (1978).

collected thus far) and lower temperatures of equilibration in the Group II Letlhakane eclogites (see Section 6.5), suggest that this group equilibrated at a shallower level and lower temperature in the mantle. The small range in composition compared to Group I eclogites may point to an extremely short-lived fractionation event or an origin by partial melting. Takahashi and Kushiro (1983) have experimentally determined the fluxing effect of K_2O on garnet lherzolite. The presence of primary metasomatic phlogopite and amphibole in the Group II eclogites at Letlhakane, indicates that a K_2O -rich fluid may have been present at some stage in the past. Partial melting of garnet lherzolite with the aid of such fluxing could possibly have resulted in the formation of the Group II eclogites.

The trends exhibited by the various eclogite types from Roberts Victor (Hatton and Gurney, 1987) are illustrated in Fig. 4.16, superimposed on those of the Letlhakane eclogites. The Group I eclogite trend from Roberts Victor is displaced towards higher Na_2O values in clinopyroxene compared to that of the eclogites from Letlhakane, but they are of approximately similar slope.

The similarity in garnet and clinopyroxene composition of the Group II eclogites and garnet websterites at Letlhakane (Fig 4.16), suggests a close relationship between these rock types. Although actual replacement of orthopyroxene by phlogopite is only evident in one metasomatized pyroxenite (JSL 252), orthopyroxene boundaries in contact with secondary material are serrated and embayed in many samples, indicating that destruction of the orthopyroxene had commenced. The role played by the exsolution of garnet from aluminous clinopyroxene, e.g. in sample JSL 77 (Plate 32), cannot be discounted either, when formulating a theory on the origin of the Group II eclogites. The close relation observed between websterites and Group II eclogites, especially in Fig. 4.16, may suggest that the Group II eclogites are in fact closer to garnet clinopyroxenites than "real" (Group I) eclogites. This possibility will be further explored in the next section.

4.5.3 A possible composite pyroxenite-Group II eclogite xenolith

Composite mantle xenoliths are relatively rare and sought after, because they provide an insight into the association of various rock types with each other. Harte and Gurney (1975), Harte et al. (1987) and Waters et al. (1989) described examples of such heterogeneous or composite xenoliths retrieved from kimberlites.

Harte et al. (1987) provided an interesting description of a pyroxenite-peridotite xenolith from Matsoku, in which the pyroxenite is interpreted as intrusive sheets with sharply defined contacts. More importantly, the sheets grade from an orthopyroxene-rich interior into a clinopyroxene-dominated margin. Garnet may also occur along the margins. These features are not universal and local variations within the

sample exist. JSL 600 contains no peridotite and it is therefore uncertain whether this xenolith is related to the pyroxenite sheets as described by Harte et al. (1987). The abrupt transition from orthopyroxenite to clinopyroxenite in JSL 600, compared to the gradational change as described by Harte et al. (1987) in their sample also adds to the uncertainty as to whether JSL 600 is indeed representative of a pyroxenite sheet.

The garnet and clinopyroxene compositions of JSL 600 are identical to those of the Group II eclogites from Letlhakane (Section 4.3). The low Na_2O -content of the garnet (< 0.05 wt%) (after the classification of McCandless and Gurney, 1989) and, in particular, the interlocking texture of garnet and clinopyroxene (after the textural classification of MacGregor and Carter, 1970), suggest that part of this xenolith is a Group II eclogite.

Orthopyroxene appears to be the least stable of the phases present in JSL 600 and has apparently undergone rapid destruction and alteration during contact with melt/kimberlite. The reader will remember that evidence for the presence of a metasomatizing agent (primary metasomatic phlogopite) is present in some of the Group II eclogites (Section 4.3.6). This destruction and/or alteration of orthopyroxene may account for the paucity of orthopyroxene-bearing eclogites at Letlhakane. Hatton and Gurney (1987) proposed a similar theory of phlogopitization of the orthopyroxenes in the Roberts Victor eclogites.

The close textural and mineralogical association between garnet websterites and Group II eclogites at Letlhakane was speculated on in Section 4.5.2. It is possible that JSL 600 may represent the evidence for this association. The following theory based on petrographic and mineralogical evidence in JSL 600 is therefore proposed: the Group II eclogites are not "true" eclogites, but rather garnet clinopyroxenites and therefore related to the pyroxenite suite.

4.5.4 C-isotope composition of graphite

Owing to the small amount of C-isotopic fractionation between diamond and graphite at mantle temperatures, C-isotopic compositions of graphite may be compared with those of diamond (Bottinga, 1969). Histograms in Fig. 4.17 compare $\delta^{13}\text{C}$ -values from Orapa (Shee, 1978; Deines et al., 1991), Letlhakane (Schulze et al., in press), Roberts Victor (Deines et al., 1987), and Finsch and Premier (Deines et al., 1984). Note the bimodal distribution of $\delta^{13}\text{C}$ -values from Roberts Victor. It is evident that $\delta^{13}\text{C}$ -values from eclogitic graphite are scattered, but within the range $+5$ ‰ to -30 ‰. Deines et al. (1991) found a greater variability of $\delta^{13}\text{C}$ in diamond eclogites, than in graphite eclogites from Orapa (not shown in Fig. 4.17). Most graphite flakes recovered from Letlhakane samples are of eclogitic paragenesis, yet the $\delta^{13}\text{C}$ -values coincide with values from a peridotitic paragenesis at Sloan (Otter, 1989). This illustrates the overlap between eclogitic and peridotitic $\delta^{13}\text{C}$ which occurs on a worldwide basis (Mattey, 1987).

The largest ever range of C-isotope compositions at a single locality was found for diamonds from the Sloan kimberlite, U.S.A. (Otter, 1989). Otter (1989) defined three diamond groups on the basis of their $\delta^{13}\text{C}$ -contents: Gp I = -3.8 to -8.9 ‰, Gp II = -8.5 to -12.8 ‰, and Gp III = -12.5 to -29.4 ‰; he proposed that diamonds from Group I belong to the peridotitic paragenesis, while diamonds from the latter groups are mostly eclogitic. Otter (op. cit.) also proposed that Group I and Group II diamonds crystallized from primordial carbon, while Group III contains diamonds that have crystallized from subducted, ^{13}C -depleted carbon. Group II may also represent a mixing of Group I and III carbon sources.

The similarity of $\delta^{13}\text{C}$ -values from MORB and eclogites suggests that there is little difference in $\delta^{13}\text{C}$ between carbon from the asthenospheric mantle and carbon from the subcontinental lithospheric mantle (Pearson et al., 1990). Pearson et al. (1990) proposed the idea that diamond and graphite may have crystallized from carbonaceous fluids of asthenospheric origin that have flowed into the more reducing subcratonic lithosphere. They suggested that the graphite in one of their peridotite samples may be of metasomatic origin, due to the variation in C-isotope results obtained from different graphite clusters in the sample. They proposed that the fluid became progressively more fractionated in terms of $\delta^{13}\text{C}$. Such a metasomatic origin may also be of relevance to graphite found in eclogites.

4.5.5 Ultradeep eclogites

Gasparik (1989) deduced from experimental results that the transformation of a two-pyroxene assemblage to garnet and residual pyroxene in the En-Di-Jd system could occur at approximately 400 km depth. This transformation would occur in a pressure interval small enough (0-3 kb) to account for the 400 km seismic discontinuity in the asthenosphere. Discovery of pyroxene solid solution in garnets included in diamond from Monastery (Moore and Gurney, 1985) and in eclogites from Jagersfontein (Haggerty and Sautter, 1990), suggests that these eclogites may have formed at ultradeep levels (300-400 km). Garnets from these eclogites are distinguished by their cusped shape, purple colour, large grain size (1-2 cm in diameter) and small amount of associated clinopyroxene (Haggerty and Sautter, 1990). However, despite a search of all available material, no such ultradeep samples have been recovered from the Letlhakane suite.

4.6 Summary

To summarize, the following features regarding the Letlhakane eclogite suite may be noted:

- 1) Compositionally, the eclogites can be classified into two groups, based on the Na₂O-content of garnet, overall texture and temperatures of equilibration.
- 2) A wide variety of accessory minerals are present. These include diamond, graphite, rutile, ilmenite, spinel, primary metasomatic amphibole and phlogopite (Group II eclogites only) and secondary metasomatic amphibole and phlogopite. The absence of kyanite and corundum may be due to a sampling bias.
- 3) The eclogites were also subdivided on the basis of their accessory minerals, e.g. diamond-bearing eclogites and graphite-bearing eclogites. This is a commonly-used practice and useful for petrographic descriptions. It was, however, not possible to employ this method as a rigid classification, owing to the many instances where several accessory phases co-exist.
- 4) C-isotope studies on several of the graphite-bearing eclogites, the graphite-bearing websterite and the diamond-graphite-bearing eclogite show a range of $\delta^{13}\text{C}$ values (-5.4 to -12.50 ‰) (Schulze et al., in press). The variation in some of the samples cannot be the result of isotopic fractionation only. It is therefore concluded that more than one (possibly three) sources of carbon were present in the mantle. Unfortunately, the relationship between these sources is not clear. The $\delta^{13}\text{C}$ -values conform to values obtained from worldwide studies (and from Orapa) and are indicative of a mantle origin.
- 5) Smyth et al. (1989) noted that eclogites have undergone copious amounts of subsolidus re-equilibration which would overprint most primary petrography. For this reason, studies involving isotopes and incompatible rare earth elements are probably the most useful in trying to determine the complex history of these rocks.
- 6) A composite orthopyroxenite-Group II eclogite xenolith (JSL 600) is taken as evidence that the Group II eclogites are more closely related to the pyroxenite suite than to the Group I eclogite suite.

CHAPTER 5

MEGACRYSTS, INTERGROWTHS AND MARID XENOLITHS

5.1 Introduction

The most common megacrysts at Letlhakane, in decreasing order of abundance, are: garnet, clinopyroxene, ilmenite and orthopyroxene. Clinopyroxene-ilmenite intergrowths are common and comprise the bulk of the samples exhibiting intergrowth textures. Two clinopyroxene-garnet intergrowths are also discussed. Two samples containing ilmenite and so-called "quench"-textured orthopyroxene crystals are among the more exotic samples present, in addition to a granular-textured ilmenite-orthopyroxene intergrowth (Table 5.1). No rutile-bearing intergrowths similar to those reported by Schulze (1990) have yet been found at Letlhakane. Zircon-bearing intergrowths and garnet-ilmenite intergrowths are also absent from the studied suite. Analyses describing the various megacrysts and the intergrown phases are contained in Appendix 3.

Because of the diverse nature of the samples in this chapter, the petrography of each rock type and the composition of the various phases will be discussed together.

5.2 Megacrysts

5.2.1 Garnet

Five garnet megacrysts have been analysed. They vary in size from 16-26mm and are orange-red in thin section. Minor kelyphite development has taken place along cracks, and other alteration products such as clinopyroxene, euhedral green-brown spinel, amphibole and serpentine(?) can be identified.

Fig. 5.1 shows that the garnet megacrysts from Letlhakane are members of the Cr-poor megacryst suite, like those from Orapa (Shee, 1978) and Monastery (Gurney et al., 1979). Four of the five megacrysts

Table 5.1: Petrographic and textural summary of the Letlhakane megacryst and intergrowth suite. The star symbol denotes primary phases. Primary (P) and secondary (S) phlogopite is also distinguished. The superscript (x) denotes phases observed in thin section only - no analyses are available.

Sample no.	Megacryst/ Intergrowth	Intergrowth Texture	GT	OLV	OPX	CPX	SP	PHL	AMP	ILM	RUT
JSL 1	opx meg	granular			*						
JSL 2	opx meg				*						
JSL 3	ilm-cpx					*				*	
JSL 4	ilm meg									*	
JSL 7	gt meg		*								
JSL 12	gt meg		*								
JSL 13	gt meg		*								
JSL 14	gt meg		*								
JSL 17	cpx meg					*					
JSL 18	cpx meg					*					
JSL 19	cpx meg	granular				*					
JSL 20	cpx meg					*					
JSL 22	cpx meg					*					
JSL 24	gt meg		*								
JSL 27	cpx meg					*					
JSL 28	cpx-gt		*			*					
JSL 29	cpx-gt		*			*					
JSL 32	ilm-cpx					*				*	
JSL 36	ilm-cpx					*				*	
JSL 44	ilm-cpx					*				*	
JSL 46	ilm-opx	opx laths			*	*		S		*	
JSL 47	ilm-cpx	granular				*				*	
JSL 51	MARID	opx laths				*		P	P	*	**x
JSL 160	ilm-opx				*	*		P		*	
JSL-181	glimmerite							P,S		*	
JSL 315	ilm-cpx	granular				*				*	
JSL 323	cpx meg	granular				*				*	
JSL 258	ilm meg									*	
JSL 503	ilm-opx				*			P,S		*	

Abbreviations used in this table:

Minerals

GT	- garnet
OLV	- olivine
OPX	- orthopyroxene
CPX	- clinopyroxene
SP	- spinel
PHL	- phlogopite
AMP	- amphibole
ILM	- ilmenite
RUT	- rutile
MEG	- megacryst

exhibit TiO_2 -contents even higher (1.10-1.24 wt% - see Fig. 5.2) than the high-Ti garnets from some of the deformed garnet lherzolites (see Fig. 2.12 in Section 2.3.4). The megacryst garnets are also characterized by lower Mg-numbers and Cr_2O_3 -contents than the peridotitic garnets (Figs. 5.1 and 5.2. See also Fig. 2.12, Section 2.3.4).

A single garnet megacryst contains small sulphide granules along a crack in the crystal. Owing to the extremely small grain size of the sulphide granules, an energy dispersive system attached to a scanning electron microscope was employed to provide a qualitative analysis of these minerals. The sulphides are 0.1-0.5mm long, 0.15mm wide and polymineralic; pyrrhotite, pentlandite and chalcopyrite were identified. Pentlandite is present as exsolved "flame-structures" in pyrrhotite associated with discrete blebs of chalcopyrite. Elsewhere, pyrrhotite-chalcopyrite intergrowths occur. The sulphides are closely associated with secondary phlogopite and amphibole and are thought to be of metasomatic origin.

5.2.2 Clinopyroxene

Seven clinopyroxene megacrysts, ranging in size from 16-33mm, have been analysed and the colours vary from pale to bright green in thin section. The pale green megacrysts tend to show more phlogopite and serpentine alteration along cracks than the bright green clinopyroxenes. All the pale green megacrysts studied are single crystals of clinopyroxene.

The bright green megacrysts (JSL 18 and 323) exhibit evidence of recrystallization. Most of JSL 18 is composed of a single crystal of clinopyroxene with limited recrystallization. JSL 323, however, is completely recrystallized (Plate 40) and grain boundaries vary from straight to undulating, indicating that equilibrium was not reached in all areas.

The clinopyroxene megacrysts can be subdivided into two groups, based on composition: a Cr-poor (pale green) and a Cr-rich (bright green) group, similar to groups reported from Orapa (Shee, 1978). Discrimination between these two groups is possible on the basis of Ca-number ($100 \cdot \text{Ca}/(\text{Ca} + \text{Mg})$) and Cr_2O_3 -content (Fig. 5.3). Fig. 5.4 shows that the Cr-rich clinopyroxene megacrysts are more Mg-rich (i.e. depleted) than the Cr-poor clinopyroxene megacrysts. Clinopyroxene from ilmenite-clinopyroxene intergrowths exhibits the most Fe-rich (i.e. evolved) composition (Fig. 5.4).

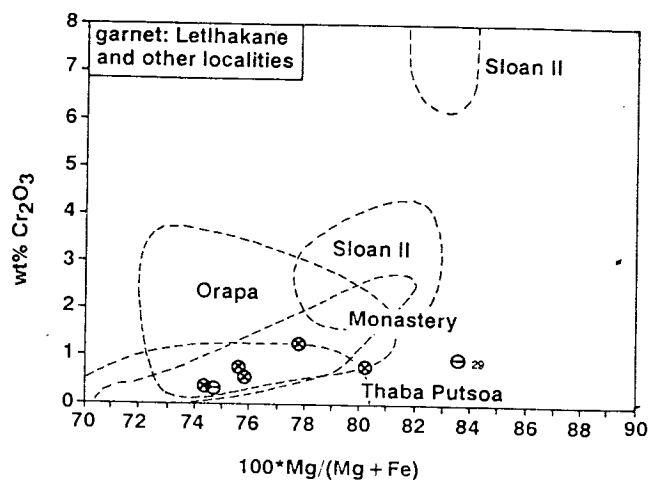


Fig. 5.1 $\text{wt}\% \text{Cr}_2\text{O}_3$ vs. Mg-number in garnet megacrysts. Note the difference in composition between the two garnet-clinopyroxene intergrowths. Other data were taken from Eggler and McCallum (1976), Shee (1978), Gurney et al. (1979) and Nixon and Boyd (1973b).

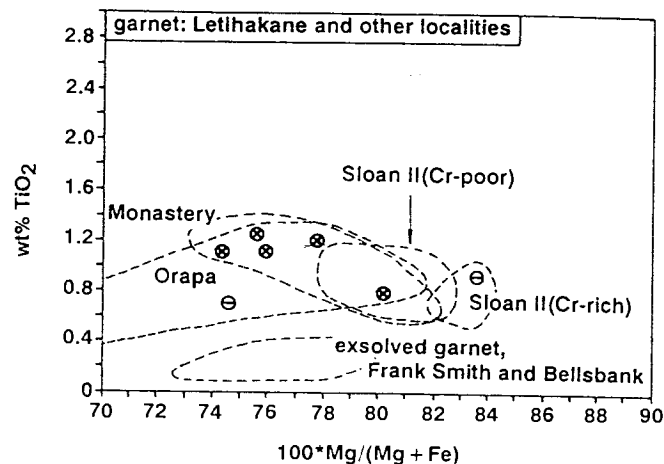


Fig. 5.2 $\text{wt}\% \text{TiO}_2$ vs. Mg-number in garnet megacrysts. Other data sets were taken from Shee and Gurney (1979), Gurney et al. (1979b), Eggler and McCallum (1976) and Aoki et al. (1980).

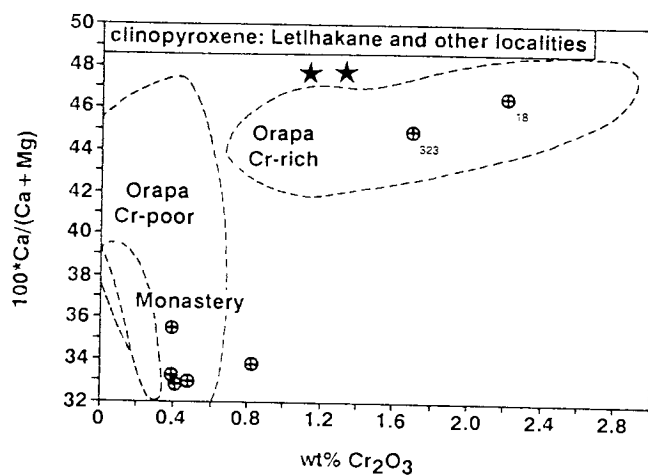


Fig. 5.3 $100 \cdot \text{Ca}/(\text{Ca} + \text{Mg})$ vs. $\text{wt}\% \text{Cr}_2\text{O}_3$ in clinopyroxene megacrysts. Note the clear difference in composition between the Cr-rich and Cr-poor suites from Letlhakane. Symbols in the form of filled stars represent Granny Smith clinopyroxene megacrysts from Kimberley (Boyd et al., 1984). The Cr-poor and Cr-rich clinopyroxene megacryst fields from Orapa were taken from Shee (1978) and the Monastery megacrysts from Gurney et al. (1979). Note the similarity in composition between the Granny Smith megacrysts and the Cr-rich megacryst suites from Orapa and Letlhakane.

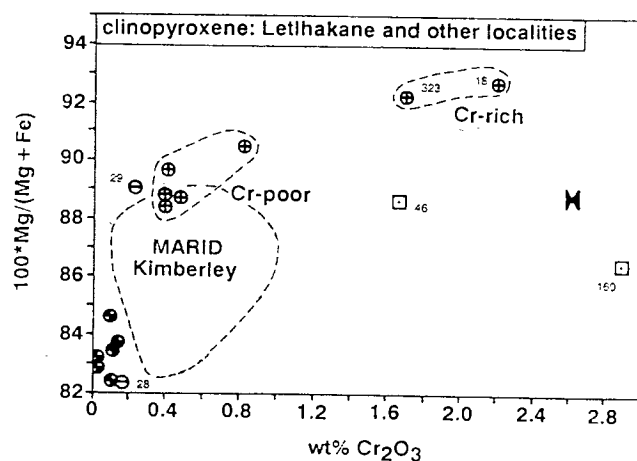


Fig. 5.4 Mg-number vs. $\text{wt}\% \text{Cr}_2\text{O}_3$, illustrating the differences in clinopyroxene composition between the various silicate intergrowth types, megacrysts and MARID xenoliths. Note the difference in clinopyroxene composition between the two orthopyroxene-ilmenite intergrowths and the Cr-rich nature of the MARID clinopyroxene from Letlhakane compared to those from Kimberley (Dawson and Smith, 1977).

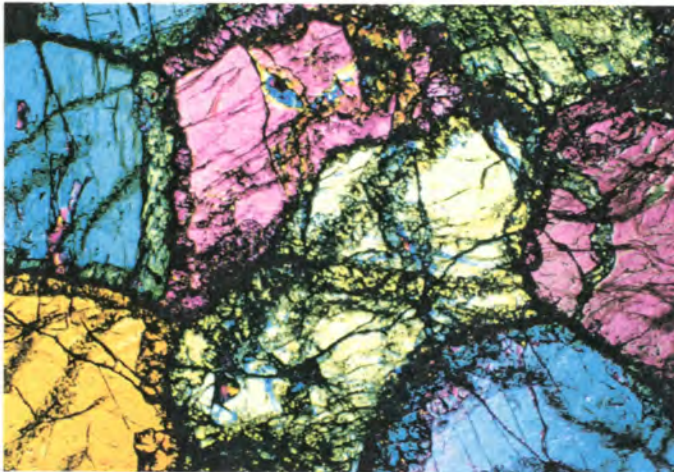


Plate 40: Recrystallization in a Granny Smith clinopyroxene megacryst. Field of view = 3.5mm wide. Crossed nicols.

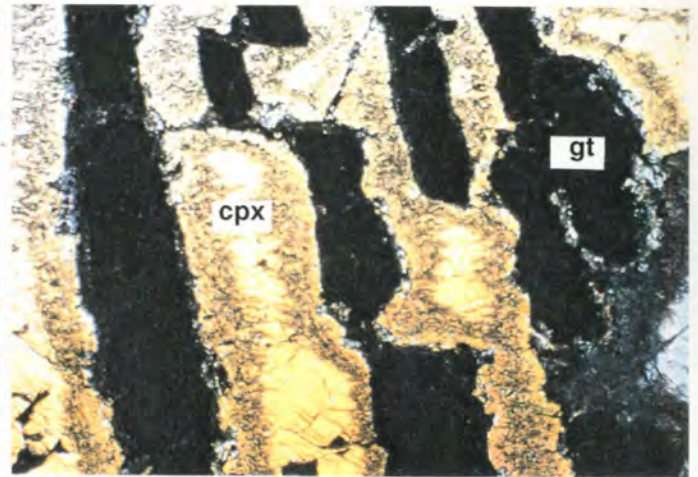


Plate 43: Exsolved garnet (gt) in clinopyroxene (cpx) (JSL 29). The clinopyroxene exhibits signs of recrystallization. Note the difference in habit of the garnet when compared to the garnet in Plate 42. Field of view = 3.5mm wide. Crossed nicols.

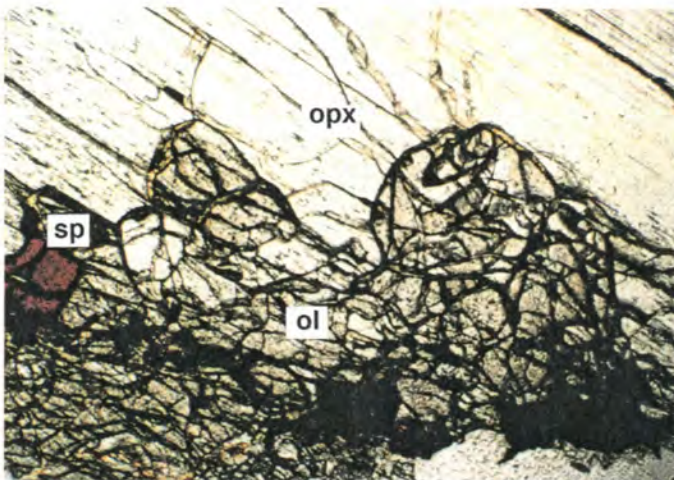


Plate 41: Orthopyroxene megacryst (JSL 2) containing material similar to a spinel lherzolite (see text for explanation). Dominant phases are brown spinel (sp) and colourless olivine (ol), embedded in orthopyroxene (opx). Field of view = 3.5mm wide. Plane polarised light.

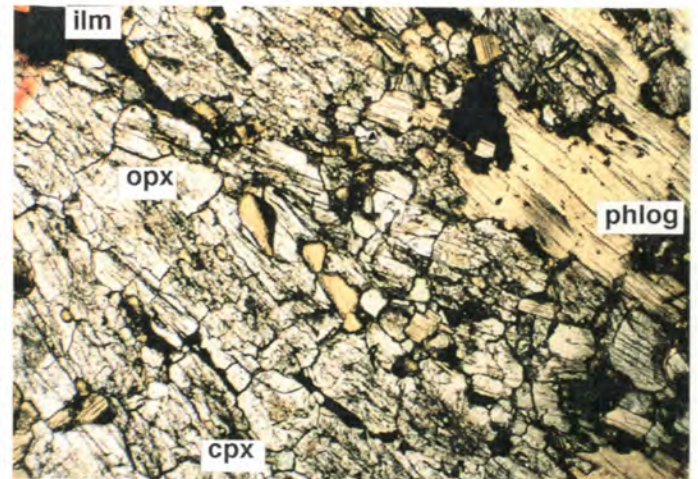


Plate 44: "Quench"-textured orthopyroxene (colourless lath-shaped grains - opx), intergrown with ilmenite (ilm) and phlogopite (phlog) from JSL 160. Note the anhedral grain of pale green clinopyroxene (cpx) and the ilmenite inclusions in a phlogopite plate (top right). Field of view = 3.5mm wide. Plane polarised light.

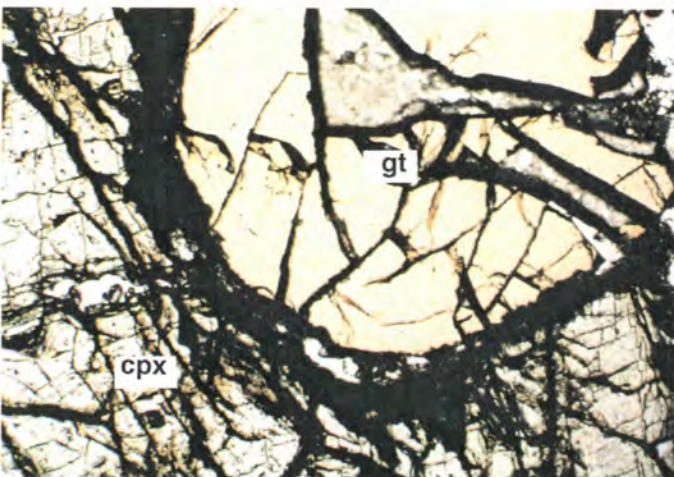


Plate 42: A rounded, orange-coloured garnet (gt) intergrown with clinopyroxene (cpx) (JSL 28). Field of view = 3.5mm wide. Plane polarised light.

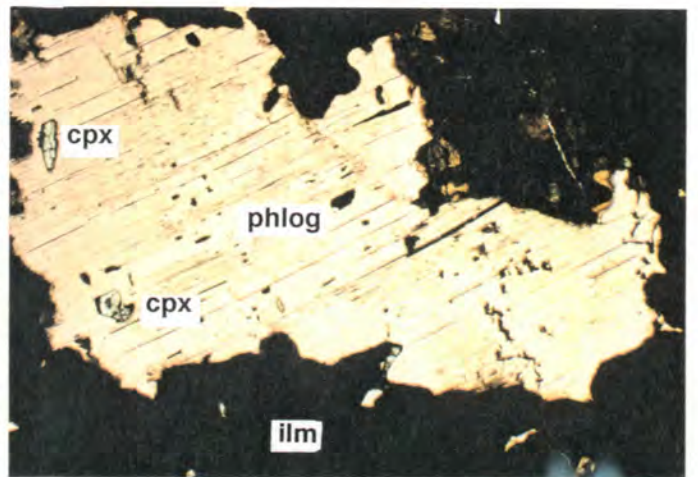


Plate 45: Phlogopite plate (phlog) included in ilmenite (ilm) from a MARID xenolith (JSL 51). Note the embayed phlogopite contacts and the two green clinopyroxene (cpx) inclusions in phlogopite. Field of view = 3.5mm wide. Plane polarised light.

5.2.3 Ilmenite

Only two examples of monomineralic ilmenites have been discovered. Many apparent ilmenite megacrysts contain, upon closer inspection, small amounts of clinopyroxene and must therefore be classified as granular-textured clinopyroxene-ilmenite intergrowths.

Unlike some localities, e.g. Frank Smith (Pasteris et al., 1979) and Monastery (Haggerty et al., 1979), monomineralic ilmenite is neither the dominant megacryst phase at Letlhakane, nor does it contain any exsolution features. Ilmenite megacrysts from Letlhakane vary in size from 13-24mm. Recrystallization has occurred, but is of limited extent and is unevenly distributed in the megacrysts. Recrystallized grains vary in shape from irregular to polygonal with 60° grain boundaries.

The Letlhakane ilmenite megacrysts are almost identical in composition to ilmenite intergrown with clinopyroxene, and are similar in composition to the ilmenites from Monastery (Schulze, 1987) (Fig. 5.5). Fig. 5.5 also illustrates the low Cr_2O_3 -content (< 0.20 wt%) of the Letlhakane megacrysts, even lower than the ilmenites from Orapa (Shee, 1978). Eclogitic ilmenites from Letlhakane (Fig. 5.6) contain similar low- Cr_2O_3 values. Fig. 5.6 also illustrates the ilmenite-bearing silicate intergrowth and megacryst field from Letlhakane, compared to intergrown ilmenite from other localities.

5.2.4 Orthopyroxene

Two orthopyroxene megacrysts, each approximately 20mm in diameter, have been analysed. No alteration is present, except for a melt rim around the perimeter where the orthopyroxene was in contact with the kimberlite magma during intrusion. The melt rims contain acicular clinopyroxene, granular olivine and a spinel phase. These are secondary features and of no further relevance to this study.

Apparent primary olivine, clinopyroxene, orthopyroxene and spinel are located along the rim of JSL 2 (Plate 41). A few olivine grains are totally enclosed by the orthopyroxene megacryst and the mineral assemblage, texture and general appearance are typical of the spinel lherzolites described in Chapter 2, Section 2.2.3.

The two orthopyroxene megacrysts differ considerably in composition (see Figs. 5.7 and 5.8). Orthopyroxenes from orthopyroxene-ilmenite intergrowths are shown for comparison. The orthopyroxene megacryst in JSL 2 contains higher Cr_2O_3 (Fig. 5.7), $100 \cdot \text{Mg}/(\text{Mg} + \text{Fe})$ (Fig. 5.8) and Al_2O_3 (not shown), but lower CaO (Fig. 5.8) and TiO_2 (not shown) than JSL 1. The orthopyroxene composition of JSL 2 is very similar to that of orthopyroxenes found in the spinel lherzolites from Letlhakane (Fig. 5.8).

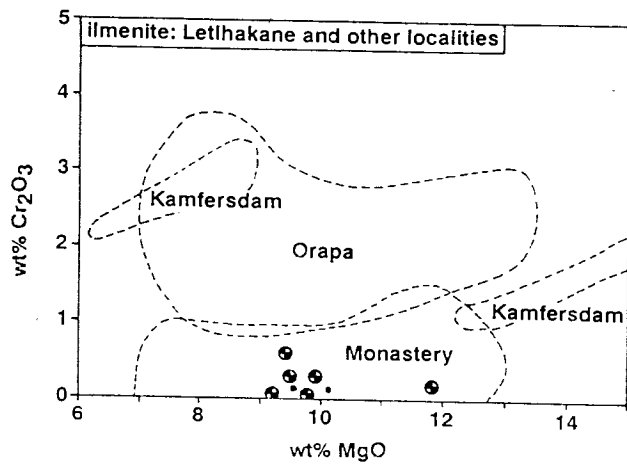


Fig. 5.5 Wt% Cr_2O_3 vs. wt% MgO in ilmenite megacrysts. Letlhakane ilmenite megacryst and intergrowth compositions correspond closely to those from Monastery. Data fields were taken from Shee (1978), Schulze (1987) and Gurney et al. (1979).

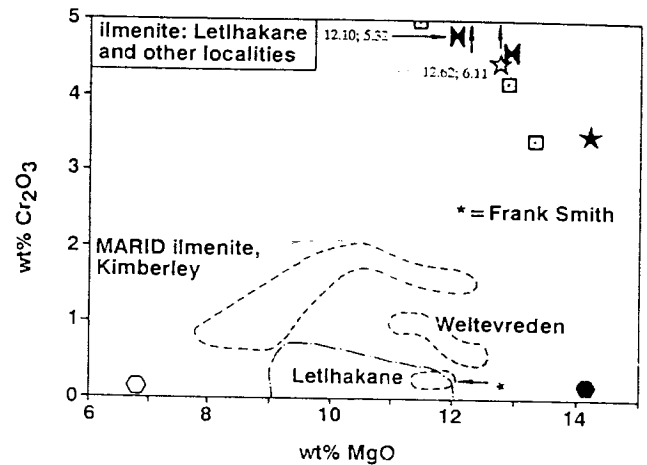


Fig. 5.6 An identical plot to Fig. 5.5, but comparing Letlhakane ilmenite megacrysts to ilmenite from eclogites, MARID xenoliths and other intergrowth types. Other data were taken from Dawson and Smith (1977), Rawlinson and Dawson (1979), Frick (1973) and Schulze (1990). The symbol in the form of a filled star represents ilmenite from an enstatite-rutile-ilmenite intergrowth, Kimberley and the open star represents ilmenite from a rutile-ilmenite intergrowth, Kamfersdam.

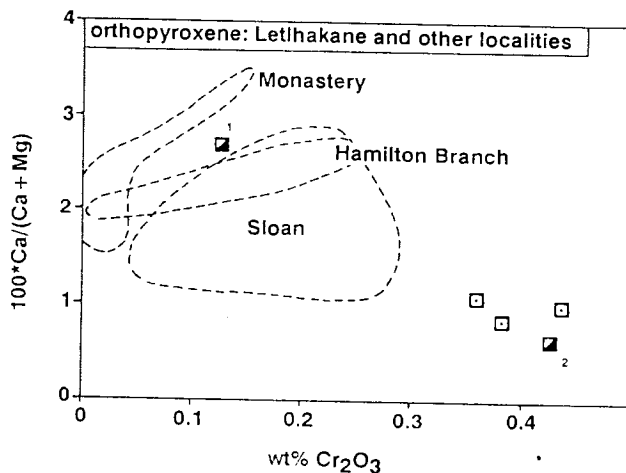


Fig. 5.7 $100 \cdot \text{Ca}/(\text{Ca} + \text{Mg})$ vs. wt% Cr_2O_3 in orthopyroxene megacrysts. Data fields are all from Schulze (1987). Note the large difference in composition between the two orthopyroxene megacrysts from Letlhakane. Orthopyroxene compositions from orthopyroxene-ilmenite intergrowths have been added for comparison.

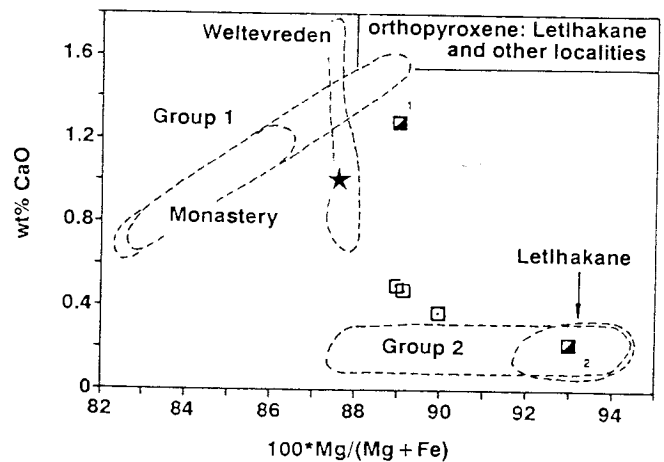


Fig. 5.8 Wt% CaO vs. Mg-number, illustrating orthopyroxene compositions from Letlhakane megacrysts and intergrowths. Group I and II orthopyroxene megacrysts from Monastery are shown (Gurney et al., 1979). Orthopyroxene from the Monastery orthopyroxene-ilmenite intergrowths plot within the Group I megacryst field from Monastery. Orthopyroxene compositions from the Letlhakane spinel lherzolites, and Weltevreden orthopyroxene-ilmenite intergrowths (Rawlinson and Dawson, 1979), are also illustrated. The filled star represents orthopyroxene from the Frank Smith orthopyroxene-ilmenite intergrowths (Frick, 1973). Note the similarity in composition of orthopyroxene from JSL 2 compared to orthopyroxene from the Letlhakane spinel lherzolites.

5.3 Intergrowths

5.3.1 Clinopyroxene-ilmenite

This is the most abundant intergrowth type found at Letlhakane (Table 5.1). Textures vary from graphic ilmenite lamellae (JSL 32) to anhedral ilmenite blebs in clinopyroxene (JSL 315). The graphic ilmenite lamellae are 0.3-1.25mm wide, 1-2mm apart and may be >20mm in length. Modal proportions of clinopyroxene and ilmenite in these intergrowths vary from rare clinopyroxene blebs in an ilmenite host to ilmenite blebs in a clinopyroxene host. The most prominent alteration features are visible in the clinopyroxene itself. The clinopyroxene forms "spongy", recrystallized rims wherever it is in contact with the ilmenite. These rims around clinopyroxene are very common in the granular-textured intergrowths, but less so in the graphic intergrowths. Other alteration products include minor phlogopite, serpentine and blood red patches, possibly an Fe-rich alteration product of ilmenite.

No evidence of zoning has been found. The intergrown ilmenites are characterized by low Cr_2O_3 -contents and intermediate (9.5 wt%) MgO values, as seen in Fig. 5.5. The intergrown clinopyroxenes exhibit a distinctly more evolved composition, different from the Cr-rich and Cr-poor megacrysts (see Fig. 5.4). The "spongy", recrystallized rims mentioned above are compositionally distinct from the primary clinopyroxene, containing higher TiO_2 and CaO (Fig. 5.9), but lower Al_2O_3 and Na_2O (not shown).

5.3.2 Clinopyroxene-garnet

Two clinopyroxene-garnet intergrowths have been studied. JSL 28 is a single crystal of pale green clinopyroxene containing approximately 6 rounded, anhedral blebs of orange-coloured garnet (Plate 42). The garnets vary from 1.25-3.50mm in diameter and both garnet and clinopyroxene show only slight alteration along cracks.

JSL 29 differs from the former in that the garnet developed as lamellae (Plate 43), while the pale green clinopyroxene host exhibits signs of recrystallization. The orange-coloured garnets exhibit a non-uniform habit. Half the intergrowth is characterized by regular, parallel garnet lamellae, approximately 0.5mm wide, while the remaining section contains anhedral, rounded blebs of garnet, 0.3-3.5mm in diameter. The clinopyroxene exhibits cloudy, recrystallized margins where in contact with the garnet. Rare secondary phlogopite is associated with alteration of the garnet.

The composition of the clinopyroxene containing the exsolved garnet (JSL 29) is similar to clinopyroxenes of the Cr-poor megacryst suite, as illustrated in Figs. 5.4 and 5.9. The intergrown and exsolved garnets are similar to those of the megacryst suite, but significant compositional differences exist between the two samples. The exsolved garnet in JSL 29 has a considerably higher Mg-number (84) than the anhedral garnet in JSL 28 (75) (see Fig. 5.1), and is also slightly more Cr-rich.

5.3.3 Orthopyroxene-ilmenite

These intergrowths are characterized by the presence of slender, prismatic orthopyroxene crystals, with the exception of JSL 503, which is coarse-grained. The prismatic habit is thought to be the result of rapid cooling, hence the name "quench"-textures (Rawlinson and Dawson, 1979).

The principal phases in these samples are orthopyroxene, phlogopite, and irregular blebs of ilmenite. No garnet has been detected. Large phlogopite plates, commonly containing ilmenite inclusions, partly enclose the orthopyroxene laths. Irregular, interstitial blebs of phlogopite are also present (Plate 44). A few orthopyroxenes in JSL 503 are partly enclosed by ilmenite rims. Rare clinopyroxene is present in JSL 46 and 160, but absent in JSL 503. JSL 160 contains anhedral blebs of bright green clinopyroxene which may poikilitically enclose the orthopyroxene. Clinopyroxene in JSL 46, by contrast, is colourless and up to 2mm in size. A single grain is poikilitically enclosed by ilmenite.

The composition of the phases differs markedly from those in other intergrowths. The ilmenite and clinopyroxene in JSL 160 are distinctly more Cr-rich (Figs. 5.6, 5.4), compared to those from other intergrowths. The orthopyroxene from the orthopyroxene-ilmenite intergrowths is more Cr_2O_3 -rich (Fig. 5.7) and CaO-poor (Fig. 5.8) than Group I orthopyroxene megacrysts from Monastery. The phlogopite compositions plot within the field of high-Ti mica as proposed by Boettcher et al. (1979) (Fig. 5.10). Phlogopite compositions from JSL 503 plot on the MARID boundary (Fig. 5.10) and may exhibit irregular zoning along the outer rims, possibly owing to secondary processes (Table 5.2). Except for the outer rims, the phlogopite exhibits the homogeneously low TiO_2 and Cr_2O_3 values typical of primary metasomatic phlogopite (Chapter 3, Section 3.3.7). Zoning trends in ilmenite from JSL 503 are shown in Table 5.3. Al_2O_3 decreases consistently towards the rims.

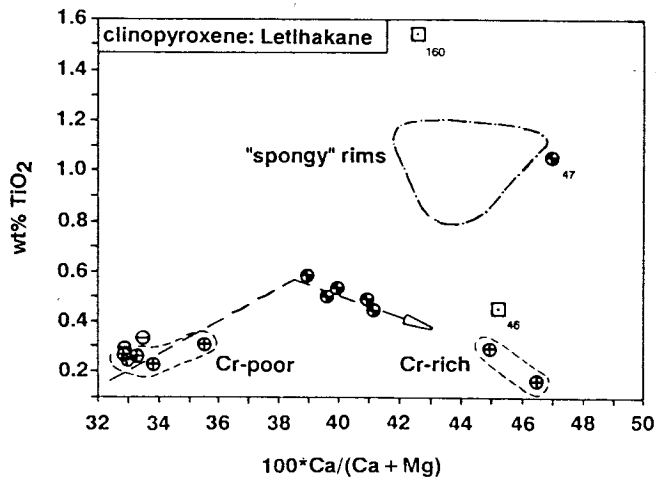


Fig. 5.9 Wt% TiO_2 vs. $100 \cdot \text{Ca}/(\text{Ca} + \text{Mg})$ in clinopyroxene intergrowths. The trend of increasing TiO_2 in clinopyroxene, followed by a decrease after ilmenite crystallization has commenced, is illustrated. The compositions of the "spongy" rims around the clinopyroxene, mentioned in the text, is also shown. The large difference in clinopyroxene composition between the Letlhakane orthopyroxene-ilmenite intergrowths, shown in Fig. 5.4, is apparent once again. The difference in composition of JSL 47 is caused by the altered nature of the clinopyroxene.

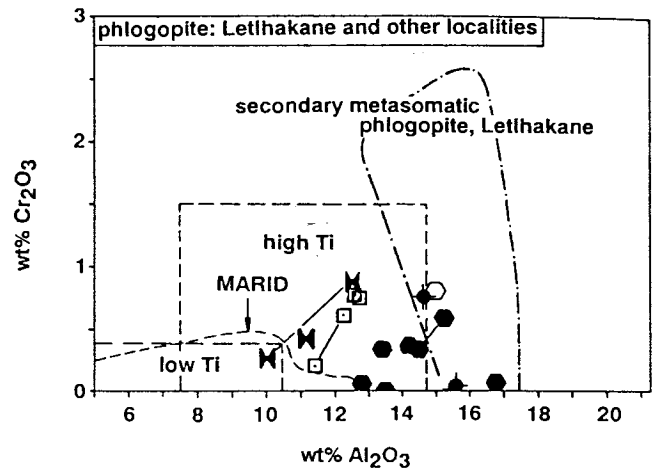


Fig. 5.10 Wt% Cr_2O_3 vs. wt% Al_2O_3 , comparing phlogopite from MARID xenoliths and other rock types. Secondary metasomatic phlogopite from the Letlhakane peridotites is included. Tielines join co-existing phases. Other data fields include those from Boettcher et al. (1979), Dawson and Smith (1977) and Delaney et al. (1980).

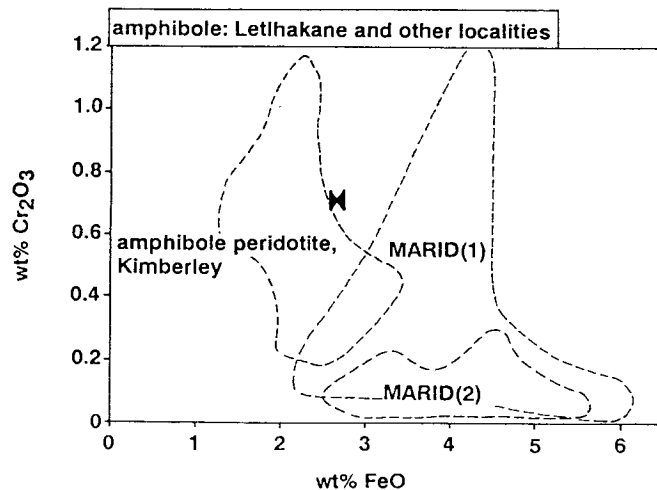


Fig. 5.11 Wt% Cr_2O_3 vs. wt% FeO in MARID and peridotite amphiboles. MARID(1)=MARID represents amphibole compositions from Kimberley, as determined by Dawson and Smith (1977). MARID(2)=MARID represents amphibole compositions, also from Kimberley, as determined by Erlank et al. (1987). A single amphibole in the MARID(1) field has a Cr_2O_3 -content of approximately 1.2 wt%, causing the extreme peak.

Table 5.2: Zoning in phlogopite.

Sample	JSL -/181			JSL -/181		JSL 503		
	primary		rim	secondary		primary		rim
	core	rim		core	rim	core	rim	
SiO ₂	41.49	41.18	40.31	40.18	39.91	41.84	41.77	41.60
TiO ₂	0.86	0.90	2.33	2.75	2.81	0.73	0.81	1.67
Al ₂ O ₃	11.46	11.92	12.18	12.72	12.72	11.54	11.77	11.25
Cr ₂ O ₃	0.31	0.32	0.64	0.68	0.73	0.19	0.21	0.25
FeO	5.15	4.96	5.17	5.00	5.27	4.72	4.79	4.91
MnO	0.03	0.03	0.05	0.03	0.03	0.03	0.00	0.04
MgO	24.50	24.15	22.96	22.45	22.64	25.19	25.12	24.83
CaO	0.01	0.00	0.02	0.00	0.00	0.00	0.03	0.18
Na ₂ O	0.17	0.20	0.18	0.26	0.27	0.15	0.18	0.31
K ₂ O	10.16	10.46	10.28	10.17	10.29	10.15	10.07	9.60
Total	94.16	94.12	94.12	94.24	94.67	94.54	94.75	94.64

Table 5.3: Zoning in discrete ilmenite grains.

Sample	JSL -/181		JSL -/181		JSL -/181		JSL 503		JSL 503	
	core	rim	core	rim	core	rim	core	rim	core	rim
TiO ₂	51.03	51.05	52.21	51.09	50.52	55.29	54.42	54.32	54.33	54.02
Al ₂ O ₃	0.34	0.22	0.42	0.32	0.45	0.06	0.40	0.10	0.41	0.19
Cr ₂ O ₃	6.04	6.11	4.19	5.45	6.08	4.00	2.23	3.17	3.25	3.32
FeO (P)	29.99	29.85	29.45	29.77	29.67	26.94	28.26	27.14	27.31	28.09
FeO (C)	24.64	24.32	23.92	24.24	23.28	25.18	24.30	24.13	24.05	24.61
Fe ₂ O ₃	5.95	6.14	6.15	6.15	7.09	1.96	4.40	3.35	3.63	3.87
MnO	0.19	0.19	0.23	0.25	0.18	0.21	0.21	0.25	0.25	0.27
NiO	0.29	0.24	0.23	0.24	0.20	0.17	0.16	0.18	0.19	0.18
MgO	11.66	11.87	12.67	11.91	12.21	13.56	13.62	13.62	13.67	13.20
Total:P	99.53	99.53	99.40	99.03	99.32	100.23	100.29	98.79	99.40	99.27
Total:C	100.13	100.15	100.01	99.65	100.03	100.42	100.73	99.13	99.77	99.66

5.4 MARID and glimmerite xenoliths

Although these rock types do not belong to the megacryst suite or its intergrowths, it is included here, because the small sample suite (only 1 MARID and 1 glimmerite were found) does not warrant a separate chapter. The petrography of the two samples differs considerably.

All five minerals contained in the acronym, i.e. mica, amphibole, rutile, ilmenite and diopside, are present in the MARID (JSL 51). Ilmenite is the dominant mineral phase and occurs as a large plate, 20x17mm in size. Irregular blebs of rutile (<1.4mm in size), containing exsolution features, are intergrown with the ilmenite. The exsolved mineral is thought to be ilmenite, but is unfortunately too small for quantitative analysis. Blebs of serpentine (after clinopyroxene?) occur in the ilmenite, close to, but not associated with the rutile. Irregular blebs of apatite with a maximum size of 0.4mm are also enclosed within the ilmenite. (This was qualitatively determined by analysis for P and Ca. No significant amounts of other common elements have been found in this mineral.)

Phlogopite is the second most abundant mineral phase in the MARID. A large plate, 3.7mm in size, is included in ilmenite (Plate 45). The phlogopite itself contains elongate inclusions of ilmenite, two prismatic rutile inclusions (<0.1mm) and two inclusions of irregular, bright green clinopyroxene, approximately 0.3mm in size. Bright green, irregular clinopyroxene, 2.5mm in size, also occurs as inclusions in the ilmenite. The amphibole is a colourless K-richterite (after the classification of Leake, 1978), and occurs as two discrete, irregular blebs, the largest of which is 2.5mm in size.

JSL -/181 differs from the MARID in that it is almost totally composed of phlogopite, with rare, irregular patches of ilmenite. Owing to the high modal proportion of phlogopite, this sample should strictly be referred to as a glimmerite. The large phlogopites are deformed with sizes varying from <0.2-3.5mm. Small, interstitial patches of green serpentine are ubiquitous. A few of these serpentine patches contain altered pseudomorphs of an unidentified mineral. Small (<0.1mm) grains of colourless clinopyroxene also occur in the serpentine, but the pristine state and small size of these grains suggests that they are of secondary origin.

The TiO_2 and Cr_2O_3 -contents of the phlogopite are similar to those of the primary metasomatic phlogopites and plot close to, or within (JSL -/181), the field of MARID phlogopite as proposed by Dawson and Smith (1977) (see Fig. 5.10). The phlogopite in the glimmerite is zoned (Table 5.2), particularly with respect to TiO_2 and Al_2O_3 . This zoning can probably be attributed to secondary processes, owing to the high TiO_2 values, the fact that the zoning is limited to the outer edges of the grains, and its uneven distribution around grains (Table 5.2).

The ilmenite composition in both the MARID and glimmerite samples is distinctive by virtue of its high Cr_2O_3 -content (4.5-5.3 wt%, but as high as 6 wt% in the glimmerite, as shown in Table 5.3) and is also more Mg-rich than the megacryst and intergrown ilmenites (see Fig. 5.6). Zoning in ilmenite from the glimmerite varies from slight to extreme (Table 5.3). These variations are once again limited to the outer edges of the grains only and a primary cause appears unlikely. The exsolution features in the rutile prevented meaningful analysis.

The composition of the K-richterite amphibole is notably different to that of amphibole from the pyroxenites and eclogites (see Fig. 4.13, Section 4.3.7), but similar to K-richterite from the Kimberley peridotites (see Fig. 4.13). The MARID clinopyroxene is characterized by a higher Cr_2O_3 -content than that of Kimberley MARID clinopyroxenes (Fig 5.4).

5.5 Discussion

It is generally believed that the megacryst suite in kimberlites formed in the presence of a liquid, i.e. as phenocrysts, which were then incorporated into the kimberlitic melt (Nixon and Boyd, 1973b; Gurney et al., 1979; Pasteris et al., 1979). Moore (1987), however, pointed out several drawbacks to this model. Deformation of the megacrysts cannot be easily explained, while an upward zonation from Mg-rich to Fe-rich liquids would also have to be accounted for. Harte and Gurney (1981) proposed the injection of small volumes of kimberlitic liquid into fractures around the main intrusion at depth, resulting in the crystallization of this liquid as pegmatitic veins. This would account for the isobaric conditions at which most megacrysts are found. Boyd and Nixon (1975) noted that compositions of megacrysts from northern Lesotho approach compositions of sheared, high-temperature lherzolites. These compositional similarities are especially notable in some of the garnet rims, enriched in Ti and Fe (Boyd and Nixon, 1975; Schulze, 1984; Smith and Boyd, 1984).

5.5.1 Garnet megacrysts

Eggler and McCallum (1974) were the first to announce the existence of a second group of garnet megacrysts, based on the mineral chemistry of garnets recovered from the Sloan II kimberlite in the U.S.A. This particular type of megacryst contains higher Cr_2O_3 (6-13 wt%) and higher Mg-numbers than the more common Cr_2O_3 -poor suite (< 5wt% Cr_2O_3). Schulze (1985) subsequently discovered polyminerally inclusions in both Cr-poor and Cr-rich suites which he interpreted as the parent kimberlite liquid from which the

megacrysts crystallized. It is concluded from Figs. 5.1 and 5.2 that Cr-poor garnet megacrysts from Letlhakane and Orapa show little or no variation compared to garnet megacrysts from the Kaapvaal craton.

The higher TiO_2 , FeO and Na_2O of the Letlhakane megacryst garnets compared to peridotitic (both coarse and deformed) garnets (see Fig. 2.11, Section 2.3.4), indicate that the megacrysts may have been derived from a more fertile source than the peridotites. Harte (1983) and Hops et al. (1989) noted that this is a common feature in most kimberlites. The TiO_2 -contents of the high-Ti peridotitic garnets (see Section 2.3.4) are similar to those of garnet megacrysts from Orapa (Shee, 1978) and Letlhakane (this study - Fig. 5.2), possibly indicating a close relation between these rock types. Similar relationships were described by Nixon and Boyd (1973a) and Boyd and Nixon (1975) for Lesotho and Hops et al. (1989) for Jagersfontein. Gurney and Harte (1980) suggested that the Fe-Ti enrichment in some deformed lherzolites may be caused by fluids derived from metasomatism of the Cr-poor megacryst suite, an idea supported by Smith and Boyd (1987) and Hops et al. (1989).

5.5.2 Clinopyroxene megacrysts

Like garnet megacrysts, clinopyroxene megacrysts may be divided into Cr-rich and Cr-poor suites (Eggler and McCallum, 1974). Cr-rich clinopyroxene megacrysts have previously been reported from Orapa by Shee (1978).

Boyd et al. (1984) reported the existence of Granny Smith (named after a South African apple variety, because of its distinctive green colour) diopside megacrysts from the Kimberley area in South Africa. These diopsides are characterized by $100 \cdot \text{Ca}/(\text{Ca} + \text{Mg}) > 45$, $100 \cdot \text{Mg}/(\text{Mg} + \text{Fe}) > 90$ and a Cr_2O_3 -content of 0.6-2.8 wt% (Fig. 5.3, Section 5.2.2). Granny Smith diopsides are commonly intergrown with ilmenite and phlogopite and may be deformed (Boyd et al., 1984). The Cr-rich clinopyroxenes from Letlhakane have all the abovementioned characteristics, except that they do not contain any ilmenite. Boyd et al. (1984) are of the opinion that the Cr-rich clinopyroxene megacrysts described by Shee (1978) and Shee and Gurney (1979) belong to the Granny Smith group of clinopyroxenes.

Considering the available data, it would therefore appear that the Cr-rich megacrysts from Letlhakane are also members of the Granny Smith clinopyroxene suite.

5.5.3 Ilmenite megacrysts

Haggerty et al. (1985) reported that kimberlitic ilmenites are recognised by high MgO, intermediate Fe_2O_3 and the presence of Cr_2O_3 . The trivalent substitution of Cr^{3+} may be a pressure dependent feature.

Haggerty (1975) and later Schulze (1987) noted that Cr_2O_3 values tend to increase towards the low and high MgO-values, e.g. Orapa (See Fig. 5.5) in the form of a parabola. Moore (1987) discussed previously unreported ilmenite megacryst data from pipe clusters in the central and southern Kalahari. Ilmenites from the central pipe cluster also define a parabolic trend on a wt% MgO vs. wt% Cr_2O_3 plot, similar to those of Hamilton Branch (Schulze, 1984). Haggerty (pers. comm., 1984, in Moore, 1987) stated that this parabolic feature has not been detected in ilmenites from an individual pipe and suggested that the two limbs may reflect different kimberlite sources.

Moore (1987) also commented on the bimodal nature of Cr_2O_3 distribution in ilmenites from the southern Kalahari cluster. The low Cr_2O_3 -suite (< 1.5wt%) from the Kalahari (not shown) corresponds to the ilmenites from Letlhakane, Monastery, Koidu (not shown) and the lower half of the Orapa field (see Fig. 5.5). The Cr_2O_3 rich-suite (> 1.5 wt%) is similar in composition to ilmenites from Kamfersdam.

Only Cr_2O_3 -poor ilmenite megacrysts have been recovered from Letlhakane during this study and the available information supports the theory of Haggerty (pers. comm., 1984, in Moore, 1987) as discussed above. However, the presence of Cr_2O_3 -rich ilmenite megacrysts in the nearby Orapa kimberlite suggests that Cr_2O_3 -rich ilmenites may still be recovered from Letlhakane.

5.5.4 Orthopyroxene megacrysts

Detailed accounts of these mineral types are scarce in the literature. The most comprehensive studies are those of Gurney et al. (1979) and Aoki et al. (1980). No orthopyroxene megacrysts were found at Orapa (Shee, 1978).

Gurney et al. (1979) illustrated the existence of two compositionally distinct groups of orthopyroxenes at Monastery. These groups are shown in Fig. 5.8, along with the orthopyroxene megacrysts from Letlhakane. Aoki et al. (1980) cautioned that some apparent orthopyroxene megacrysts may in fact be derived from higher levels in the form of disaggregated coarse-grained ultramafic rocks. An example of this was found at Letlhakane and will be discussed below. Gurney et al. (1979) suggested a process of disaggregation as one of two possible origins for the Group II megacrysts at Monastery. The Mg-numbers of

this group, especially the more Mg-rich end of the scale, coincide with Mg-numbers for orthopyroxenes found in peridotites. However, Gurney et al. (1979) favoured association of the Group II megacrysts with those in Group I, because of the continuity of the Mg-number which they considered to represent a differentiation index.

JSL 1 plots close to, but not within fields representing orthopyroxene megacrysts from Monastery (Gurney et al., 1979), Hamilton Branch (Schulze, 1987) and Sloan (Schulze, 1987) (see Figs. 5.7 and 5.8). It is therefore more than likely that this sample belongs to the megacryst suite in contrast to JSL 2 which is of considerably different composition (Figs. 5.7 and 5.8). Orthopyroxene from spinel peridotites at Letlhakane is characterized by $100 \cdot \text{Mg}/(\text{Mg} + \text{Fe}) = 92-94$ (see Fig. 2.3, Section 2.3.2). Fig. 5.8 illustrates that the Mg-number of orthopyroxene in JSL 2 falls within this range, and also within the range of Group II orthopyroxene megacrysts from Monastery. This, combined with the petrographic evidence presented in Section 5.2.4, suggests that JSL 2 is not a true orthopyroxene megacryst, but rather part of a disaggregated spinel peridotite.

5.5.5 Clinopyroxene-ilmenite intergrowths

Clinopyroxene-ilmenite intergrowths have been reported from a host of localities, e.g. Monastery (Gurney et al., 1979), Sloan (Eggler et al., 1979), Hamilton Branch (Schulze, 1984) and the Northern Lesotho pipes (Nixon and Boyd, 1973a) to name but a few. A more complete listing of localities may be found in Gurney et al. (1979) and Mitchell (1986).

Both lamellar and granular-textured intergrowths are common and clinopyroxene-ilmenite lamellar intergrowths are found in most kimberlite provinces (Mitchell, 1986). The lamellar intergrowth texture is commonly described as a graphic intergrowth, similar to graphic quartz-feldspar intergrowths in granite (Mitchell, 1977a). These intergrowths may or may not be deformed, e.g. at Frank Smith Mine (Pasteris et al., 1979). Favoured theories for the origin of these intergrowths include eutectic or cotectic crystallization (Gurney et al., 1979 and Wyatt, 1977). Mitchell (1977a), however, does not agree with either the eutectic or cotectic origin. He argued that the known ranges in the composition of ilmenite and clinopyroxene are not possible unless the eutectic composition and temperature were changing with respect to pressure and vapour composition. Mitchell (1977a) proposed instead that these intergrowths are the product of simultaneous crystallization under vapour-rich conditions.

Fig. 5.9 reveals a positive correlation between TiO_2 and $100 \cdot \text{Ca}/(\text{Ca} + \text{Mg})$ in the Cr-poor clinopyroxene megacrysts. However, clinopyroxene from clinopyroxene-ilmenite intergrowths exhibits a negative correlation with respect to TiO_2 and Ca-number. It is suggested that these two trends may be

related and form part of a process of igneous differentiation. The start of ilmenite crystallization depletes the melt in TiO_2 , resulting in the negative correlation between $100 \cdot \text{Ca}/(\text{Ca} + \text{Mg})$ and TiO_2 (Fig. 5.9). Shee (1978), Gurney et al. (1979) and Schulze (1987) have observed similar relationships between garnet megacrysts and garnet-ilmenite intergrowths and have interpreted their observations in a similar way.

5.5.6 Clinopyroxene-garnet intergrowths

Eggler et al. (1979) and Hops et al. (1989) noted that megacrysts occasionally contain silicate inclusions. Garnet and clinopyroxene appear to be the most common phases included in each other. Nonetheless, silicate intergrowths are rare and they are totally absent in many kimberlites (Mitchell, 1986). Only two examples have been reported from Monastery (Gurney et al., 1979).

Two clinopyroxene megacrysts containing garnet inclusions have been studied, one containing garnet blebs and the other garnet exsolution lamellae (see Section 5.3.2). Clinopyroxene from ilmenite-clinopyroxene intergrowths is similar in composition to that of garnet-clinopyroxene intergrowths with respect to TiO_2 content and Ca-number (Fig. 5.9). However, the Mg-numbers of both clinopyroxene (Fig. 5.4) and garnet (Figs. 5.1 and 5.2) in the two garnet-clinopyroxene intergrowths differ considerably, reflecting different processes involved in their formation. The composition of the granular-textured garnet falls within the Orapa megacryst field (Fig. 5.1) and is similar in composition to the garnet megacrysts found at Letlhakane. The origin of these samples is not apparent, but it is thought that the granular-textured garnet forms part of a clinopyroxene-garnet intergrowth, whereas the garnet lamellae in JSL 29 exsolved from clinopyroxene and underwent partial recrystallization.

Exsolved garnets from JSL 29 contain higher TiO_2 and Mg-numbers compared to those of exsolved garnets in clinopyroxene host megacrysts from the Bellsbank and Frank Smith kimberlites (Aoki et al., 1980). Similar intergrowths have been reported by Clarke and Pe-Piper (1983) and Meyer and McCallister (1984) from Koffiefontein, Bellsbank and Frank Smith. Meyer and McCallister (1984) demonstrated that exsolution of garnet occurred over a wide temperature and pressure range and that the garnets are of low-Cr and low-Ti composition, like the megacrysts. Some of the lamellar garnet intergrowths in a sample from Frank Smith (Clarke and Pe-Piper, 1983) also exhibit recrystallization to granular shapes, like the garnet in JSL 29.

5.5.7 Orthopyroxene-ilmenite intergrowths

These intergrowths are less common than the clinopyroxene-ilmenite intergrowths and the best known account is given by Rawlinson and Dawson (1979) on a nodule from the Weltevreden Mine, close to the more famous Frank Smith Mine, northwest of Kimberley. The xenolith consists of acicular bronzite irregularly intergrown with ilmenite. Rare bronzite-, pyrope- and diopside-ilmenite intergrowths are also present. A 10-15mm thick ilmenite vein transects the nodule. The comb layering and spherulitic intergrowths were interpreted by Rawlinson and Dawson (1979) as quench products of a high-Ti liquid and cooling was interpreted to have taken place in a small upper-mantle dyke. Clinopyroxene and ilmenite compositions exhibit a strong similarity to those of the MARID suite. Other orthopyroxene-ilmenite intergrowths have also been recovered from Frank Smith (Frick, 1973) and Monastery (Gurney et al., 1979).

Rawlinson and Dawson (1979) proposed that garnet and orthopyroxene would be the first minerals to crystallize, followed by ilmenite at a lower temperature. The crystallization of clinopyroxene followed from late-stage fluids enriched in CaO, K₂O and volatiles (Rawlinson and Dawson, 1979). The absence of garnet in the Letlhakane intergrowths may point to insufficient Al₂O₃ in the liquid at the time of crystallization. The ilmenite in the Letlhakane samples may have high Cr₂O₃ simply because the potential Cr₂O₃ hosts were not present (i.e. garnet and clinopyroxene). Although the textures in these rocks were named "quench"-textures by Rawlinson and Dawson (1979), they could equally well have resulted from rapid crystallization out of a supersaturated liquid or magma. Such a process could also account for the bladed, prismatic crystals.

The granular-textured orthopyroxene-ilmenite-phlogopite intergrowths and the orthopyroxene from the "quench" intergrowths exhibit a close petrographic resemblance to orthopyroxenes and textures found in extensively veined and metasomatized peridotites (JSL 500 and 511), as described in Chapter 3, Section 3.2.3. Obviously, the bladed, prismatic habit of orthopyroxene is not present in the peridotitic orthopyroxene, but the spinel and/or clinopyroxene exsolution in orthopyroxene is common to both types, and compositions are similar, although not identical. The author speculates that orthopyroxene-ilmenite intergrowths could be related to extensively metasomatized peridotites.

5.5.8 MARID and glimmerite xenoliths

MARID and glimmerite xenoliths are known to occur in some South African kimberlites, in particular those from Kimberley (Dawson and Smith, 1977; Apter et al., 1984, and Waters, 1987a).

Ilmenite in the single MARID xenolith from Letlhakane has a MgO-content similar to that of MARID ilmenites reported by Dawson and Smith (1977) and Waters (1987a). Furthermore, the phlogopite compositions from both JSL 51 and JSL -/181 are similar to other MARID phlogopites (shown in Fig. 5.10) studied by Dawson (1987). The Letlhakane MARID and glimmerite xenoliths are, however, characterized by more Cr_2O_3 -rich ilmenite (Fig. 5.6), clinopyroxene (Fig. 5.4) and K-richterite (Fig. 5.11), compared to those from the Kimberley MARID xenoliths. It is possible that the higher Cr_2O_3 and lower FeO reflect more primitive and reducing conditions for the Letlhakane MARID and glimmerite xenoliths compared to those in South Africa.

5.6 Summary

To summarize, the following important points regarding the megacrysts, intergrowths and MARID xenoliths may be noted:

- 1) Garnet, clinopyroxene, ilmenite and orthopyroxene megacrysts (listed in order of decreasing abundance) have been described. Clinopyroxene-ilmenite intergrowths are abundant and comprise the bulk of samples exhibiting intergrowth textures. Other intergrown phases include clinopyroxene-garnet and orthopyroxene-ilmenite.
- 2) O'Hara and Yoder (1967) reported Ca-numbers of approximately 13 for garnet that crystallized in the presence of pyroxenes. The garnet megacrysts and intergrowths from Letlhakane show Ca-numbers of 12-14 (similar to Monastery, Gurney et al., 1979) and it is therefore concluded that the Letlhakane garnet, orthopyroxene and clinopyroxene megacrysts may have crystallized together.
- 3) The granular garnet intergrown with clinopyroxene is of similar composition to garnet of the megacryst suite, unlike the exsolved graphic garnet. This may suggest separate origins for these garnets.
- 4) The clinopyroxene megacrysts may be divided into a Cr-poor (0.4-0.8 wt% Cr_2O_3) and a Cr-rich suite (1.6-2.1 wt% Cr_2O_3), as may megacrysts from Orapa. It is proposed that the Cr-rich megacrysts form part of the Granny Smith suite. No other Cr-rich megacryst types have thus far been discovered.
- 5) The ilmenite megacrysts are homogeneous and similar in composition to the Monastery ilmenites. The Letlhakane ilmenite field overlaps the Orapa ilmenite field, but the former appears to be poorer in Cr_2O_3 . The sample suite is too small to provide definite conclusions and further study is needed.

- 6) Two orthopyroxene megacrysts were studied, each representing a distinct group. JSL 1 is of similar composition to Group I orthopyroxene megacrysts from Monastery. JSL 2 represents a coarse orthopyroxene grain from a disaggregated spinel peridotite and is similar to Group II compositions from Monastery.
- 7) The Cr-poor clinopyroxene megacrysts and clinopyroxene-ilmenite intergrowths exhibit a possible differentiation trend, owing to the depletion of TiO_2 in the liquid after ilmenite crystallization had commenced. This is similar to the differentiation trend of TiO_2 in garnet, as observed by Shee (1978) at Orapa and Gurney et al. (1979) at Monastery.
- 8) Minerals from the orthopyroxene-ilmenite intergrowths are characterized by their elevated Cr_2O_3 -contents (especially the ilmenite) compared to similar intergrowths from other localities. In contrast to intergrowths from Weltevreden, the Letlhakane samples do not contain garnet.

CHAPTER 6

GEOTHERMOBAROMETRY

6.1 Introduction

To date no published fossil geotherms have been constructed from mantle xenoliths for the Zimbabwe craton and one of the principal objectives of this study was to provide one. Previous thermobarometric studies at Orapa (Shee, 1978) were inconclusive owing to the lack of garnet-bearing peridotites. He then analysed three coarse-textured garnet lherzolites from Letlhakane, all of which are included in this study.

6.2 Geothermometers and geobarometers - which combination is the best?

Chapter 1, Section 1.4.2, contains a brief review of thermobarometry and some of the problems encountered in applying mineral thermometers and barometers to mantle xenoliths. Carswell and Gibb (1987) tested approximately 12 different barometers and 20 different thermometers. With regard to the barometers available at the time of their review, these authors concluded that the barometer of Nickel and Green (1985) provided satisfactory results. Although the barometer of MacGregor (1974) is popular in the literature, conflicting opinions exist as to its accuracy (see Carswell and Gibb (1987) & Finnerty and Boyd, (1984 and 1987)). Carswell and Gibb (1987) maintain that the barometer overestimates pressures.

With respect to thermometers, Carswell and Gibb (1987) consider the Wells (1977) formulation of the two-pyroxene thermometer to be the best available for xenoliths exhibiting pressures of <37kbar. The Wood and Banno (1973) formulation yields better results at higher pressures (Carswell and Gibb, 1987). Finnerty and Boyd (1984, 1987), however, considered the Lindsley and Dixon (1976) (20kbar) calibration to be the best thermometer. The Ellis and Green (1979) and Powell (1985) thermometers based on Fe^{2+} - Mg^{2+} exchange between garnet and clinopyroxene have also gained acceptance. The former is more suitable for temperatures in excess of 1200°C, and the latter for temperatures below 1200°C (Carswell and Gibb, 1987).

Clearly, there is no consensus among workers with regard to a single, ideal thermometer. A combination of thermometers covering the low and high temperature ends of the range respectively, should rather be considered. Brey, Köhler and Nickel (1990) and Brey and Köhler (1990) addressed this problem by carrying out experiments in a 10-60 kbar pressure range and 900-1400°C temperature range. This resulted in the development of a new two-pyroxene thermometer. Brey and Köhler (1990) also proposed thermometers based on the Ca-content of orthopyroxene and the partitioning of Na between ortho- and clinopyroxene. However, these authors note that more work needs to be done in refining the above two thermometers. The calibration of Harley (1984a,b) for a thermometer based on Fe^{2+} - Mg^{2+} exchange between garnet and orthopyroxene is preferred by Carswell and Gibb (1987) to that of Mori and Green (1978). This thermometer is one of the few clinopyroxene-independent thermometers which can be used for the study of garnet harzburgites. Brey and Köhler (1990) noted that only the thermometers of O'Neill and Wood (1979, 1980) and Krogh (1988) produced repeatable results. The Krogh (1988) thermometer is a more recent calibration of the Ellis and Green (1979) thermometer.

Carswell and Gibb (1987), Finnerty and Boyd (1984) and Luth et al. (1990) caution against the use of Fe^{2+} - Mg^{2+} exchange thermometers if significant amounts of Fe^{3+} are present in minerals. If any doubt exists as to analytical accuracy, then all Fe present should be taken to be Fe^{2+} (Carswell and Gibb, 1987).

To summarize, the following factors have to be considered in any thermobarometric study:

- 1) The chosen thermometer or barometer should be calibrated over the same temperature/pressure range as the xenoliths that are to be studied. Long extrapolations to higher or lower temperatures and pressures should be avoided.
- 2) The type of thermometer/barometer used will obviously be restricted by the mineral assemblage of the rock. Rocks with a large selection of minerals will ensure a much wider choice of thermometers and barometers.
- 3) Analytical data must be of high quality, especially if Fe^{3+} is to be calculated (Carswell and Gibb, 1987).
- 4) The barometer/thermometer used should be tested to ascertain the accuracy of the method. This is possible by using data from published calibration experiments, where the mineral composition of the equilibrated assemblage is known, along with the temperature and pressure of equilibration. The relevant mineral compositions and parameters are inserted into the barometer/thermometer equation and if the barometer/thermometer is well-formulated, results should correspond closely to experimental pressure/temperature values.
- 5) Adjacent mineral phases are often neglected during the study of a particular mineral grain, but could be of great importance, especially if certain elements have a high distribution coefficient in the mineral, e.g. Cr and Al in spinel. Such an adjacent phase may cause depletion in an element critical for obtaining good quality thermobarometric values.

- 6) Diffusion is commonly associated with subsolidus cooling and may change primary element concentrations.
- 7) The trace elements may have a profound effect on major element concentrations in a mineral (Nickel and Green, 1985; Brey and Köhler, 1990).
- 8) Thermometers estimating the highest temperatures are most likely to represent primary conditions of crystallization. Lower temperatures may be the result of re-equilibration and diffusion at subsolidus temperatures.
- 9) It is vital to distinguish between primary and metasomatic mineral phases (by using mineral chemistry, grain size, textural relations, etc.) to ensure the determination of equilibrium temperatures and not metasomatic temperatures. The distinction between primary and primary metasomatic clinopyroxene is a good example of this.

6.3 The peridotite-pyroxenite suite.

The thermometers and barometers and the abbreviations by which they are referred to in this study, are listed in Table 6.1. These represent some of the most reliable, accurate and commonly used (except for the most recent) thermometers and barometers as discussed in Section 6.2. The new formulation by Finnerty and Boyd (1984) is used for the MacGregor (1974) barometer. All thermometers and barometers employed have been tested for reliability by using the published analyses of Akella (1976), Kushiro et al. (1972) and Brey and Köhler (1990). Results are shown in Table 6.2 and are compared to calculated values obtained by Carswell and Gibb (1987). Recent calibrations are more difficult to test, since no comparative studies on their performance have been published by independent authors.

An iterative procedure for solving the simultaneous equations is used in all combinations. For each xenolith, temperatures and pressures were calculated using several of the relevant phases and the results averaged to obtain a single temperature and pressure value for that particular sample. To avoid any contact metasomatic effects, only analyses of cores were used. At this point, mention must be made of an unavoidable factor in the study of thin sections of any type: different sections through a grain will produce different profiles, the center of which may not necessarily be the real core. This will result in analytical scatter if the grains are not compositionally homogeneous, a feature of unequilibrated xenoliths. Although one cannot distinguish real cores from apparent cores in a two-dimensional view, it is possible to estimate if a mineral is well-equilibrated by considering the compositional variation of this mineral in a sample. This was regularly done during mineral analysis and the majority of samples exhibit little intragrain mineral heterogeneity, other than that of analytical uncertainty. However, intergrain variability, particularly in clinopyroxene (Section 3.4.3), is more common and this may well affect temperature and pressure values.

Table 6.1: Thermometers and barometers used in this study:

<u>Thermometer</u>	<u>Principle employed</u>
Harley (1984b)	Fe ²⁺ -Mg ²⁺ exchange between garnet and orthopyroxene (HA84)
O'Neill & Wood (1979, 1980)	Fe ²⁺ -Mg ²⁺ exchange between garnet and olivine (OW79)
Ellis & Green (1979)	Fe ²⁺ -Mg ²⁺ exchange between garnet and clinopyroxene (EG79)
Krogh (1988)	Recalibration of the Ellis and Green (1979) thermometer (KR88)
Wood & Banno (1973)	Two-pyroxene solvus (WB73)
Wells (1977)	Two-pyroxene solvus (WE77)
Brey & Köhler (1990)	Two-pyroxene solvus recalibrated (T _{bkn})
Brey & Köhler (1990)	Ca-content in orthopyroxene (T _{Ca-in-opx})

<u>Barometer</u>	<u>Principle employed</u>
Finnerty & Boyd (1984)	Al ₂ O ₃ -content of orthopyroxene coexisting with garnet, based on experimental work by MacGregor (1974) (FB84)
Brey & Köhler (1990)	New calibration of the above barometer (P _{bkn})

Table 6.2: Test temperatures and pressures obtained from published analyses for the thermometers and barometers employed in this study, compared with values obtained by the author for the same analyses.Thermometers

Analysis	Thermometer	T(published) (Carswell & Gibb, 1987)	T(this study)
1	HA84	1538.0	1538.2
3	OW79	1308.0	1308.1
2	EG79	939.0	937.8
4	KR88	1411.0	1411.3
1	WB73	1278.0	1281.9
1	WE77	1258.0	1264.1
4	T _{bkn}	1389.0	1388.9
4	T _{Ca-in-opx}	1421.0	1427.2

Barometers

Analysis	Barometer	P(published) (Carswell & Gibb, 1987)	P(this study)
2	FB84	34.5	34.3
4	P _{bkn}	59.1	59.1

Analyses

- 1 : Analysis N-7 from Akella (1976) at 31 kbar and 1300°C
 2 : Analysis N-8 from Akella (1976) at 31 kbar and 1100°C
 3 : Table 3 from Kushiro et al. (1972) at 30 kbar and 1450°C
 4 : Worked example in Brey & Köhler (1990)

Results obtained from the Nickel and Green (1985) barometer were discarded, because it is only calibrated up to 40 kbar and 1400°C. The maximum pressure obtained for a deformed Letlhakane peridotite was approximately 70-80 kbar, depending on the thermometer used. The discrepancy in pressure between the Nickel and Green (1985) barometer and that of Finnerty and Boyd (1984) increased as the upper limit of calibration was overstepped. A similar problem was encountered with the barometer of Harley (1984a,b). The temperatures and pressures obtained in this study are summarized in Table 6.3 and Fig. 6.1 (a-h).

Pressure-temperature results obtained from the various thermometer and barometer combinations are illustrated in Fig. 6.1 (a-h). The MacGregor (1974) barometer and Finnerty and Boyd (1987) thermometer combination is used to compare the Letlhakane data with geotherms inferred from other localities. Owing to the small number of published mineral analyses from these localities, it was decided instead to plot the Letlhakane data by using the TEMPEST program of Finnerty and Boyd (1984) and to compare the results to the published temperature-pressure arrays of Finnerty and Boyd (1987). The following localities were chosen: Frank Smith, Finsch, Premier, Jagersfontein, Koffiefontein, northern Lesotho, Udachnaya (Siberia), Louwrensia and Hanaus (Namibia), East Griqualand, The Thumb (U.S.A) and Somacuanza in Angola (Finnerty and Boyd, 1987 and references therein) (see Fig. 6.2 a-f).

The calculated pressures and temperatures of equilibration plot close to the 40 mWm⁻² continental geotherm for conductive heatflow of Pollack and Chapman (1977). The Letlhakane kimberlites have sampled xenoliths over a considerable depth in the lithosphere (40-70 kb and 600-1000°C variation), depending on the thermobarometer combination. Both coarse-textured and deformed xenoliths have been found, including a possible coarse-textured high-temperature peridotite, JSL 116 (see Fig. 6.1). Some of the deformed peridotites deviate from the 40 mWm⁻² geotherm (Fig. 6.1) and exhibit a scatter similar to deformed peridotites from Jagersfontein (Fig. 6.2 b). Although clustering of rock types is not as prominent as in the case of northern Lesotho, deformed peridotites are restricted to the high-pressure end of the data array with coarse-textured peridotites and harzburgites at lower pressures. The garnet harzburgite suite overlaps the high-temperature end of the websterite field (Fig. 6.1 a,b,h) and straddles the diamond-graphite boundary of Kennedy and Kennedy (1976). The garnet websterites are restricted to the low-pressure end of the data array, the single exception being JSL 296. A single garnet websterite (JSL 202) containing small flakes of graphite plots well within the graphite stability field of Kennedy and Kennedy (1976). Three coarse-textured peridotites from Letlhakane, the mineral phases which Shee (1978) analysed, are also included in Fig. 6.1 (symbols in the form of filled stars). Temperatures and pressures obtained from his analyses of the coarse-textured peridotites, using the author's program, are in good agreement with similar peridotites from this study, as is evident from Fig. 6.1.

Table 6.3: Temperature and pressure results for the peridotite-pyroxenite suite. Metasomatized samples are indicated by an asterisk.

Sample no.	gt-opx HA84/FB84	gt-olv OW79/FB84	gt-cpx EG79/FB84	gt-cpx KR88/FB84	Sample no.	cpx-opx WB73/FB84	cpx-opx WE77/FB84	cpx-opx Tbkn/Pbkn	opx-opx Tca/FB84
JSL 25*	878.0/37.5	-	-	-	JSL 25*	-	-	-	827.4/34.1
JSL 75*	851.0/26.3	-	855.0/26.7	751.0/26.7	JSL 75*	796.7/23.4	655.2/15.2	627.8/19.4	738.3/20.0
JSL -/91*	920.0/40.5	986.0/44.8	1171.7/57.1	1121.3/53.8	JSL -/91*	821.9/45.8	743.4/28.8	799.1/28.1	895.0/27.7
JSL 108	1250.4/60.3	1532.7/78.6	1352.1/66.9	1345.4/66.7	JSL 108	1230.8/59.0	1152.9/53.9	1310.1/55.1	1317.9/64.6
JSL 110*	984.7/42.1	-	921.8/38.1	828.7/38.1	JSL 110*	737.5/26.2	601.1/17.5	432.9/ 9.5	811.3/31.0
JSL 111*	1038.7/47.5	-	1223.9/59.6	1176.0/59.6	JSL 111*	998.4/44.8	873.9/36.7	1003.2/38.1	950.5/41.7
JSL 112	1493.3/71.0	1705.3/84.1	1445.9/68.1	1439.8/68.1	JSL 112	1298.5/58.9	1254.9/56.2	1382.7/55.2	1413.8/66.1
JSL 113	1210.2/59.1	1330.7/67.5	-	-	JSL 113	-	-	-	972.1/43.5
JSL 116	1102.9/57.6	1251.6/68.0	1534.5/87.7	1647.5/95.6	JSL 116	1195.7/64.0	1093.8/56.9	1283.4/62.2	1064.5/54.9
JSL 119	1220.0/60.6	1406.9/73.0	1311.0/66.7	1296.7/66.7	JSL 119	1235.9/61.7	1160.5/56.7	1318.8/60.3	1309.4/66.6
JSL 126	1217.2/60.8	1530.3/81.7	1237.7/62.2	1212.9/62.2	JSL 126	1191.4/59.1	1100.3/53.0	1203.1/53.1	1320.9/67.8
JSL 134	974.9/43.8	1081.2/50.8	1186.5/57.7	1139.2/54.6	JSL 134	891.0/45.4	829.3/34.2	980.1/41.1	911.3/29.6
JSL 140	1268.6/59.7	1495.1/74.1	1357.7/65.4	1336.3/65.4	JSL 140	1240.0/57.9	1169.7/53.4	1333.8/56.4	1320.5/63.0
JSL 142*	1118.1/54.3	1326.7/68.2	1201.5/59.9	1145.0/59.9	JSL 142*	1075.0/51.4	951.0/43.2	1101.5/46.0	956.9/43.6
JSL 143*	1030.8/47.9	1031.9/48.0	1156.2/56.2	1076.6/50.9	JSL 143*	924.3/45.8	862.1/36.7	1061.4/42.3	903.8/29.6
JSL 151*	1065.3/53.5	-	1108.5/56.4	1065.5/53.5	JSL 151*	1029.5/49.0	990.3/48.3	1146.0/58.5	1072.1/30.3
JSL 170	930.1/37.7	1011.0/42.8	-	-	JSL 170	-	-	-	826.1/31.1
JSL 171	961.8/41.2	-	912.0/38.0	818.3/38.0	JSL 171	730.1/26.3	591.5/17.3	412.2/10.2	817.0/31.9
JSL-/177*	1042.0/49.8	1201.0/60.5	1247.8/63.7	1216.9/61.6	JSL-/177*	911.2/47.0	851.3/37.0	1065.9/44.8	950.6/32.3
JSL-/193	951.0/41.7	994.5/44.5	1167.1/55.8	1106.8/51.9	JSL-/193	831.8/44.9	753.0/28.7	839.1/29.1	888.6/29.7
JSL 202	836.0/28.7	-	788.4/25.8	670.0/25.8	JSL 202	819.5/27.7	719.8/21.7	739.0/20.8	782.2/25.5
JSL 209	791.6/24.2	-	796.5/24.5	690.3/24.5	JSL 209	851.2/26.7	703.8/19.0	616.0/16.6	779.2/23.4
JSL 252*	804.0/21.7	-	812.5/22.2	715.4/22.2	JSL 252*	804.3/21.8	655.3/13.4	507.0/10.3	726.8/17.4
JSL 261	920.3/41.9	1063.8/51.6	1162.4/58.3	1132.2/56.2	JSL 261	941.0/47.3	878.8/39.1	1062.7/45.2	943.9/32.0
JSL 262	891.9/41.4	1108.9/56.7	-	-	JSL 262	-	-	-	942.6/44.8
JSL 263	1177.5/56.4	1344.6/67.4	-	-	JSL 263	-	-	-	1405.1/71.1
JSL 266	1124.3/55.7	1390.1/75.5	-	-	JSL 266	-	-	-	803.4/34.1
JSL 267	997.6/46.7	1176.8/58.7	-	-	JSL 267	-	-	-	899.0/40.1
JSL 268	997.0/42.0	1000.2/42.2	-	-	JSL 268	-	-	-	842.6/32.0
JSL 278*	946.2/40.1	1033.4/45.7	1031.7/45.6	956.3/45.6	JSL 278*	889.3/36.4	750.8/27.5	710.6/24.7	854.5/34.2
JSL 279	1212.2/62.8	1430.3/77.7	1258.4/66.0	1236.3/66.0	JSL 279	1220.6/63.4	1137.4/57.7	1251.1/62.4	1384.8/74.6
JSL 280	1296.0/59.0	1491.5/71.2	1415.7/66.5	1402.0/66.5	JSL 280	1313.3/60.1	1270.6/57.5	1412.0/58.5	1453.9/68.9
JSL 296	1067.1/50.2	-	1194.2/58.6	1122.8/58.6	JSL 296	1030.7/47.8	911.3/39.9	1085.5/46.7	1029.2/47.7
JSL 298*	906.9/37.0	-	890.3/35.9	800.0/35.9	JSL 298*	852.3/33.5	711.2/24.5	576.5/18.1	866.8/34.4
JSL 504*	953.5/43.4	1063.9/50.7	1105.0/53.5	1043.1/49.4	JSL 504*	886.5/46.5	821.9/34.6	966.8/39.6	896.4/28.3
JSL 533*	932.9/41.2	978.0/44.2	1186.3/58.0	1138.9/54.8	JSL 533*	879.4/45.6	813.2/33.3	1006.5/38.4	871.0/27.4
JSL 600A	1036.8/47.4	-	1228.1/60.0	1140.1/54.2	JSL 600A	830.5/45.0	751.9/28.7	837.3/32.0	874.9/26.4
DK1/B	948.6/43.5	1001.5/46.0	1160.2/56.5	1104.4/52.8	DK1/B	965.0/43.6	915.8/40.3	1121.5/47.3	987.1/45.1
DK1/3	984.0/43.8	1102.7/51.5	1138.0/53.9	1067.5/49.2	DK1/3	1036.5/47.2	1011.3/45.6	1222.5/46.7	960.8/42.3
DK1/5	937.9/40.1	992.3/43.6	1208.2/57.7	1157.0/54.3	DK1/5	900.0/37.6	838.0/33.6	1036.5/38.2	936.5/40.0

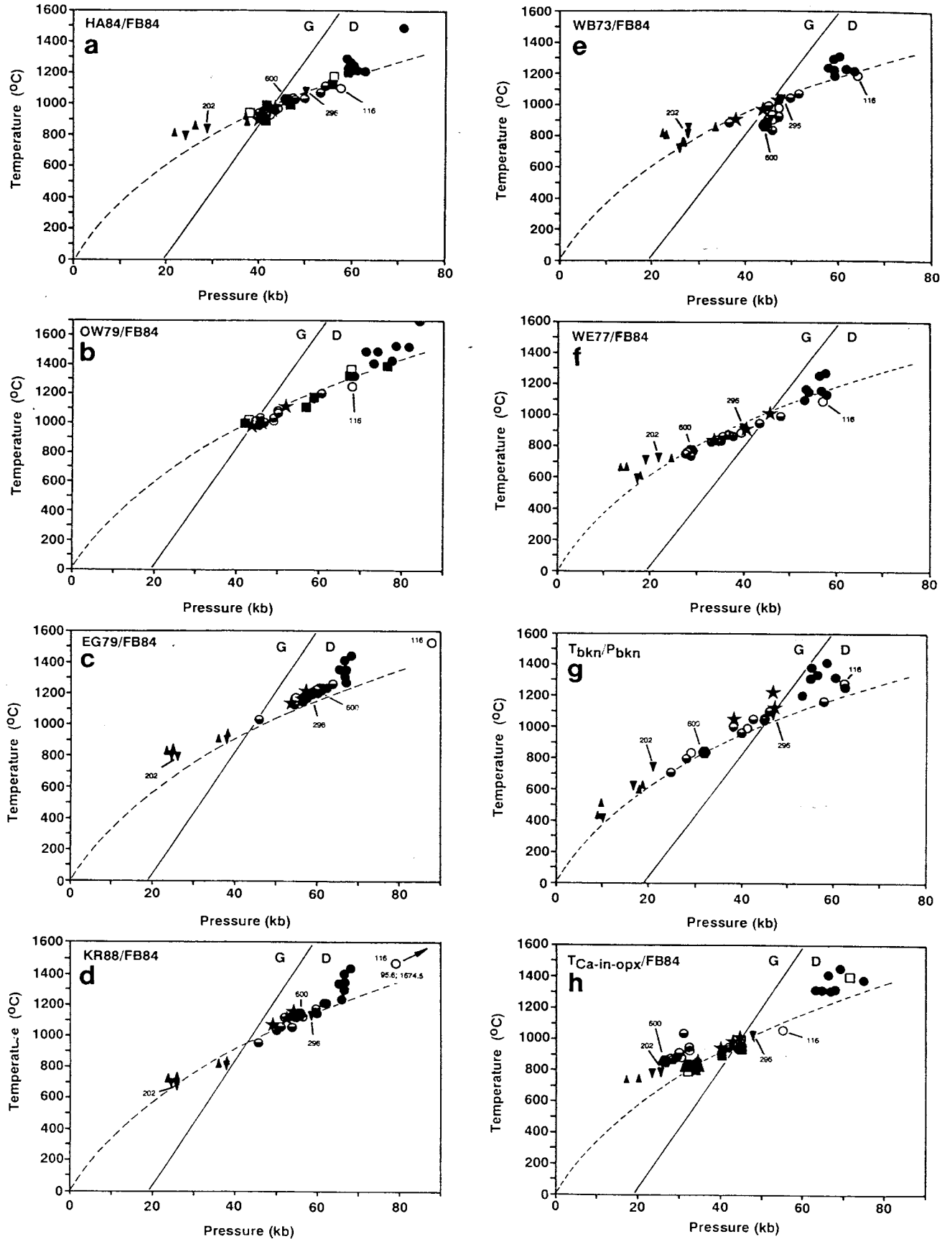


Fig. 6.1(a-h) Pressure-temperature results obtained from the peridotite-pyroxenite suite. The pressure-temperature array is inferred to define the geotherm beneath Letlthakane at approximately 90 Ma ago. The solid line represents the graphite-diamond boundary (Kennedy and Kennedy, 1976). The dashed line represents the 40 mW m^{-2} continental geotherm of Pollack and Chapman (1977). Filled stars represent three coarse-textured garnet lherzolites from Letlthakane, analyzed by Shree (1978).

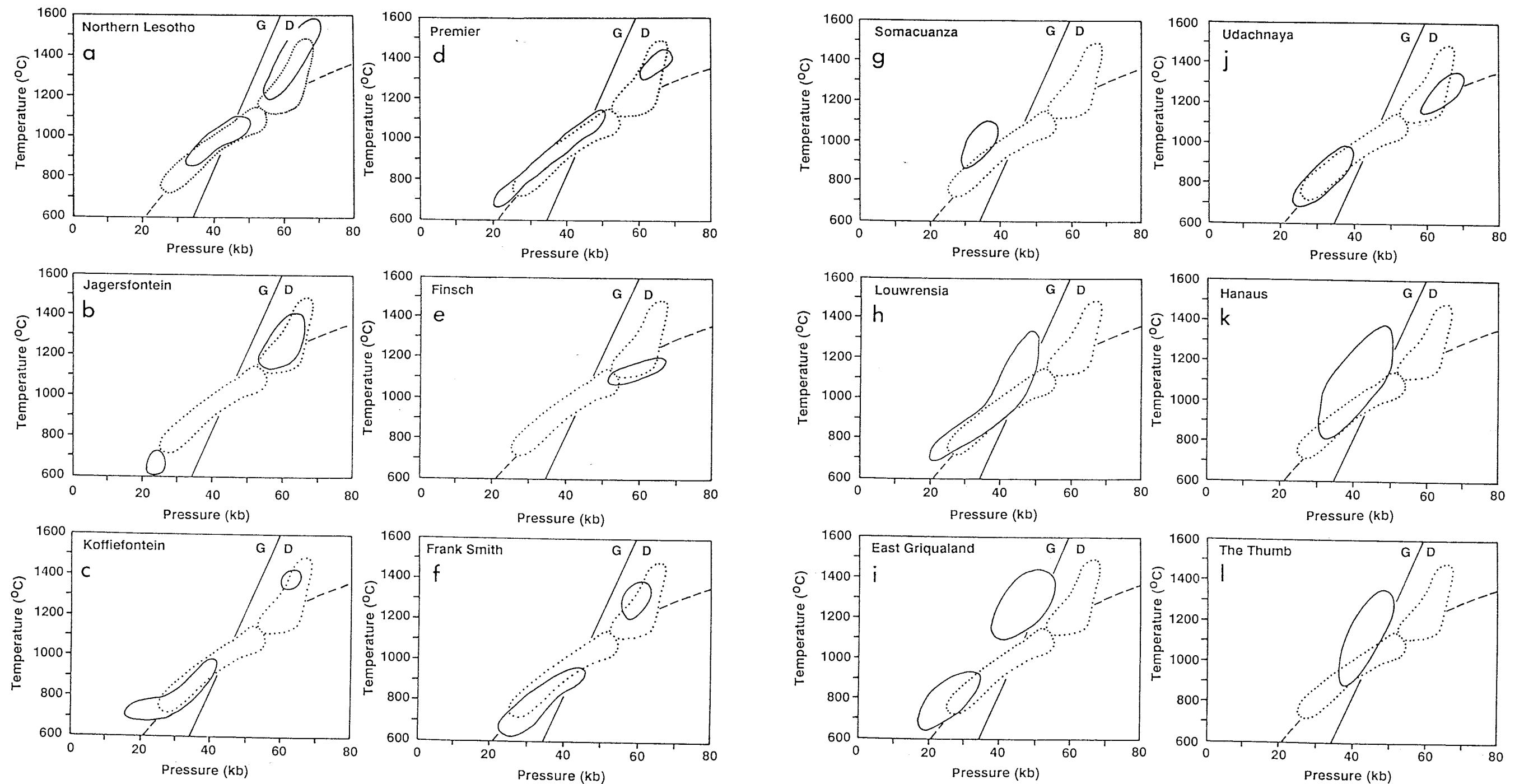


Fig. 6.2(a-l) Pressure-temperature arrays from a number of different localities worldwide (solid lines) modified from Finnerty and Boyd (1987). The data is limited to peridotite xenoliths only. For some localities, eg. Thumb, Hanaus and Louwrensia, the field defined by the solid line represents both high- and low-temperature peridotites. The stippled fields in each figure represent the high- and low-temperature peridotites from Letihakane. In all cases the geobarometer-geothermometer combination is that of MacGregor (1974) and Finnerty and Boyd (1987). The solid line represents the graphite-diamond boundary (Kennedy and Kennedy, 1976), while the curved, dashed line represents the 40mWm^{-2} continental geotherm of Pollack and Chapman (1977).

A comparison of the Letlhakane pressure-temperature array with those of other well-known diamond-bearing localities on the Kaapvaal craton and in Siberia indicates that only minor differences exist between these localities. The variable shape of some geotherms from on-craton localities, e.g. Fig. 6.2 a-f, may partly be a function of the number of samples plotted. A large sample suite obviously defines a better geotherm than a small sample suite. Maximum depth of derivation of the deformed peridotites appears to be similar to samples from Jagersfontein. Unfortunately, little is known with regard to the pressure-temperature values of pyroxenites from the Kaapvaal craton. This can be ascribed to the close proximity of these pyroxenites to the lower limits of calibration of most thermometers and barometers currently employed for the study of mantle xenoliths. The distinct grouping of websterites and deformed lherzolites in terms of pressure and temperatures of equilibration (Fig. 6.1), indicates that each of these rock groups has formed under similar temperature and pressure conditions and thus it can be inferred that they were derived from distinct areas of the mantle. This is in contrast to the coarse lherzolites and harzburgites which apparently equilibrated over a 20 kb range along the geotherm. The deformed garnet lherzolites plot within the diamond stability field and have a tendency to plot at a higher temperature than the 40 mWm^{-2} geotherm.

6.4 The metasomatized peridotite-pyroxenite suite

The general methodology for the calculation of these temperatures and pressures is identical to that outlined in Section 6.3. Garnet-free peridotites (PP) could obviously not be included here, owing to the required presence of garnet for pressure calculations. Temperature-pressure values for the metasomatized (i.e. phlogopite-bearing) garnet peridotites are included with those of the non-metasomatized peridotites in Table 13 and shown in Fig. 6.1 (a-h). Owing to the paucity of true GP xenoliths in the mantle (most GP xenoliths in Chapter 2, Section 2.2 had to be reclassified because of the presence of phlogopite), temperature and pressure comparisons between metasomatized and non-metasomatized xenoliths cannot easily be made. The WE77/FB84 thermobarometer combination was used in all comparisons between these two suites, owing to the suitability of this combination at lower pressures (Section 6.2).

The metasomatized garnet-bearing samples exhibit a large variation in temperature and pressure. The low temperature and pressure segment of the geotherm is characterized by the presence of amphibole-bearing websterites (Fig. 6.1). Where present, e.g. Fig. 6.1 a,b,h, the harzburgite suite is overlapped by the metasomatized suite on the 40 mWm^{-2} geotherm. Note the scattering of some metasomatized peridotites below (Fig. 6.1e) and above (Fig. 6.1h) the 40 mWm^{-2} geotherm. It is perhaps significant that this scattering is only limited to certain thermobarometer combinations and is therefore not universally present, e.g. Fig. 6.1 f. Some of the samples exhibiting scatter are classified as class II samples (Chapter 3, Section 3.4.3) and

are therefore not completely equilibrated. The instability of phlogopite at depth is reflected by the absence of this mineral at pressures greater than 50 kb (Fig. 6.1 f), depending on the thermobarometer combination. The edenitic hornblendes reported from two garnet websterites (Chapter 3, Section 3.2.4) appear stable up to a maximum of 30 kb (Fig. 6.1 f).

A combination of temperature-pressure and REE data (Chapter 7) for selected samples reveal a concomitant increase in the Sm, Nd and Sr contents of clinopyroxene with decreasing temperature and pressure, as shown below:

Sample no.	T(°C)/P(kb)	Sm(ppm)	Nd(ppm)	Sr(ppm)
JSL 280 DEF	1270.6/57.5	-	5.980	101.7
JSL 114 GP	-	1.090	4.600	103.3
JSL 151 GP/GPP	990.3/48.3	0.299	4.840	350.3
JSL 504 GPP	821.9/34.6	4.080	19.490	333.0
JSL 278 GPP	750.8/27.5	5.420	31.580	345.8

Some irregularity does exist in the values, but the overall trend is one of increasing Sm, Nd and Sr with decreasing depth. Note the sudden increase of Sr in clinopyroxene from phlogopite-bearing GPP xenoliths, compared to clinopyroxene in the phlogopite-free GP and deformed peridotite. Unfortunately, the only GP for which REE data are available (JSL 114) does not contain orthopyroxene (Chapter 2, Section 2.2.1 and Table 2.1), and an equilibration pressure can therefore not be calculated. These results correspond with the overall findings of Waters and Erlank (1988) for the metasomatized suite at Kimberley. Waters (1987a) and Waters and Erlank (1988) correlated this feature with the increase in metasomatic effects (observed as Sm, Nd and Sr increases in clinopyroxene) as depth decreases. It should also be borne in mind that the PP suite is not represented here, because of the difficulties experienced in the isotopic analysis of these clinopyroxenes (Chapter 7, Section 7.2), while samples of the PKP suite were not recovered during this study (Chapter 3, Section 3.4.1). The overall trend has, however, been established.

6.5 The eclogite suite

The thermometer of Ellis and Green (1979), based on Fe-Mg exchange between garnet and clinopyroxene, has been used to calculate equilibrium temperatures for the eclogites. Pressure-temperature

calculations for eclogites are unfortunately rather limited, owing to the lack of orthopyroxene in these rocks. However, the presence of certain accessory minerals, notably diamond and graphite, assist in ascertaining depth of derivation.

Coleman et al. (1965) demonstrated that the K_d -ratio (Fe-Mg distribution between garnet and clinopyroxene) is a useful classification parameter of eclogite type, as well as an indicator of temperature (Raheim and Green, 1974; Ellis and Green, 1979). Low K_d -values generally point to high temperatures of equilibration. K_d -values from Roberts Victor eclogites range from 2.19-4.92 (Bishop et al., 1978) and the entire Koidu suite from approximately 2-8 (Hills and Haggerty, 1989). Unfortunately, the former authors do not state whether the reported values for the Roberts Victor eclogites are for one particular group only, or relevant to the complete suite. The entire eclogite suite from Letlhakane exhibits a range in K_d -values from 1.64-8.2 ($\ln K_d = 0.5-2.1$ - see Fig. 6.3), i.e. very similar to the Koidu eclogite suite, despite the absence of corundum and kyanite-bearing varieties in the Letlhakane suite. K_d -values for eclogitic mineral inclusions in Orapa diamonds vary from 2.1-3.3, i.e. the most restricted range of all localities mentioned thus far (Gurney et al., 1984), while the entire Orapa eclogite suite exhibits K_d -values of approximately 2-7 (Shee, 1978). Fig. 6.3 reveals that the Group I and Group II eclogites (identified earlier on the basis of the Na_2O -content in garnet; see Section 4.3.1 and Fig. 4.3) plot as two trends, each with a different slope. Group I eclogites display a gentle positive slope, while the slope for Group II eclogites is near vertical. The Ca-content in Group I garnets increases with a decrease in temperature, which is consistent with igneous differentiation (Robinson et al., 1984). The Ca-content of Group II garnets is almost constant with decreasing temperature. The difference in slope of the Group I and Group II trends may indicate that two distinct processes were responsible for the formation of these eclogite groups. The scatter of some points to high K_d -values ($K_d > 6$) may be explained by possible disequilibrium, since Fe and Mg concentrations vary considerably between garnets within the sample. The disequilibrium may have been caused by metasomatism with associated diffusion, since these samples also record the lowest equilibration temperatures of all the eclogites analysed.

The Letlhakane eclogites equilibrated in a temperature range of 700-1300°C (assuming $P = 45$ kbar and all iron to be Fe^{2+}). Fig. 6.4 illustrates that the majority of Group I eclogites (including the diamond- and/or graphite-bearing samples) equilibrated at between 1000 and 1300°C. A few eclogites plot down to 700°C, but these form a distinct minority. Fig. 6.5 shows that Group II eclogites have equilibrated at lower temperatures (100°C difference in the peaks) than Group I eclogites. The higher and greater range in equilibration temperatures of Group I eclogites corroborates an igneous origin for these rocks, as suggested in the previous paragraph.

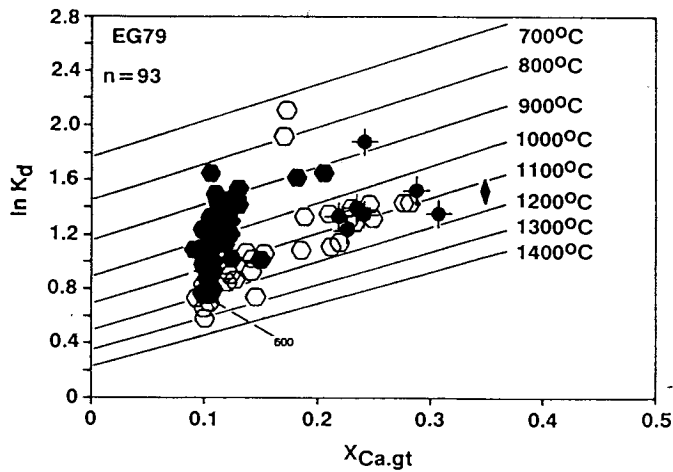


Fig. 6.3 $\ln K_d$ vs. $X_{Ca.gt}$ and isotherms derived from the EG79 geothermometer ($P=45\text{kbar}$ and total $\text{Fe}=\text{Fe}^{2+}$). Group I and Group II eclogites from Letlhakane are illustrated. Note the different trends exhibited by the two eclogite groups.

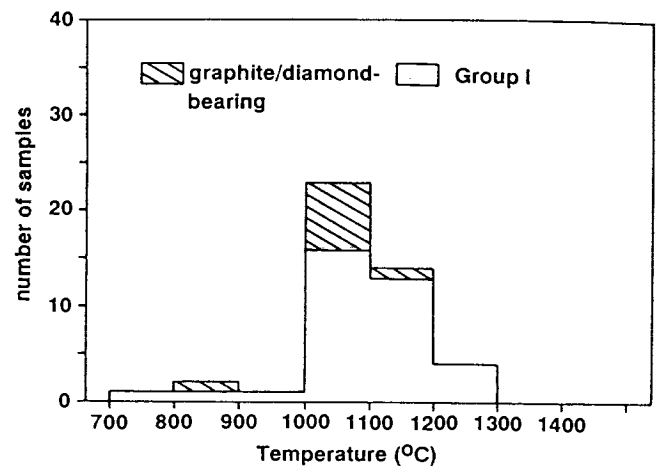


Fig. 6.4 Equilibration temperatures recorded by the Group I and graphite- and graphite-diamond-bearing eclogites, using the EG79 geothermometer ($P=45\text{kbar}$ and total $\text{Fe}=\text{Fe}^{2+}$).

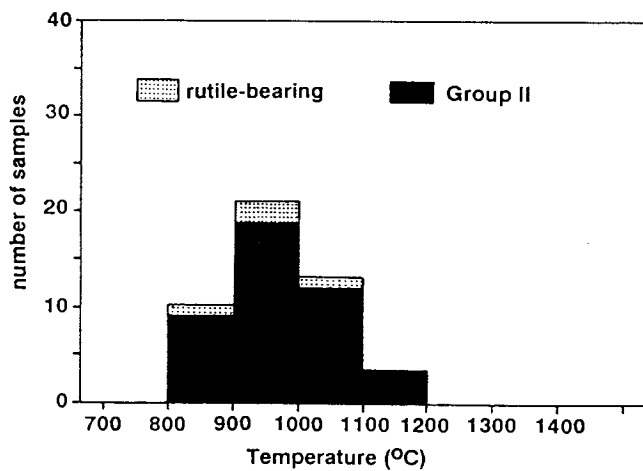


Fig. 6.5 Equilibration temperatures recorded by the Group II and rutile-bearing eclogites. Similar pressure and analytical conditions apply as in Fig. 6.3.

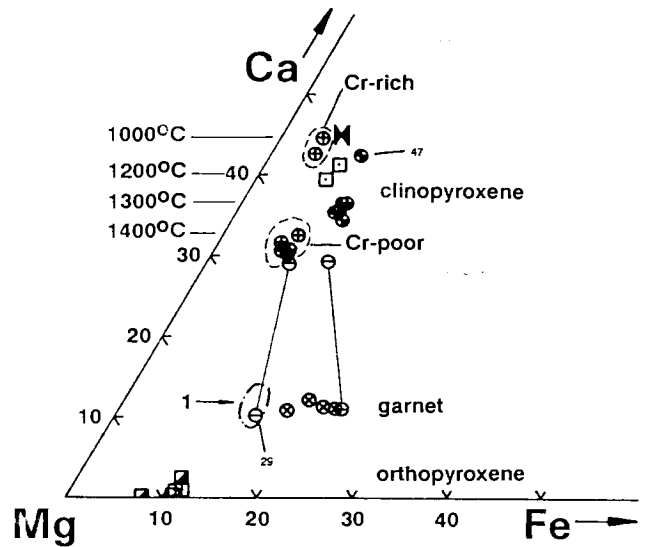


Fig. 6.6 Ternary Mg-Ca-Fe plot of the silicate intergrowths and megacrysts. Temperature gradations are taken from Lindsley (1983). Tie-lines join co-existing phases. Field 1 represents the high-Ti, deformed peridotitic garnets from Letlhakane.

6.6 The megacryst suite

The compositions of silicate megacrysts are presented in Fig. 6.6. Approximate temperature gradations are also shown (Lindsley, 1983). The clinopyroxenes indicate the following approximate order of decreasing temperature: Cr-poor megacrysts > clinopyroxene-ilmenite intergrowths (both graphic and granular textures) > orthopyroxene-ilmenite "quench" intergrowths > Cr-rich megacrysts and MARID clinopyroxenes. JSL 47, also a granular clinopyroxene-ilmenite intergrowth, plots at a significantly lower temperature than the other members of the same suite. This shift in composition is possibly due to the large amount of alteration in the clinopyroxene (see Section 5.3.1 and Fig. 5.9).

6.7 Discussion

Important points included in the following discussion are: the scatter of the deformed peridotites along the temperature-pressure array, the harzburgite gap and the choice of thermometers and the effect it has on temperature and pressure calculations.

6.7.1 Deformed peridotites

The reason for the deviation of the deformed nodules from the geotherm is not clear. Stress heating at the top of the asthenosphere (Boyd, 1973), convection (Green and Gueguen, 1974) and diapirism (Boyd, 1976 and Mitchell, 1984) have been quoted as possible reasons. Harte and Gurney (1981) proposed that the high-temperature peridotites are derived from contact aureoles around a range in pressure similar to pressures calculated for deformed peridotites from Letlhakane. The depth at which the deformed nodules are derived is indicative of a deep, cool root. Mitchell (1978) proposed that the restite in equilibrium with a kimberlite melt at the site of generation contains material that is subsequently incorporated into the kimberlite by the diapiric flow during its upward movement. He further suggested that xenoliths trapped in this flow do not retain thermobarometric evidence of their origin, because of continuous re-equilibration in the diapir. The rising diapir would further disturb isotherms in its immediate vicinity. Mitchell (1984) and Nixon and Boyd (1973a) suggested that the xenoliths trapped in this diapir are those that give rise to the inflected part of the geotherm. Thermally unperturbed mantle is represented by coarse-textured xenoliths.

6.7.2 The harzburgite gap

Finnerty and Boyd (1987) noted the common occurrence of a gap, separating high and low temperature garnet peridotite suites in temperature-pressure space, e.g. Fig. 6.2 a. They suggested that the gap may be occupied by low-Ca garnet harzburgite or magmas. From the comparisons made in this study, it is apparent that the choice of thermometer/barometer combination may be partly responsible for this gap (compare Fig. 6.1 g and h). In constructing geotherms from several localities, Finnerty and Boyd (1987) and others have shown preference for the use of thermometers dependent on the two-pyroxene solvus. Harzburgites, which lack clinopyroxene, can therefore not be represented on these geotherms. Fig. 6.1 b illustrates that the potential gap in the Letlhakane geotherm may indeed be partly filled by harzburgites and this result therefore supports the suggestion of Finnerty and Boyd (1987).

6.7.3 Choice of thermometers

Table 6.3 shows that several samples exhibit large differences in calculated temperature and pressure, depending on the barometer-thermometer combination used. Since the Finnerty and Boyd (1984) calibration of the MacGregor (1974) barometer is used in most combinations, these differences must be caused by the thermometer. Owing to the iterative nature of the procedure, any error in the thermometer calculation will unfortunately be carried over to the pressure determination. Although most minerals are homogeneous, the clinopyroxene may be zoned (Ca and Mg), possibly as a result of decompressive and other effects (Chapter 2, Section 2.4.4). Intergrain variation in clinopyroxene (Section 6.4) may also have contributed to these variations. This is unfortunate, since the diopside solvus is one of the principal thermometers in thermobarometric studies.

The choice of thermometer may also be partly responsible for the temperature discrepancies observed in Table 6.3. The Wells (1977) thermometer reproduces experimental temperatures at 900°C well, but at higher temperatures increasingly underestimates these temperatures; e.g. by up to 170°C at 1300°C (Brey and Köhler, 1990). Lindsley and Dixon (1976) have noted the influence of pressure on the diopside-enstatite solvus. It is this pressure effect which is probably responsible for the temperature underestimation in the Wells thermometer. Despite several attempts (Nickel and Brey, 1984; Brey and Huth, 1984), the problem of temperature underestimation does not appear to be completely resolved. Carswell and Gibb (1980) consider the pressure effect upon the solvus to be significant at temperatures > 1200°C. An even greater source of error could be extrapolation of data from simple systems to the more complex natural pyroxenes. Ross et al. (1973), Akella (1976) and Mori (1977) have illustrated that significant amounts of Na, Al and especially Fe, have an important effect on the extent of solid solution between coexisting pyroxenes. This

may be of importance when trying to estimate the temperature of fertile, deformed lherzolites. The Wells (1977) formulation is considered superior to that of Wood and Banno (1973), because of errors in the formulation of the latter (Carswell and Gibb, 1987). Table 6.3 shows that the Wood and Banno (1973) thermometer consistently overestimates temperatures when compared to the Wells (1977) thermometer. A comparative study of the thermometers formulated by Brey and Köhler (1990) and that of Harley (1984b), reveals that the new thermometers overestimate high and underestimate low temperatures.

The above discussion serves to illustrate that even the widely used thermometers suffer from certain drawbacks. One of the main reasons appears to be a limited knowledge of cation distribution and substitution, e.g. the problem of correcting for "other" components in the enstatite-diopside thermometer (Lindsley, 1983). Another reason is that the thermodynamics of many systems are not yet fully understood. For a thermometer to be sufficiently temperature-sensitive, a large entropy change in the system is required. Similarly, a successful geobarometer must contain phases which exhibit a large change in volume during pressure changes. Lastly, one of the most common difficulties is errors in normalizing the mineral formula, a prime example being the $\text{Fe}^{3+}/\text{Fe}^{2+}$ problem in pyroxenes and amphiboles.

6.8 Summary

To conclude, the following points may be summarized:

- 1) The Letlhakane geotherm corresponds closely to the 40mWm^{-2} geotherm of Pollack and Chapman (1977), indicative of a deep, cool cratonic root. The shape of the geotherm is similar to those determined from various localities on the Kaapvaal craton and many diamond-bearing localities on other continents.
- 2) The wide variety of garnet-bearing peridotites and pyroxenites included in the kimberlite reflects the large mantle interval sampled by the kimberlite. Using the WE77/FB84 thermobarometer combination, this interval is characterized by temperatures ranging from 1271°C to 600°C and pressures from 58 to 13 kbar. The three garnet lherzolites analysed by Shee (1978) yield pressure-temperature data that are consistent with the coarse-textured lherzolites analysed in this study.

- 3) Some deformed peridotites plot at temperatures and pressures well away from the majority of samples. This may reflect incomplete equilibration amongst constituent phases. Similar scatter is observed in the garnet websterite group at the low-pressure end of the geotherm and amongst the metasomatized peridotites in particular thermobarometer combinations. Certain thermobarometer combinations result in geotherms that appear slightly inflected, but this impression may be influenced by the scattering mentioned above.
- 4) Metasomatized garnet-bearing samples exhibit a large variation in temperature and pressure. Selected clinopyroxenes reveal an increase in Sm, Nd and Sr concentrations with decreasing temperature and pressure. This correlates with previous results from earlier studies where it was found that metasomatic effects increase with a decrease in depth.
- 5) The Letlhakane eclogites equilibrated within a temperature range of 750 to 1300°C, assuming $P = 45$ kbar and all Fe to be Fe^{2+} . This range is similar to that observed in eclogites from Koidu, Sierra Leone. Histograms of temperature values indicate a 100°C difference in average temperature between Group I and Group II eclogites, Group II eclogites having formed at lower temperatures. A trend of increasing X_{Ca} ($X_{\text{Ca}} = \text{Ca}/(\text{Ca} + \text{Mg} + \text{Fe} + \text{Mn})$) with decreasing temperature in the garnet of the Group I eclogites suggests an origin by igneous differentiation for these rocks. Group II garnets recorded a constant X_{Ca} with decreasing temperature, implying that a process different to that of the Group I eclogites was active during crystallization.
- 6) The Letlhakane and Koidu eclogites exhibit very similar K_d -values. This similarity, and the fact that kyanite and corundum-bearing eclogites are present at Koidu, leads to the conclusion that kyanite and corundum-bearing eclogites are more than likely present at Letlhakane, but have probably not been recognized during sampling.
- 7) A range of possible equilibration temperatures is exhibited by the megacryst and intergrowth suites. The clinopyroxenes in these rock types recorded a temperature decrease in the following order: Cr-poor megacrysts > clinopyroxene-ilmenite intergrowths (both graphic and granular textured) > orthopyroxene-ilmenite intergrowths > Cr-rich clinopyroxenes and MARID clinopyroxenes.

CHAPTER 7

RADIOGENIC ISOTOPES

7.1 Introduction

The radiogenic isotope study presented in this chapter is the first ever undertaken at Letlhakane DK 1 and DK 2. A small, but wide selection of peridotite xenoliths representing the major rock groups have been analysed for Sm, Nd, Rb and Sr to provide some indication of whether or not the Letlhakane peridotites exhibit significant differences in Nd and Sr isotopic ratios when compared to other localities. Isotopic study of eclogite xenoliths and megacrysts from the neighbouring Orapa kimberlite is in progress elsewhere (Viljoen, in prep.; Smith et al., in prep.) and it was therefore considered appropriate to concentrate on the Letlhakane peridotite suite.

7.2 Sample selection

Samples for study were selected from each of the peridotite groups as identified in Chapters 2 & 3, and garnet peridotite; garnet phlogopite peridotite; phlogopite peridotite; hot, deformed peridotite; subcalcic garnet harzburgite and spinel lherzolite xenoliths are all represented. An unusual composite pyroxenite-Group II eclogite xenolith (JSL 600) was also included (Chapter 4, Section 4.2.8). Nd- and Sr-isotopic ratios were obtained from hand-picked, acid-washed garnet and clinopyroxene separates. Details of the preparation procedure can be found in Appendix 4. As sufficient quantities of pure, unaltered clinopyroxene could not be obtained from the phlogopite peridotites, isotopic study of this group had to be abandoned. The clinopyroxene in JSL 600 also proved to be of insufficient purity for isotopic analysis. Low modal abundances of phlogopite in the GPP xenoliths (JSL 278, 504) prevented the preparation of sufficient material for mica analysis.

The small size of many of the samples (Chapter 2, Section 2.1) complicated separate preparation and in most instances sufficient material was available for only one attempt at mass spectrometry. The isotopic composition of whole peridotites was not determined because of the risk of analysing unknown amounts of secondary contaminant. Erlank (1970) has shown that much of the K (and therefore Rb) present in

kimberlite-derived xenoliths is of secondary origin and located along grain boundaries, cracks and in alteration products. Richardson et al. (1985) reported 400 ppm Sr in CaCO_3 intergrown with a Mg-silicate in cracks traversing garnet, while phlogopite often contains secondary interlaminated calcite (Allsopp and Barrett, 1975) of extraneous origin. Interlaminated calcite in phlogopite is present in a few of the phlogopite-bearing peridotites from Letlhakane (see also Plate 13, Chapter 3).

Determination of the isotopic composition of the DK 1 kimberlite was not possible, as current mining levels are situated in tuffisitic kimberlite breccia (TKB). Isotopic study of TKB is known to produce inaccurate results owing to the contaminating effect of country rock xenoliths and circulating groundwater with elevated $^{87}\text{Sr}/^{86}\text{Sr}$ (Berg and Allsopp, 1972; Barrett and Berg, 1973).

7.3 Results

A description of the various rock types selected for analysis is provided in Table 7.1. Sm, Nd, Rb and Sr concentrations of clinopyroxene and garnet separates, as well as isotopic ratios and calculated model ages, are presented in Table 7.2. Rb concentrations are generally barely above the blank and are not discussed in detail. The trace element concentrations of clinopyroxene and garnet will be discussed separately in the following two sections. A key to the symbols used in the plots can be found in the back folder.

7.3.1 Trace element concentrations

7.3.1.1 Clinopyroxene

There is a regular increase in Sm, Nd and Sr concentrations in clinopyroxene from garnet peridotites (GP) to garnet phlogopite peridotites (GPP) (i.e. non-metasomatized to metasomatized, phlogopite-bearing peridotites). The GPP xenolith JSL 151 is considered to be an exception. Rare, low- TiO_2 phlogopite grains in thin section suggest that the xenolith is a GPP. However, crushing of the remaining sample did not produce any more phlogopite. Furthermore, although the Sr-content of the clinopyroxene is typical of a GPP, the low Sm, Nd, Cr_2O_3 and Na_2O concentrations and low Sm/Nd suggest a composition typical of a GP clinopyroxene.

Table 7.1: A summary of textural features and modal mineralogy of samples selected for isotopic analyses.

Sample no.	Rock type	Modal mineralogy	Texture
JSL 113	Subcalcic gt. harz.	ol + opx + gt + Cr-sp	coarse, cold
JSL 114	GP (Gt. wehrl.)	cpx + gt	coarse, cold
JSL 124	Spinel lherz.	ol + opx + cpx + sp	coarse
JSL 151	GP/GPP (Gt. lherz.)	opx + cpx + gt + phl	coarse, cold
JSL 154	Spinel lherz.	ol + opx + cpx + sp	coarse
JSL 278	GPP (Gt. lherz.)	ol + opx + cpx + gt + phl	coarse, cold
JSL 280	GP (Gt. lherz.)	ol + opx + cpx + gt	deformed, hot
JSL 504	GPP (Gt. lherz.)	ol + opx + cpx + gt + phl	coarse, cold
JSL 600	Pyrox. (composite)	opx + cpx + gt + phl	coarse, cold

Table 7.2: Sr- and Nd- isotopic data for selected Letlhakane peridotites and a pyroxenite. Failed runs are indicated by a "f" symbol. Model ages calculated from Nd data.

Sample no. Mineral	JSL 114 cpx	JSL 151 cpx	JSL 278 cpx	JSL 280 cpx	JSL 504 cpx	JSL 124 cpx	JSL 154 cpx
$^{87}\text{Sr}/^{86}\text{Sr}$	0.702663(26)	0.708458(38)	0.705548(26)	0.702645(24)	0.704761(24)	0.702302(26)	0.7113908(28)
$^{143}\text{Nd}/^{144}\text{Nd}$	0.512924(18)	0.511694(20)	0.512290(20)	0.512904(16)	0.512691(20)	0.511551(18)	0.51178(11)
Sm (ppm)	1.090	0.299	5.420	1.639	4.080	4.590	f
Nd (ppm)	4.600	4.840	31.580	5.980	19.490	18.820	f
Rb (ppm)	0.036	-	0.020	0.050	-	-	-
Sr (ppm)	103.250	350.760	345.750	101.700	333.040	127.1	f
$^{147}\text{Sm}/^{144}\text{Nd}$	0.143134	0.037307	0.103660	0.165563	0.126448	0.147279	
$^{87}\text{Rb}/^{86}\text{Sr}$	0.001008	0.000000	0.000167	0.001422	0.000000		
$(^{143}/^{144})_i$							
$(^{143}/^{144})_{90}$	0.512716	0.511672	0.512229	0.512807	0.512617	0.511464	
$(^{87}/^{86})_i$							
$(^{87}/^{86})_{90}$	0.702662	0.708458	0.705548	0.702643	0.704761	0.702302	
age _{CHUR} (Ma)		903±19	571±33			3327±55	
age _{DM} (Ma)		1171±17	1061±26			3165±37	
Gt-cpx age							
E(Nd)	3.16	-18.41	-6.79	5.19	1.03	-21.20	
E(Sr)	-28.91	53.33	12.03	-29.16	0.87	-34.03	

Sample no. Mineral	JSL 113 gt	JSL 114 gt	JSL 151 gt	JSL 278 gt	JSL 280 gt	JSL 504 gt	JSL 600 gt
$^{87}\text{Sr}/^{86}\text{Sr}$	0.709121(38)	f	0.710509(88)	f	0.704465(36)	f	f
$^{143}\text{Nd}/^{144}\text{Nd}$	0.511877(32)	f	0.511834(90)	0.512877(36)	0.513071(18)	0.512964(38)	0.513000(36)
Sm (ppm)	0.481	1.000	0.402	1.330	1.160	1.694	1.030
Nd (ppm)	1.878	0.930	1.620	1.330	1.460	2.150	0.908
Rb (ppm)	0.009	-	0.003	0.009	0.004	0.120	-
Sr (ppm)	3.380	f	0.751	f	0.702	f	f
$^{147}\text{Sm}/^{144}\text{Nd}$	0.154678	0.571058	0.149860	0.604063	0.479963	0.475955	0.685246
$^{87}\text{Rb}/^{86}\text{Sr}$	0.007705		0.011561		0.016481		
$(^{143}/^{144})_i$			0.511648	0.512168	0.512816	0.512592	
$(^{143}/^{144})_{90}$	0.511877		0.511746	0.512521	0.512684	0.512684	0.512597
$(^{87}/^{86})_i$			0.708458		0.702473		
$(^{87}/^{86})_{90}$	0.709111		0.710494		0.704444		
age _{CHUR} (Ma)	2744±114		2602±289				
age _{DM} (Ma)	2784±71		2689±188				
Gt-cpx age			190±149	179±17	81±17	119±25	
E(Nd)	-14.84		-15.68	4.66	8.45	6.36	7.06
E(Sr)	62.74		82.43		-3.33		

Although JSL 278 was initially classified as a GP, phlogopite was subsequently found in this xenolith and it has been reclassified as a GPP. The single GP sample (JSL 114) is characterized by low Sm, Nd, and particularly Sr, in the clinopyroxene (Table 7.2). This is also a characteristic of clinopyroxene from the deformed peridotite (JSL 280).

Chondrite-normalized Sm and Nd concentration patterns of the clinopyroxenes (Fig. 7.1) are characterized by light rare earth element (LREE) enrichment which is typical of clinopyroxenes in mantle xenoliths (Shimizu, 1975; Menzies et al., 1987; Waters, 1987a; Hops, 1989). The elevated Nd and Sm concentrations of clinopyroxene from most GPP xenoliths, relative to GP sample JSL 114, is readily apparent. Overall, the range in Sm and Nd concentrations of clinopyroxene from the Letlhakane peridotites is comparable with data for clinopyroxene from other localities, e.g. Kimberley (Waters, 1987a; Erlank et al. 1987, 1990), Lesotho (Shimizu, 1975) and Jagersfontein (Hops, 1989).

7.3.1.2 Garnet

Garnets are characterized by extremely low Sm, Nd, Sr and Rb concentrations. Rb is barely above blank and will not be discussed further. Subcalcic garnet from harzburgite JSL 113 shows a high Sr content (3.38 ppm, Table 7.2) when compared to garnets from the rest of the xenoliths.

Chondrite-normalized Sm and Nd concentration patterns of garnet are illustrated in Fig 7.2. A subcalcic harzburgite (JSL 113) and GPP xenolith (151) are characterized by LREE-enriched garnet. This contrasts with the more typical LREE-depleted nature of peridotitic garnet (Shimizu, 1975). LREE-enriched garnets are characteristic of subcalcic garnet peridotites and diamond inclusions from Kimberley and Finsch (Richardson et al., 1984; Shimizu and Richardson, 1987). The LREE-enriched nature of the lherzolite garnet in GP/GPP sample JSL 151 is therefore somewhat surprising. Rare earth element (REE) concentrations in Letlhakane garnets are generally similar to REE concentrations in garnets from Kimberley (Erlank et al., 1990), but are slightly lower than those of garnets from the Lesotho peridotites (Shimizu, 1975).

7.3.2 Sr- and Nd-isotope data

The low Rb content of both garnet and clinopyroxene implies that radiogenic isotope decay of Rb did not contribute significantly to Sr-isotopic compositions. All Sr isotope values are therefore essentially initial ratios. Present day $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in clinopyroxene vary from 0.702645 (JSL 280) to 0.711391 (JSL 154) and

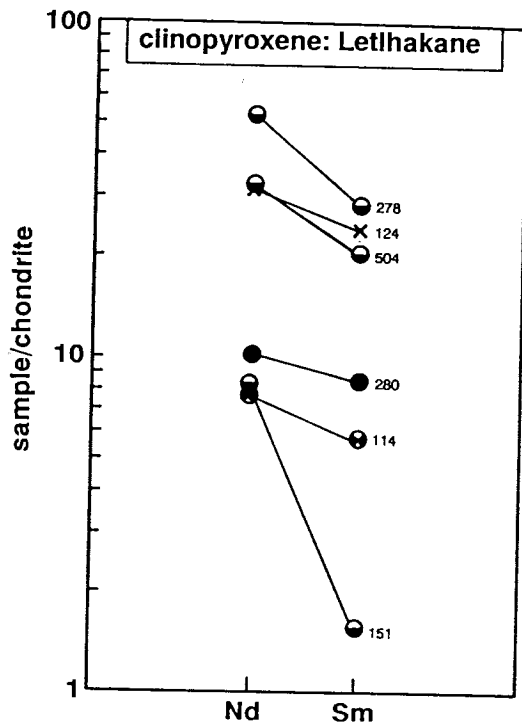


Fig. 7.1 Chondrite-normalized Nd and Sm concentrations in clinopyroxenes from various peridotite types. Note the negative Nd-Sm slope, typical of clinopyroxenes in mantle peridotites.

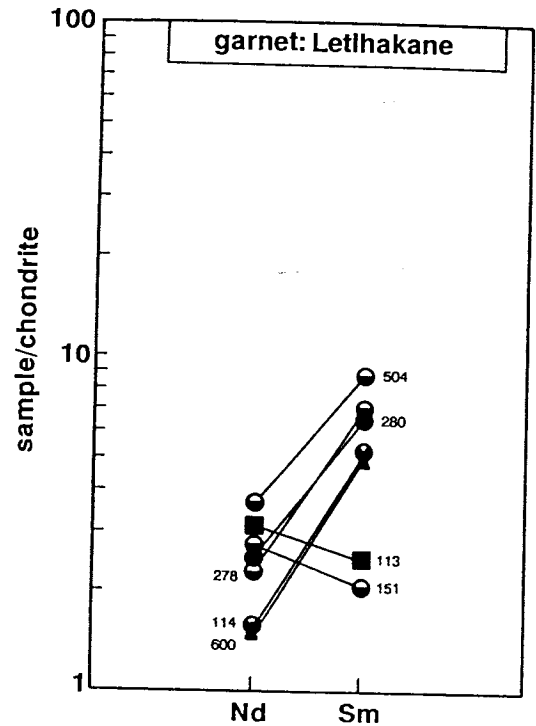


Fig. 7.2 Chondrite-normalized Nd and Sm concentrations in garnets from various peridotites and a pyroxenite (JSL 600). Peridotitic and pyroxenitic garnets typically exhibit a positive Nd-Sm slope, except for subcalcic garnets, where the Nd-Sm slope is negative (JSL 113). Surprisingly, the Iherzolite garnet of JSL 151 also exhibits a negative Nd-Sm slope.

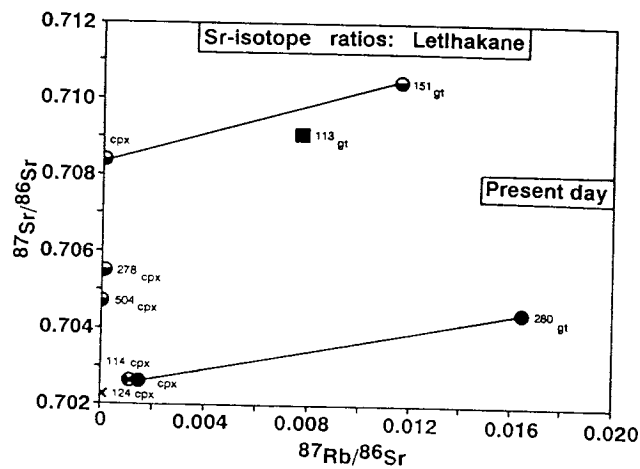


Fig. 7.3 Present day $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $^{87}\text{Rb}/^{86}\text{Sr}$ for clinopyroxene and garnet from the Letlhakane peridotites. Tielines join co-existing phases.

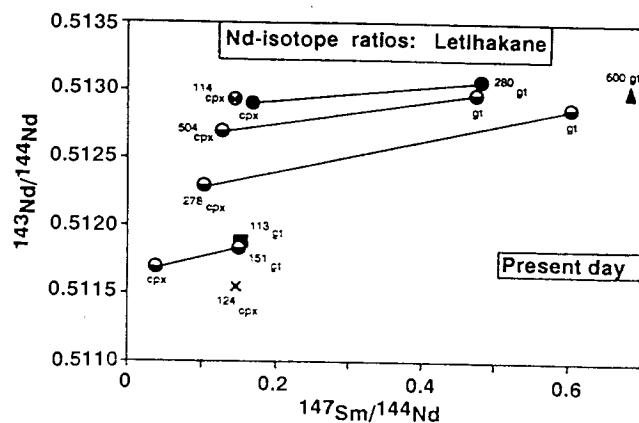


Fig. 7.4 Present day $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{147}\text{Sm}/^{144}\text{Nd}$ for clinopyroxene and garnet from the peridotites and a pyroxenite.

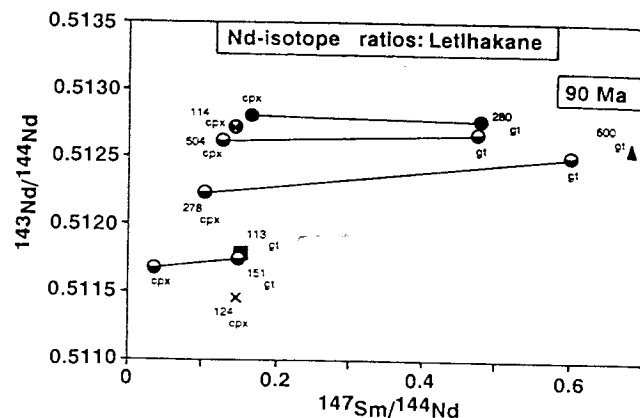


Fig. 7.5 $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{147}\text{Sm}/^{144}\text{Nd}$ at 90 Ma for clinopyroxene and garnet from the Letihakane peridotites and a pyroxenite. Two-point garnet-clinopyroxene ages have been calculated for a GP/GPP xenolith and two GPP xenoliths (JSL 151 = 190 ± 149 Ma; JSL 278 = 179 ± 17 Ma; JSL 504 = 119 ± 25 Ma) and a hot deformed peridotite (JSL 280 = 81 ± 17 Ma).

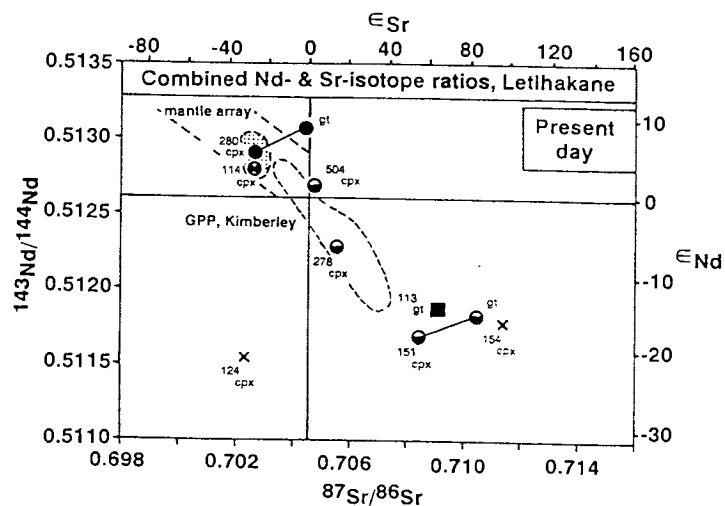


Fig. 7.6 $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ for the Letihakane peridotites. Note the wide range of values and the unusual isotopic composition of JSL 124. Tielines join co-existing phases. The Kimberley data were taken from Waters (1987a). The enclosed, dotted field represents Nd- and Sr-isotopic ratios of clinopyroxenes from Jagersfontein hot, deformed peridotites, taken from Hops (1989).

in garnet from 0.704465 (JSL 280) to 0.710509 (JSL 151). Low $^{87}\text{Sr}/^{86}\text{Sr}$ compositions are evident in clinopyroxene and garnet in a GP (JSL 114), in a hot, deformed peridotite (JSL 280), and in the clinopyroxene of one of the spinel lherzolites (JSL 124) (Fig. 7.3). High $^{87}\text{Sr}/^{86}\text{Sr}$ compositions are seen in clinopyroxene and garnet from the GPP xenoliths.

Relatively high concentrations of both Sm and Nd facilitates interpretation. ϵ_{Nd} values of clinopyroxene vary from -21.2 (JSL 124) to +3.2 (JSL 114), while those for garnet vary from -15.7 (JSL 151) to +8.5 (JSL 280) (Table 7.2). Present day $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of clinopyroxene and garnet are shown in Fig. 7.4. The high $^{143}\text{Nd}/^{144}\text{Nd}$ of clinopyroxene from GP JSL 114 is apparent and is consistent with the low $^{87}\text{Sr}/^{86}\text{Sr}$. Two-point garnet-clinopyroxene ages of two GPP xenoliths, a GP/GPP and a hot, deformed peridotite vary from 81 Ma (JSL 280) to 190 Ma (JSL 151) and are all within error of the 90 Ma emplacement age of the kimberlite (McClenaghan, 1989), except for one of the GPP xenoliths (JSL 278), which provided a garnet-clinopyroxene age of 179 ± 17 Ma, i.e. slightly older than emplacement age (Fig. 7.5). These ages suggest the possibility that the last recorded metasomatic event may have been associated with, or just preceded, kimberlite emplacement. However, any genetic relationship that may have existed between metasomatism and kimberlite emplacement is still poorly understood. A Nd_{CHUR} (garnet) model age of 2744 Ma has been calculated for a subcalcic garnet harzburgite (JSL 113). Maximum and minimum Nd model ages, based on garnet (2602 Ma) and clinopyroxene (903 Ma), have been calculated for a GP/GPP (JSL 151).

Combined Nd- and Sr-isotopic ratios of the garnets and clinopyroxenes are illustrated in Fig. 7.6. Isotopic compositions of clinopyroxene and garnet from the Letlhakane xenoliths in Fig. 7.6 are very similar to those obtained for similar peridotites from Kimberley (Waters, 1987a; Erlank et al., 1987). However, the subcalcic garnet from Letlhakane (JSL 113) has lower $^{87}\text{Sr}/^{86}\text{Sr}$ than the subcalcic garnets from Kimberley and Finsch (Richardson et al., 1984; Shimizu and Richardson, 1987) (not shown). Clinopyroxene and garnet in the hot, deformed peridotite (JSL 280) are isotopically similar to those in hot, deformed xenoliths from Jagersfontein (Hops, 1989) (Fig. 7.6).

7.4 Discussion

7.4.1 Distinction between clinopyroxene from phlogopite-free and phlogopite-bearing peridotites on the basis of isotopic ratios and REE concentrations

Isotopic analyses of clinopyroxene and garnet in three GP samples from Kimberley (Richardson et al., 1985) are plotted together with those of Letlhakane GP (JSL 114) and GP/GPP (JSL 151) xenoliths (Fig. 7.7). JSL 151 has been included in Fig. 7.7 due to its affinities with both GP and GPP suites (Section 7.3.1.1). The garnet-clinopyroxene pairs from the Letlhakane and Kimberley GP xenoliths exhibit considerable variation. Note that two anomalous samples (BD 2435 and JSL 151) are responsible for most of this variation.

In contrast to the evidence in Fig. 7.7, Menzies et al. (1987) found that non-metasomatized peridotites are, with rare exception, restricted to the depleted mantle segment of a ϵ_{Nd} vs. ϵ_{Sr} plot, as shown in Fig. 7.8. It must, however, be stressed that the peridotites discussed by Menzies (op. cit.) originate from a variety of settings, including stable craton, rift valleys and continental alkali basalts. If the anomalous xenoliths (BD 2435 and JSL 151) are excluded from Fig. 7.7, clinopyroxenes from GP xenoliths are mostly restricted to low $^{87}\text{Sr}/^{86}\text{Sr}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ and correspond to isotopic ratios of the non-metasomatized samples illustrated by Menzies et al. (1987). The range of the Nd- and Sr-isotopic ratios of GP xenoliths in Fig. 7.7 is therefore critically dependent on the identity of JSL 151. Interpretations are further complicated by the very small data set of coarse-textured GP xenoliths. Owing to the uncertainty surrounding JSL 151, this sample is tentatively interpreted as being transitional between the GP and GPP suites. The author speculates that further isotopic study of kimberlite-derived GP clinopyroxenes by future workers may reveal a trend similar to that found by Menzies et al. (1987).

Fig. 7.1 in Section 7.3.1.1 illustrated the higher Sm and Nd concentrations of Cr_2O_3 - and Na_2O -rich clinopyroxene from metasomatized samples in comparison to non-metasomatized xenoliths (bearing in mind that JSL 151 contains rare, primary metasomatic phlogopite). When the Letlhakane data are combined with those of Kimberley (Fig. 7.9) however, this distinction disappears and there is a large overlap between Sm and Nd concentrations of the two clinopyroxene suites. However, the Sm and Nd concentrations of clinopyroxene from the metasomatized suite do extend to higher values than those in the non-metasomatized suite, despite the overlap (Fig. 7.9). This overlap of Sm and Nd concentrations between the two suites has also been observed by Menzies et al. (1987) and by Waters (1987a) and Erlank et al. (1990) at

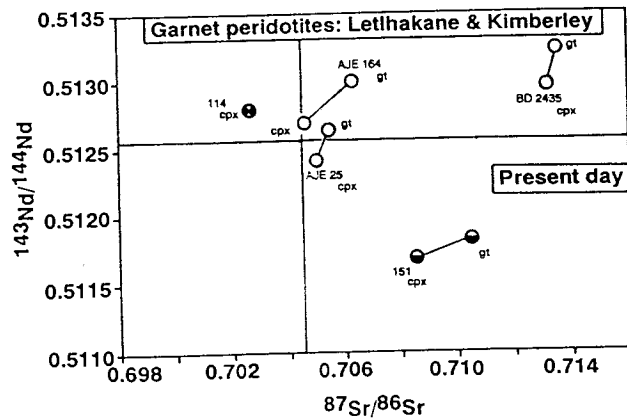


Fig. 7.7 $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ for garnet-clinopyroxene pairs in garnet peridotites from Letlhakane and Kimberley. Note the large range in isotopic ratios of these samples. Data from Richardson et al. (1985) and Waters (1987a).

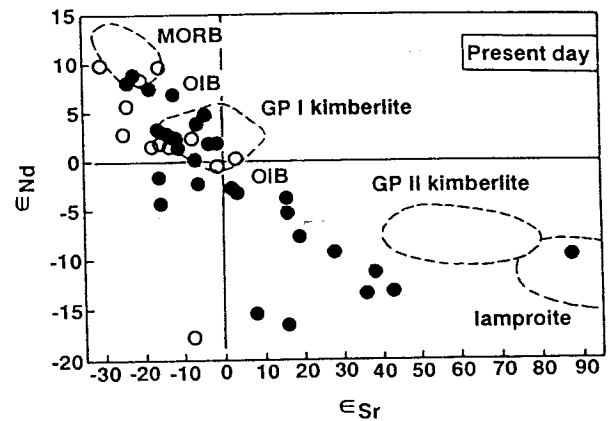


Fig. 7.8 ϵ_{Nd} vs. ϵ_{Sr} of clinopyroxene reproduced from Menzies et al. (1987). Open circles represent non-metasomatized peridotites, while filled circles represent those containing evidence of metasomatism. See text for a list of the various localities from which these peridotites originated. See Menzies et al. (1987) for data sources.

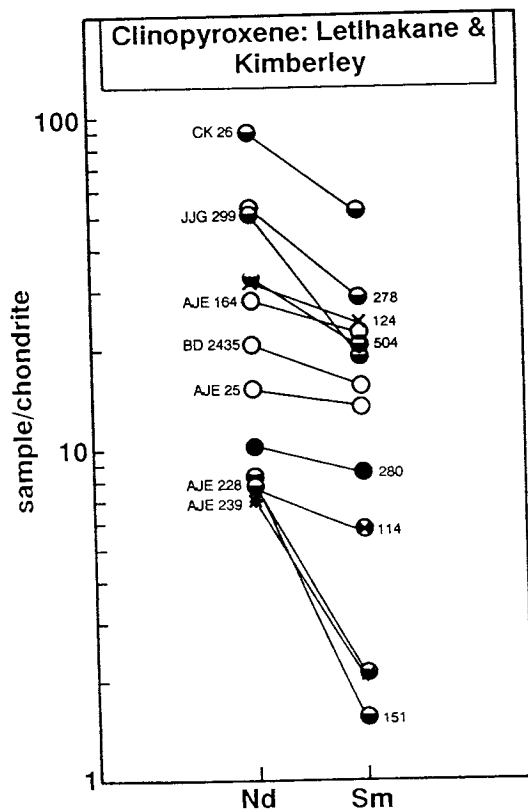


Fig. 7.9 Chondrite-normalized Nd and Sm concentrations of clinopyroxenes in metasomatized and non-metasomatized peridotites from both Letlhakane and Kimberley. A large overlap in Sm and Nd concentrations in clinopyroxenes from the metasomatized and non-metasomatized peridotites is apparent, but note that clinopyroxene from the metasomatized suite can contain more Nd and Sm than clinopyroxenes from the non-metasomatized suite. Kimberley sample numbers are shown on the left and those from Letlhakane on the right. GP sample AJE 164 represents the upper limit of chondrite-normalized Nd and Sm in clinopyroxene from non-metasomatized peridotites. Data from Richardson et al. (1985) and Waters (1987a).

Kimberley. Owing to the variable nature of the melt or fluid fraction, pressure and temperature, such an overlap in the REE concentrations is expected. Thus it appears possible that REE concentrations offer a means of distinguishing between clinopyroxene from metasomatized and non-metasomatized peridotites, but should only be employed in conjunction with other discriminatory features.

In the above discussion, clear distinction must be drawn between metasomatism in the shallow mantle, as represented by amphibole- and apatite-bearing pyroxenites and spinel peridotites from alkali basalts on the one hand, compared to metasomatism in the deeper mantle, represented by the GPP, PP, PKP and the MARID suites on the other. Metasomatic effects in deep and shallow parts of the mantle are unlikely to be similar and distinctions applicable to shallow mantle xenoliths may not always be apparent in deeper, garnet-bearing xenoliths. The large variation in shallow metasomatic effects alone is evident from the notable REE differences in the clinopyroxenes from Type Ia and Ib peridotites and differences between the Cr-diopside and Al-augite series (Kempton, 1987, and references therein). Obvious differences in REE contents of clinopyroxenes from garnet peridotites and spinel peridotites (Menzies et al., 1987) also exist. From the results presented by Menzies et al. (1987), it is apparent that mineralogical changes in clinopyroxenes affected by deep mantle metasomatism are more subtle than the large variations present in clinopyroxenes affected by shallow metasomatism.

7.4.2 Sm and Nd concentrations of melts and vapours in equilibrium with garnet and clinopyroxene

An attempt has been made in Chapter 3, Section 3.4.4 to determine the composition of fluids (vapours) responsible for the breakdown of garnet in the mantle. This has proved to be quite difficult and at best only a rough approximation of total transfer of major element components has been made and not an accurate estimation of the actual fluid composition. In this section, an attempt is made to obtain some idea of the Sm and Nd contents of metasomatizing melt and vapour in equilibrium with clinopyroxene in the GPP xenoliths. Sm and Nd contents of a melt in equilibrium with peridotitic garnets have also been calculated. It must be pointed out here that the calculations in this section are based on the simplistic assumption that total equilibrium existed during metasomatism. The true relationship between mineral and metasomatizing medium is likely to have been far more complex, perhaps in the form of continuous flow in an open system. However, more complex models will merely add to the many uncertainties already caused by a lack of knowledge regarding the variable factors in metasomatic reactions. Calculated values of Sm and Nd merely serve to illustrate the effects of temperature and composition on the REE concentration of the metasomatizing medium and should not be interpreted as being exact.

In order to estimate trace element concentrations in the metasomatizing medium a knowledge of appropriate distribution coefficients (D) is necessary. Distribution coefficients vary with temperature,

Table 7.3: Distribution coefficients used to calculate melt and vapour compositions, assuming equilibrium.

Mineral	Sm	Nd	Source
crystal-melt garnet	0.321	0.053	Harrison (1981) for Sm. 8% partial melting of a garnet lherzolite at 35 kb, 1585°C.
cpx	0.309	0.270	
crystal-vapour garnet	0.500	0.056	Mysen (1979) for Sm at 20 kb, 1100°C and >10% pure H ₂ O.
cpx	0.091	0.057	
cpx	0.025	-	Mysen (1983), equation 5 at 20 kb, 900°C and $X_{CO_2}=0.2$.

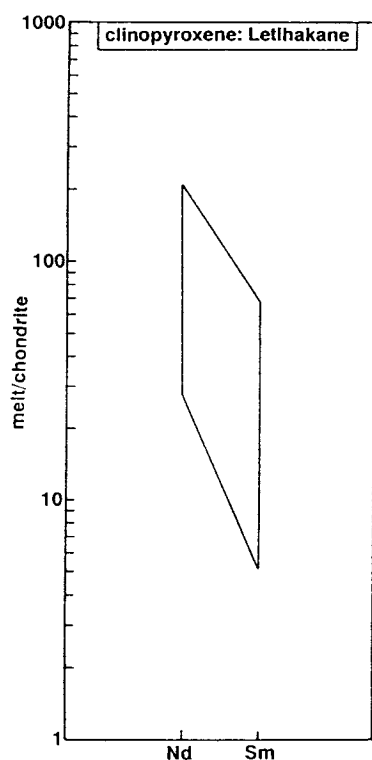


Fig. 7.10 Chondrite-normalized Sm and Nd of a volatile-free melt in equilibrium with clinopyroxene from the GPP suite. The chondrite-normalized Nd and Sm of GPP clinopyroxenes are shown in Fig. 7.1. Crystal-melt D values were obtained from Harrison (1981).

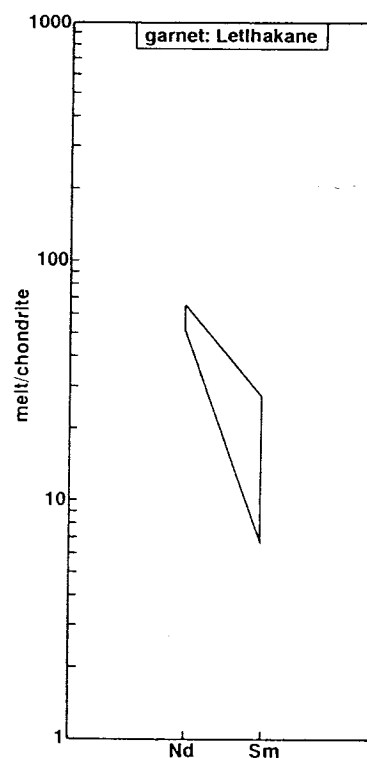


Fig. 7.11 Chondrite-normalized Sm and Nd of a volatile-free melt in equilibrium with garnet from the GPP suite. Chondrite-normalized Nd and Sm of GPP garnets are shown in Fig. 7.2.

pressure and composition (e.g. Harrison, 1981) and for this reason, different sets of D values are used. Harrison (1981) determined crystal-melt D values at 35 kb for 8% melting of a garnet lherzolite nodule with chondritic REE abundances. The D_{Nd} used here, was derived from these data by graphical interpolation. Crystal-melt D values are in reasonable agreement with those from other systems, e.g. Irving (1978), but are only relevant to a volatile-free system. Since most metasomatic activity takes place in the presence of some volatile, e.g. H_2O , CO_2 or CH_4 , the experimental data of Mysen (1979) have been used to obtain some idea of crystal-vapour D values at 20 kb and 1100°C. The crystal-melt D values obtained from Harrison (1981) and the crystal-vapour D values obtained from Mysen (1979) are listed in Table 7.3. Sm and Nd melt concentrations of a volatile-free melt in equilibrium with clinopyroxene and garnet are illustrated in Figs. 7.10 and 7.11. Note that the patterns are very similar to those of Figs. 7.1 and 7.2, but because $D_{Nd} < D_{Sm}$, the tie lines have steeper slopes. The range of chondrite-normalized Sm and Nd in a melt in equilibrium with clinopyroxene is greater than Sm and Nd in a melt in equilibrium with garnet.

Sm and Nd concentrations of a melt in equilibrium with subcalcic garnet (JSL 113) are shown separately in Fig. 7.12 and compared to those of the Kimberley and Finsch subcalcic garnets (Shimizu and Richardson, 1987). Garnet from GP/GPP JSL 151 is included in Fig. 7.12 because of its unusual LREE-enriched composition (Section 7.3.1.2). Note that Sm and Nd concentrations of a melt in equilibrium with the subcalcic garnet are almost identical to those of a melt in equilibrium with JSL 151.

The use of mineral-vapour D values illustrates that H_2O -rich vapours at 20kb and 1100°C, in equilibrium with peridotitic clinopyroxene, are more enriched in Nd and Sm than melts in equilibrium with similar clinopyroxene (compare Figs 7.10 and 7.13). The net effect is a steeper, LREE-enriched trend, i.e. greater LREE enrichment in a vapour, as shown in Fig. 7.13. Average Sm and Nd of a hypothetical H_2O -rich vapour in equilibrium with the Wesselton kimberlite (Kaminskii et al., 1978), an olivine lamproite from West Kimberley (Table 7.18 in Mitchell and Bergman, 1991, and references therein) and a single Bultfontein kimberlite analysis (Erlank et al., 1987) are shown for comparison. Note that if D values for a CO_2 -vapour-bearing system at 20kb are used (Mysen, 1983), then projected Sm and Nd concentrations of the vapour in equilibrium with clinopyroxene at low temperature are greatly increased: e.g. for JSL 504, if $X_{CO_2} = 0.2$ at 20kb and 900°C, and if equation 5 of Mysen (1983) is used (Fig. 7.13). It is also assumed that REE do not fractionate (Mysen, 1979, 1983).

The effects of temperature and vapour and/or melt compositions clearly have a large influence on the Sm and Nd concentrations in a metasomatizing medium. The LREE-enriched nature of the metasomatizing medium in equilibrium with clinopyroxene is evident from Figs. 7.10 and 7.13. Owing to the uncertainty regarding the proportions of CO_2 and H_2O which may have been present in the metasomatizing medium, Sm and Nd concentrations cannot be further constrained.

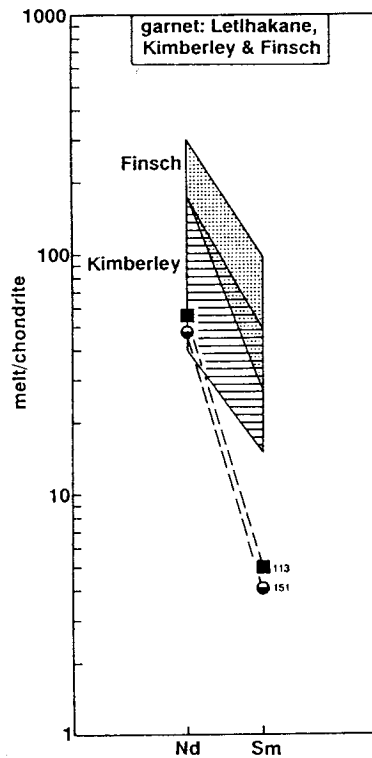


Fig. 7.12 Chondrite-normalized Sm and Nd concentrations of a volatile-free melt in equilibrium with subcalcic garnet from Finsch and Kimberley. The dashed lines represent volatile-free melt compositions in equilibrium with subcalcic garnet (JSL 113) and garnet from a GP/GPP (JSL 151), Letlhakane. Other data from Shimizu and Richardson (1987).

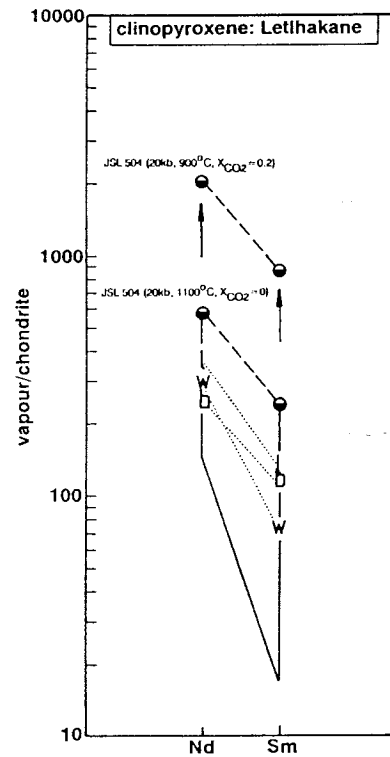


Fig. 7.13 Chondrite-normalized Sm and Nd of a H_2O -rich vapour in equilibrium with clinopyroxene from the GPP suite. Note the enrichment in Nd and Sm compared to a volatile-free melt (Fig. 7.10). Also note the effect of reduced temperature and increased CO_2 -vapour on Nd and Sm content, as shown for vapour in equilibrium with a GPP (JSL 504). Hypothetical H_2O -rich vapour in equilibrium with the Wesselton kimberlite (w), an olivine lamproite (l) and the Bultfontein kimberlite (b) is also shown. Data from Kaminskii et al. (1978), Mitchell and Bergman (1991) and Erlank et al. (1987).

7.4.3 Cryptic trace element variations and metasomatism

It is apparent from this study (Chapters 3 & 7) that the mantle below Letlhakane is similar to that at many other localities (Menzies et al., 1987, and references therein) and underwent an ancient enrichment process.

Previous workers, e.g. Menzies (1990), have suggested that the underlying asthenosphere may be a convenient source for small, metasomatizing melt fractions. Many workers, e.g. Menzies et al. (1987, and references therein), have commented on the inextricable link between modal metasomatism and trace-element enrichment in peridotites and pyroxenites. However, in many instances hydrous metasomatic minerals are absent in peridotites, despite REE enrichment in the clinopyroxenes. It is therefore quite possible that these ancient enrichments, represented for example by high Sr concentrations in clinopyroxene from many of the GP xenoliths (Erlank et al., 1987), were part of/accompanied by metasomatic processes, the modal evidence for which has long since been destroyed by remobilization and recrystallization. The existence of rare, "old" micas from Bultfontein exhibiting low $^{143}\text{Nd}/^{144}\text{Nd}$ ratios (Menzies and Murthy, 1980) may bear testimony to ancient metasomatism. A model involving the mobility and re-equilibration capability of minerals has already been discussed in Chapter 3, Section 3.4.3.

The greater range in $^{143}\text{Nd}/^{144}\text{Nd}$ observed in the Archaean lithospheric mantle, compared to the post-Archaean lithosphere (Menzies and Hawkesworth, 1987a, b), belies the refractory origin indicated by major element chemistry. Anderson (1990) proposed that the initial, unaltered sub-Archaean lithosphere did indeed represent a reduced, refractory residue as a result of partial melting processes, but that the upward movement of numerous small melt fractions from the asthenosphere over millions of years transformed the residue, producing both enriched and depleted components. The range in the Nd-isotopes observed in the Letlhakane peridotites implies that the movement of small partial melts has led to a redistribution of elements in the peridotite and that a time-integrated response to this fractionation produced the present-day variation in $^{143}\text{Nd}/^{144}\text{Nd}$ ratios.

It has become increasingly evident throughout this study that the identification of a metasomatic history in a sample should not only be based on the presence or absence of modal metasomatism, but should also take the trace element and isotope geochemistry of garnet and clinopyroxene into account. The absence of hydrous primary metasomatic minerals is not necessarily synonymous with the total absence of metasomatism.

7.4.4 Isotopically discrete mantle domains and their possible mixing chronologies in the mantle below Botswana

The existence of 4 isotopically discrete, hypothetical mantle domains have been advocated by several workers in the past and a comprehensive review of the development of these theories can be found in Zindler and Hart (1986). It is assumed that these components are of reasonably fixed isotopic composition and that any heterogeneity which may occur in these components is small compared to the data range. Furthermore, these components are mostly located at the outer extreme of the data arrays. The domains reviewed by Zindler and Hart (op. cit.) are defined in terms of the following acronyms:

DMM (depleted MORB mantle)

HIMU (high μ , where $\mu = {}^{238}\text{U}/{}^{204}\text{Pb}$)

EM₁ (enriched mantle 1)

EM₂ (enriched mantle 2)

These domains and their isotopic characteristics are illustrated in Fig. 7.14, along with the Letlhakane data. Zindler and Hart (1986) also defined a 5th component, PREMA (prevalent mantle), but the existence of this component is not always required (Hart, 1988). Although other workers have proposed additional domains (e.g. White, 1985; Zindler et al., 1982), Hart (1988) considered these to be closely related to EM₁ or EM₂, or the result of mixing between these components. Although only Sm/Nd and Rb/Sr isotope systems will be discussed in this section, other radiogenic systems, e.g. U/Pb, also show the isotopic differences between the domains; in some cases even better than Sm/Nd or Rb/Sr, e.g. for HIMU. It must be stressed that the above is merely a summary of terminology relevant to this discussion and by no means a complete representation of this broad and complex field.

It is evident from Fig. 7.14 that the Letlhakane peridotites are located within a triangle defined by the DMM-EM₁-EM₂ domains. Owing to the absence of Pb-isotope data on the Letlhakane peridotite suite, no clear conclusions with regard to the involvement of the HIMU component can be drawn. Some peridotites, e.g. JSL 113 and 151 plot between EM₁ and EM₂, suggesting possible mixing between these two components. The DMM component appears to be more relevant to the Proterozoic and Phanerozoic lithospheric mantle, as illustrated by Menzies (1990) and references therein. Menzies (1990) remarked on the apparent series of Archaean and post-Archaean enrichment events that affected the lithospheric keel beneath South Africa. Enriched domains are evident in mantle xenoliths from the Archaean (diamond inclusions: 3.2-3.3 Ga) (Richardson et al., 1984, 1985), the Proterozoic (GP, GPP ages: 1.0-1.4 Ga) (Erlank et al., 1987, and Waters, 1987a), and the Phanerozoic (PKP, MARID and megacrysts: <0.2 Ga) (Erlank et al., 1987, and Waters, 1987a). Although diamond inclusions from Letlhakane were not included in this study, subcalcic harzburgites, one of which provided an Archaean age, Proterozoic GPP xenoliths and

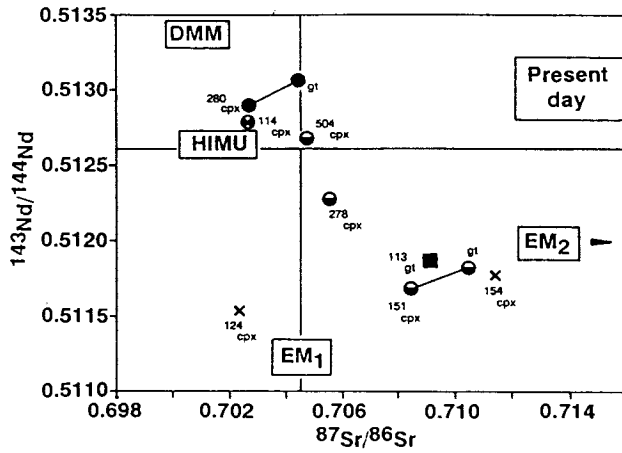


Fig. 7.14 Present day $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ for clinopyroxene and garnet from the Letlhakane peridotite suite, shown in conjunction with the isotopically discrete mantle domains.

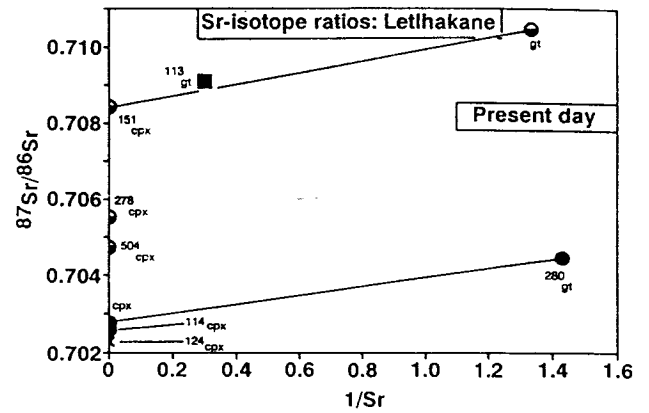


Fig. 7.15 Present day $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $1/\text{Sr}$ for the Letlhakane peridotite suite. Both garnet and clinopyroxene are included to illustrate the large difference in Sr-content between these phases.

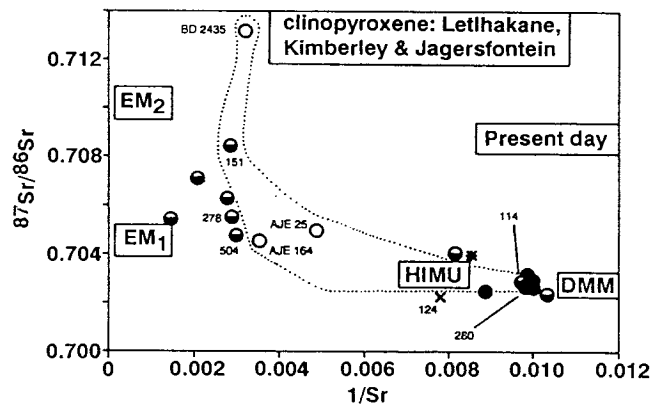


Fig. 7.16 Present day $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $1/\text{Sr}$ for the Letlhakane, Kimberley and Jagersfontein peridotite suites - clinopyroxene only. The dotted field encloses clinopyroxene from GP xenoliths (Kimberley and Letlhakane). Most of the datapoints from the samples plot on an array of lines ranging from EM_1 -DMM to EM_2 -DMM. Most GP and GPP datapoints cluster between EM and HIMU, while hot, deformed peridotites are located between HIMU and DMM. Additional data from Hops (1989), Richardson et al. (1985) and Waters (1987a).

younger MARID xenoliths and megacrysts are all present at Letlhakane. It is apparent that the series of enrichment events, as described for Kimberley, also took place in the mantle below Botswana, with the possible exception of the PKP stage.

The Letlhakane peridotites retain evidence of mixing between EM_1 and EM_2 and DMM, as mentioned above, and this is shown on a plot of $^{86}Sr/^{86}Sr$ vs. $1/Sr$ (Figs. 7.15 and 7.16). Data from Richardson et al. (1985), Waters (1987a) and Hops (1989) is also included. It is evident that most of the data plot on an array of lines extending from DMM towards EM_1 - EM_2 (Fig. 7.16). Note that most of the GPP datapoints cluster close to the EM domains. Only clinopyroxenes from hot, deformed peridotites and depleted, coarse peridotites (the clinopyroxene-rich peridotites of Waters, 1987a) plot close to DMM. This indicates that the GP-GPP-PP-PKP sequence is dominated by increasing amounts of EM_1 - EM_2 components. Sr- and Nd-isotopic compositions of the metasomatized peridotites are therefore influenced by mixing between at least 3 isotopic components.

It has been suggested that a DUPAL-type hotspot, which is characterized by the EM_2 component, interacted with the Southern African lithosphere during the late Proterozoic and that a HIMU-type hotspot was active during the Phanerozoic, accounting for the EM_2 and HIMU components in mantle xenoliths (Erlank et al., 1987; Kramers, 1977; Menzies, 1990). The isotopic similarity of GP and GPP xenoliths from Letlhakane and Kimberley, suggests that the proposed DUPAL-type hotspot must have extended to Botswana at least. U/Pb studies need to be conducted on some Botswana peridotites to confirm the extent of HIMU enrichment.

7.4.5 Spinel lherzolites: crustal or mantle origin?

The unusual nature of the spinel lherzolites from Letlhakane, compared to those from Kimberley, was noted in Chapter 2, Section 2.2.3. Thus two spinel-bearing xenoliths (JSL 124 and JSL 154) were included in the radiogenic isotope study and the results presented in Table 7.2. Unfortunately, the low modal proportion of clinopyroxene in JSL 154 prevented accurate determinations of Sm, Nd, Sr and Rb concentrations in this mineral.

The following are important observations regarding the spinel-bearing xenoliths:

- (1) Olivine and orthopyroxene compositions are depleted ($100 \cdot Mg/(Mg + Fe)_{Ol} = 91-94$ and $100 \cdot Mg/(Mg + Fe)_{Opx} = 92-94$, Chapter 2, Section 2.3), indicating that these rocks are ultramafic xenoliths.

(2) Chondrite-normalized Sm and Nd concentrations in clinopyroxene from JSL 124 are similar to those in clinopyroxenes from the metasomatized samples (Fig. 7.1). Although it is tempting to suggest, on this basis, that JSL 124 may have undergone metasomatism, it should be borne in mind that no primary metasomatic hydrous phases are present in any of the spinel lherzolites (Chapter 2, Section 2.2.3). The difference in clinopyroxene trends between spinel lherzolites (Chapter 2, Fig. 2.10) and the metasomatized peridotites (Chapter 3, Fig. 3.7) suggests that clinopyroxene in the spinel lherzolites may not be related to those in the metasomatized peridotites. The Sm and Nd enrichment in clinopyroxene from JSL 124 may, however, also be explained by crystallization from a LREE-enriched melt.

(3) Fig. 7.6 illustrates the extreme differences in $^{87}\text{Sr}/^{86}\text{Sr}$ in clinopyroxene of JSL 124 and JSL 154. The low $^{87}\text{Rb}/^{86}\text{Sr}$ correlates with the low $^{87}\text{Sr}/^{86}\text{Sr}$ of the clinopyroxene in JSL 124 (Fig. 7.3), but lack of Rb/Sr data for clinopyroxene in JSL 154 does not permit an assessment of the high $^{87}\text{Sr}/^{86}\text{Sr}$ in the clinopyroxene of JSL 154 (Fig. 7.6).

(4) Clinopyroxene in JSL 124 has a Nd_{CHUR} model age of 3327 Ma (Table 7.2). This age is similar to calculated model ages of subcalcic garnets included in diamonds (3200-3300 Ma) from Bultfontein and Finsch (Richardson et al., 1984). Evidence for an ancient differentiation event in the Archaean mantle is therefore preserved in JSL 124.

From the above observations it is evident that JSL 124 underwent a different petrogenesis to that of the GPP, PP and PKP xenoliths from Letlhakane and Kimberley. The latter have been metasomatized by H_2O - and K-rich fluids containing high $^{87}\text{Sr}/^{86}\text{Sr}$ and low $^{143}\text{Nd}/^{144}\text{Nd}$ (Waters, 1987a; Erlank et al., 1987 and this study). The spinel lherzolites from Letlhakane are undoubtedly of shallower origin than the GPP and PP xenoliths, but may still form part of the upper mantle. Unfortunately, the absence of published isotopic analyses on kimberlite-derived (cratonic) spinel peridotites precludes comparison of the Letlhakane xenoliths with those from other localities.

The possibility that one of the spinel lherzolites (JSL 124) may be of crustal origin should also be considered, especially in the light of its isotopic similarity to the Lewisian gneisses (Hamilton et al., 1979), the Lashaine granulites (Cohen et al., 1984) and other $^{87}\text{Sr}/^{86}\text{Sr}$ -depleted granulites (Ben Othman et al., 1984, and references therein).

The present data are inconclusive as to whether these xenoliths are of lower crustal or mantle derivation. It is speculated that the spinel lherzolites were initially attached to the base of the cratonic lithosphere, possibly as a melt. They are clearly unusual, compared to the spinel lherzolites recovered from Kimberley, and it is suggested that further isotopic study be conducted on these rocks.

7.5 Summary

In summary, the following important features regarding the isotope systematics and trace element concentrations of selected Letlhakane peridotites can be listed:

- 1) The Letlhakane peridotites exhibit a wide range in $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$, varying from depleted (JSL 114, 280), to ancient and enriched (JSL 113, 151). All samples plot along the mantle array, or an extension thereof. Sr- and Nd-isotopic ratios extend over a similar range compared to the coarse-textured peridotites from Kimberley (Waters, 1987a) and the hot, deformed peridotites from Jagersfontein (Hops, 1989).
- 2) A single, isotopically depleted, coarse-textured GP (JSL 114) was analysed and its isotope systematics correspond to that of the "diopside-rich peridotites" (Waters, 1987a) at Kimberley, but unlike the Kimberley samples, contains no phlogopite.
- 3) Garnet-clinopyroxene ages, varying from 81-190 Ma, have been calculated for two GPP xenoliths, a GP/GPP, and a hot, deformed peridotite. With the exception of one GPP (179 ± 17 Ma), all other ages are indistinguishable from the pipe emplacement age. It would therefore appear that at least one metasomatic event was associated with kimberlite emplacement. T_{CHUR} (garnet) is calculated as 2744 Ma for a subcalcic harzburgite (JSL 113) and 2602 for a GP/GPP (JSL 151).
- 4) Clinopyroxenes from stable craton, non-metasomatized peridotites exhibit an extreme variation in $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$, partly caused by two anomalous samples. However, a larger data set, consisting of peridotites from stable cratons, rift valleys and continental alkali basalts (Menzies et al., 1987), indicates that clinopyroxenes derived from non-metasomatized peridotites are isotopically depleted, compared to those from metasomatized peridotites.
- 5) An increase in Nd, Sm and Sr is discernable in clinopyroxene from the metasomatized peridotites, when compared to those of the non-metasomatized peridotites, although a large overlap in composition is present. This increase in Nd, Sm and Sr does not extend into the coexisting garnets and the variation in concentration of these elements in garnet appears to be irregular.
- 6) Calculated Sm and Nd concentrations of melts/vapours in equilibrium with garnet and clinopyroxene indicate a steep LREE-enriched profile in the melts/vapours. This is in accordance with the Sm and Nd values of profiles obtained for Kimberley peridotites (Waters, 1987a; Shimizu and Richardson, 1987).

7) Plots of $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $1/\text{Sr}$ indicate that the Letlhakane peridotites may have undergone isotopic mixing from the EM_1 - EM_2 -DMM domains. U/Pb isotopic study is needed to confirm the involvement of the HIMU component. EM_1 - EM_2 appear to be the dominant domains involved in the formation of metasomatized peridotites, with lesser involvement of DMM.

8) An Archaean (3327 Ma) Nd model age relative to CHUR has been calculated for a spinel-bearing xenolith, JSL 124. The origin of this sample (i.e. lower crust or upper mantle) is uncertain, although an upper mantle origin is suspected.

CHAPTER 8

CONCLUSIONS AND SUGGESTIONS FOR FURTHER STUDY

Most of the important conclusions reached in this study have already been presented at the end of each relevant chapter. Some of the major conclusions are reviewed below:

- 1) The absence of peridotite xenoliths at Orapa and their abundance at Letlhakane may be the result of erosion and not a mantle-related feature. The Orapa kimberlite has not been significantly eroded and the crater facies kimberlite is still preserved. The tuff ring of the kimberlite represents an unstable environment and any mantle xenoliths are likely to be eroded along with the kimberlite to form crater facies deposits. Rapid decomposition of olivine and orthopyroxene is likely, owing to the combined effects of an oxidizing environment at the surface and a variable climate. Garnet and clinopyroxene, which form the main constituents of eclogite, are more resistant to weathering, particularly the garnet, hence the abundance of eclogite nodules. Letlhakane contains only small remnants of diatreme facies kimberlite and has therefore been eroded to a deeper level, where there is a greater chance of finding peridotitic xenoliths intact, than at Orapa. Future mining activity towards the hypabyssal facies kimberlite at Orapa may well uncover peridotitic xenoliths.
- 2) From this study, it is concluded that the mantle material derived from Letlhakane, in particular the peridotites, is representative of a deep, cool lithospheric root below a stable craton. The DK 1 and DK 2 kimberlites are considered to be located on the western edge of the Zimbabwe craton. Evidence for this conclusion includes: the similar nature of the 40mWm^{-2} geotherm when compared to that of other on-craton localities; the presence of subcalcic garnets; the presence of diamond and graphite accessory minerals in eclogite; the high quality of the diamonds produced from DK 1 and DK 2; the C-isotope composition of the graphite and the general similarity of mineral compositions to that of minerals in mantle xenoliths from on-craton kimberlites.
- 3) The mantle below Letlhakane suffered multiple metasomatic events. Deep metasomatism is represented by the TiO_2 and Na_2O zonation in the garnets of JSL 112 and JSL 113, and possibly the TiO_2 -rich garnet group (Chapter 2, Section 2.4.1). TiO_2 - and Na_2O -enriched garnets are absent in the GPP xenoliths from shallower levels (except JSL 572, which also underwent extensive secondary metasomatism - Chapter 3, Section 3.2.1) and it is therefore concluded that Ti-metasomatism of this type is restricted to the deep mantle only.

4) Another metasomatic episode is represented by the primary metasomatic mineral suite, consisting of low-TiO₂ and low-Cr₂O₃ phlogopite, high-Cr₂O₃ and high-Na₂O clinopyroxene, ilmenite, rutile, sulphides, Cr-spinel and edenitic hornblende (pyroxenites only). The presence of phlogopite suggests that this event occurred at shallower levels in the mantle. The presence of edenitic hornblende in a few of the metasomatized pyroxenites indicates that this phase of metasomatism must have extended into the shallow mantle where amphibole is stable. The metasomatizing agent responsible for garnet destruction in the peridotites appears to have been an oxidizing, H₂O-rich, peralkaline medium. The lack of carbonate minerals suggests that the role of CO₂ in the metasomatizing medium may not have been significant. The composition of the metasomatizing medium appears to have been quite variable, particularly with respect to CaO and TiO₂. This is evident from the absence of clinopyroxene in an extensively metasomatized harzburgite (JSL 511) and the abundance of ilmenite in JSL 511 and an ilmenite-bearing, veined harzburgite (JSL 500) (Chapter 3, Section 3.2.3). The sequence garnet peridotite, garnet phlogopite peridotite and phlogopite peridotite represents an increase in the intensity of metasomatism, similar to that of peridotites at Kimberley. This is particularly evident in the degree of garnet destruction. It was not possible to determine whether several primary metasomatic events, each overprinting the previous one, occurred, or whether all the observed petrographic features were the result of a single metasomatic event of highly variable nature.

5) It has become evident that greater emphasis should be placed on the use of trace element and isotope geochemistry of garnet and clinopyroxene in the identification of primary metasomatic processes. The absence of modal metasomatism in a sample is no sure guarantee that enrichment has not taken place in the past.

6) A relationship was found between depth and intensity of primary metasomatism, comparable to the results of studies conducted on samples from Kimberley by other workers. Sm, Nd and Sr concentrations in clinopyroxenes from selected peridotites increase with a decrease in temperatures and pressures of equilibration. The effectiveness of this correlation will be dependent on the thermobarometer combination employed.

7) The secondary metasomatic mineral suite, especially high-TiO₂ phlogopite, calcite, serpentine, clinopyroxene, Al-spinel and pargasitic hornblende, resulted from the late-stage effects of kimberlite emplacement. A clear compositional distinction was found between primary and secondary metasomatic mineral phases. Emphasis was placed on the chemical distinction between primary and secondary metasomatic phlogopite, spinel and amphibole, since petrographic features may in some instances be ambiguous, particularly in the case of phlogopite. Secondary clinopyroxene was not discussed in any great detail, owing to the obvious petrographic differences between secondary and primary clinopyroxene.

8) Primary metasomatic phlogopite and amphibole compositions in the peridotite-pyroxenite suite are similar to those in the eclogite suite. It is therefore possible that all the rocks were affected by the same metasomatic event.

9) A composite garnet orthopyroxenite-garnet clinopyroxenite xenolith (JSL 600) was found at DK 1 (Chapter 4, Section 4.2.8). Textural evidence and the mineral composition of phases in the garnet clinopyroxenite segment suggest that part of this xenolith is identical to the Group II eclogites at Letlhakane. The author suggests the possibility that Group II eclogites may in fact be pyroxenites and not "true" eclogites.

10) Clinopyroxene in the Letlhakane peridotites exhibits a wide range of $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$. All these peridotites, with the exception of JSL 124, plot along the mantle array, or an extension thereof and values are very similar to those reported from Kimberley and Jagersfontein. Two-point garnet-clinopyroxene ages vary from 81-190 Ma and are within emplacement age of the kimberlite. Although these ages suggest that the timing of the last metasomatic event and kimberlite emplacement may have been similar, the genetic relationship between the two processes is complex and still uncertain. The possibility of earlier metasomatic events should not be overlooked, even though the evidence for this may have been destroyed. The only subcalcic harzburgite analysed, JSL 113, provided a Nd model age of 2744 Ma relative to CHUR. Results of the Sr- and Nd-isotopic study suggest that complex mixing of the EM₁-EM₂-DMM mantle components occurred below Botswana.

11) Clinopyroxene from kimberlite-derived (stable craton), non-metasomatized peridotites (GP xenoliths) exhibits a large variation in $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$. This variation can be attributed to two anomalous samples. Clinopyroxene in non-metasomatized peridotites from a variety of tectonic settings appears to exhibit an isotopically depleted composition (Menzies et al., 1987).

Suggestions for future study:

1) A further search for PKP xenoliths and corundum- and kyanite-bearing eclogites should be conducted. The possibility still exists that these rocks are present at Letlhakane, but have been overlooked.

2) The author is of the opinion that a search for further clinopyroxene-bearing subcalcic harzburgites and further study into the high- and low-Cr₂O₃ clinopyroxene association with diamond is vital to an understanding of the effects of metasomatism on diamonds. It has been shown in this study and by other studies on xenoliths from Kimberley, that evidence of metasomatism is ubiquitous in the mantle. It is therefore of considerable importance also to study the effects of metasomatism on subcalcic harzburgites and diamond-bearing peridotites.

REFERENCES

- Adams, G.E., Bishop, F.C. (1986). The olivine-clinopyroxene geobarometer: experimental results in the CaO-FeO-MgO-SiO₂ system. Contr. Miner. Petrol., 94, 230-237.
- Akella, J. (1976). Garnet-pyroxene equilibria in the system CaSiO₃-MgSiO₃-Al₂O₃ and in a natural mixture. Am. Mineral., 61, 589-598.
- Allsopp, H.L., Barrett, D.R. (1975). Rb-Sr age determinations on South African kimberlite pipes, 605-617. In Ahrens, L.H., Press, F., Runcorn, S.K., Urey, H.C., (eds.), Physics and Chemistry of the Earth, vol. 9. Pergamon Press, 940pp.
- Anderson, D.L. (1990). Geophysics of the continental mantle: an historical perspective. In Menzies, M.A., (ed.), Continental Mantle. Clarendon Press, Oxford, 184pp.
- Aoki, K. (1974). Phlogopite and potassic richterites from mica nodules in South African kimberlites. Contr. Miner. Petrol., 48, 1-8.
- Aoki, K, Fujimaki, H., Kitamura, M. (1980). Exsolved garnet-bearing pyroxene megacrysts from some South African kimberlites. Lithos, 13, 269-279.
- Apter, D.B., Harper, F.J., Wyatt, B.A., Smith, B.H.S. (1984). The geology of the Mayeng kimberlite sill complex, South Africa, 43-57. In Kornprobst, J., (ed.), Kimberlites:II, The Mantle and Crust-Mantle Relationships. Devs. Petrology, vol. IIB, 393pp. Elsevier, Amsterdam.
- Arai, S. (1986). K/Na variation in phlogopite and amphibole of upper mantle peridotites due to fractionation of the metasomatizing fluids. J. Geol., 94, 436-444.
- Bailey, D.K. (1987). Mantle metasomatism - perspective and prospect, 1-13. In Fitton, J.G. & Upton, B.G.J., (eds.), Alkaline Igneous Rocks, Geol. Soc. Spec. Publ. No. 30.
- Baldock, J.W., Hepworth, J.V., Marengwa, B.S. (1976). Gold, Base Metals, and Diamonds in Botswana. Econ. Geol., 71, 139-156.
- Barrett, D.R., Berg, G.W. (1973). Complementary petrographic and strontium-isotope ratio-studies of South African kimberlites, 27-30. In Ahrens, L.H., Duncan, A.R., Erlank, A.J., (eds.), International conference on kimberlites, (extended abstracts). Cape Town, South Africa, 322pp.

- Barton, J.M. (1983). Our understanding of the Limpopo Belt - a summary with proposals for future research, 191-203. In van Biljon, W.J., Legg, J.H., (eds.), The Limpopo Belt: A contribution to the national geodynamics programme, Spec. Publ. Geol. Soc. S. Afr., 8, 203pp.
- Barton, J.M., Key, R.M. (1981). The tectonic development of the Limpopo Mobile Belt and the evolution of the Archaean cratons of southern Africa, 185-212. In Kroner, A., (ed.), Precambrian Plate Tectonics, Elsevier, Amsterdam, 781pp.
- Barton, J.M., Key, R.M. (1983). Rb/Sr ages and geological settings of certain rock units from the Central Zone of the Limpopo Mobile Belt, eastern Botswana, 19-25. In van Biljon, W.J., Legg, J.H., (eds.), The Limpopo Belt: A contribution to the national geodynamics programme, Spec. Publ. Geol. Soc. S. Afr., 8, 203pp.
- Bates, R.L., Jackson, J.A. (1984). Dictionary of geological terms. Third edition. Anchor Press, New York, 571pp.
- Bayly, B., Reid, A., Gurney, J.J. (1979). Zircon-bearing rocks from the Kimberley mines, 19-23. In Geocongress 79: 18th Congress Geol. Soc. S. Afr., (abstract).
- Ben Othman, D., Polve, M., Allegre, C.J. (1984). Nd-Sr isotopic composition of granulites and constraints on the evolution of the lower continental crust. Nature, 307, 510-515.
- Berg, G.W., Allsopp, H.L. (1972). Low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in fresh South African kimberlites. Earth Planet. Sci. Lett., 16, 27-30.
- Bishop, F.C., Smith, J.V., Dawson, J.B. (1978). Na, K, P and Ti in garnet, pyroxene and olivine from peridotite and eclogite xenoliths from African kimberlites. Lithos, 11, 155-173.
- Bobrievich, A.P., Bondarenko, M.N., Gnevushev, M.A., Kind, N.V., Koreshkov, B. Yu., Kuryleva, N.A., Nefedoca, Z.D., Popugeva, L.A., Popova, E.Z., Skuiskii, V.D., Smirnov, G.I., Yurkevtsi, R.K., Fayunshteyeyuh, G.H., Shukin, V.I. (1959). Almazny Sibirii (Diamonds of Siberia). Gozgeol tekhnizdat, Moscow.
- Boctor, N.Z., Boyd, F.R., Nixon, P.H. (1983). Pyroxenite, eclogites and megacrysts in kimberlite from the De Bruyn and Martin mine, Bellsbank, South Africa, 346-349. In Annual Report of the Director of the Geophysical Laboratory, Carnegie Instn. Washington, 1982-1983. Geophysical Laboratory, Washington D.C.

- Boettcher, A.L., O'Neil, J.R., Windom, K.E., Stewart, D.C., Wilshire, H.G. (1979). Metasomatism of the upper mantle and the genesis of kimberlites and alkali basalts, 173-182. In Boyd, F.R., Meyer, H.O.A., (eds.), The mantle sample: inclusions in kimberlites and other volcanics. (Proc. Int. Kimberlite Conf., No. 2., Vol. 2), 424pp. American Geophysical Union, Washington, D.C.
- Bottinga, Y. (1969). Calculated fractionation factors for carbon and hydrogen isotope exchange in the system calcite - carbon dioxide - graphite methane - hydrogen - water vapour. Geochim. cosmochim. Acta., 33, 49-64.
- Boyd, F.R. (1973). A pyroxene geotherm. Geochim. cosmochim. Acta., 37, 2533-2546.
- Boyd, F.R. (1974). Ultramafic nodules from the Frank Smith kimberlite pipe, South Africa, 285-294. In Annual Report of the Director of the Geophysical Laboratory, Carnegie Instn. Washington, 1973-1974. Geophysical Laboratory, Washington D.C.
- Boyd, F.R. (1976). Inflected and noninflected geotherms, 521-523. In Annual Report of the Director of the Geophysical Laboratory, Carnegie Instn. Washington, 1974-1975. Geophysical Laboratory, Washington D.C.
- Boyd, F.R. (1989). Kaapvaal Spinel Peridotites: Evidence of Craton Origin, 3-6. In Annual Report of the Director of the Geophysical Laboratory, Carnegie Instn. Washington, 1988-1989. Geophysical Laboratory, Washington D.C.
- Boyd, F.R., Dawson, J.B. (1972). Kimberlite garnets and pyroxene-ilmenite intergrowths, 373-378. In Annual Report of the Director of the Geophysical Laboratory, Carnegie Instn. Washington, 1971-1972. Geophysical Laboratory, Washington D.C.
- Boyd, F.R., Gurney, J.J. (1982). Low-calcium garnets: keys to craton structure and diamond crystallization, 261-267. In Annual Report of the Director of the Geophysical Laboratory, Carnegie Instn. Washington, 1981-1982. Geophysical Laboratory, Washington D.C.
- Boyd, F.R., Nixon, P.H. (1972). Ultramafic nodules from the Thaba Putsoa kimberlite pipe, 362-373. In Annual Report of the Director of the Geophysical Laboratory, Carnegie Instn. Washington, 1971-1972. Geophysical Laboratory, Washington D.C.

- Boyd, F.R., Nixon, P.H. (1975). Origins of the ultramafic nodules from some kimberlites of northern Lesotho and the Monastery Mine, South Africa, 431-454. In Ahrens, L.H., Press, F., Runcorn, S.K., Urey, H.C., (eds.), Physics and Chemistry of the Earth, vol. 9. Pergamon Press, 940pp.
- Boyd, F.R., Nixon, P.H. (1988). Low-Ca garnet harzburgites: Origin and Role in Craton Structure, 9-13. In Annual Report of the Director of the Geophysical Laboratory, Carnegie Instn. Washington, 1987-1988. Geophysical Laboratory, Washington D.C.
- Boyd, F.R., Dawson, J.B., Smith, J.V. (1984). Granny Smith diopside megacrysts from the kimberlites of the Kimberley area and Jagersfontein, South Africa. Geochim. cosmochim. Acta., 48, 381-384.
- Boyd, F.R., Pearson, D.G., Nixon, P.H., Mertzman, S.A. (1993). Low-calcium garnet harzburgites from Southern Africa: their relations to craton structure and diamond crystallization. Contr. Miner. Petrol., 113, 352-366.
- Brey, G.P., Huth, J. (1984). The enstatite-diopside solvus at 60 kbar, 257-264. In Kornprobst, J., (ed.), Kimberlites:II, The Mantle and Crust-Mantle Relationships. Devs. Petrology, vol. IIB, 393pp. Elsevier, Amsterdam.
- Brey, G.P., Köhler, T. (1990). Geothermobarometry in four-phase lherzolites II. New thermobarometers, and practical assessment of existing thermobarometers. J. Petrol., 31, 1353-1378.
- Brey, G.P., Köhler, T., Nickel, K.G. (1990). Geothermobarometry in four-phase lherzolites I. Experimental results from 10 to 60 kb. J. Petrol., 31, 1313-1352.
- Burns, R.G. (1970). Mineralogical Application of Crystal Field Theory. Cambridge University Press, 224pp.
- Canil, D. (1992). Orthopyroxene stability along the peridotite solidus and the origin of cratonic lithosphere beneath southern Africa. Earth Planet. Sci. Lett., 111, 83-95.
- Carmichael, I.S.E. (1967). The mineralogy and petrology of the volcanic rocks of the Leucite Hills, Wyoming. Contr. Miner. Petrol., 15, 24-66.
- Carney, J.N., Dowsett, J.S. (1991). Lithological information from a borehole cored through cover and basement rocks near Gweta and its bearing on the distribution of major crustal boundaries in Botswana. The Botswana Journal of Earth Sciences, 1, 1-13.

- Carswell, D.A. (1973). Primary and secondary phlogopites and clinopyroxenes in garnet lherzolite xenoliths, 59-62. In Ahrens, L.H., Duncan, A.R., Erlank, A.J., (eds.), International conference on kimberlites, (extended abstracts). Cape Town, South Africa, 322pp.
- Carswell, D.A. (1975). Primary and secondary phlogopites and clinopyroxenes in garnet lherzolite xenoliths, 417-429. In Ahrens, L.H., Press, F., Runcorn, S.K., Urey, H.C., (eds.), Physics and Chemistry of the Earth, vol. 9. Pergamon Press, 940pp.
- Carswell, D.A., Gibb, F.G.F. (1980). Geothermometry of garnet lherzolite nodules with special reference to those from the kimberlites of Northern Lesotho. Contr. Miner. Petrol., 74, 403-416.
- Carswell, D.A., Gibb, F.G.F. (1987). Garnet lherzolite xenoliths in the kimberlites of northern Lesotho: revised P-T equilibration conditions and upper mantle palaeogeotherm. Contr. Miner. Petrol., 97, 473-487.
- Carswell, D.A., Clarke, D.B., Mitchell, R.H. (1979). The petrology and geochemistry of ultramafic nodules from Pipe 200, northern Lesotho, 127-144. In Boyd, F.R., Meyer, H.O.A., (eds.), The mantle sample: inclusions in kimberlites and other volcanics. (Proc. Int. Kimberlite Conf., No. 2., Vol. 2), 424pp. American Geophysical Union, Washington, D.C.
- Carswell, D.A., Griffin, W.L., Kresten, P. (1984). Peridotite nodules from the Ngopetsoeu and Lipelaneng kimberlites, Lesotho: a crustal or mantle origin?, 229-243. In Kornprobst, J., (ed.), Kimberlites:II, The Mantle and Crust-Mantle Relationships. Devs. Petrology, vol. IIB, 393pp. Elsevier, Amsterdam.
- Clarke, D.B., Pe-Piper, G.G. (1983). Multiply exsolved clinopyroxene megacrysts from the Frank Smith Mine, Cape Province, South Africa. Lithos, 16, 75-84.
- Cohen, R.S., O'Nions, R.K., Dawson, J.B. (1984). Isotope geochemistry of xenoliths from East Africa: implications for development of mantle reservoirs and their interaction. Earth Planet. Sci. Lett., 68, 209-220.
- Coleman, R.G., Lee, E.D., Beatty, L.B., Brannock, W.W. (1965). Eclogites and eclogites: their difference and similarities. Geol. Soc. Am. Bull., 76, 483-508.

- Coward, M.P. (1983). Some thoughts on the Tectonics of the Limpopo Belt. In van Biljon, W.J., Legg, H., (eds.), The Limpopo Belt: A contribution to the national geodynamics programme. Spec. Publ. Geol. Soc. S. Afr., 8, 203pp.
- Cox, K.G., Gurney, J.J., Harte, B. (1973). Xenoliths from the Matsoku pipe, 76-100. In Nixon, P.H., (ed.), Lesotho kimberlites. Lesotho National Development Corporation, Maseru, 356pp.
- Danchin, R.F. (1979). Mineral and bulk chemistry of garnet lherzolite and garnet harzburgite from the Premier mine, South Africa, 104-126. In Boyd, F.R., Meyer, H.O.A., (eds.), The mantle sample: inclusions in kimberlites and other volcanics. (Proc. Int. Kimberlite Conf., No. 2., Vol. 2), 424pp. American Geophysical Union, Washington, D.C.
- Danchin, R.F., Boyd, F.R. (1976). Ultramafic nodules from the Premier kimberlite pipe, South Africa, 531-538. In Annual Report of the Director of the Geophysical Laboratory, Carnegie Instn. Washington, 1975-1976. Geophysical Laboratory, Washington D.C.
- Dawson, J.B. (1972). Kimberlites and their relationship to the upper mantle. Phil. Trans. Roy. Soc. Lond., A271, 297-311.
- Dawson, J.B. (1980). Kimberlites and their Xenoliths. Springer - Verlag Berlin - Heidelberg, 252pp.
- Dawson, J.B. (1982). Contrasting types of mantle metasomatism. Terra Cognita, 2, 232-233.
- Dawson, J.B. (1987). The MARID suite of xenoliths in kimberlite: relationship to veined and metasomatised peridotite xenoliths, 465-473. In Nixon, P.H., (ed.), Mantle Xenoliths. John Wiley & Sons Ltd., New York, 844pp.
- Dawson, J.B., Smith, J.V. (1977). The MARID (mica-amphibole-rutile-ilmenite-diopside) suite of xenoliths in kimberlite. Geochim. cosmochim. Acta., 41, 309-323.
- Dawson, J.B., Stephens, W.E. (1975). Statistical classification of garnets from kimberlite and associated xenoliths. J. Geol., 83, 589-607.
- Deines, P., Gurney, J.J., Harris, J.W. (1984). Associated chemical and carbon isotopic composition variations in diamonds from Finsch and Premier kimberlite, South Africa. Geochim. cosmochim. Acta., 48, 325-342.

- Deines, P., Harris, J.W., Gurney, J.J. (1987). Carbon isotopic composition, nitrogen content and inclusion composition of diamonds from the Roberts Victor kimberlite, South Africa: evidence for ^{13}C depletion in the mantle. Geochim. cosmochim. Acta., 51, 1227-1243.
- Deines, P., Harris, J.W., Robinson, D.N., Gurney, J.J., Shee, S.R. (1991). Carbon and oxygen isotope variations in diamond and graphite eclogites from Orapa, Botswana, and the nitrogen content of their diamonds. Geochim. cosmochim. Acta., 55, 515-524.
- Delaney, J.S., Smith, J.V., Carswell, D.A., Dawson, J.B. (1980). Chemistry of micas from kimberlites and xenoliths. II, Primary- and secondary-textured micas from peridotite xenoliths. Geochim. Cosmochim. Acta., 44, 857-872.
- Eales, H.V., Marsh, J.S., Cox, K.G. (1984). The Karoo Igneous Province: An Introduction. In Erlank, A. J., (ed.), Petrogenesis of the volcanic rocks of the Karoo Province. Spec. Publ. Geol. Soc. S. Afr., 13, 305pp.
- Eggler, D.H. (1987). Experimental evaluation of fluid transport, 21-41. In Menzies, M.A. and Hawkesworth, C.J., (eds.), Mantle Metasomatism. Academic Press, London, 472pp.
- Eggler, D.H., McCallum, M.E. (1974). Preliminary upper mantle-lower crust model for the Colorado-Wyoming Front Range, 295-300. In Annual Report of the Director of the Geophysical Laboratory, Carnegie Instn. Washington, 1974-1975. Geophysical Laboratory, Washington D.C.
- Eggler, D.H., McCallum, M.E. (1976). A geotherm from megacrysts in the Sloan kimberlite pipes, Colorado, 538-541. In Annual Report of the Director of the Geophysical Laboratory, Carnegie Instn. Washington, 1975-1976. Geophysical Laboratory, Washington D.C.
- Eggler, D.H., McCallum, M.E., Smith, C.B. (1979). Megacryst assemblages in kimberlites from northern Colorado and southern Wyoming, 213-226. In Boyd, F.R., Meyer, H.O.A., (eds.), The mantle sample: inclusions in kimberlites and other volcanics. (Proc. Int. Kimberlite Conf., No. 2., Vol. 2), 424pp. American Geophysical Union, Washington, D.C.
- Ehrenberg, S.N. (1982). Petrogenesis of garnet lherzolite and megacrystalline nodules from the Thumb, Navajo Volcanic Field. J. Petrol., 23, 507-547.

- Ellis, D.J., Green, D.H. (1979). An experimental study of Ca upon garnet-clinopyroxene Fe-Mg exchange equilibria. Contr. Miner. Petrol., 71, 13-22.
- Erlank, A.J. (1970). Distribution of potassium in mafic and ultramafic nodules, 433-439. In Annual Report of the Director of the Geophysical Laboratory, Carnegie Instn. Washington, 1968-1969. Geophysical Laboratory, Washington D.C.
- Erlank, A.J. (1973). Kimberlite potassic richterite and the distribution of potassium in the upper mantle, 103-106. In Ahrens, L.H., Duncan, A.R., Erlank, A.J., (eds.), International conference on kimberlites, (extended abstracts). Cape Town, South Africa, 322pp.
- Erlank, A.J., Finger, L.W. (1970). The occurrence of potassic richterite in a mica nodule from the Wesselton kimberlite, South Africa, 320-324. In Annual Report of the Director of the Geophysical Laboratory, Carnegie Instn. Washington, 1968-1969. Geophysical Laboratory, Washington D.C.
- Erlank, A.J., Rickard, R.S. (1977). Potassic richterite-bearing peridotites from kimberlite and the evidence they provide for upper mantle metasomatism. In Second Int. Kimberlite Conf., Santa Fe, New Mexico, (extended abstracts, unpagged).
- Erlank, A.J., Allsopp, H.L., Hawkesworth, C.J., Menzies, M. (1982). Chemical and isotopic characterisation of upper mantle metasomatism in peridotite nodules from the Bultfontein kimberlite. Terra Cognita, 2, 261-263.
- Erlank, A.J., Shimizu, N., Haggerty, S.E., Richardson, S.H., Waters, F.G. (1990). Trace element distributions in minerals from metasomatised peridotite and other kimberlitic xenoliths, 758-761. In 23rd Earth Science Congress of the Geol. Soc. S.A., Cape Town, (extended abstracts).
- Erlank, A.J., Waters, F.G., Hawkesworth, C.J., Haggerty, S.E., Allsopp, H.L., Rickard, R.S., Menzies, M. (1987). Evidence for Mantle Metasomatism in Peridotite Nodules from the Kimberley Pipes, South Africa, 221-311. In Menzies, M.A. and Hawkesworth, C.J., (eds.), Mantle Metasomatism. Academic Press, London, 472pp.
- Field, S.W., Haggerty, S.E., Erlank, A.J. (1989). Subcontinental metasomatism in the region of Jagersfontein, South Africa, 771-783. In Ross, J., (ed.), Fourth International Kimberlite Conference, Kimberlites and Related Rocks, Vol. 2, Geol. Soc. Aust. Spec. Publ., 14.

- Finnerty, A.A. (1989). Xenolith-derived mantle geotherms: whither the inflection? Contr. Miner. Petrol., 102, 367-375.
- Finnerty, A.A., Boyd, F.R. (1978). Pressure-dependant solubility of calcium in forsterite coexisting with diopside and enstatite, 713-717. In Annual Report of the Director of the Geophysical Laboratory, Carnegie Instn. Washington, 1978-1979. Geophysical Laboratory, Washington D.C.
- Finnerty, A.A., Boyd, F.R. (1984). Evaluation of thermobarometers for garnet peridotites. Geochim. cosmochim. Acta., 48, 15-27.
- Finnerty, A.A., Boyd, F.R. (1987). Thermobarometry for garnet peridotite xenoliths: basis for the determination of thermal and compositional structure of the upper mantle, 381-402. In Nixon, P.H., (ed.), Mantle Xenoliths. John Wiley & Sons Ltd., New York, 844pp.
- Freer, R., Carpenter, M.A., Long, J.V.P., Reed, S.J.B. (1982). "Null result" diffusion experiments with diopside: implications for pyroxene equilibria. Earth Planet. Sci. Lett., 58, 185-292.
- Frick, C. (1973). Intergrowths of orthopyroxene and ilmenite from Frank Smith Mine, near Barkly West, South Africa. Trans. Geol. Soc. S. Afr., 76, 195-200.
- Ganguly, J., Bhattacharya, P.K. (1987). Xenoliths in Proterozoic kimberlites from southern India: Petrology and geophysical implications, 249-265. In Nixon, P.H., (ed.), Mantle Xenoliths. John Wiley & Sons Ltd., New York, 844pp.
- Gasparik, T. (1989). Transformation of enstatite - diopside - jadeite pyroxenes to garnet. Contr. Miner. Petrol., 102, 389-405.
- Gibson, J.G. (1983). Field guide to the Orapa and Letlhakane diamond mine. De Beers Consolidated Mines Geology Internal Report No.1657, (unpubl.).
- Gilbert, M.C., Briggs, D.F. (1974). Comparison of the stabilities of OH- and F-potassic richterites - a preliminary report. EOS, 55, 480-481.
- Gilbert, M.C., Helt, R.T., Popp, R.K., Spear, F.S. (1982). Experimental studies of amphibole stability, 229-353. In Veblen, D.R., Ribbe, P.H., (eds.), Amphiboles: Petrology and experimental phase relations. Mineral. Soc. America Rev. Mineral., 9B.

- Gould, D., Rathbone, P.A., Kimbell, G.S. (1987). The geology of the Molopo Farms Complex, Southern Botswana. Botswana Geol. Survey Bull., 23(1).
- Green, H.W. II, Gueguen, Y. (1974). Origin of kimberlite pipes by diapiric upwelling in the upper mantle. Nature, 249, 617-620.
- Gurney, J.J. (1984). A correlation between garnets and diamonds in kimberlites, 143-166. In Glover, J.E., Harris, P.G., (eds.), Kimberlite occurrence and origin: A basis for conceptual models in exploration. Publs. Geol. Dep. & Univ. Extension, Univ. West. Aust., 8.
- Gurney, J.J. (1990). The diamondiferous roots of our wandering continent. S. Afr. J. Geol., 93, 424-437.
- Gurney, J.J., Boyd, F.R. (1982). Mineral intergrowths with polycrystalline diamonds from the Orapa mine, Botswana. In Annual Report of the Director of the Geophysical Laboratory, Carnegie Instn. Washington, 1981-1982. Geophysical Laboratory, Washington D.C.
- Gurney, J.J., Harte, B. (1980). Chemical variations in upper mantle nodules from southern African kimberlites. Phil. Trans. Roy. Soc. Lond., A297, 273-293.
- Gurney, J.J., Switzer, G.S. (1973). The discovery of garnets closely related to diamonds in the Finsch pipe, South Africa. Contr. Miner. Petrol., 39, 103-116.
- Gurney, J.J., Harris, J.W., Rickard, R.S. (1984). Silicate and oxide inclusions in diamonds from the Orapa mine, Botswana, 3-10. In Kornprobst, J., (ed.), Kimberlites: II, The Mantle and Crust-Mantle Relationships. Devs. Petrology, vol. IIB, 393pp. Elsevier, Amsterdam.
- Gurney, J.J., Jakob, W.R.O., Dawson, J.B. (1979). Megacrysts from the Monastery kimberlite pipe, South Africa, 227-243. In Boyd, F.R., Meyer, H.O.A., (eds.), The mantle sample: inclusions in kimberlites and other volcanics. (Proc. Int. Kimberlite Conf., No. 2., Vol. 2), 424pp. American Geophysical Union, Washington, D.C.
- Haggerty, S.E. (1975). The chemistry and genesis of opaque minerals in kimberlites, 295-307. In Ahrens, L.H., Press, F., Runcorn, S.K., Urey, H.C., (eds.), Physics and Chemistry of the Earth, vol. 9. Pergamon Press, 940pp.
- Haggerty, S.E. (1986). Diamond genesis in a multiply-constrained model. Nature, 320, 34-38.

- Haggerty, S.E. (1987). Metasomatic mineral titanates in upper mantle xenoliths, 671-690. In Nixon, P.H., (ed.), Mantle Xenoliths. John Wiley & Sons Ltd., New York, 844pp.
- Haggerty, S.E., Sautter, V. (1990). Ultradeep (greater than 300km) ultramafic upper mantle xenoliths. Science, 248, 993.
- Haggerty, S.E., Hardie, R.B. III, MacMahon, B.M. (1979). The mineral chemistry of ilmenite nodule associations from the Monastery diatreme, 249-256. In Boyd, F.R., Meyer, H.O.A., (eds.), The mantle sample: inclusions in kimberlites and other volcanics. (Proc. Int. Kimberlite Conf., No. 2, Vol. 2), 424pp. American Geophysical Union, Washington D.C.
- Haggerty, S.E., Moore, A.E., Erlank, A.J. (1985). Macrocryst Fe-Ti oxides in olivine melilitites from Namaqualand-Bushmanland, South Africa. Contr. Miner. Petrol., 91, 163-170.
- Haggerty, S.E., Smyth, J.R., Erlank, A.J., Rickard, R.S., Danchin, R.V. (1983). Lindsleyite (Ba) and mathiasite (K): two new chromium titanates in the crichtonite series from the upper mantle. Am. Mineral., 68, 494-505.
- Hamilton, P.J., Evensen, N.M., O'Nions, R.K., Tarney, J. (1979). Sm-Nd systematics of Lewisian gneisses: implications for the origin of granulites. Nature, 277, 25-28.
- Hariya, Y. (1976). Water in the upper mantle - the stability of amphibole and some hydrous silicate minerals. Jap. Assoc. Mineral. Petrol. Econ. Geol. Spec. Paper 1, 175-184 (in Japanese).
- Harley, S.L. (1984a). The solubility of alumina in orthopyroxene coexisting with garnet in $\text{FeO-MgO-Al}_2\text{O}_3\text{-SiO}_2$ and $\text{CaO-FeO-MgO-Al}_2\text{O}_3\text{-SiO}_2$. J. Petrol., 25, 665-696.
- Harley, S.L. (1984b). An experimental study of the partitioning of Fe and Mg between garnet and orthopyroxene. Contr. Miner. Petrol., 86, 359-373.
- Harrison, W.J. (1981). Partitioning of REE between minerals and coexisting melts during partial melting of a garnet lherzolite. Am. Mineral., 66, 242-259.
- Hart, S.R. (1988). Heterogeneous mantle domains: signatures, genesis and mixing chronologies. Earth Planet. Sci. Lett., 90, 273-296.

- Harte, B. (1977). Rock nomenclature with particular relation to deformation and recrystallisation textures in olivine-bearing xenoliths. J. Geol., 85, 279-288.
- Harte, B. (1983). Mantle Peridotites and Processes - the Kimberlite Sample, 46-91. In Hawkesworth, C.J., Norry, M.J., (eds.), Continental Basalts and Mantle Xenoliths. Shiva, 272pp.
- Harte, B., Gurney, J.J. (1975). Evolution of clinopyroxene and garnet in an eclogite nodule from the Roberts Victor kimberlite pipe, South Africa, 367-387. In Ahrens, L.H., Press, F., Runcorn, S.K., Urey, H.C., (eds.), Physics and Chemistry of the Earth, vol. 9. Pergamon Press, 940pp.
- Harte, B., Gurney, J.J. (1981). The mode of formation of chromium-poor megacryst suites from kimberlites. J. Geol., 89, 749-753.
- Harte, B., Cox, K.G., Gurney, J.J. (1975). Petrography and geological history of upper mantle xenoliths from the Matsoku kimberlite pipe, 477-506. In Ahrens, L.H., Press, F., Runcorn, S.K., Urey, H.C., (eds.), Physics and Chemistry of the Earth, vol. 9. Pergamon Press, 940pp.
- Harte, B., Winterburn, P.A., Gurney, J.J. (1987). Metasomatic and enrichment phenomena in garnet peridotite facies mantle xenoliths from the Matsoku kimberlite pipe, Lesotho, 145-219. In Menzies, M.A. and Hawkesworth, C.J., (eds.), Mantle Metasomatism. Academic Press, London, 472pp.
- Hartnady, C., Joubert, P., Stowe, C. (1985). Proterozoic Crustal Evolution in Southwestern Africa. Episodes, 8, no. 4, 236-243.
- Hatton, C.J. (1978). The geochemistry and origin of xenoliths from the Roberts Victor mine. Unpubl. Ph.D. thesis, University of Cape Town.
- Hatton, C.J., Gurney, J.J. (1987). Roberts Victor eclogites and their relation to the mantle, 453-463. In Nixon, P.H., (ed.), Mantle Xenoliths. John Wiley & Sons Ltd., 844pp.
- Haüy, R.J. (1822). Traite de mineralogie. Bachelier, Paris.
- Hawkesworth, C.J., Bickle, M.J., Gledhill, A.R., Wilson, J.F., Orpen, J.L. (1979). A 2.9 b.y. event in the Rhodesian Archaean. Earth Planet. Sci. Lett., 43, 285-297.
- Henderson, P. (1982). Inorganic geochemistry. Pergamon Press, Oxford, 353pp.

- Hills, D.V., Haggerty, S.E. (1989). Petrochemistry of eclogites from the Koidu kimberlite Complex, Sierra Leone. Contr. Miner. Petrol., 103, 397-422.
- Hops, J.J. (1989). Some aspects of the geochemistry of high-temperature peridotites and megacrysts from the Jagersfontein kimberlite pipe, South Africa. Unpubl. Ph.D. thesis, University of Cape Town.
- Hops, J.J., Gurney, J.J., Harte, B., Winterburn, P. (1989). Megacrysts and high temperature nodules from the Jagersfontein kimberlite pipe, 759-770. In Ross, J., (ed.), Fourth International Kimberlite Conference, Kimberlites and Related Rocks, Vol. 2, Geol. Soc. Aust. Spec. Publ., 14.
- Hutton, L.G., Hutton, S.M., Key, R.M. (1974). Chemical analyses of rocks, ores and minerals of Botswana. Botswana Geol. Survey Bull., 3.
- Hynes, A. (1982). A comparison of amphiboles from medium- and low-pressure metabasites. Contr. Miner. Petrol., 81, 119-125.
- Irving, A.J. (1978). A review of experimental studies of crystal/liquid trace element partitioning. Geochim. cosmochim. Acta., 42, 743-771.
- Jaques, A.L., O'Neill, H.St.C., Smith, C.B., Moon, J., Chappel, B.W. (1990). Diamondiferous peridotite xenoliths from the Argyle (AK1) lamproite pipe, Western Australia. Contr. Miner. Petrol., 104, 255-276.
- Jianxiong, Z., Guiojie, Y., Jianhong, Z. (1984). Mathiasite in a kimberlite from China. Acta Mineral. Sinica., 9, 193-200.
- Jones, A.P., Smith, J.V., Dawson, J.B. (1982). Mantle metasomatism in 14 veined peridotites from Bultfontein Mine, South Africa. J. Geol., 90, 435-453.
- Kaminskii, F.V., Sazonova, O.F., Frantsesson, Y.V. (1978). Rare earth levels in kimberlites and ultrabasic xenoliths. Geochem. Int., 15, 68-74.
- Kempton, P.D. (1987). Mineralogic and geochemical evidence for differing styles of metasomatism in spinel lherzolite xenoliths: enriched mantle source regions of basalts? In Menzies, M.A. and Hawkesworth, C.J., (eds.), Mantle Metasomatism. Academic Press, London, 472pp.

- Kennedy, C.S., Kennedy, G.C. (1976). The equilibrium boundary between graphite and diamond. J. Geophys. Res., 81, 2467-2470.
- Key, R.M., Hutton, S.M. (1974). The western extremity of the Limpopo Mobile Belt. Botswana Geol. Survey unpubl. rept.
- Key, R.M., Hutton, S.M. (1976). The tectonic generation of the Limpopo Mobile Belt and a definition of its western extremity. Precambrian Research, 3, 79-90.
- Key, R.M., Rundle, C.C. (1981). The regional significance of new isotopic ages from Precambrian windows through the Kalahari Beds in northwestern Botswana. Trans. Geol. Soc. S. Afr., 84, 51-66.
- Kingery, W.D., Bowen, H.K., Uhlmann, D.R. (1976). Introduction to Ceramics. John Wiley & Sons, New York, 1032pp.
- Kinny, P.D., Dawson, J.B. (1992). A mantle metasomatic injection event linked to late Cretaceous kimberlite magmatism. Nature, 360, 726-728.
- Kramers, J. (1977). Lead and strontium isotopes in Cretaceous kimberlites and mantle-derived xenoliths from southern Africa. Earth Planet. Sci. Lett., 34, 419-431.
- Kramers, J., Roddick, J., Dawson, J. (1983). Trace element and isotope studies on veined, metasomatic and "MARID" xenoliths from Bultfontein, South Africa. Earth Planet. Sci. Lett., 65, 90-106.
- Krogh, E.J. (1988). The garnet-clinopyroxene Fe-Mg geothermometer - a reinterpretation of existing experimental data. Contr. Miner. Petrol., 99, 8-44.
- Kushiro, I., Erlank, A.J. (1970). Stability of potassic richterite, 231-233. In Annual Report of the Director of the Geophysical Laboratory, Carnegie Instn. Washington, 1968-1969. Geophysical Laboratory, Washington D.C.
- Kushiro, I., Shimizu, N., Nakamura, Y. (1972). Compositions of coexisting liquid and solid phases formed upon melting of natural garnet and spinel lherzolites at high pressures: a preliminary report. Earth Planet. Sci. Lett., 14, 19-25.
- Lawless, P.J., Gurney, J.J., Dawson, J.B. (1979). Polymict peridotites from the Bultfontein and De Beers Mines, Kimberley, South Africa, 145-155. In Boyd, F.R., Meyer, H.O.A., (eds.), The mantle sample: inclusions in kimberlites and other volcanics. (Proc. Int. Kimberlite Conf., No. 2., Vol. 2), 424pp. American Geophysical Union, Washington, D.C.

- Leake, B.E. (1978). Nomenclature of amphiboles. The Canadian Mineralogist, 16, 501-520.
- Lindsley, D.H. (1983). Pyroxene thermometry. Am. Mineral., 68, 477-493.
- Lindsley, D.H., Dixon, S.A. (1976). Coexisting diopside and enstatite at 20kbar and 900°-1200°C. Am. J. Sci., 276, 1285-1301.
- Luth, R.W., Virgo, D., Boyd, F.R., Wood, B.J. (1990). Ferric iron in mantle-derived garnets. Contr. Miner. Petrol., 104, 56-72.
- MacGregor, I.D. (1974). The system MgO-Al₂O₃-SiO₂: Solubility of Al₂O₃ in enstatite for spinel and garnet peridotite compositions. Am. Mineral., 59, 110-119.
- MacGregor, I.D. (1979). Mafic and ultramafic xenoliths from the Kao kimberlite pipe, 156-172. In Boyd, F.R., Meyer, H.O.A., (eds.), The mantle sample: inclusions in kimberlites and other volcanics. (Proc. Int. Kimberlite Conf., No. 2., Vol. 2), 424pp. American Geophysical Union, Washington, D.C.
- MacGregor, I.D., Carter, J.L. (1970). The chemistry of clinopyroxenes and garnets of eclogite and peridotite xenoliths from the Roberts Victor mine, South Africa. Phys. Earth Planet. Interiors., 3, 391-397.
- MacGregor, I.D., Manton, W.I. (1986). The Roberts Victor eclogites: ancient ocean crust? J. Geophys. Res., 91, 14063-14079.
- Mattey, D.P. (1987). Carbon isotopes in the mantle. Terra Cognita, 7, 31-37.
- Mattey, D.P., Carr, R.H., Wright, I.P., Pillinger, C.T. (1984). Carbon isotopes in submarine basalts. Earth Planet. Sci. Lett., 70, 196-206.
- Mazzone, P., Haggerty, S.E. (1989). Peraluminous xenoliths in kimberlite: Metamorphosed restites produced by partial melting of pelites. Geochim. cosmochim. Acta., 53, 1531-1561.
- McCallum, M.E., Eggler, D.H. (1976). Diamonds in an upper mantle peridotite nodule from kimberlite in southern Wyoming. Science, 192, 253-256.

- McCandless, T.E., Collins, D.S. (1989). A diamond-graphite eclogite from the Sloan 2 kimberlite, Colorado, U.S.A., 1063-1069. In Ross, J., (ed.), Fourth International Kimberlite Conference, Kimberlites and Related Rocks, Vol. 2, Geol. Soc. Aust. Spec. Publ., 14.
- McCandless, T.E., Gurney, J.J. (1989). Sodium in garnet and potassium in clinopyroxene: criteria for classifying mantle eclogites, 827-832. In Ross, J., (ed.), Fourth International Kimberlite Conference, Kimberlites and Related Rocks, Vol. 2, Geol. Soc. Aust. Spec. Publ., 14.
- McClenaghan, B.J. (1989). Letlhakane mine review, De Beers Botswana Mining Company (Pty) Limited. Internal report, (unpubl.).
- McKenzie, D. (1989). Some remarks on the movement of small melt fractions in the mantle. Earth Planet. Sci. Lett., 95, 53-72.
- Meixner, H.M., Peart, R.J. (1983). The Kalahari Drilling Project: a report on the geophysical and geological results of follow-up drilling of the Aeromagnetic Survey 1979-1983. Botswana Geol. Survey unpubl. rept. GS-12 project.
- Menzies, M.A. (1990). Archaean, Proterozoic, and Phanerozoic lithospheres. In Menzies, M.A. (ed.) Continental Mantle. Clarendon Press, Oxford, 184pp.
- Menzies, M.A., Hawkesworth, C.J. (1987a). Upper mantle processes and composition. In Nixon, P.H., (ed.), Mantle Xenoliths. John Wiley & Sons Ltd., New York, 844pp.
- Menzies, M.A., Hawkesworth, C.J. (1987b). Mantle metasomatism. Academic Press, London, 472pp.
- Menzies, M.A., Murthy, V.R., (1980). Enriched mantle: Nd and Sr isotopes in diopsides from kimberlite nodules. Nature, 283, 634-636.
- Menzies, M.A., Kempton, P., Dungan, M. (1985). Interaction of Continental Lithosphere and Asthenospheric Melts below the Geronimo Volcanic Field, Arizona, U.S.A. J. Petrol., 26, 663-693.
- Menzies, M.A., Rogers, N., Tindle, A., Hawkesworth, C.J. (1987). Metasomatic and enrichment processes in lithospheric peridotites, an effect of asthenosphere-lithosphere interaction, 313-361. In Menzies, M.A. and Hawkesworth, C.J., (eds.), Mantle Metasomatism. Academic Press, London, 472pp.

- Meyer, H.O.A., Bector, N.Z. (1975). Sulfide-oxide minerals in eclogite from Stockdale kimberlite, Kansas. Contr. Miner. Petrol., 52, 57-68.
- Meyer, H.O.A., McAllister, R.H. (1984). Two-pyroxene megacrysts from South African kimberlites, 133-144. In Kornprobst, J., (ed.), Kimberlites: II, The Mantle and Crust-Mantle Relationships. Devs. Petrology, vol. IIB, 393pp. Elsevier, Amsterdam.
- Miller, R.McG. (1983). The Pan-African Damara Orogen of South West Africa/Namibia, 431-515. In Miller, R.McG., (ed.), Evolution of the Damara Orogen of South West Africa/Namibia. Spec. Publ. Geol. Soc. S. Afr., 11, 515pp.
- Mitchell, R.H. (1977a). Geochemistry of magnesian ilmenites from kimberlites in South Africa and Lesotho. Lithos, 10, 29-37.
- Mitchell, R.H. (1978). Garnet lherzolites from Somerset Island, Canada and aspects of the nature of perturbed geotherms. Contr. Miner. Petrol., 67, 341-347.
- Mitchell, R.H. (1984). Garnet lherzolite from the Hanaus-I and Louwrensia kimberlites of Namibia. Contr. Miner. Petrol., 86, 178-188.
- Mitchell, R.H. (1986). Kimberlites: Mineralogy, Geochemistry, and Petrology. Plenum Press, New York, 442 pp.
- Mitchell, R.H., Bergman, S.C. (1991). Petrology of Lamproites. Plenum Press, New York, 447pp.
- Moore, R.O. (1987). A model for the origin of ilmenite in kimberlite and diamond: implications for the genesis of the discrete nodule (megacryst) suite. Contr. Miner. Petrol., 95, 245-253.
- Moore, R.O., Gurney, J.J. (1985). Pyroxene solid solution in garnets included in diamond. Nature, 318, 553-555.
- Moore, R.O., Gurney, J.J. (1989). Mineral inclusions in diamonds from the Monastery kimberlite, South Africa, 827-832. In Ross, J., (ed.), Fourth International Kimberlite Conference, Kimberlites and Related Rocks, Vol. 2, Geol. Soc. Aust. Spec. Publ., 14.
- Mori, T. (1977). Geothermometry of spinel lherzolites. Contr. Miner. Petrol., 59, 261-279.

- Mori, T., Green, D.H. (1978). Laboratory duplication of phase equilibria observed in natural garnet lherzolites. J. Geol., 86, 83-97.
- Mysen, B.O. (1979). Trace element partitioning between garnet peridotite minerals and water-rich vapour: Experimental data from 5 to 30 kbar. American Mineralogist, 64, 274-288.
- Mysen, B.O. (1983). Rare earth element partitioning between (H₂O + CO₂) vapour and upper mantle minerals: experimental data bearing on the conditions of formation of alkali basalt and kimberlite. N. Jb. Miner. Abh., 146, 41-65.
- Nickel, K.G., Brey, G. (1984). Subsolidus orthopyroxene-clinopyroxene systematics in the system CaO-MgO-SiO₂ to 60kb: a re-evaluation of the regular solution model. Contr. Miner. Petrol., 87, 35-42.
- Nickel, K.G., Green, D.H. (1985). Empirical geothermobarometry for garnet peridotites and implications for the nature of the lithosphere, kimberlites and diamonds. Earth Planet. Sci. Lett., 73, 158-170.
- Nixon, P.H., Boyd, F.R. (1973a). Petrogenesis of the granular and sheared ultrabasic nodule suite in kimberlites, 48-56. In Nixon, P.H., (ed.), Lesotho kimberlites. Lesotho National Development Corporation, Maseru, 356pp.
- Nixon, P.H., Boyd, F.R. (1973b). The discrete nodule association in kimberlites in northern Lesotho, 67-75. In Nixon, P.H., (ed.), Lesotho kimberlites. Lesotho National Development Corporation, Maseru, 356pp.
- Nixon, P.H., Chapman, N.A., Gurney, J.J. (1978). Pyrope-spinel (alkremite) xenoliths from kimberlite. Contr. Miner. Petrol., 65, 341-346.
- Nixon, P.H., van Calsteren, P.W.C., Boyd, F.R., Hawkesworth, C.J. (1987). Harzburgites with garnets of diamond facies from southern African kimberlites, 523-533. In Nixon, P.H., (ed.), Mantle Xenoliths. John Wiley & Sons Ltd., 844pp.
- Nowicky, T.E. (1990). Mantle xenoliths from the Abrahamskraal kimberlite: a craton-margin geotherm. Unpubl. M.Sc. dissertation, Rhodes University.

- O'Hara, M.J., Saunders, M.J., Mercy, E.L.P. (1975). Garnet peridotite, primary ultrabasic magma and eclogite; interpretation of upper mantle processes in kimberlite, 571-604. In Ahrens, L.H., Press, F., Runcorn, S.K., Urey, H.C., (eds.), Physics and Chemistry of the Earth, vol. 9. Pergamon Press, 940pp.
- O'Hara, M.J., Yoder, H.S. (1967). Formation and fractionation of basic magmas at high pressure. Scottish J. Geol., 3, 67-117.
- O'Neill, H.St.C., Wood, B.J. (1979). An experimental study of Fe-Mg partitioning between garnet and olivine and its calibration as a geothermometer. Contr. Miner. Petrol., 70, 59-70.
- O'Neill, H.St.C., Wood, B.J. (1980). An experimental study of Fe-Mg partitioning between garnet and olivine and its calibration as a geothermometer: Corrections. Contr. Miner. Petrol., 70, 59-70.
- Ongley, J.S., Basu, A.R., Kyser, T.K. (1987). Oxygen isotopes in coexisting garnets, clinopyroxenes and phlogopites of Roberts Victor eclogites: implications for petrogenesis and mantle metasomatism. Earth Planet. Sci. Lett., 83, 80-84.
- Otter, M.L. (1989). Diamonds and their mineral inclusions from the Sloan diatremes of the Colorado-Wyoming State line kimberlite district, North America. Unpubl. Ph.D. thesis, University of Cape Town.
- Pasteris, J.D., Boyd, F.R., Nixon, P.H. (1979). The ilmenite association at the Frank Smith mine, R.S.A., 265-278. In Boyd, F.R., Meyer, H.O.A., (eds.), The mantle sample: inclusions in kimberlites and other volcanics. (Proc. Int. Kimberlite Conf., No. 2., Vol. 2), 424 pp. American Geophysical Union, Washington, D.C.
- Pearson, D.G., Boyd, F.R., Nixon, P.H. (1990). Graphite-bearing mantle xenoliths from the Kaapvaal Craton: Implications for graphite and diamond genesis, 11-19. Annual Report of the Director of the Geophysical Laboratory, 1989-1990. Geophysical Laboratory, Washington D.C.
- Pearson, D.G., Davies, G.R., Nixon, P.H. (1993). Geochemical constraints on the Petrogenesis of Diamond Facies Pyroxenites from the Beni Bousera Peridotite Massif, North Morocco. J. Petrol., 34, 125-172.
- Pearson, D.G., Davies, G.R., Nixon, P.H., Greenwood, P.B., Matthey, D.P. (1991). Oxygen isotope evidence for the origin of pyroxenites in the Beni Bousera peridotite massif, North Morocco: derivation from subducted oceanic lithosphere. Earth Planet. Sci. Lett., 102, 289-301.

- Pokhilenko, N.P., Sobolev, N.V., Lavrent'ev, Yu.G. (1977). Xenoliths of diamondiferous ultramafic rocks from Yakutian kimberlites. In Second Int. Kimberlite Conf., Santa Fe, New Mexico, (extended abstracts, unpagged).
- Pollack, H.N., Chapman, D.S. (1977). On the regional variation of heat flow, geotherms and lithospheric thickness. Tectonophysics, **38**, 279-296.
- Powell, R. (1985). Regression diagnostics and robust regression in geothermometer/geobarometer calibration: the garnet-clinopyroxene geothermometer revised. J. Metam. Geol., **3**, 231-243.
- Raase, P. (1974). Al and Ti contents of hornblende, indicators of pressure and temperature of regional metamorphism. Contr. Miner. Petrol., **45**, 231-236.
- Raheim, A., Green, D.H. (1974). Experimental determination of the temperature and pressure dependance of the Fe-Mg partition coefficient for coexisting garnet and clinopyroxene. Contr. Miner. Petrol., **48**, 179-203.
- Rawlinson, P.J., Dawson, J.B. (1979). A quench pyroxene-ilmenite xenolith from kimberlite: implications for pyroxene-ilmenite intergrowths, 292-299. In Boyd, F.R., Meyer, H.O.A., (eds.), The mantle sample: inclusions in kimberlites and other volcanics. (Proc. Int. Kimberlite Conf., No. 2., Vol. 2), 424pp. American Geophysical Union, Washington, D.C.
- Reeves, C.V. (1978). Reconnaissance aeromagnetic survey of Botswana 1975-1977: Final interpretation report. Botswana Geol. Survey rept., 199pp.
- Reid, A.M., Brown, R.W., Dawson, J.B., Whitfield, G.G., Siebert, J.C. (1976). Garnet and clinopyroxene compositions in some diamondiferous eclogites. Contr. Miner. Petrol., **53**, 203-220.
- Richardson, S.H., Erlank, A.J., Hart, S.R. (1985). Kimberlite-borne garnet peridotite xenoliths from old enriched subcontinental lithosphere. Earth Planet. Sci. Lett., **75**, 116-128.
- Richardson, S.H., Gurney, J.J., Erlank, A.J., Harris, J.W. (1984). Origin of diamonds in old enriched mantle. Nature, **310**, 198-202.
- Ringwood, A.E. (1966). Composition and origin of the earth, 287-356. In Hurley, P.M., (ed.), Advances in Earth Science, MIT Press, Cambridge.

- Ringwood, A.E. (1975). Composition and Petrology of the Earth's mantle. McGraw-Hill Book Company, 618pp.
- Robinson, D.N. (1979). Surface texture and other features of diamonds. Unpubl. Ph.D. thesis, University of Cape Town.
- Robinson, D.N., Gurney, J.J., Shee, S.R. (1984). Diamond eclogite and graphite eclogite xenoliths from Orapa, Botswana, 11-24. In Kornprobst, J., (ed.), Kimberlites: II, The Mantle and Crust-Mantle Relationships. Devs. Petrology, vol. IIB, 393pp. Elsevier, Amsterdam.
- Ross, M., Huebner, J.S., Dowty, E. (1973). Delineation of the one atmosphere augite-pigeonite miscibility gap for pyroxenes from Lunar basalt 12021. Am. Mineral., 58, 619-635.
- Schandl, E.S., Clarke, D.B. (1982). Metasomatism in the mantle beneath Pipe 200, northern Lesotho, 265-266. In Third International Kimberlite Conference, (extended abstracts).
- Schneider, M.E., Eggler, D.H. (1984). Compositions of fluids in equilibrium with peridotite: implications for alkaline magmatism-metasomatism, 383-394. In Kornprobst, J., (ed.), Kimberlites: I, Kimberlites and Related Rocks. Devs. Petrology, vol. IIA, 466pp. Elsevier, Amsterdam.
- Schneider, M.E., Eggler, D.H. (1986). Fluids in equilibrium with peridotite minerals: Implications for mantle metasomatism. Geochim. cosmochim. Acta., 50, 711-724.
- Schulze, D.J. (1984). Inhomogeneities in garnet peridotite xenoliths from eastern Kentucky kimberlites. Geol. Soc. Amer. Abstr. Progr., 16, 648.
- Schulze, D.J. (1985). Evidence for primary kimberlitic liquids in megacrysts from kimberlites in Kentucky, U.S.A. J. Geol., 93, 75-79.
- Schulze, D.J. (1986). Calcium anomalies in the mantle and a subducted metaserpentinite origin for diamonds. Nature, 319, 483-485.
- Schulze, D.J. (1987). Megacrysts from alkalic volcanic rocks, 433-451. In Nixon, P.H., (ed.), Mantle Xenoliths. John Wiley & Sons Ltd., New York, 844pp.
- Schulze, D.J. (1990). Silicate-bearing rutile-dominated nodules from South African kimberlites: Metasomatized cumulates. Am. Mineral., 75, 97-104.

- Schulze, D.J., Helmstaedt, H. (1988). Coesite-sanidine eclogites from kimberlite: products of mantle fractionation or subduction? J. Geol., 96, 435-443.
- Schulze, D.J., Valley, J.W., Viljoen, K.S., Spicuzza, M. (in press). Carbon isotope composition of graphite in mantle eclogites.
- Shee, S.R. (1978). The mineral chemistry of xenoliths from the Orapa kimberlite pipe, Botswana. Unpubl. M.Sc. thesis, University of Cape Town.
- Shee, S.R., Gurney, J.J. (1979). The mineralogy of xenoliths from Orapa, Botswana, 37-49. In Boyd, F.R., Meyer, H.O.A., (eds.), The mantle sample: inclusions in kimberlites and other volcanics. (Proc. Int. Kimberlite Conf., No. 2, Vol. 2), 424pp. American Geophysical Union, Washington, D.C.
- Shee, S.R., Gurney, J.J., Robinson, D.N. (1982). Two diamond-bearing peridotite xenoliths from the Finsch kimberlite, South Africa. Contr. Miner. Petrol., 81, 79-87.
- Shimizu, N. (1975). Rare earth elements in garnets and clinopyroxenes from garnet lherzolite nodules in kimberlites. Earth Planet. Sci. Lett., 25, 26-32.
- Shimizu, N., Allegre, C.J. (1978). Transition elements in garnet lherzolite nodules. Contr. Miner. Petrol., 67, 41-50.
- Shimizu, N., Richardson, S.H. (1987). Trace element abundance patterns of garnet inclusions in peridotite-suite diamonds. Geochim. cosmochim. Acta., 51, 755-758.
- Skinner, C.P. (1989). The petrology of peridotite xenoliths from the Finsch kimberlite, South Africa. S. Afr. J. Geol., 92(3), 197-206.
- Smith, C.B. (1983). Pb, Sr and Nd isotopic evidence for sources of southern African Cretaceous kimberlites. Nature, 304, 51-54.
- Smith, C.B., Schulze, D.J., Viljoen, K.S., Kramers, J.D., Barton, E.S., Jagoutz, E. (in prep.) Sr, Nd and Pb isotopic character of the Cr-poor, subcalcic megacryst suite in kimberlite: derivation from HIMU in the subcontinental lithosphere.
- Smith, D., Boyd, F.R. (1984). Mineral heterogeneities in high-T lherzolite nodules. EOS, 65, 1154.

- Smith, D., Boyd, F.R. (1987). Compositional heterogeneities in a high-temperature lherzolite nodule and implications for mantle processes, 551-561. In Nixon, P.H., (ed.), Mantle Xenoliths. John Wiley & Sons Ltd., 844pp.
- Smith, D., Boyd, F.R. (1989). Compositional heterogeneities in minerals of sheared lherzolite inclusions from African kimberlites, 709-724. In Ross, J., (ed.), Fourth International Kimberlite Conference, Kimberlites and Related Rocks, Vol. 2, Geol. Soc. Aust. Spec. Publ., 14.
- Smith, D., Ehrenberg, S.N. (1984). Zoned minerals in garnet peridotite nodules from the Colorado Plateau: implications for mantle metasomatism and kinetics. Contr. Miner. Petrol., 86, 274-285.
- Smyth, J.R., Caporuscio, F.A., McCormick, T.C. (1989). Mantle eclogites: evidence of igneous fractionation in the mantle. Earth Planet. Sci. Lett., 93, 133-141.
- Sobolev, N.V. (1977). Deep-seated inclusions in kimberlites and the problem of the composition of the upper mantle. (English translation of the Russian edition, 1974. Izdatel'stvo Mauka). American Geophysical Union, Washington, 279pp.
- Sobolev, N.V. (1984). Crystalline inclusions in diamonds from New South Wales, Australia, 213-226. In Glover, J.E., Harris, P.G., (eds.), Kimberlite occurrence and origin: A basis for conceptual models in exploration. Publs. Geol. Dep. & Univ. Extension, Univ. West. Aust., 8.
- Sobolev, V.S., Sobolev, N.V. (1964). Xenoliths in the kimberlites of Northern Yakutia and the problem of the structure of the earth's mantle. Dokl. Acad. Sci. SSSR, 158, 108-111 (in Russian).
- Sobolev, N.V., Kuznetsova, I.K., Zyuzin, N.I. (1968). The petrology of grosspyrite xenoliths from the Zagadochnaya kimberlite pipe in Yakutia. J. Petrol., 9, 253-280.
- Sobolev, N.V., Lavrent'ev, Yu.G., Pokhilenko, N.P., Usova, L.V. (1973). Chrome-rich garnets from the kimberlites of Yakutia and their parageneses. Contr. Miner. Petrol., 40, 39-52.
- Sobolev, N.V., Lavrent'ev, Yu.G., Pospelova, L.N. (1969). Chrome pyrope from Yakut diamonds. Akad. Nauk. USSR, Doklady, 189, 162-165 (in Russian).
- Sobolev, V.S., Sobolev, N.V., Lavrent'ev, Yu.G. (1975). Chrome-rich clinopyroxenes from the kimberlites of Yakutia. N. Jb. Miner. Abh., 123, 213-218.

- Stephens, W.E., Dawson, J.B. (1977). Statistical comparison between pyroxenes from kimberlites and their associated xenoliths. J. Geol., 85, 433-449.
- Stowe, C.W., Hartnady, C.J.H., Joubert, P. (1984). Proterozoic tectonic provinces of Southern Africa. Precambrian Research, 25, 229-231.
- Switzer, G., Melson, W.G. (1969). Partially melted kyanite eclogite from the Roberts Victor Mine, South Africa. Smithson. Contrib. Earth Sci., 1, 7pp.
- Takahashi, E., Kushiro, I. (1983). Melting of a dry peridotite at high pressures and basalt magma genesis. Amer. Mineral., 68, 859-879.
- Taylor, W.R., Green, D.H. (1989). The role of reduced C-O-H fluids in mantle partial melting, 592-602. In Ross, J., (ed.), Fourth International Kimberlite Conference, Kimberlites and Related Rocks, Vol. 1, Geol. Soc. Aust. Spec. Publ., 14.
- Treloar, P.J. (1988). The geological evolution of the Magondi Mobile Belt, Zimbabwe. Precambrian Research, 38, 55-73.
- Tsai, H., Shieh, Y., Meyer, H.O.A. (1979). Mineralogy and S^{34}/S^{32} ratios of sulfides associated with kimberlite, xenoliths and diamonds. In Boyd, F.R., Meyer, H.O.A., (eds.), The mantle sample: inclusions in kimberlites and other volcanics. (Proc. Int. Kimberlite Conf., No. 2., Vol. 2), 424pp. American Geophysical Union, Washington, D.C.
- Viljoen, K.S. (in prep.). The Petrology and Geochemistry of a suite of mantle-derived eclogite xenoliths from the Kaalvallei kimberlite pipe, South Africa. Unpubl. Ph.D. thesis, University of the Witwatersrand.
- Viljoen, K.S., Robinson, D.N., Swash, P.M., Griffin, W.L., Otter, M.L., Ryan, C.G., Win, T.T. (in press). Diamond- and graphite-bearing peridotite xenoliths from the Roberts Victor kimberlite, South Africa.
- Vredevoogd, J.J., Forbes, W.C. (1975). The System diopside-ureyite at 20 kb. Contr. Miner. Petrol., 52, 147-156.
- Waters, F.G. (1987a). A geochemical study of metasomatised peridotite and MARID nodules from the Kimberley pipes, South Africa. Unpubl. Ph.D. thesis, University of Cape Town.

- Waters, F.G. (1987b). A suggested origin of MARID xenoliths in kimberlites by high pressure crystallization of an ultrapotassic rock such as lamproite. Contr. Miner. Petrol., **95**, 523-533.
- Waters, F.G., Erlank, A.J. (1988). Assessment of the vertical extent and distribution of mantle metasomatism below Kimberley, South Africa. J. Petrol., Special Lithosphere Issue, 185-204.
- Waters, F.G, Erlank, A.J., Daniels, L.R.M. (1989). Contact relationships between MARID rock and metasomatised peridotite in a kimberlite xenolith. Geochemical Journal, **23**, 11-17.
- Wells, P.R.A. (1977). Pyroxene thermometry in simple and complex systems. Contr. Miner. Petrol., **62**, 129-139.
- Wendlandt, R.F., Eggler, D.H. (1980). The origins of potassic magmas: 2. Stability of phlogopite in natural spinel lherzolite and in the system $\text{KAlSiO}_4\text{-MgO-SiO}_2\text{-H}_2\text{O-CO}_2$ at high pressures and high temperatures. American Journal of Science, **280**, 421-458.
- White, W.M. (1985). Sources of oceanic basalts: radiogenic isotopic evidence. Geology, **13**, 115-118.
- Winterburn, P.A., Harte, B., Gurney, J.J. (1990). Peridotite xenoliths from the Jagersfontein kimberlite pipe: I. Primary and primary-metasomatic mineralogy. Geochim. cosmochim. Acta., **54**, 329-341.
- Wood, B.J., Banno, S. (1973). Garnet-orthopyroxene and orthopyroxene-clinopyroxene relationships in simple and complex systems. Contr. Miner. Petrol., **42**, 109-124.
- Wyatt, B.A. (1977). The melting and crystallization behaviour of a natural clinopyroxene-ilmenite intergrowth. Contr. Miner. Petrol., **61**, 1-9.
- Wyllie, P.J., Huang, W.L., Otto, J., Byrnes, A.P. (1983). Carbonation of peridotites and decarbonation of siliceous dolomites represented in the system $\text{CaO-MgO-SiO}_2\text{-CO}_2$ to 30 kbar. Tectonophysics, **100**, 359-388.
- Zindler, A., Hart, S.R. (1986). Chemical geodynamics. Ann. Rev. Earth Planet. Sci., **14**, 493-571.
- Zindler, A., Jagoutz, E., Goldstein, S. (1982). Nd, Sr and Pb isotopic systematics in a three-component mantle: a new perspective. Nature, **58**, 519-523.

APPENDIX 1 : MICROPROBE ANALYTICAL CONDITIONS AND COUNTING STATISTICS

All microprobe analyses were executed on the JEOL Superprobe at Rhodes University. A beam current of 25nA and an EHT of 15kV was used. Peak and background counting times were set at 20 and 10 seconds respectively. The beam diameter was set at 10 μ m for silicate analyses (including phlogopite and amphibole) and at 1 μ m for opaque oxides. The ZAF correction procedure was used. Total FeO concentrations were recalculated to FeO and Fe₂O₃ by using the method of Carmichael (1967) on a LOTUS package.

The use of minor and trace elements in some minerals, eg. Na₂O and TiO₂ in garnet, necessitated the use of counting statistics to determine counting errors and lower limits of determination. A worked example is provided below:

$$\text{counting error (C.E.)} = [\sqrt{(R_p/T_p + R_b/T_b)}] / N_p * \text{element conc in wt\%}$$

where: R_b = average background count in counts per second (cps)

N_p = nett peak count in cps

R_p = gross peak = $N_p + R_b$ in cps

T_p = peak counting time = 20 seconds

T_b = total background (lower & upper) counting time = 10 + 10
= 20 seconds

eg. JSL 200 - Na in garnet

$$R_b = 8.1$$

$$N_p = 11.2$$

$$R_p = 11.2 + 8.1 = 19.3$$

$$T_p = 20$$

$$T_b = 20$$

Na concentration is 0.11 wt%

$$\text{====> C.E.} = 0.012 \text{ wt\%}$$

$$\text{detection limit (D.L.)} = 3/M * \sqrt{R_b/T_b}$$

where: $M = N_p$ of the standard/concentration of the standard
other symbols as defined above

$$\text{for Na, } M = 1778.2/15.29$$

$$\implies \text{D.L} = 0.016 \text{ wt\%}$$

$$\text{lower limit of determination (L.L.D.)} = 6/M * \sqrt{R_b/T_b}$$

symbols as defined above

$$\implies \text{L.L.D.} = 0.033 \text{ wt\%}$$

These calculations have been performed on samples representing
compositional extremes in their various groups:

Mineral : garnet

Sample no.: JSL 200

Oxide	Analysis	C.E.	D.L.	L.L.D.
SiO ₂	40.58	0.099	0.020	0.039
TiO ₂	0.27	0.016	0.022	0.045
Al ₂ O ₃	22.62	0.071	0.016	0.032
Cr ₂ O ₃	0.01	0.010	0.019	0.037
FeO	10.48	0.111	0.043	0.086
MnO	0.23	0.025	0.037	0.074
NiO	0.03	0.024	0.046	0.092
MgO	11.67	0.059	0.014	0.029
CaO	13.29	0.071	0.017	0.033
Na ₂ O	0.11	0.012	0.016	0.033

Mineral : garnet

Sample no.: JSL 203

Oxide	Analysis	C.E.	D.L.	L.L.D.
SiO ₂	38.77	0.097	0.021	0.041
TiO ₂	0.35	0.017	0.023	0.046
Al ₂ O ₃	21.55	0.071	0.016	0.032
Cr ₂ O ₃	0.03	0.010	0.019	0.038
FeO	22.14	0.158	0.042	0.084
MnO	0.42	0.030	0.039	0.078
NiO	0.00	0.000	0.049	0.097
MgO	7.81	0.051	0.014	0.029
CaO	8.40	0.056	0.018	0.036
Na ₂ O	0.14	0.014	0.017	0.033

Mineral : garnet

Sample no.: JSL 86

Oxide	Analysis	C.E.	D.L.	L.L.D.
SiO ₂	41.97	0.101	0.020	0.039
TiO ₂	0.16	0.015	0.023	0.045
Al ₂ O ₃	22.55	0.073	0.015	0.031
Cr ₂ O ₃	0.67	0.016	0.018	0.036
FeO	7.75	0.095	0.036	0.072
MnO	0.35	0.029	0.041	0.082
NiO	0.02	0.025	0.043	0.087
MgO	2.24	0.008	0.015	0.029
CaO	4.16	0.040	0.016	0.031
Na ₂ O	0.05	0.010	0.017	0.034

Mineral : garnet

Sample no.: JSL 14

Oxide	Analysis	C.E.	D.L.	L.L.D.
SiO ₂	41.28	0.101	0.020	0.039
TiO ₂	1.45	0.028	0.023	0.045
Al ₂ O ₃	20.62	0.070	0.015	0.030
Cr ₂ O ₃	0.53	0.015	0.018	0.035
FeO	11.35	0.115	0.037	0.074
MnO	0.32	0.029	0.042	0.083
NiO	0.02	0.024	0.044	0.089
MgO	20.19	0.078	0.014	0.027
CaO	4.70	0.043	0.017	0.033
Na ₂ O	0.16	0.013	0.016	0.033

Mineral : garnet

Sample no.: JSL 112

Oxide	Analysis	C.E.	D.L.	L.L.D.
SiO ₂	42.70	0.102	0.020	0.040
TiO ₂	0.79	0.022	0.022	0.044
Al ₂ O ₃	20.66	0.069	0.015	0.031
Cr ₂ O ₃	1.81	0.023	0.018	0.036
FeO	7.29	0.092	0.038	0.076
MnO	0.25	0.027	0.041	0.083
NiO	0.02	0.024	0.044	0.089
MgO	22.39	0.080	0.014	0.028
CaO	4.72	0.043	0.016	0.031
Na ₂ O	0.09	0.011	0.016	0.032

Mineral : garnet

Sample no.: JSL 113

Oxide	Analysis	C.E.	D.L.	L.L.D.
SiO ₂	42.01	0.101	0.020	0.040
TiO ₂	0.04	0.012	0.022	0.044
Al ₂ O ₃	17.20	0.064	0.016	0.032
Cr ₂ O ₃	7.21	0.043	0.019	0.037
FeO	6.21	0.086	0.040	0.080
MnO	0.36	0.027	0.033	0.065
NiO	0.00	0.000	0.047	0.094
MgO	24.47	0.084	0.014	0.029
CaO	2.35	0.031	0.017	0.034
Na ₂ O	0.05	0.010	0.016	0.032

Mineral : clinopyroxene

Sample no.: JSL 106

Oxide	Analysis	C.E.	D.L.	L.L.D.
SiO ₂	53.98	0.109	0.021	0.042
TiO ₂	0.32	0.017	0.022	0.044
Al ₂ O ₃	8.35	0.043	0.016	0.032
Cr ₂ O ₃	0.02	0.010	0.019	0.037
FeO	5.26	0.079	0.037	0.074
MnO	0.06	0.020	0.036	0.072
NiO	0.00	0.000	0.049	0.098
MgO	10.25	0.056	0.014	0.028
CaO	16.49	0.079	0.016	0.032
Na ₂ O	4.68	0.048	0.017	0.035

Mineral : clinopyroxene

Sample no.: JSL 200

Oxide	Analysis	C.E.	D.L.	L.L.D.
SiO ₂	55.03	0.111	0.020	0.040
TiO ₂	0.31	0.017	0.022	0.044
Al ₂ O ₃	11.85	0.051	0.015	0.031
Cr ₂ O ₃	0.04	0.010	0.019	0.037
FeO	2.00	0.051	0.037	0.075
MnO	0.03	0.019	0.039	0.078
NiO	0.00	0.000	0.047	0.094
MgO	9.56	0.053	0.014	0.027
CaO	15.60	0.077	0.015	0.031
Na ₂ O	6.16	0.054	0.017	0.035

Mineral : clinopyroxene

Sample no.: JSL 86

Oxide	Analysis	C.E.	D.L.	L.L.D.
SiO ₂	53.81	0.110	0.021	0.041
TiO ₂	0.30	0.017	0.022	0.043
Al ₂ O ₃	3.70	0.030	0.016	0.031
Cr ₂ O ₃	0.91	0.018	0.018	0.036
FeO	2.14	0.054	0.040	0.080
MnO	0.05	0.023	0.042	0.084
NiO	0.04	0.026	0.045	0.089
MgO	16.14	0.069	0.013	0.027
CaO	20.18	0.088	0.015	0.031
Na ₂ O	2.90	0.038	0.017	0.034

Mineral : clinopyroxene

Sample no.: JSL 203

Oxide	Analysis	C.E.	D.L.	L.L.D.
SiO ₂	50.47	0.106	0.021	0.042
TiO ₂	1.13	0.025	0.023	0.045
Al ₂ O ₃	6.41	0.039	0.015	0.031
Cr ₂ O ₃	0.05	0.011	0.019	0.038
FeO	6.16	0.086	0.043	0.086
MnO	0.13	0.024	0.040	0.080
NiO	0.04	0.026	0.045	0.090
MgO	14.34	0.066	0.014	0.029
CaO	18.89	0.084	0.015	0.029
Na ₂ O	2.14	0.034	0.018	0.036

Mineral : orthopyroxene

Sample no.: JSL 75

Oxide	Analysis	C.E.	D.L.	L.L.D.
SiO ₂	57.59	0.117	0.020	0.039
TiO ₂	0.09	0.013	0.022	0.043
Al ₂ O ₃	1.54	0.021	0.015	0.030
Cr ₂ O ₃	0.10	0.012	0.019	0.039
FeO	4.88	0.076	0.037	0.073
MnO	0.09	0.022	0.038	0.076
NiO	0.09	0.026	0.044	0.087
MgO	35.44	0.097	0.016	0.031
CaO	0.15	0.010	0.014	0.029
Na ₂ O	0.04	0.009	0.017	0.033

Mineral : orthopyroxene

Sample no.: JSL 75

Oxide	Analysis	C.E.	D.L.	L.L.D.
SiO ₂	57.77	0.118	0.347	0.694
TiO ₂	0.05	0.003	0.027	0.053
Al ₂ O ₃	4.43	0.063	0.052	0.103
Cr ₂ O ₃	0.07	0.004	0.023	0.046
FeO	4.71	0.071	0.211	0.422
MnO	0.05	0.007	0.045	0.089
NiO	0.04	0.004	0.051	0.101
MgO	36.04	0.099	0.300	0.600
CaO	0.09	0.005	0.026	0.051
Na ₂ O	0.04	0.004	0.019	0.038

Mineral : orthopyroxene

Sample no.: JSL 143

Oxide	Analysis	C.E.	D.L.	L.L.D.
SiO ₂	57.74	0.117	0.348	0.696
TiO ₂	0.09	0.005	0.029	0.057
Al ₂ O ₃	0.69	0.014	0.039	0.078
Cr ₂ O ₃	0.48	0.009	0.038	0.075
FeO	3.97	0.067	0.190	0.380
MnO	0.09	0.009	0.050	0.101
NiO	0.07	0.006	0.054	0.109
MgO	35.45	0.098	0.300	0.599
CaO	0.41	0.013	0.038	0.077
Na ₂ O	0.16	0.009	0.030	0.059

Mineral : orthopyroxene

Sample no.: JSL 140

Oxide	Analysis	C.E.	D.L.	L.L.D.
SiO ₂	57.56	0.118	0.344	0.689
TiO ₂	0.15	0.007	0.032	0.064
Al ₂ O ₃	0.89	0.016	0.042	0.084
Cr ₂ O ₃	0.26	0.010	0.029	0.058
FeO	5.49	0.079	0.221	0.443
MnO	0.16	0.016	0.052	0.103
NiO	0.13	0.013	0.051	0.101
MgO	34.16	0.097	0.290	0.580
CaO	1.05	0.021	0.057	0.114
Na ₂ O	0.30	0.013	0.036	0.072

Mineral : orthopyroxene

Sample no.: JSL 142

Oxide	Analysis	C.E.	D.L.	L.L.D.
SiO ₂	57.90	0.120	0.340	0.680
TiO ₂	0.01	0.001	0.024	0.048
Al ₂ O ₃	0.64	0.013	0.039	0.077
Cr ₂ O ₃	0.16	0.006	0.027	0.055
FeO	4.52	0.072	0.201	0.402
MnO	0.13	0.012	0.053	0.106
NiO	0.12	0.013	0.049	0.097
MgO	36.23	0.100	0.300	0.600
CaO	0.34	0.012	0.037	0.074
Na ₂ O	0.16	0.009	0.029	0.058

Mineral : olivine

Sample no.: JSL 108

Oxide	Analysis	C.E.	D.L.	L.L.D.
SiO ₂	40.24	0.100	0.296	0.592
FeO	9.01	0.103	0.283	0.567
MnO	0.10	0.013	0.014	0.028
NiO	0.41	0.034	0.058	0.117
MgO	50.34	0.117	0.353	0.706
CaO	0.06	0.009	0.013	0.027

Mineral : amphibole

Sample no.: JSL 67

Oxide	Analysis	C.E.	D.L.	L.L.D.
SiO ₂	40.91	0.099	0.249	0.498
TiO ₂	1.62	0.028	0.069	0.137
Al ₂ O ₃	15.18	0.063	0.185	0.370
Cr ₂ O ₃	0.04	0.011	0.009	0.017
FeO	12.67	0.121	0.336	0.671
MnO	0.21	0.026	0.046	0.092
MgO	13.56	0.063	0.156	0.313
CaO	9.30	0.059	0.173	0.345
Na ₂ O	3.10	0.042	0.101	0.201
K ₂ O	1.03	0.022	0.061	0.121

Mineral : phlogopite

Sample no.: JSL 67

Oxide	Analysis	C.E.	D.L.	L.L.D.
SiO ₂	37.49	0.095	0.238	0.476
TiO ₂	6.41	0.053	0.136	0.273
Al ₂ O ₃	15.54	0.064	0.187	0.375
Cr ₂ O ₃	0.05	0.011	0.010	0.021
FeO	8.49	0.100	0.274	0.549
MnO	0.03	0.021	0.016	0.033
MgO	18.15	0.071	0.185	0.371
CaO	0.02	0.008	0.008	0.016
Na ₂ O	0.52	0.019	0.042	0.084
K ₂ O	8.80	0.058	0.176	0.352

A comparison between microprobe analyses from the Cameca SX-50 at the
Anglo American Research Laboratories and the JEOL
Superprobe at Rhodes University.

Mineral : orthopyroxene

Sample no.: JSL 516

Oxide	AARL	Rhodes
SiO ₂	57.301	57.870
TiO ₂	0.009	0.000
Al ₂ O ₃	0.696	0.734
Cr ₂ O ₃	0.423	0.382
FeO	4.512	4.623
MnO	0.119	0.104
NiO	0.092	0.115
MgO	36.261	35.789
CaO	0.342	0.256
Na ₂ O	0.173	0.168
Total	99.929	100.041

Mineral : olivine

Sample no.: JSL 511

Oxide	AARL	Rhodes
SiO ₂	39.705	40.036
FeO	11.306	11.655
MnO	0.115	0.090
NiO	0.299	0.276
MgO	48.311	48.035
CaO	0.018	0.006
Total	99.755	100.099

APPENDIX 2 : GEOTHERMOBAROMETRIC EQUATIONS EMPLOYED IN THIS STUDY

In all cases temperature values are in Kelvin (K) and pressure in kilobar (kb).

Geothermometers

Harley (1984b)

$$T = \frac{3740 + 1400(x^{\text{Gt.Ca}}) + 22.86P}{R \ln K_d + 1.96}$$

where: $x^{\text{Gt.Ca}} = \text{Ca}/(\text{Ca} + \text{Mg} + \text{Fe})$ in garnet

$$K_d = (\text{Fe/Mg})^{\text{Gt}}/(\text{Fe/Mg})^{\text{Opx}}$$

O'Neill and Wood (1979, 1980)

$$T = \frac{902 + DV + (x^{\text{Ol.Mg}} - x^{\text{Ol.Fe}})[498 + 1.51(P - 30)] - 98(x^{\text{Gt.Mg}} - x^{\text{Gt.Fe}}) + 1347(x^{\text{Gt.Ca}})}{\ln K_d + 0.357}$$

where:

$$\begin{aligned} DV = & -\{462.5[1.0191 + (T - 1073)(2.87 \times 10^{-5})][P - (2.63 \times 10^{-4})P^2 - 29.76]\} \\ & -\{262.4[1.0292 + (T - 1073)(4.5 \times 10^{-5})][P - (3.9 \times 10^{-4})P^2 - 29.65]\} \\ & +\{454[1.020 + (T - 1073)(2.84 \times 10^{-5})][P - (2.36 \times 10^{-4})P^2 - 29.79]\} \\ & +\{278.3[1.0234 + (T - 1073)(2.3 \times 10^{-5})][P - (4.5 \times 10^{-4})P^2 - 29.6]\} \end{aligned}$$

$$x^{\text{Ol.Mg}} = \text{Mg}/(\text{Mg} + \text{Fe}) \text{ in olivine}$$

$$x^{\text{Ol.Fe}} = \text{Fe}/(\text{Fe} + \text{Mg}) \text{ in olivine}$$

$$x^{\text{Gt.Mg}} = \text{Mg}/(\text{Mg} + \text{Fe} + \text{Ca}) \text{ in garnet}$$

$$x^{\text{Gt.Fe}} = \text{Fe}/(\text{Mg} + \text{Fe} + \text{Ca}) \text{ in garnet}$$

$$x^{\text{Gt.Ca}} = \text{Ca}/(\text{Mg} + \text{Fe} + \text{Ca}) \text{ in garnet}$$

$$K_d = (x^{\text{Ol.Mg}}.x^{\text{Gt.Fe}})/(x^{\text{Ol.Fe}}.x^{\text{Gt.Mg}})$$

Ellis and Green (1979)

$$T = \frac{3104(x^{\text{Gt.Ca}}) + 3030 + 10.86P}{\ln K_d + 1.9034}$$

where: $x^{\text{Gt.Ca}} = \text{Ca}/(\text{Ca} + \text{Mg} + \text{Fe} + \text{Mn})$ in garnet
 $K_d = [(\text{Fe}^{2+}/\text{Mg}^{2+})^{\text{Gt}}]/[(\text{Fe}^{2+}/\text{Mg}^{2+})^{\text{Cpx}}]$

Krogh (1988)

$$T = \frac{-6173(x^{\text{Gt.Ca}})^2 + 6731.x^{\text{Gt.Ca}} + 1879 + 10P}{\ln K_d + 1.393}$$

where: $x^{\text{Gt.Ca}} = \text{Ca}/(\text{Ca} + \text{Mg} + \text{Fe} + \text{Mn})$ in garnet
 $K_d = [(\text{Fe}^{2+}/\text{Mg}^{2+})^{\text{Gt}}]/[(\text{Fe}^{2+}/\text{Mg}^{2+})^{\text{Cpx}}]$

Wood and Banno (1973)

$$T = \frac{-10202}{\ln K - 7.65(x^{\text{Opx.Fe}}) + 3.88(x^{\text{Opx.Fe}})^2 - 4.6}$$

where: $K = (\text{activity of } \text{Mg}_2\text{Si}_2\text{O}_6 \text{ in Cpx})/(\text{activity of } \text{Mg}_2\text{Si}_2\text{O}_6 \text{ in Opx})$
 $\text{activity of } \text{Mg}_2\text{Si}_2\text{O}_6 = [\text{Mg}^{2+}/(\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Fe}^{2+} + \text{Mn}^{2+} + \text{Na}^+)]_{\text{M2}} \times$
 $[\text{Mg}^{2+}/(\text{Fe}^{3+} + \text{Fe}^{2+} + \text{Al}^{3+} + \text{Ti}^{4+} + \text{Cr}^{3+} + \text{Mg}^{2+})]_{\text{M1}}$
 $x^{\text{Opx.Fe}} = \text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Mg}^{2+})$ in Opx

Wells (1977)

$$T = \frac{7341}{3.355 + 2.44(x^{\text{Opx.Fe}}) - \ln K}$$

where: $K = (\text{activity of } \text{Mg}_2\text{Si}_2\text{O}_6 \text{ in Cpx}) / (\text{activity of } \text{Mg}_2\text{Si}_2\text{O}_6 \text{ in Opx})$
 $\text{activity of } \text{Mg}_2\text{Si}_2\text{O}_6 = [\text{Mg}^{2+} / (\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Fe}^{2+} + \text{Mn}^{2+} + \text{Na}^+)]_{\text{M2}} \cdot$
 $[\text{Mg}^{2+} / (\text{Fe}^{3+} + \text{Fe}^{2+} + \text{Al}^{3+} + \text{Ti}^{4+} + \text{Cr}^{3+} + \text{Mg}^{2+})]_{\text{M1}}$
 $x^{\text{Opx.Fe}} = \text{Fe}^{2+} / (\text{Fe}^{2+} + \text{Mg}^{2+}) \text{ in Opx}$

Brey and Köhler (1990)

$$T_{\text{bkn}} = \frac{23664 + [24.9 + (126.3x^{\text{Cpx.Fe}})]P}{13.38 + (\ln K_d)^2 + (11.59x^{\text{Opx.Fe}})}$$

where: $x^{\text{Px.Fe}} = \text{Fe} / (\text{Fe} + \text{Mg})$
 $K_d = (1 - \text{Ca}^*)^{\text{Cpx}} / (1 - \text{Ca}^*)^{\text{Opx}}$
 $\text{Ca}^* = \text{Ca}^{\text{M2}} / (1 - \text{Na}^{\text{M2}})$

Brey and Köhler (1990)

$$T_{\text{Ca-in-opx}} = \frac{6425 + 26.4P}{-\ln \text{Ca}^{\text{Opx}} + 1.843}$$

Geobarometers

Finnerty and Boyd (1984)

$$P = \frac{1.46T - 3736 - \ln(\text{wt\% Al}_2\text{O}_3/100)T}{97.1}$$

where: Al_2O_3 = weight percent Al_2O_3 in orthopyroxene coexisting
with garnet

Brey and Köhler 1990)

$$P_{\text{bkn}} = \frac{-C_2 - \sqrt{[(C_2)^2 + 4C_3C_1/1000]}}{2C_3}$$

where:

$$C_1 = -RT \ln K_d - 5510 + 88.91T - 19T^{1.2} + 3(x^{\text{Gt.Ca}})^2 \times 82458$$

$$+ x^{\text{Mg.M1}} x^{\text{Fe.M1}} (80942 - 46.7T) - 3x^{\text{Gt.Fe}} x^{\text{Gt.Ca}} 17793$$

$$- x^{\text{Gt.Ca}} x^{\text{Gt.Cr}} (1.164 \times 10^6 - 420.4T)$$

$$- x^{\text{Gt.Fe}} x^{\text{Gt.Cr}} (-1.25 \times 10^6 + 565T)$$

$$C_2 = -0.832 - 8.78 \times 10^{-5}(T - 298) + 3(x^{\text{Gt.Ca}})^2 \times 3.305$$

$$- x^{\text{Gt.Ca}} x^{\text{Gt.Cr}} 13.45 + x^{\text{Gt.Fe}} x^{\text{Gt.Cr}} 10.5$$

$$C_3 = 16.6 \times 10^{-4}$$

$$K_d = [(1 - x^{\text{Gt.Ca}})^3 (x^{\text{Gt.Al}})^2] / [x^{\text{MF.M1}} (x^{\text{MF.M2}})^2 x^{\text{AlTs.M1}}]$$

Site occupancy:

$$x^{\text{Al.M1}} = (\text{Al} + \text{Na} - \text{Cr} - \text{Fe}^{3+} - 2\text{Ti})/2$$

$$x^{\text{AlTs.M1}} = x^{\text{Al.M1}} \text{ due to Tschermak's component}$$

$$\text{jadeite} = \text{Na} - \text{Cr} - \text{Fe}^{3+} - 2\text{Ti}$$

$$\text{if jadeite} < 0, \text{ then } x^{\text{AlTs.M1}} = (\text{Al} + \text{jadeite})/2$$

$$\text{if jadeite} > 0, \text{ then } x^{\text{AlTs.M1}} = (\text{Al} - \text{jadeite})/2$$

$$x^{\text{Mg.M1}} = x^{\text{MF.M1}} \times x^{\text{MF}}$$

$$x^{\text{Mg.M2}} = x^{\text{MF.M2}} \times x^{\text{MF}}$$

$$x^{\text{Fe.M1}} = x^{\text{MF.M1}} \times (1 - x^{\text{MF}})$$

$$x^{\text{MF.M1}} = (1 - x^{\text{Al.M1}} - \text{Cr} - \text{Fe}^{3+} - \text{Ti})$$

$$x^{\text{MF.M2}} = (1 - \text{Ca} - \text{Na} - \text{Mn})$$

$$x^{\text{MF}} = \text{Mg}/(\text{Mg} + \text{Fe})$$

$$x^{\text{Gt.Al}} = \text{Al}/(\text{Al} + \text{Cr})$$

$$x^{\text{Gt.Cr}} = \text{Cr}/(\text{Cr} + \text{Al})$$

$$x^{\text{Gt.Ca}} = \text{Ca}/(\text{Ca} + \text{Mg} + \text{Fe} + \text{Mn})$$

$$x^{\text{Gt.Fe}} = \text{Fe}/(\text{Ca} + \text{Mg} + \text{Fe} + \text{Mn})$$

$$x^{\text{Gt.Mg}} = \text{Mg}/(\text{Ca} + \text{Mg} + \text{Fe} + \text{Mn})$$

APPENDIX 3 : ANALYTICAL RESULTS

The following abbreviations are in use throughout this appendix:

Rocktypes

Peridotite-pyroxenite suite

GLd	- deformed garnet lherzolite
GLc	- coarse-textured garnet lherzolite
Lc	- coarse-textured lherzolite
GWc	- coarse-textured garnet wehrlite
GHS	- subcalcic garnet harzburgite
GH	- garnet harzburgite
Sp	- spinel lherzolite
P	- pyroxenite
D	- dunite
A	- alkremite

Metasomatized peridotite-pyroxenite suite

GPP	- phlogopite-bearing garnet peridotite
PP	- phlogopite-bearing peridotite
MP	- metasomatized pyroxenite

Eclogites

I	- Group I eclogite (i.e. $\text{Na}_2\text{O} > 0.07 \text{ wt\%}$)
II	- Group II eclogite (i.e. $\text{Na}_2\text{O} \leq 0.07 \text{ wt\%}$)

Megacrysts and intergrowths

M	- megacryst
GS	- Granny Smith clinopyroxene megacryst
CII	- clinopyroxene-ilmenite intergrowth
OII	- orthopyroxene-ilmenite intergrowth
CGI	- clinopyroxene-garnet intergrowth
MARID	- mica-amphibole-rutile-ilmenite-diopside rock
GLM	- glimmerite

Ratios

Gr	- $100 * (\text{Ca} / (\text{Ca} + \text{Mg} + \text{Fe}))$
Py	- $100 * (\text{Mg} / (\text{Ca} + \text{Mg} + \text{Fe}))$
Al	- $100 * (\text{Fe} / (\text{Ca} + \text{Mg} + \text{Fe}))$
Jd	- $100 * (\text{Na} + \text{Al} + \text{Cr}) / (\text{Na} + \text{Al} + \text{Cr} + \text{Ca} + \text{Mg} + \text{Fe} + \text{Mn})$
Wo	- $100 * (\text{Ca}) / (\text{Na} + \text{Al} + \text{Cr} + \text{Ca} + \text{Mg} + \text{Fe} + \text{Mn})$
Hy	- $100 * (\text{Mg} + \text{Fe} + \text{Mn}) / (\text{Na} + \text{Al} + \text{Cr} + \text{Ca} + \text{Mg} + \text{Fe} + \text{Mn})$
$X_{\text{Ca.gt}}$	- $\text{Ca} / (\text{Ca} + \text{Mg} + \text{Fe} + \text{Mn})$ in garnet
K_d	- $(\text{Fe}/\text{Mg})_{\text{gt}} / (\text{Fe}/\text{Mg})_{\text{cpx}}$ where $\text{Fe} = \text{Fe}^{2+}$

All mineral phases which have been analyzed in this study are included here. Data are presented as averages and accompanied by a standard deviation about the mean to provide some indication of the variation of oxides in the minerals. All analyses represent cores of the various minerals. Examples of zoning traverses have been presented in the various chapters. All Fe in these analyses and in $\text{Mg}/(\text{Mg}+\text{Fe})$ ratios should be taken as Fe^{2+} .

A separate appendix containing representative analyses of phases in each sample is provided on computer diskette in the back folder along with lists of the various files. The datafiles have been saved in ASCII format and it is therefore possible to import these files into most wordprocessors and/or DOS.

APPENDIX 3a : OLIVINE

Olivine

Sample numbers followed by a letter, eg. JSL 565A, indicate that more than one polished thin section of the particular sample was prepared.

Each average is followed by the standard deviation about the mean.

Sample no. Rocktype n	JSL108 GLd 5		JSL112 GLd 6		JSL119 GLd 6		JSL126 GLd 6		JSL140 GLd 3		JSL279 GLd 6	
SiO ₂	40.51	0.13	40.28	0.26	39.71	0.22	40.81	0.19	40.73	0.05	40.98	0.17
FeO	9.43	0.07	10.24	0.10	9.46	0.04	9.38	0.19	9.79	0.12	9.17	0.12
MnO	0.10	0.01	0.10	0.01	0.09	0.01	0.11	0.01	0.09	0.00	0.12	0.01
NiO	0.37	0.02	0.36	0.02	0.35	0.02	0.44	0.05	0.28	0.02	0.39	0.02
MgO	48.96	0.14	49.10	0.19	50.29	0.10	49.37	0.20	49.72	0.13	49.48	0.20
CaO	0.02	0.01	0.03	0.01	0.02	0.01	0.01	0.01	0.02	0.00	0.01	0.01
Total	99.39	0.26	100.12	0.24	99.92	0.28	100.12	0.21	100.62	0.29	100.16	0.22

Cations (recalculated to 4 oxygens)

Si	0.998	0.001	0.990	0.005	0.976	0.002	0.998	0.004	0.993	0.001	1.001	0.003
Fe	0.194	0.001	0.210	0.002	0.194	0.001	0.192	0.004	0.200	0.002	0.187	0.003
Mn	0.002	0.000	0.002	0.000	0.002	0.000	0.002	0.000	0.002	0.000	0.002	0.000
Ni	0.007	0.000	0.007	0.000	0.007	0.000	0.009	0.001	0.006	0.000	0.008	0.000
Mg	1.799	0.003	1.799	0.008	1.843	0.004	1.800	0.007	1.807	0.002	1.801	0.005
Ca	0.001	0.000	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	3.002	0.001	3.010	0.005	3.024	0.002	3.002	0.004	3.007	0.001	2.999	0.003
Mg/(Mg+Fe)	0.903	0.001	0.895	0.001	0.905	0.000	0.904	0.002	0.901	0.001	0.906	0.001

Sample no. Rocktype n	JSL280 GLd 6		JSL113 GHs 6		JSL262 GHs 3		JSL266 GHs 3		JSL267 GHs 3		JSL268 GHs 3	
SiO ₂	40.80	0.28	40.85	0.09	41.09	0.16	41.47	0.13	41.21	0.07	41.69	0.10
FeO	9.91	0.05	7.03	0.10	7.29	0.13	6.48	0.05	6.74	0.04	6.46	0.05
MnO	0.11	0.00	0.08	0.00	0.08	0.01	0.09	0.02	0.08	0.00	0.10	0.01
NiO	0.37	0.04	0.35	0.02	0.43	0.02	0.39	0.01	0.39	0.05	0.42	0.04
MgO	48.75	0.31	51.34	0.13	50.64	0.06	51.47	0.19	50.78	0.03	51.40	0.10
CaO	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00
Total	99.98	0.60	99.66	0.24	99.54	0.23	99.89	0.35	99.21	0.14	100.09	0.21

Cations (recalculated to 4 oxygens)

Si	1.001	0.001	0.994	0.002	1.001	0.002	1.003	0.001	1.004	0.001	1.006	0.001
Fe	0.203	0.002	0.143	0.002	0.149	0.002	0.131	0.001	0.137	0.001	0.130	0.001
Mn	0.002	0.000	0.002	0.000	0.002	0.000	0.002	0.000	0.002	0.000	0.002	0.000
Ni	0.007	0.001	0.007	0.000	0.008	0.000	0.007	0.000	0.008	0.001	0.008	0.001
Mg	1.783	0.001	1.861	0.003	1.839	0.006	1.855	0.002	1.844	0.002	1.848	0.001
Ca	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	2.999	0.001	3.006	0.002	2.999	0.002	2.997	0.001	2.996	0.001	2.994	0.001
Mg/(Mg+Fe)	0.898	0.001	0.929	0.001	0.925	0.001	0.934	0.000	0.931	0.000	0.934	0.001

Sample no. Rocktype n	JSL170 GH 4		JSL263 GH 7		JSL124 Sp 7		JSL153 Sp 9		JSL154 Sp 7		JSL156 Sp 9	
SiO ₂	40.99	0.08	41.05	0.22	40.88	0.16	41.04	0.16	41.13	0.17	40.90	0.14
FeO	8.12	0.11	8.08	0.16	7.61	0.16	6.74	0.12	6.29	0.09	7.56	0.15
MnO	0.07	0.02	0.11	0.01	0.08	0.01	0.08	0.01	0.08	0.01	0.09	0.01
NiO	0.35	0.03	0.37	0.03	0.37	0.02	0.40	0.02	0.36	0.03	0.41	0.02
MgO	49.98	0.05	50.30	0.31	51.12	0.27	51.48	0.22	51.90	0.20	50.77	0.18
CaO	0.00	0.01	0.02	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Total	99.51	0.19	99.93	0.46	100.09	0.40	99.74	0.35	99.76	0.16	99.73	0.37

Cations (recalculated to 4 oxygens)

Si	1.001	0.001	1.000	0.004	0.993	0.004	0.996	0.002	0.996	0.004	0.996	0.002
Fe	0.167	0.003	0.165	0.003	0.155	0.003	0.137	0.002	0.127	0.002	0.154	0.003
Mn	0.001	0.001	0.002	0.000	0.002	0.000	0.002	0.000	0.002	0.000	0.002	0.000
Ni	0.008	0.001	0.007	0.001	0.007	0.000	0.008	0.000	0.007	0.001	0.008	0.000
Mg	1.821	0.002	1.826	0.005	1.850	0.005	1.862	0.005	1.873	0.007	1.843	0.002
Ca	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	2.999	0.001	3.000	0.004	3.007	0.004	3.004	0.002	3.004	0.004	3.004	0.002
Mg/(Mg+Fe)	0.918	0.002	0.917	0.001	92.290	0.129	0.932	0.001	0.936	0.001	0.923	0.001

Sample no. Rocktype n	JSL157 Sp 3		JSL158 Sp 9		JSL166 D 10		JSL116 GLc 3		JSL134 GLc 5		JSL-/193 GLc 9	
SiO2	40.43	0.32	41.07	0.16	40.86	0.13	41.03	0.14	40.61	0.24	40.67	0.25
FeO	7.23	0.08	8.31	0.46	8.16	0.09	7.84	0.05	8.00	0.05	7.36	0.10
MnO	0.07	0.01	0.11	0.01	0.10	0.01	0.07	0.01	0.16	0.01	0.14	0.02
NiO	0.43	0.01	0.38	0.02	0.38	0.02	0.41	0.04	0.40	0.01	0.43	0.01
MgO	51.55	0.09	49.56	0.25	50.45	0.18	50.68	0.16	50.15	0.20	51.32	0.37
CaO	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.01	0.01	0.02	0.00
Total	99.71	0.35	99.44	0.23	99.97	0.32	100.03	0.32	99.34	0.25	99.94	0.30

Cations (recalculated to 4 oxygens)

Si	0.985	0.004	1.006	0.003	0.996	0.002	0.997	0.001	0.996	0.004	0.989	0.005
Fe	0.147	0.001	0.170	0.010	0.166	0.002	0.159	0.001	0.164	0.001	0.150	0.002
Mn	0.001	0.000	0.002	0.000	0.002	0.000	0.001	0.000	0.003	0.000	0.003	0.000
Ni	0.009	0.000	0.008	0.000	0.008	0.000	0.008	0.001	0.008	0.000	0.008	0.000
Mg	1.872	0.010	1.809	0.009	1.833	0.003	1.836	0.001	1.833	0.008	1.860	0.012
Ca	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000
Total	3.015	0.004	2.994	0.003	3.004	0.002	3.003	0.001	3.004	0.004	3.011	0.005

Mg/(Mg + Fe)	0.927	0.001	0.914	0.005	0.917	0.001	0.920	0.001	91.790	0.046	92.553	0.133

Sample no. Rocktype n	JSL261 GLc 2		JSL306 Lc 1	JSL306 Lc 2		JSL-/91 GPP 3		JSL142 GPP 6		JSL143 GPP 5	
SiO2	41.63	0.06	40.49	40.67	0.04	40.62	0.07	40.69	0.10	41.44	0.21
FeO	6.87	0.02	9.08	8.83	0.09	7.96	0.05	7.95	0.07	6.51	0.04
MnO	0.08	0.00	0.21	0.21	0.01	0.17	0.01	0.10	0.01	0.07	0.01
NiO	0.40	0.02	0.36	0.30	0.00	0.35	0.01	0.34	0.03	0.42	0.04
MgO	51.48	0.04	49.06	49.17	0.03	50.78	0.16	51.15	0.23	51.50	0.11
CaO	0.00	0.00	0.03	0.02	0.00	0.01	0.00	0.01	0.01	0.01	0.01
Total	100.46	0.02	99.23	99.20	0.15	99.89	0.22	100.24	0.29	99.94	0.20

Cations (recalculated to 4 oxygens)

Si	1.002	0.001	0.999	1.001	0.000	0.991	0.000	0.989	0.003	1.001	0.003
Fe	0.138	0.000	0.187	0.182	0.002	0.162	0.001	0.162	0.001	0.131	0.001
Mn	0.002	0.000	0.004	0.004	0.000	0.004	0.000	0.002	0.000	0.001	0.001
Ni	0.008	0.000	0.007	0.006	0.000	0.007	0.000	0.007	0.001	0.008	0.001
Mg	1.848	0.002	1.803	1.805	0.001	1.846	0.002	1.852	0.005	1.855	0.006
Ca	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	2.998	0.001	3.002	2.999	0.000	3.009	0.000	3.011	0.003	2.999	0.003

Mg/(Mg + Fe)	0.930	0.000	90.590	90.845	0.075	91.917	0.059	0.920	0.001	0.933	0.002

Sample no. Rocktype n	JSL-/177 GPP 4		JSL278 GPP 5		JSL504 GPP 3		JSL533 GPP 4		JSL572 GPP 4	
SiO2	40.67	0.23	40.99	0.13	40.18	0.13	40.03	0.12	40.24	0.07
FeO	8.15	0.07	8.50	0.06	8.42	0.10	7.76	0.03	8.30	0.11
MnO	0.17	0.01	0.07	0.01	0.10	0.02	0.11	0.02	0.12	0.01
NiO	0.42	0.02	0.40	0.01	0.40	0.01	0.37	0.01	0.35	0.02
MgO	50.38	0.23	49.78	0.36	50.85	0.03	51.04	0.17	50.37	0.17
CaO	0.03	0.00	0.00	0.00	0.02	0.01	0.02	0.01	0.02	0.01
Total	99.82	0.28	99.74	0.42	99.98	0.15	99.33	0.19	99.40	0.25

Cations (recalculated to 4 oxygens)

Si	0.994	0.004	1.002	0.003	0.982	0.002	0.982	0.002	0.988	0.002
Fe	0.166	0.001	0.174	0.001	0.172	0.002	0.159	0.001	0.170	0.002
Mn	0.003	0.000	0.002	0.000	0.002	0.000	0.002	0.000	0.003	0.000
Ni	0.008	0.000	0.008	0.000	0.008	0.000	0.007	0.000	0.007	0.000
Mg	1.834	0.007	1.813	0.007	1.853	0.004	1.867	0.004	1.844	0.003
Ca	0.001	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.001	0.000
Total	3.006	0.004	2.998	0.003	3.018	0.002	3.018	0.002	3.012	0.002

Mg/(Mg + Fe)	91.678	0.033	0.913	0.001	0.915	0.001	0.921	0.000	0.915	0.001

Sample no. Rocktype n	JSL-93 PP 3		JSL167 PP 5		JSL273 PP 3		JSL303 PP 3		JSL304 PP 3		JSL500A PP 8	
SiO ₂	40.90	0.10	41.18	0.22	40.03	0.05	39.70	0.09	41.06	0.19	39.96	0.17
FeO	7.42	0.02	6.61	0.09	8.64	0.01	10.70	0.02	6.93	0.07	11.37	0.07
MnO	0.16	0.01	0.07	0.01	0.12	0.01	0.22	0.01	0.14	0.00	0.16	0.01
NiO	0.44	0.01	0.36	0.04	0.40	0.02	0.33	0.01	0.38	0.01	0.33	0.01
MgO	51.00	0.24	51.42	0.19	50.42	0.15	48.56	0.04	51.18	0.20	47.91	0.18
CaO	0.03	0.00	0.00	0.00	0.02	0.01	0.02	0.00	0.03	0.01	0.02	0.00
Total	99.96	0.28	99.64	0.13	99.63	0.19	99.52	0.08	99.73	0.36	99.75	0.26

Cations (recalculated to 4 oxygens)

Si	0.994	0.002	0.999	0.004	0.983	0.001	0.985	0.001	0.998	0.001	0.991	0.002
Fe	0.151	0.001	0.134	0.002	0.177	0.000	0.222	0.001	0.141	0.001	0.236	0.002
Mn	0.003	0.000	0.001	0.000	0.002	0.000	0.005	0.000	0.003	0.000	0.003	0.000
Ni	0.009	0.000	0.007	0.001	0.008	0.000	0.007	0.000	0.007	0.000	0.007	0.000
Mg	1.848	0.004	1.859	0.008	1.846	0.002	1.796	0.002	1.853	0.003	1.771	0.004
Ca	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000
Total	3.006	0.002	3.001	0.004	3.017	0.001	3.015	0.001	3.002	0.001	3.009	0.002

Mg/(Mg+Fe)	92.450	0.050	0.933	0.001	0.912	0.000	89.000	0.024	92.937	0.076	88.251	0.099

Sample no. Rocktype n	JSL500B PP 12		JSL511A PP 5		JSL511B PP 6		JSL516 PP 3		JSL520 PP 6	
SiO ₂	39.71	0.26	40.04	0.17	40.38	0.14	40.08	0.14	39.49	0.42
FeO	11.18	0.10	11.66	0.16	11.27	0.14	7.76	0.20	8.50	0.14
MnO	0.19	0.02	0.09	0.01	0.06	0.01	0.12	0.00	0.12	0.01
NiO	0.32	0.03	0.28	0.01	0.30	0.01	0.38	0.02	0.34	0.03
MgO	48.49	0.31	48.03	0.09	48.09	0.10	51.14	0.16	51.22	0.38
CaO	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.03	0.00
Total	99.92	0.55	100.10	0.29	100.12	0.30	99.49	0.22	99.70	0.17

Cations (recalculated to 4 oxygens)

Si	0.984	0.002	0.990	0.002	0.996	0.002	0.982	0.002	0.970	0.009
Fe	0.232	0.002	0.241	0.003	0.232	0.002	0.159	0.004	0.175	0.003
Mn	0.004	0.000	0.002	0.000	0.001	0.000	0.002	0.000	0.003	0.000
Ni	0.006	0.001	0.005	0.000	0.006	0.000	0.007	0.000	0.007	0.001
Mg	1.790	0.005	1.771	0.005	1.768	0.003	1.867	0.007	1.875	0.017
Ca	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000
Total	3.016	0.002	3.010	0.002	3.004	0.002	3.018	0.002	3.030	0.009

Mg/(Mg+Fe)	88.545	0.116	0.880	0.001	0.884	0.001	0.922	0.002	0.915	0.001

Sample no. Rocktype n	JSL520A PP 4		JSL532 PP 4		JSL547 PP 4		JSL565 PP 4		JSL565A PP 5	
SiO ₂	39.73	0.31	39.85	0.09	40.44	0.19	40.53	0.21	40.57	0.16
FeO	9.59	0.07	8.89	0.05	7.47	0.07	8.23	0.09	8.34	0.09
MnO	0.13	0.00	0.13	0.01	0.12	0.02	0.11	0.01	0.12	0.01
NiO	0.34	0.02	0.34	0.02	0.39	0.03	0.37	0.02	0.34	0.03
MgO	50.64	0.07	49.94	0.10	51.11	0.13	50.50	0.19	50.43	0.21
CaO	0.02	0.00	0.03	0.02	0.02	0.01	0.02	0.01	0.02	0.01
Total	99.44	0.31	99.17	0.11	99.55	0.20	99.75	0.43	99.82	0.33

Cations (recalculated to 4 oxygens)

Si	0.978	0.004	0.984	0.002	0.988	0.003	0.991	0.001	0.991	0.002
Fe	0.177	0.002	0.184	0.001	0.153	0.002	0.168	0.002	0.170	0.002
Mn	0.003	0.000	0.003	0.000	0.002	0.000	0.002	0.000	0.003	0.000
Ni	0.007	0.000	0.007	0.000	0.008	0.000	0.007	0.000	0.007	0.001
Mg	1.858	0.006	1.838	0.004	1.861	0.005	1.840	0.003	1.837	0.005
Ca	0.001	0.000	0.001	0.001	0.001	0.000	0.000	0.000	0.001	0.000
Total	3.022	0.004	3.016	0.002	3.012	0.003	3.009	0.001	3.009	0.002

Mg/(Mg+Fe)	0.913	0.001	0.909	0.000	0.924	0.001	0.916	0.001	0.915	0.001

APPENDIX 3b : GARNET

Garnet

Sample numbers followed by a letter, eg. JSL 600A, indicate that more than one polished thin section of the particular sample was prepared.

Each average is followed by the standard deviation about the mean. Grainmounts of eclogite minerals are represented by single analyses.

Sample no. Rocktype n	JSL108 GLd 5	JSL112 GLd 6	JSL119 GLd 6	JSL126 GLd 6	JSL140 GLd 3	JSL279 GLd 6						
SiO ₂	41.72	0.11	42.42	0.12	41.95	0.17	41.77	0.24	41.76	0.09	41.79	0.18
TiO ₂	1.02	0.03	0.74	0.04	0.31	0.07	0.17	0.04	0.90	0.04	0.14	0.01
Al ₂ O ₃	18.02	0.39	20.43	0.07	19.83	0.14	19.89	0.21	19.56	0.08	19.77	0.07
Cr ₂ O ₃	5.36	0.43	2.45	0.14	3.72	0.03	4.22	0.08	3.15	0.05	4.10	0.07
FeO	7.04	0.09	7.13	0.19	7.37	0.10	7.04	0.11	7.36	0.08	7.24	0.12
MnO	0.31	0.03	0.26	0.03	0.31	0.02	0.33	0.02	0.32	0.02	0.31	0.02
NiO	0.01	0.02	0.02	0.01	0.02	0.02	0.01	0.01	0.02	0.01	0.02	0.02
MgO	21.25	0.22	22.29	0.18	21.12	0.15	21.25	0.12	21.75	0.06	21.08	0.10
CaO	5.27	0.10	4.47	0.08	5.36	0.13	5.54	0.09	4.64	0.04	5.49	0.05
Na ₂ O	0.09	0.01	0.08	0.01	0.04	0.01	0.03	0.01	0.11	0.01	0.02	0.00
Total	100.08	0.16	100.30	0.52	100.04	0.46	100.24	0.57	99.57	0.19	99.96	0.43
Cations (recalculated to 12 oxygens)												
Si	3.003	0.005	3.007	0.006	3.005	0.004	2.988	0.008	2.999	0.002	2.998	0.003
Ti	0.055	0.001	0.039	0.002	0.017	0.004	0.009	0.002	0.048	0.002	0.007	0.001
Al	1.528	0.029	1.707	0.006	1.674	0.006	1.676	0.010	1.655	0.005	1.672	0.006
Cr	0.305	0.025	0.137	0.008	0.210	0.003	0.238	0.004	0.179	0.003	0.232	0.003
Fe	0.424	0.006	0.423	0.010	0.442	0.005	0.421	0.005	0.442	0.004	0.434	0.007
Mn	0.019	0.002	0.016	0.002	0.019	0.001	0.020	0.001	0.020	0.001	0.019	0.001
Ni	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Mg	2.279	0.023	2.355	0.010	2.255	0.016	2.266	0.014	2.327	0.010	2.254	0.005
Ca	0.406	0.008	0.339	0.006	0.411	0.010	0.424	0.007	0.357	0.003	0.422	0.004
Na	0.013	0.001	0.012	0.001	0.006	0.002	0.004	0.001	0.015	0.001	0.002	0.001
Total	8.032	0.009	8.037	0.008	8.039	0.006	8.048	0.006	8.043	0.004	8.043	0.002
Gr	13.064	0.299	10.885	0.213	13.223	0.266	13.643	0.259	11.414	0.084	13.578	0.113
Py	73.312	0.348	75.549	0.182	72.568	0.391	72.815	0.202	74.441	0.192	72.457	0.182
Al	13.624	0.129	13.566	0.239	14.209	0.193	13.542	0.162	14.145	0.116	13.965	0.208

Sample no. Rocktype n	JSL280 GLd 6	JSL113 GHs 6	JSL262 GHs 3	JSL266 GHs 3	JSL267 GHs 4	JSL268 GHs 3						
SiO ₂	42.44	0.13	41.55	0.19	41.06	0.08	41.39	0.04	41.67	0.20	42.02	0.05
TiO ₂	0.91	0.01	0.02	0.01	0.06	0.02	0.04	0.01	0.02	0.00	0.06	0.01
Al ₂ O ₃	20.49	0.12	17.05	0.08	18.45	0.07	15.85	0.04	19.32	0.10	20.55	0.18
Cr ₂ O ₃	2.08	0.04	9.19	0.10	7.00	0.05	11.02	0.03	6.12	0.06	4.71	0.36
FeO	7.63	0.09	5.86	0.19	6.73	0.06	5.37	0.03	6.09	0.05	6.38	0.02
MnO	0.27	0.03	0.32	0.02	0.38	0.02	0.34	0.02	0.35	0.04	0.43	0.01
NiO	0.01	0.01	0.03	0.02	0.01	0.01	0.01	0.02	0.00	0.00	0.00	0.00
MgO	22.03	0.10	23.88	0.29	20.83	0.13	23.50	0.10	22.40	0.13	23.28	0.35
CaO	4.45	0.02	2.18	0.04	4.87	0.11	2.43	0.01	3.79	0.28	2.71	0.53
Na ₂ O	0.08	0.01	0.04	0.01	0.04	0.00	0.00	0.00	0.01	0.01	0.04	0.00
Total	100.39	0.25	100.11	0.40	99.41	0.13	99.95	0.03	99.78	0.26	100.18	0.06
Cations (recalculated to 12 oxygens)												
Si	3.009	0.007	2.980	0.006	2.979	0.007	2.986	0.002	2.983	0.007	2.977	0.003
Ti	0.049	0.001	0.001	0.001	0.003	0.001	0.002	0.001	0.001	0.000	0.003	0.000
Al	1.712	0.008	1.441	0.006	1.578	0.005	1.348	0.004	1.630	0.004	1.716	0.015
Cr	0.117	0.002	0.521	0.006	0.401	0.003	0.628	0.002	0.346	0.003	0.264	0.020
Fe	0.452	0.005	0.351	0.010	0.408	0.004	0.324	0.002	0.365	0.002	0.378	0.001
Mn	0.016	0.002	0.020	0.001	0.023	0.001	0.021	0.001	0.021	0.002	0.026	0.001
Ni	0.001	0.001	0.002	0.001	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.000
Mg	2.329	0.011	2.553	0.033	2.253	0.012	2.526	0.010	2.390	0.011	2.459	0.038
Ca	0.338	0.001	0.168	0.003	0.379	0.008	0.188	0.001	0.291	0.022	0.205	0.040
Na	0.011	0.001	0.005	0.001	0.005	0.000	0.001	0.000	0.001	0.001	0.006	0.000
Total	8.033	0.006	8.041	0.010	8.031	0.004	8.024	0.003	8.029	0.008	8.033	0.001
Gr	10.830	0.057	5.463	0.134	12.453	0.269	6.193	0.052	9.546	0.674	6.748	1.301
Py	74.671	0.148	83.103	0.498	74.117	0.328	83.153	0.123	78.478	0.581	80.821	1.318
Al	14.499	0.142	11.434	0.391	13.430	0.162	10.654	0.072	11.975	0.106	12.430	0.026

Sample no. Rocktype n	JSL170 GH 4		JSL263 GH 7		JSL114 GWc 8		JSL116 GLc 3		JSL134 GLc 3		JSL-/193 GLc 3	
SiO2	41.56	0.21	41.69	0.16	41.06	0.26	40.95	0.10	41.42	0.15	41.34	0.13
TiO2	0.05	0.01	0.08	0.02	0.40	0.02	0.10	0.01	0.30	0.01	0.03	0.00
Al2O3	21.25	0.49	16.42	0.10	17.97	0.30	18.59	0.03	20.00	0.05	19.45	0.01
Cr2O3	2.87	0.57	8.54	0.06	7.11	0.31	6.29	0.07	5.13	0.06	6.41	0.08
FeO	7.67	0.10	6.37	0.16	6.29	0.08	6.84	0.05	7.27	0.04	6.95	0.10
MnO	0.48	0.02	0.29	0.02	0.34	0.02	0.36	0.01	0.36	0.02	0.35	0.03
NiO	0.02	0.02	0.02	0.02	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01
MgO	20.32	0.33	20.50	0.14	20.46	0.24	21.26	0.10	20.12	0.17	20.47	0.18
CaO	5.42	0.27	6.13	0.07	6.61	0.13	5.30	0.11	5.33	0.02	5.06	0.00
Na2O	0.01	0.01	0.01	0.01	0.03	0.01	0.04	0.00	0.08	0.01	0.06	0.01
Total	99.65	0.16	100.05	0.36	100.28	0.16	99.74	0.21	100.02	0.27	100.13	0.20
Cations (recalculated to 12 oxygens)												
Si	2.984	0.005	3.025	0.011	2.966	0.016	2.964	0.002	2.978	0.006	2.974	0.003
Ti	0.003	0.001	0.004	0.001	0.022	0.001	0.005	0.001	0.016	0.000	0.002	0.000
Al	1.798	0.034	1.404	0.006	1.530	0.025	1.586	0.004	1.695	0.000	1.649	0.004
Cr	0.163	0.033	0.490	0.003	0.406	0.018	0.360	0.003	0.292	0.003	0.365	0.006
Fe	0.461	0.007	0.386	0.009	0.380	0.005	0.414	0.002	0.437	0.001	0.418	0.006
Mn	0.029	0.001	0.018	0.001	0.021	0.001	0.022	0.001	0.022	0.001	0.021	0.002
Ni	0.001	0.001	0.001	0.001	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.001
Mg	2.175	0.026	2.217	0.017	2.203	0.025	2.293	0.014	2.156	0.019	2.195	0.014
Ca	0.417	0.022	0.477	0.004	0.512	0.011	0.411	0.008	0.411	0.001	0.390	0.001
Na	0.001	0.001	0.002	0.001	0.004	0.001	0.006	0.001	0.012	0.001	0.009	0.001
Total	8.033	0.006	8.024	0.011	8.046	0.013	8.061	0.002	8.019	0.008	8.023	0.004
Gr	13.654	0.706	15.477	0.101	16.540	0.378	13.178	0.261	13.673	0.107	12.997	0.085
Py	71.256	0.911	71.977	0.313	71.181	0.495	73.543	0.353	71.777	0.221	73.087	0.228
Al	15.090	0.210	12.546	0.260	12.279	0.148	13.279	0.094	14.550	0.110	13.923	0.200

Sample no. Rocktype n	JSL261 GLc 2		JSL250 A 3		JSL171 P 3		JSL202 P 4		JSL209 P 4		JSL296 P 3	
SiO2	41.07	0.07	41.90	0.17	41.54	0.08	40.74	0.03	42.01	0.18	42.00	0.33
TiO2	0.15	0.02	0.08	0.02	0.08	0.01	0.05	0.01	0.08	0.02	0.31	0.01
Al2O3	17.78	0.05	22.66	0.03	22.91	0.04	22.89	0.06	23.28	0.12	22.44	0.11
Cr2O3	7.61	0.11	1.36	0.02	0.61	0.06	0.23	0.02	0.44	0.06	1.41	0.09
FeO	6.38	0.04	8.51	0.11	9.35	0.03	15.31	0.23	7.90	0.10	7.95	0.10
MnO	0.35	0.01	0.32	0.01	0.36	0.01	0.42	0.01	0.40	0.01	0.34	0.01
NiO	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.03	0.02
MgO	20.09	0.07	20.39	0.10	20.33	0.31	16.65	0.16	21.72	0.07	21.55	0.14
CaO	6.16	0.04	4.87	0.08	4.49	0.06	3.73	0.03	4.44	0.04	3.96	0.03
Na2O	0.03	0.00	0.02	0.00	0.02	0.01	0.02	0.00	0.03	0.01	0.07	0.00
Total	99.63	0.18	100.14	0.14	99.71	0.28	100.06	0.34	100.29	0.34	100.06	0.69
Cations (recalculated to 12 oxygens)												
Si	2.986	0.001	2.982	0.010	2.973	0.011	2.976	0.006	2.967	0.003	2.979	0.003
Ti	0.008	0.001	0.004	0.001	0.005	0.001	0.003	0.001	0.004	0.001	0.017	0.000
Al	1.524	0.001	1.901	0.002	1.932	0.004	1.970	0.002	1.938	0.005	1.875	0.009
Cr	0.438	0.007	0.077	0.001	0.034	0.003	0.013	0.001	0.024	0.003	0.079	0.005
Fe	0.388	0.002	0.507	0.007	0.560	0.002	0.935	0.012	0.467	0.006	0.472	0.003
Mn	0.022	0.000	0.019	0.000	0.022	0.001	0.026	0.001	0.024	0.001	0.020	0.000
Ni	0.001	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.002	0.001
Mg	2.177	0.003	2.163	0.013	2.169	0.028	1.812	0.014	2.286	0.003	2.278	0.004
Ca	0.480	0.002	0.371	0.006	0.344	0.004	0.292	0.002	0.336	0.003	0.301	0.002
Na	0.004	0.001	0.003	0.000	0.002	0.001	0.003	0.001	0.004	0.001	0.010	0.000
Total	8.027	0.003	8.027	0.010	8.041	0.015	8.031	0.007	8.050	0.002	8.032	0.001
Gr	15.755	0.037	12.214	0.141	11.206	0.038	9.605	0.099	10.886	0.107	9.863	0.064
Py	71.511	0.067	71.126	0.301	70.573	0.218	59.624	0.346	74.007	0.109	74.677	0.132
Al	12.734	0.030	16.661	0.160	18.221	0.213	30.770	0.350	15.107	0.186	15.460	0.097

Sample no. Rocktype n	JSL/91 GPP 3		JSL111 GPP 6		JSL142 GPP 6		JSL143 GPP 4		JSL151 GPP 3		JSL-/177 GPP 1
SiO2	41.28	0.21	41.05	0.12	42.32	0.09	41.38	0.21	41.18	0.13	41.63
TiO2	0.27	0.01	0.33	0.02	0.11	0.02	0.13	0.11	0.19	0.01	0.09
Al2O3	19.16	0.13	19.11	0.18	21.63	0.10	17.92	0.28	19.15	0.08	19.85
Cr2O3	6.66	0.05	5.31	0.09	2.85	0.08	7.83	0.19	6.14	0.06	5.20
FeO	7.31	0.08	7.92	0.20	6.60	0.11	6.37	0.09	6.11	0.03	7.00
MnO	0.39	0.03	0.41	0.03	0.34	0.02	0.38	0.01	0.30	0.02	0.36
NiO	0.04	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.04	0.01	0.00
MgO	19.87	0.29	21.11	0.13	22.07	0.14	22.01	0.21	20.41	0.15	20.46
CaO	5.38	0.10	4.62	0.12	4.46	0.08	4.44	0.30	6.20	0.02	5.45
Na2O	0.09	0.01	0.08	0.01	0.04	0.01	0.04	0.02	0.01	0.00	0.07
Total	100.43	0.42	99.95	0.62	100.43	0.41	100.50	0.14	99.72	0.21	100.09

Cations (recalculated to 12 oxygens)

Si	2.972	0.003	2.965	0.011	2.988	0.009	2.971	0.008	2.972	0.008	2.988
Ti	0.015	0.001	0.018	0.001	0.005	0.002	0.007	0.006	0.010	0.001	0.005
Al	1.626	0.016	1.627	0.011	1.800	0.004	1.516	0.020	1.629	0.005	1.679
Cr	0.379	0.003	0.303	0.004	0.160	0.004	0.444	0.012	0.351	0.004	0.295
Fe	0.440	0.006	0.478	0.010	0.389	0.005	0.382	0.006	0.369	0.003	0.420
Mn	0.024	0.002	0.025	0.002	0.020	0.001	0.023	0.001	0.018	0.001	0.022
Ni	0.002	0.001	0.000	0.001	0.000	0.000	0.000	0.001	0.003	0.001	0.000
Mg	2.132	0.024	2.273	0.008	2.322	0.008	2.355	0.018	2.196	0.012	2.188
Ca	0.415	0.007	0.357	0.008	0.338	0.005	0.341	0.024	0.479	0.002	0.419
Na	0.012	0.001	0.011	0.001	0.006	0.002	0.005	0.002	0.002	0.000	0.010
Total	8.017	0.008	8.058	0.009	8.030	0.007	8.045	0.005	8.029	0.007	8.026
Gr	13.883	0.106	11.492	0.219	11.068	0.169	11.085	0.751	15.743	0.082	13.840
Py	71.383	0.224	73.126	0.330	76.161	0.131	76.496	0.773	72.133	0.198	72.280
Al	14.733	0.326	15.381	0.271	12.772	0.143	12.419	0.172	12.123	0.111	13.830

Sample no. Rocktype n	JSL278 GPP 5		JSL504 GPP 3		JSL533 GPP 2		JSL572 GPP 5		JSL25 MP 2		JSL75 MP 4	
SiO2	41.82	0.17	40.48	0.38	40.49	0.18	40.77	0.32	41.66	0.11	42.36	0.09
TiO2	0.08	0.01	0.25	0.01	0.21	0.00	1.28	0.49	0.07	0.00	0.05	0.00
Al2O3	22.17	0.12	19.30	0.14	18.34	0.03	19.54	0.68	23.04	0.03	23.78	0.09
Cr2O3	1.82	0.06	6.15	0.07	7.26	0.01	3.74	1.37	0.39	0.06	0.08	0.00
FeO	7.91	0.07	7.70	0.14	7.46	0.01	7.77	0.42	10.74	0.06	8.97	0.51
MnO	0.48	0.02	0.42	0.03	0.43	0.02	0.35	0.09	0.45	0.01	0.34	0.01
NiO	0.03	0.01	0.01	0.01	0.01	0.00	0.02	0.01	0.00	0.00	0.03	0.03
MgO	20.58	0.05	20.17	0.11	20.17	0.01	19.92	1.26	19.47	0.10	20.73	0.37
CaO	4.62	0.01	5.56	0.10	5.38	0.03	6.28	1.25	4.59	0.01	4.28	0.10
Na2O	0.02	0.01	0.04	0.00	0.06	0.01	0.08	0.02	0.02	0.00	0.03	0.01
Total	99.53	0.26	100.08	0.52	99.81	0.16	99.74	0.27	100.43	0.05	100.65	0.20

Cations (recalculated to 12 oxygens)

Si	2.991	0.006	2.933	0.012	2.948	0.007	2.952	0.010	2.977	0.007	2.986	0.003
Ti	0.004	0.001	0.014	0.001	0.012	0.000	0.070	0.027	0.004	0.000	0.003	0.000
Al	1.869	0.007	1.648	0.006	1.574	0.005	1.667	0.045	1.940	0.003	1.975	0.003
Cr	0.103	0.003	0.352	0.005	0.418	0.001	0.214	0.079	0.022	0.003	0.004	0.000
Fe	0.473	0.004	0.467	0.006	0.454	0.002	0.471	0.028	0.642	0.004	0.529	0.031
Mn	0.029	0.001	0.026	0.002	0.026	0.001	0.021	0.006	0.027	0.000	0.020	0.001
Ni	0.002	0.001	0.001	0.001	0.001	0.000	0.001	0.001	0.000	0.000	0.002	0.001
Mg	2.194	0.010	2.179	0.023	2.189	0.005	2.148	0.119	2.073	0.011	2.178	0.034
Ca	0.354	0.001	0.432	0.007	0.420	0.001	0.487	0.100	0.351	0.001	0.323	0.007
Na	0.002	0.001	0.006	0.001	0.008	0.001	0.012	0.003	0.003	0.000	0.004	0.002
Total	8.021	0.006	8.056	0.010	8.049	0.004	8.044	0.007	8.040	0.008	8.024	0.003
Gr	11.717	0.046	14.024	0.272	13.708	0.061	15.676	3.116	11.460	0.029	10.674	0.210
Py	72.622	0.115	70.811	0.297	71.463	0.037	69.171	3.933	67.606	0.009	71.868	0.958
Al	15.661	0.116	15.165	0.261	14.829	0.024	15.153	0.910	20.934	0.020	17.458	1.067

Sample no. Rocktype n	JSL110 MP 4		JSL180 MP 6		JSL252 MP 2		JSL298 MP 4		JSL67 I 3		JSL83 I 5	
SiO2	41.43	0.07	41.09	0.20	41.89	0.10	42.02	0.14	40.15	0.08	41.28	0.15
TiO2	0.12	0.02	0.05	0.01	0.00	0.00	0.05	0.01	0.22	0.02	0.21	0.02
Al2O3	22.23	0.05	22.88	0.13	24.01	0.00	23.36	0.13	22.39	0.02	22.74	0.07
Cr2O3	1.18	0.08	0.50	0.01	0.40	0.04	0.62	0.05	0.04	0.00	0.23	0.02
FeO	9.64	0.19	11.38	0.08	7.00	0.07	8.13	0.11	14.97	0.17	10.30	0.26
MnO	0.42	0.02	0.44	0.01	0.32	0.05	0.39	0.02	0.30	0.00	0.23	0.03
NiO	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
MgO	20.26	0.10	18.82	0.14	21.65	0.01	20.48	0.08	11.26	0.04	16.62	0.29
CaO	4.50	0.05	4.63	0.04	4.76	0.06	4.65	0.02	10.55	0.18	8.44	0.19
Na2O	0.03	0.00	0.01	0.01	0.02	0.00	0.01	0.00	0.07	0.01	0.10	0.01
Total	99.85	0.10	99.81	0.38	100.05	0.02	99.71	0.29	99.95	0.03	100.15	0.22

Cations (recalculated to 12 oxygens)

Si	2.973	0.004	2.967	0.005	2.953	0.005	2.987	0.003	2.989	0.003	2.983	0.007
Ti	0.007	0.001	0.003	0.001	0.000	0.000	0.002	0.001	0.012	0.001	0.012	0.001
Al	1.880	0.003	1.947	0.005	1.995	0.002	1.957	0.005	1.965	0.002	1.936	0.005
Cr	0.067	0.004	0.028	0.000	0.022	0.002	0.035	0.003	0.002	0.000	0.013	0.001
Fe	0.579	0.012	0.687	0.005	0.413	0.004	0.483	0.006	0.932	0.011	0.622	0.016
Mn	0.025	0.001	0.027	0.001	0.019	0.003	0.023	0.001	0.019	0.000	0.014	0.002
Ni	0.002	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mg	2.167	0.009	2.025	0.014	2.275	0.000	2.170	0.011	1.249	0.006	1.790	0.029
Ca	0.346	0.003	0.358	0.004	0.360	0.005	0.354	0.002	0.841	0.013	0.653	0.016
Na	0.004	0.001	0.002	0.001	0.002	0.000	0.002	0.001	0.011	0.001	0.013	0.001
Total	8.049	0.004	8.044	0.006	8.039	0.003	8.015	0.006	8.020	0.002	8.037	0.008
Gr	11.181	0.120	11.655	0.141	11.801	0.157	11.777	0.055	27.837	0.477	21.309	0.513
Py	70.104	0.253	65.959	0.188	74.650	0.030	72.156	0.211	41.326	0.138	58.387	0.901
Al	18.715	0.365	22.386	0.165	13.549	0.128	16.067	0.182	30.837	0.339	20.304	0.486

Sample no. Rocktype n	JSL106 I 8		JSL200 I 7		JSL201 I 7		JSL203 I 4		JSL204 I 5		JSL205 I 7	
SiO2	39.48	0.16	40.73	0.08	40.58	0.21	38.90	0.18	39.37	0.16	39.76	0.21
TiO2	0.29	0.02	0.28	0.01	0.31	0.01	0.34	0.02	0.25	0.01	0.19	0.01
Al2O3	21.95	0.10	22.37	0.11	22.39	0.08	21.43	0.11	21.96	0.06	21.93	0.10
Cr2O3	0.04	0.01	0.07	0.01	0.16	0.01	0.02	0.01	0.04	0.01	0.07	0.01
FeO	18.66	0.44	10.92	0.12	11.39	0.12	21.80	0.20	18.62	0.23	17.78	0.16
MnO	0.43	0.02	0.22	0.01	0.25	0.01	0.41	0.03	0.41	0.01	0.33	0.01
NiO	0.02	0.01	0.02	0.01	0.01	0.01	0.00	0.00	0.02	0.01	0.03	0.01
MgO	8.37	0.43	11.78	0.10	12.81	0.09	7.70	0.18	9.83	0.16	10.81	0.09
CaO	10.69	0.73	13.46	0.07	11.88	0.20	8.88	0.48	9.00	0.37	8.90	0.09
Na2O	0.10	0.01	0.09	0.01	0.12	0.01	0.13	0.01	0.11	0.00	0.08	0.01
Total	100.04	0.29	99.95	0.25	99.89	0.29	99.62	0.45	99.61	0.06	99.89	0.52

Cations (recalculated to 12 oxygens)

Si	2.994	0.002	3.000	0.006	2.986	0.007	2.994	0.003	2.984	0.009	2.990	0.004
Ti	0.016	0.001	0.015	0.001	0.017	0.001	0.020	0.001	0.014	0.000	0.011	0.001
Al	1.962	0.007	1.942	0.007	1.942	0.003	1.943	0.006	1.962	0.006	1.944	0.005
Cr	0.002	0.001	0.004	0.001	0.009	0.001	0.001	0.000	0.003	0.001	0.004	0.001
Fe	1.184	0.030	0.673	0.006	0.701	0.006	1.403	0.015	1.180	0.015	1.118	0.006
Mn	0.028	0.001	0.014	0.001	0.015	0.001	0.026	0.002	0.026	0.001	0.021	0.001
Ni	0.001	0.001	0.001	0.001	0.000	0.001	0.000	0.000	0.001	0.001	0.002	0.001
Mg	0.946	0.045	1.294	0.009	1.405	0.007	0.884	0.022	1.111	0.018	1.212	0.010
Ca	0.868	0.060	1.063	0.006	0.937	0.018	0.732	0.037	0.731	0.030	0.717	0.006
Na	0.014	0.001	0.013	0.001	0.017	0.002	0.020	0.002	0.016	0.001	0.012	0.001
Total	8.015	0.004	8.018	0.004	8.030	0.006	8.024	0.001	8.027	0.006	8.031	0.004
Gr	28.959	1.922	35.078	0.279	30.792	0.495	24.245	1.221	24.193	1.010	23.539	0.163
Py	31.564	1.544	42.709	0.221	46.170	0.300	29.272	0.721	36.753	0.591	39.763	0.281
Al	39.478	1.087	22.213	0.166	23.039	0.231	46.483	0.525	39.054	0.456	36.698	0.252

Sample no.	JSL206	JSL207	JSL208	JSL211	JSL212	JSL214					
Rocktype	1	1	1	1	1	1					
n	6	1	7	6	5	4					
SiO2	41.35	0.16	39.37	41.86	0.46	39.83	0.72	40.14	0.64	40.92	0.20
TiO2	0.21	0.02	0.25	0.17	0.01	0.57	0.17	0.54	0.09	0.27	0.02
Al2O3	22.92	0.11	22.24	23.16	0.14	21.40	0.39	21.40	0.31	23.00	0.07
Cr2O3	0.12	0.01	0.02	0.66	0.09	0.04	0.02	0.03	0.01	0.11	0.01
FeO	10.96	0.25	19.41	8.04	0.18	16.39	2.83	15.95	2.47	13.75	0.14
MnO	0.22	0.02	0.46	0.40	0.03	0.44	0.02	0.45	0.04	0.36	0.03
NiO	0.03	0.01	0.02	0.03	0.01	0.00	0.00	0.00	0.00	0.01	0.01
MgO	15.64	0.24	10.29	21.99	0.13	14.37	2.42	14.43	2.03	16.27	0.16
CaO	8.89	0.23	8.25	4.15	0.05	6.76	0.62	6.82	0.37	5.55	0.23
Na2O	0.08	0.01	0.13	0.07	0.01	0.07	0.01	0.08	0.01	0.11	0.01
Total	100.42	0.37	100.44	100.55	0.34	99.88	0.68	99.85	0.45	100.35	0.38

Cations (recalculated to 12 oxygens)

Si	2.990	0.006	2.964	2.953	0.019	2.965	0.009	2.981	0.008	2.974	0.005
Ti	0.011	0.001	0.014	0.009	0.000	0.032	0.009	0.030	0.005	0.015	0.001
Al	1.953	0.007	1.973	1.926	0.015	1.878	0.007	1.873	0.007	1.970	0.003
Cr	0.007	0.001	0.001	0.037	0.005	0.003	0.001	0.002	0.000	0.006	0.000
Fe	0.663	0.015	1.222	0.475	0.013	1.023	0.190	0.994	0.167	0.835	0.008
Mn	0.013	0.001	0.029	0.024	0.002	0.028	0.001	0.028	0.002	0.022	0.002
Ni	0.002	0.001	0.001	0.002	0.001	0.000	0.000	0.000	0.000	0.001	0.001
Mg	1.685	0.026	1.155	2.313	0.010	1.590	0.236	1.594	0.197	1.762	0.023
Ca	0.689	0.018	0.666	0.314	0.004	0.540	0.057	0.543	0.035	0.432	0.017
Na	0.012	0.001	0.020	0.009	0.001	0.011	0.002	0.012	0.002	0.015	0.001
Total	8.025	0.005	8.045	8.061	0.012	8.069	0.009	8.057	0.009	8.031	0.005

Gr	22.672	0.547	21.878	10.118	0.127	17.116	1.778	17.352	1.095	14.251	0.584
Py	55.500	0.931	37.961	74.581	0.361	50.456	7.655	50.907	6.276	58.170	0.644
Al	21.828	0.456	40.160	15.302	0.335	32.427	5.909	31.741	5.364	27.579	0.255

Sample no.	JSL254		JSL54	JSL57	JSL70	JSL72	JSL73	JSL74	JSL80	JSL85	JSL92	JSL93
Rocktype												
n	3		1	1	1	1	1	1	1	1	1	1
	grainmounts ==>											
SiO2	40.13	0.03	42.47	42.27	39.85	41.94	41.32	41.37	41.51	41.64	42.06	41.83
TiO2	0.16	0.01	0.69	0.36	0.40	0.19	0.42	0.38	0.42	0.20	0.24	0.53
Al2O3	22.55	0.11	21.55	23.12	22.20	23.06	22.77	23.21	22.63	22.02	22.11	21.23
Cr2O3	0.07	0.02	1.10	0.19	0.19	0.73	0.57	0.22	0.65	1.83	1.54	2.23
FeO	16.85	0.13	8.37	9.84	16.54	8.46	10.79	9.00	9.38	7.51	8.24	7.26
MnO	0.58	0.00	0.28	0.34	0.38	0.35	0.32	0.31	0.40	0.38	0.40	0.33
NiO	0.01	0.01	0.00	0.00	0.03	0.00	0.02	0.01	0.00	0.00	0.03	0.00
MgO	13.76	0.04	21.35	19.91	12.95	21.61	20.20	21.92	20.97	22.27	21.97	22.50
CaO	5.43	0.05	4.04	4.16	7.11	4.15	4.10	3.91	4.18	4.35	4.13	4.41
Na2O	0.07	0.00	0.08	0.10	0.11	0.07	0.12	0.10	0.08	0.09	0.08	0.10
Total	99.60	0.19	99.94	100.30	99.75	100.56	100.62	100.44	100.22	100.28	100.80	100.42

Cations (recalculated to 12 oxygens)

Si	2.983	0.003	3.018	3.003	2.971	2.962	2.949	2.931	2.958	2.953	2.971	2.964
Ti	0.009	0.001	0.037	0.019	0.022	0.010	0.023	0.020	0.023	0.011	0.013	0.028
Al	1.976	0.007	1.805	1.936	1.950	1.920	1.916	1.938	1.901	1.840	1.841	1.773
Cr	0.004	0.001	0.062	0.011	0.011	0.041	0.032	0.013	0.037	0.103	0.086	0.125
Fe	1.048	0.007	0.498	0.584	1.031	0.500	0.644	0.533	0.559	0.445	0.487	0.430
Mn	0.037	0.000	0.017	0.021	0.024	0.021	0.019	0.019	0.024	0.023	0.024	0.020
Ni	0.000	0.001	0.000	0.000	0.002	0.000	0.001	0.001	0.000	0.000	0.002	0.000
Mg	1.525	0.007	2.261	2.108	1.439	2.275	2.149	2.315	2.227	2.354	2.313	2.376
Ca	0.432	0.004	0.308	0.317	0.568	0.314	0.313	0.297	0.319	0.331	0.312	0.335
Na	0.009	0.000	0.012	0.013	0.016	0.010	0.016	0.013	0.011	0.012	0.011	0.014
Total	8.023	0.001	8.017	8.012	8.034	8.052	8.062	8.080	8.057	8.071	8.059	8.066

Gr	14.384	0.115	10.030	10.533	18.682	10.169	10.082	9.437	10.271	10.569	10.038	10.656
Py	50.742	0.192	73.743	70.049	47.367	73.646	69.189	73.615	71.732	75.206	74.320	75.655
Al	34.875	0.256	16.227	19.419	33.951	16.185	20.729	16.949	17.997	14.225	15.642	13.688

Sample no. Rocktype n	JSL59 II 5		JSL60 II 8		JSL61 II 4		JSL62 II 5		JSL63 II 7		JSL65 II 6	
SiO2	42.35	0.08	42.48	0.14	41.53	0.22	41.57	0.22	40.54	0.07	41.33	0.16
TiO2	0.02	0.01	0.04	0.01	0.06	0.00	0.08	0.01	0.02	0.01	0.26	0.02
Al2O3	23.48	0.10	22.97	0.06	23.10	0.26	23.36	0.07	22.71	0.06	22.60	0.05
Cr2O3	0.58	0.02	0.97	0.07	0.06	0.00	0.12	0.01	0.05	0.01	0.51	0.01
FeO	8.22	0.03	7.07	0.04	13.63	0.21	9.31	0.12	15.41	0.19	10.35	0.16
MnO	0.40	0.01	0.24	0.03	0.39	0.03	0.37	0.05	0.29	0.01	0.45	0.03
NiO	0.00	0.00	0.02	0.02	0.01	0.01	0.01	0.01	0.00	0.01	0.03	0.03
MgO	21.09	0.08	21.46	0.08	17.85	0.20	20.85	0.07	12.76	0.20	20.38	0.04
CaO	4.43	0.07	5.10	0.10	3.91	0.03	4.07	0.05	7.77	0.08	4.02	0.04
Na2O	0.01	0.00	0.03	0.01	0.03	0.01	0.03	0.00	0.04	0.01	0.06	0.01
Total	100.59	0.18	100.39	0.22	100.55	0.21	99.76	0.35	99.58	0.27	99.98	0.28
Cations (recalculated to 12 oxygens)												
Si	2.983	0.007	2.992	0.007	2.991	0.009	2.964	0.008	3.006	0.006	2.963	0.006
Ti	0.001	0.000	0.002	0.001	0.003	0.000	0.004	0.001	0.001	0.000	0.014	0.001
Al	1.950	0.006	1.906	0.004	1.961	0.024	1.964	0.004	1.985	0.004	1.909	0.003
Cr	0.032	0.001	0.054	0.004	0.003	0.000	0.007	0.001	0.003	0.001	0.029	0.001
Fe	0.484	0.001	0.416	0.002	0.821	0.014	0.555	0.007	0.956	0.012	0.621	0.009
Mn	0.024	0.001	0.014	0.002	0.024	0.002	0.022	0.003	0.018	0.001	0.027	0.002
Ni	0.000	0.000	0.001	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.002	0.002
Mg	2.215	0.007	2.253	0.009	1.916	0.018	2.216	0.008	1.410	0.020	2.177	0.007
Ca	0.334	0.006	0.385	0.008	0.301	0.003	0.311	0.004	0.617	0.007	0.309	0.003
Na	0.002	0.001	0.004	0.001	0.004	0.001	0.004	0.000	0.005	0.002	0.008	0.001
Total	8.025	0.005	8.028	0.007	8.026	0.007	8.048	0.007	8.001	0.006	8.058	0.006
Gr	11.022	0.181	12.598	0.220	9.922	0.121	10.099	0.141	20.697	0.272	9.931	0.068
Py	73.016	0.174	73.766	0.167	63.057	0.419	71.891	0.106	47.259	0.542	70.088	0.269
Al	15.962	0.017	13.635	0.067	27.021	0.353	18.011	0.171	32.044	0.375	19.980	0.236
Sample no. Rocktype n	JSL69 II 8		JSL77 II 6		JSL86 II 5		JSL91 II 7		JSL95 II 5		JSL98 II 3	
SiO2	41.37	0.15	41.67	0.19	42.23	0.12	42.65	0.13	42.23	0.06	42.15	0.12
TiO2	0.05	0.01	0.10	0.02	0.18	0.02	0.16	0.01	0.18	0.01	0.04	0.01
Al2O3	23.15	0.13	23.00	0.12	22.67	0.12	22.21	0.22	21.89	0.07	22.95	0.19
Cr2O3	0.08	0.01	0.16	0.02	1.35	0.03	2.18	0.28	2.30	0.04	0.68	0.05
FeO	10.58	0.13	13.55	0.10	7.68	0.04	6.47	0.07	8.47	0.10	8.23	0.14
MnO	0.37	0.02	0.44	0.02	0.39	0.03	0.35	0.02	0.42	0.02	0.47	0.03
NiO	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01
MgO	18.72	0.10	17.04	0.13	22.04	0.07	22.26	0.17	20.68	0.05	20.99	0.13
CaO	5.18	0.08	4.41	0.08	4.11	0.05	4.36	0.12	4.32	0.04	4.69	0.04
Na2O	0.02	0.01	0.03	0.01	0.06	0.00	0.05	0.01	0.06	0.01	0.02	0.00
Total	99.53	0.28	100.41	0.35	100.73	0.18	100.71	0.17	100.58	0.10	100.22	0.18
Cations (recalculated to 12 oxygens)												
Si	2.982	0.007	3.008	0.009	2.972	0.006	2.993	0.007	2.996	0.004	2.987	0.002
Ti	0.003	0.000	0.006	0.001	0.010	0.001	0.009	0.001	0.010	0.000	0.002	0.001
Al	1.967	0.008	1.957	0.005	1.881	0.009	1.837	0.017	1.830	0.005	1.917	0.011
Cr	0.005	0.001	0.009	0.001	0.075	0.002	0.121	0.016	0.129	0.002	0.038	0.003
Fe	0.638	0.008	0.818	0.006	0.452	0.002	0.380	0.004	0.503	0.006	0.488	0.009
Mn	0.022	0.001	0.027	0.001	0.023	0.002	0.021	0.001	0.025	0.001	0.028	0.002
Ni	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Mg	2.011	0.009	1.834	0.010	2.312	0.006	2.328	0.016	2.187	0.004	2.217	0.016
Ca	0.400	0.006	0.341	0.007	0.310	0.004	0.328	0.009	0.328	0.003	0.356	0.002
Na	0.003	0.001	0.004	0.001	0.008	0.000	0.007	0.001	0.008	0.002	0.002	0.001
Total	8.031	0.005	8.005	0.008	8.044	0.003	8.023	0.005	8.018	0.003	8.035	0.006
Gr	13.113	0.226	11.400	0.185	10.086	0.083	10.803	0.316	10.880	0.130	11.636	0.139
Py	65.968	0.124	61.275	0.188	75.216	0.095	76.695	0.456	72.459	0.046	72.420	0.248
Al	20.919	0.202	27.326	0.233	14.698	0.060	12.502	0.142	16.661	0.148	15.943	0.263

Sample no. Rocktype n	JSL100 II 5		JSL104 II 8		JSL210 II 5		JSL213 II 4		JSL251 II 5		JSL600A II 8	
SiO2	41.63	0.03	42.16	0.56	42.32	0.21	41.44	0.08	42.00	0.28	42.05	0.13
TiO2	0.25	0.01	0.09	0.02	0.04	0.01	0.09	0.00	0.09	0.01	0.14	0.02
Al2O3	18.24	0.06	23.23	0.07	23.31	0.17	23.42	0.05	23.29	0.07	22.65	0.24
Cr2O3	6.91	0.08	0.59	0.02	0.29	0.10	0.22	0.01	0.82	0.02	1.28	0.14
FeO	6.76	0.06	7.73	0.29	7.88	0.16	12.81	0.10	7.72	0.09	7.32	0.25
MnO	0.39	0.03	0.41	0.02	0.35	0.01	0.47	0.03	0.44	0.02	0.39	0.03
NiO	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.01
MgO	20.29	0.09	21.93	0.31	21.64	0.16	18.15	0.10	21.36	0.11	21.53	0.16
CaO	5.97	0.06	4.07	0.06	4.34	0.09	4.00	0.07	4.23	0.05	4.06	0.05
Na2O	0.05	0.01	0.04	0.01	0.03	0.00	0.05	0.01	0.05	0.00	0.05	0.01
Total	100.49	0.20	100.27	0.25	100.20	0.61	100.66	0.18	100.01	0.19	99.48	0.30

Cations (recalculated to 12 oxygens)

Si	2.996	0.005	2.974	0.028	2.986	0.009	2.974	0.002	2.973	0.014	2.989	0.009
Ti	0.013	0.000	0.005	0.001	0.002	0.001	0.005	0.000	0.005	0.000	0.008	0.001
Al	1.547	0.005	1.931	0.007	1.939	0.008	1.982	0.006	1.943	0.007	1.898	0.016
Cr	0.393	0.004	0.033	0.001	0.016	0.005	0.012	0.001	0.046	0.001	0.072	0.008
Fe	0.407	0.003	0.456	0.018	0.465	0.009	0.769	0.007	0.457	0.006	0.435	0.015
Mn	0.024	0.002	0.025	0.001	0.021	0.001	0.029	0.002	0.026	0.001	0.023	0.002
Ni	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001
Mg	2.177	0.008	2.305	0.040	2.276	0.010	1.941	0.009	2.253	0.017	2.281	0.017
Ca	0.460	0.004	0.308	0.005	0.328	0.006	0.307	0.005	0.321	0.004	0.309	0.004
Na	0.006	0.001	0.006	0.001	0.004	0.000	0.008	0.001	0.007	0.001	0.007	0.001
Total	8.024	0.004	8.043	0.026	8.036	0.010	8.027	0.004	8.031	0.010	8.022	0.011
Gr	15.113	0.155	10.033	0.081	10.678	0.146	10.184	0.128	10.583	0.156	10.222	0.173
Py	71.512	0.153	75.109	0.505	74.168	0.317	64.333	0.227	74.336	0.213	75.391	0.279
Al	13.375	0.095	14.858	0.520	15.154	0.213	25.483	0.231	15.082	0.148	14.387	0.415

Sample no. Rocktype n	JSL55 II 1	JSL56 II 1	JSL58 II 1	JSL64 II 1	JSL66 II 1	JSL68 II 1	JSL71 II 1	JSL76 II 1	JSL78 II 1	JSL79 II 1	JSL81 II 1	JSL82 II 1
grainmounts ==>												
SiO2	42.25	42.11	41.79	41.93	41.03	42.15	41.21	41.18	41.49	41.82	41.20	41.07
TiO2	0.04	0.10	0.07	0.10	0.03	0.16	0.01	0.05	0.05	0.07	0.06	0.09
Al2O3	22.62	23.50	23.43	23.58	22.98	23.22	23.06	23.73	23.70	23.74	23.06	22.95
Cr2O3	1.37	0.35	0.42	0.28	0.40	0.96	0.55	0.12	0.10	0.27	0.39	0.38
FeO	8.09	9.54	9.54	10.15	14.37	8.03	12.36	9.36	9.91	7.84	9.88	11.25
MnO	0.40	0.51	0.39	0.41	0.56	0.36	0.41	0.43	0.35	0.35	0.43	0.32
NiO	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
MgO	20.44	19.89	20.01	19.93	16.61	21.22	17.73	20.84	20.34	22.23	20.37	19.36
CaO	4.70	4.15	4.51	4.09	4.68	4.39	4.82	4.64	4.14	4.25	4.45	4.65
Na2O	0.01	0.02	0.01	0.04	0.03	0.05	0.01	0.02	0.03	0.03	0.05	0.02
Total	99.92	100.18	100.18	100.52	100.70	100.55	100.15	100.39	100.12	100.60	99.90	100.09

Cations (recalculated to 12 oxygens)

Si	3.004	2.993	2.975	2.977	2.975	2.973	2.977	2.928	2.955	2.941	2.951	2.954
Ti	0.002	0.006	0.004	0.005	0.002	0.008	0.001	0.003	0.003	0.003	0.003	0.005
Al	1.895	1.968	1.966	1.974	1.964	1.930	1.963	1.988	1.990	1.968	1.947	1.945
Cr	0.077	0.020	0.023	0.015	0.023	0.053	0.031	0.007	0.006	0.015	0.022	0.022
Fe	0.481	0.567	0.568	0.603	0.872	0.474	0.746	0.557	0.591	0.461	0.592	0.677
Mn	0.024	0.031	0.023	0.025	0.034	0.022	0.025	0.026	0.021	0.021	0.026	0.020
Ni	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mg	2.166	2.107	2.123	2.109	1.796	2.231	1.908	2.208	2.160	2.331	2.175	2.075
Ca	0.358	0.316	0.344	0.311	0.364	0.332	0.373	0.353	0.316	0.321	0.342	0.358
Na	0.001	0.003	0.001	0.006	0.004	0.006	0.001	0.003	0.004	0.004	0.007	0.003
Total	8.008	8.010	8.028	8.026	8.032	8.030	8.026	8.073	8.046	8.066	8.065	8.059
Gr	11.923	10.566	11.337	10.287	12.004	10.928	12.322	11.327	10.299	10.297	10.987	11.515
Py	72.070	70.471	69.949	69.773	59.241	73.469	63.028	70.822	70.440	74.890	69.975	66.725
Al	16.007	18.964	18.714	19.940	28.755	15.603	24.650	17.851	19.261	14.813	19.038	21.761

Sample no. Rocktype n	JSL87 II 1	JSL88 II 1	JSL89 II 1	JSL90 II 1	JSL94 II 1	JSL96 II 1	JSL97 II 1	JSL101 II 1	JSL228 II 1	JSL229 II 1	JSL230 II 1	JSL232 II 1
SiO2	41.41	41.69	41.17	41.51	41.50	41.57	40.76	42.26	41.72	42.15	41.59	41.70
TiO2	0.16	0.16	0.16	0.04	0.09	0.05	0.11	0.06	0.03	0.10	0.02	0.04
Al2O3	22.68	22.56	21.23	23.16	22.69	23.34	22.24	23.23	23.66	23.62	23.29	23.25
Cr2O3	1.39	1.68	2.93	0.58	0.64	0.77	1.61	0.64	0.07	0.06	0.37	0.07
FeO	8.01	7.40	7.29	8.77	8.90	8.49	11.06	9.78	9.80	12.22	11.44	12.94
MnO	0.40	0.34	0.44	0.41	0.32	0.30	0.50	0.38	0.30	0.46	0.37	0.36
NiO	0.02	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.02	0.01
MgO	21.65	22.13	22.17	20.90	18.57	21.12	19.25	19.67	19.84	18.56	18.26	16.83
CaO	4.29	4.08	3.88	4.49	7.30	4.65	4.71	4.40	4.21	3.61	4.51	4.78
Na2O	0.05	0.05	0.05	0.02	0.05	0.04	0.04	0.03	0.05	0.04	0.03	0.03
Total	100.07	100.09	99.33	99.87	100.06	100.34	100.28	100.45	99.67	100.82	99.90	100.01

Cations (recalculated to 12 oxygens)

Si	2.944	2.954	2.952	2.959	2.977	2.947	2.940	3.001	2.981	3.002	2.992	3.014
Ti	0.009	0.009	0.009	0.002	0.005	0.003	0.006	0.003	0.001	0.005	0.001	0.002
Al	1.900	1.884	1.795	1.945	1.919	1.950	1.891	1.944	1.992	1.983	1.975	1.981
Cr	0.078	0.094	0.166	0.033	0.036	0.043	0.092	0.036	0.004	0.004	0.021	0.004
Fe	0.476	0.438	0.437	0.523	0.534	0.503	0.667	0.581	0.585	0.728	0.688	0.782
Mn	0.024	0.020	0.027	0.024	0.019	0.018	0.031	0.023	0.018	0.028	0.022	0.022
Ni	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000
Mg	2.295	2.336	2.370	2.220	1.986	2.232	2.070	2.081	2.113	1.971	1.958	1.814
Ca	0.327	0.310	0.298	0.343	0.561	0.353	0.364	0.334	0.322	0.276	0.347	0.371
Na	0.007	0.007	0.007	0.003	0.007	0.005	0.006	0.004	0.007	0.006	0.004	0.004
Total	8.061	8.052	8.062	8.052	8.044	8.056	8.066	8.008	8.024	8.002	8.011	7.993
Gr	10.550	10.048	9.595	11.118	18.208	11.431	11.741	11.162	10.667	9.268	11.601	12.491
Py	74.072	75.746	76.318	71.940	64.455	72.279	66.745	69.460	69.951	66.261	65.409	61.147
Al	15.379	14.206	14.087	16.942	17.337	16.290	21.514	19.377	19.382	24.471	22.990	26.361

Sample no. Rocktype n	JSL233 II 1	JSL234 II 1	JSL236 II 1	JSL237 II 1	JSL239 II 1	JSL240 II 1	JSL242 II 1	JSL7 M 18		JSL12 M 11	
						<== grainmounts					
SiO2	41.20	41.53	40.98	42.25	40.92	41.50	42.63	41.76	0.26	42.40	0.12
TiO2	0.08	0.09	0.08	0.05	0.11	0.08	0.17	1.20	0.07	0.78	0.05
Al2O3	22.58	23.04	23.02	23.39	22.58	22.80	23.20	20.56	0.15	21.42	0.10
Cr2O3	0.46	0.23	0.14	0.46	0.33	0.41	1.07	1.28	0.05	0.81	0.03
FeO	14.14	13.73	15.48	9.37	15.96	12.81	7.28	10.18	0.27	9.22	0.22
MnO	0.52	0.46	0.42	0.37	0.52	0.40	0.37	0.34	0.03	0.28	0.03
NiO	0.00	0.00	0.02	0.00	0.04	0.03	0.00	0.00	0.01	0.01	0.02
MgO	15.89	16.44	15.11	19.89	15.03	17.00	21.79	19.96	0.19	20.95	0.15
CaO	4.79	4.75	4.52	4.54	4.76	5.08	4.06	4.85	0.07	4.40	0.05
Na2O	0.03	0.03	0.03	0.02	0.03	0.02	0.05	0.11	0.01	0.10	0.01
Total	99.69	100.31	99.81	100.35	100.27	100.12	100.64	100.24	0.41	100.38	0.24

Cations (recalculated to 12 oxygens)

Si	3.013	3.008	3.005	2.997	3.000	3.004	2.990	3.000	0.013	3.014	0.006
Ti	0.004	0.005	0.005	0.003	0.006	0.004	0.009	0.065	0.004	0.041	0.003
Al	1.946	1.966	1.989	1.956	1.951	1.945	1.918	1.741	0.011	1.794	0.009
Cr	0.027	0.013	0.008	0.026	0.019	0.023	0.059	0.073	0.003	0.045	0.002
Fe	0.865	0.831	0.949	0.556	0.979	0.775	0.427	0.611	0.016	0.548	0.012
Mn	0.032	0.028	0.026	0.022	0.032	0.024	0.022	0.021	0.002	0.017	0.002
Ni	0.000	0.000	0.001	0.000	0.002	0.002	0.000	0.000	0.000	0.001	0.001
Mg	1.732	1.775	1.651	2.103	1.643	1.834	2.278	2.137	0.021	2.220	0.017
Ca	0.376	0.369	0.355	0.345	0.374	0.394	0.305	0.373	0.006	0.335	0.004
Na	0.005	0.004	0.005	0.003	0.004	0.003	0.007	0.015	0.002	0.014	0.002
Total	7.999	8.000	7.994	8.011	8.010	8.009	8.016	8.036	0.014	8.031	0.007
Gr	12.637	12.395	12.010	11.489	12.478	13.108	10.138	11.960	0.228	10.803	0.116
Py	58.270	59.657	55.862	70.000	54.844	61.068	75.671	68.458	0.325	71.530	0.380
Al	29.093	27.948	32.129	18.511	32.678	25.825	14.191	19.582	0.372	17.667	0.397

Sample no. Rocktype n	JSL13 M 12		JSL14 M 14		JSL24 M 8		JSL28 CGI 3		JSL29 CGI 4	
SiO2	41.44	0.14	41.78	0.12	41.92	0.11	42.25	0.17	42.85	0.05
TiO2	1.11	0.06	1.24	0.05	1.06	0.06	0.70	0.01	0.91	0.01
Al2O3	20.68	0.23	20.48	0.22	20.90	0.16	21.90	0.09	21.26	0.08
Cr2O3	0.37	0.04	0.77	0.04	0.54	0.03	0.32	0.01	0.96	0.09
FeO	11.88	0.16	11.06	0.20	11.23	0.13	11.58	0.09	7.84	0.06
MnO	0.41	0.03	0.27	0.02	0.32	0.02	0.21	0.01	0.30	0.02
NiO	0.04	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01
MgO	19.32	0.15	19.25	0.10	19.80	0.15	19.10	0.13	22.32	0.06
CaO	4.52	0.14	4.50	0.24	4.35	0.18	4.04	0.04	4.32	0.02
Na2O	0.13	0.02	0.15	0.01	0.12	0.01	0.12	0.01	0.11	0.01
Total	99.90	0.42	99.50	0.32	100.25	0.31	100.24	0.46	100.89	0.06
Cations (recalculated to 12 oxygens)										
Si	3.002	0.008	3.026	0.011	3.013	0.006	3.028	0.002	3.013	0.003
Ti	0.060	0.003	0.067	0.003	0.057	0.003	0.038	0.001	0.048	0.001
Al	1.766	0.014	1.748	0.016	1.770	0.009	1.849	0.001	1.762	0.007
Cr	0.021	0.002	0.044	0.002	0.031	0.002	0.018	0.001	0.054	0.005
Fe	0.720	0.009	0.670	0.011	0.675	0.009	0.694	0.004	0.461	0.003
Mn	0.025	0.002	0.016	0.001	0.019	0.001	0.013	0.001	0.018	0.001
Ni	0.002	0.001	0.001	0.001	0.000	0.000	0.001	0.001	0.001	0.001
Mg	2.087	0.020	2.078	0.008	2.121	0.013	2.040	0.009	2.340	0.006
Ca	0.351	0.010	0.349	0.018	0.335	0.014	0.310	0.003	0.325	0.001
Na	0.019	0.002	0.021	0.001	0.017	0.001	0.017	0.001	0.015	0.001
Total	8.053	0.006	8.020	0.007	8.038	0.007	8.009	0.002	8.038	0.004
Gr	11.123	0.330	11.273	0.578	10.708	0.403	10.191	0.089	10.407	0.025
Py	66.087	0.478	67.093	0.338	67.740	0.319	67.013	0.230	74.841	0.100
Al	22.790	0.269	21.634	0.378	21.552	0.340	22.796	0.142	14.752	0.103

APPENDIX 3c : CLINOPYROXENE

Clinopyroxene

Sample numbers followed by a letter, eg. JSL 565A, indicate that more than one polished thin section of the particular sample was prepared.

Each average is followed by the standard deviation about the mean. Grainmounts of eclogite minerals are represented by single analyses.

Sample no. Rocktype n	JSL108 GLd 5		JSL112 GLd 6		JSL119 GLd 6		JSL126 GLd 6		JSL140 GLd 3		JSL279 GLd 6	
SiO ₂	54.55	0.18	54.81	0.22	54.71	0.22	54.75	0.32	54.49	0.07	54.34	0.22
TiO ₂	0.29	0.01	0.25	0.03	0.17	0.02	0.06	0.03	0.35	0.01	0.02	0.00
Al ₂ O ₃	1.92	0.11	2.10	0.03	1.84	0.06	1.01	0.11	2.35	0.04	0.87	0.01
Cr ₂ O ₃	1.47	0.03	0.60	0.02	0.73	0.05	0.54	0.04	0.99	0.01	0.42	0.01
FeO	3.30	0.07	4.09	0.05	3.32	0.02	2.82	0.04	3.58	0.06	3.06	0.06
MnO	0.13	0.01	0.12	0.03	0.13	0.02	0.09	0.02	0.10	0.01	0.11	0.02
NiO	0.05	0.03	0.10	0.03	0.10	0.01	0.08	0.03	0.05	0.00	0.08	0.03
MgO	19.23	0.17	20.75	0.21	19.61	0.16	19.51	0.27	19.40	0.09	20.16	0.20
CaO	17.18	0.33	15.51	0.09	17.68	0.16	20.31	0.20	16.50	0.10	20.09	0.11
Na ₂ O	1.76	0.07	1.53	0.03	1.40	0.06	0.75	0.10	1.92	0.05	0.51	0.02
Total	99.88	0.16	99.87	0.36	99.70	0.21	99.92	0.51	99.73	0.03	99.66	0.15
Cations (recalculated to 6 oxygens)												
Si	1.967	0.004	1.969	0.005	1.974	0.004	1.978	0.004	1.965	0.003	1.970	0.007
Ti	0.008	0.000	0.007	0.001	0.005	0.001	0.002	0.001	0.009	0.000	0.001	0.000
Al	0.082	0.004	0.089	0.001	0.078	0.003	0.043	0.005	0.100	0.002	0.037	0.001
Cr	0.042	0.001	0.017	0.001	0.021	0.002	0.015	0.001	0.028	0.000	0.012	0.000
Fe	0.100	0.002	0.123	0.002	0.100	0.001	0.085	0.001	0.108	0.002	0.093	0.002
Mn	0.004	0.000	0.004	0.001	0.004	0.001	0.003	0.001	0.003	0.000	0.003	0.001
Ni	0.001	0.001	0.003	0.001	0.003	0.000	0.002	0.001	0.002	0.000	0.002	0.001
Mg	1.034	0.008	1.111	0.009	1.055	0.009	1.051	0.010	1.042	0.004	1.089	0.012
Ca	0.664	0.014	0.597	0.004	0.683	0.006	0.786	0.007	0.637	0.004	0.780	0.004
Na	0.123	0.005	0.107	0.002	0.098	0.004	0.052	0.007	0.134	0.004	0.036	0.001
Total	4.025	0.005	4.025	0.006	4.021	0.004	4.017	0.003	4.029	0.003	4.023	0.007
Mg/(Mg+Fe)	0.912	0.001	0.900	0.001	0.913	0.001	0.925	0.002	0.906	0.001	0.922	0.001
Ca/(Ca+Mg)	0.391	0.006	0.350	0.003	0.393	0.002	0.428	0.002	0.379	0.002	0.417	0.003

Sample no. Rocktype n	JSL280 GLd 6		JSL114 GWc 9		JSL124 Sp 7		JSL153 Sp 3		JSL154 Sp 1		JSL156 Sp 6	
SiO ₂	54.82	0.34	54.91	0.09	53.26	0.14	54.22	0.24	54.66	54.44	0.16	
TiO ₂	0.28	0.01	0.08	0.01	0.35	0.02	0.02	0.00	0.39	0.05	0.01	
Al ₂ O ₃	2.18	0.04	0.83	0.07	6.00	0.13	2.86	0.21	6.42	4.48	0.11	
Cr ₂ O ₃	0.63	0.02	0.93	0.02	1.75	0.20	1.20	0.05	2.04	2.31	0.02	
FeO	4.29	0.27	2.06	0.07	1.38	0.10	1.27	0.01	1.36	1.42	0.03	
MnO	0.15	0.01	0.09	0.02	0.06	0.02	0.06	0.01	0.04	0.06	0.02	
NiO	0.16	0.23	0.09	0.02	0.01	0.01	0.03	0.01	0.07	0.06	0.02	
MgO	20.77	0.10	19.06	0.10	13.71	0.31	16.22	0.13	13.62	14.34	0.13	
CaO	14.88	0.12	21.43	0.17	20.37	0.29	22.16	0.16	17.46	19.80	0.16	
Na ₂ O	1.59	0.04	0.76	0.05	3.07	0.10	1.59	0.06	3.74	3.19	0.11	
Total	99.75	0.25	100.23	0.21	99.96	0.41	99.64	0.28	99.80	100.15	0.43	
Cations (recalculated to 6 oxygens)												
Si	1.970	0.006	1.979	0.002	1.923	0.008	1.965	0.003	1.960	1.961	0.003	
Ti	0.008	0.000	0.002	0.000	0.010	0.001	0.000	0.000	0.010	0.001	0.000	
Al	0.092	0.001	0.035	0.003	0.255	0.005	0.122	0.009	0.270	0.190	0.004	
Cr	0.018	0.001	0.026	0.000	0.050	0.006	0.034	0.002	0.060	0.066	0.001	
Fe	0.129	0.009	0.062	0.002	0.042	0.003	0.039	0.000	0.040	0.043	0.001	
Mn	0.005	0.000	0.003	0.001	0.002	0.001	0.002	0.000	0.000	0.002	0.001	
Ni	0.005	0.007	0.003	0.001	0.000	0.000	0.001	0.000	0.000	0.002	0.001	
Mg	1.113	0.005	1.024	0.004	0.738	0.015	0.876	0.008	0.730	0.770	0.009	
Ca	0.573	0.003	0.828	0.007	0.788	0.011	0.860	0.006	0.670	0.764	0.004	
Na	0.111	0.003	0.053	0.004	0.215	0.007	0.112	0.004	0.270	0.223	0.008	
Total	4.023	0.006	4.014	0.003	4.022	0.005	4.012	0.003	4.000	4.021	0.002	
Mg/(Mg+Fe)	0.896	0.006	0.943	0.002	0.946	0.003	0.958	0.001	0.950	0.947	0.001	
Ca/(Ca+Mg)	0.340	0.002	0.447	0.003	0.517	0.008	0.495	0.002	0.480	0.498	0.002	

Sample no. Rocktype n	JSL157 Sp 3		JSL158 Sp 6		JSL116 GLc 3		JSL134 GLc 4		JSL-/193 GLc 3		JSL261 GLc 2	
SiO2	53.86	0.25	52.63	0.36	53.19	1.03	53.94	0.20	54.58	0.15	54.28	0.14
TiO2	0.13	0.02	0.84	0.13	0.38	0.03	0.30	0.04	0.00	0.00	0.40	0.06
Al2O3	3.35	0.40	5.92	0.25	2.11	1.47	2.62	0.30	2.94	0.03	1.79	0.43
Cr2O3	0.38	0.05	1.07	0.08	1.23	0.41	2.48	0.10	3.76	0.06	3.10	0.15
FeO	1.21	0.05	1.75	0.14	3.65	0.18	2.33	0.10	2.08	0.03	2.09	0.14
MnO	0.05	0.01	0.08	0.02	0.21	0.04	0.07	0.01	0.05	0.01	0.12	0.03
NiO	0.07	0.02	0.05	0.02	0.01	0.01	0.04	0.01	0.07	0.01	0.04	0.02
MgO	16.63	0.23	14.49	0.22	18.50	0.51	16.12	0.23	15.08	0.05	16.93	0.46
CaO	22.94	0.05	20.59	0.26	19.01	0.21	18.86	0.61	18.61	0.14	19.07	0.74
Na2O	1.06	0.05	2.46	0.06	0.98	0.22	2.81	0.24	3.38	0.02	2.39	0.49
Total	99.67	0.17	99.89	0.21	99.27	0.15	99.57	0.33	100.56	0.19	100.21	0.20

Cations (recalculated to 6 oxygens)

Si	1.949	0.010	1.904	0.009	1.943	0.035	1.963	0.003	1.969	0.002	1.964	0.005
Ti	0.004	0.001	0.023	0.004	0.011	0.001	0.008	0.001	0.000	0.000	0.011	0.002
Al	0.143	0.017	0.252	0.011	0.091	0.064	0.112	0.013	0.125	0.002	0.076	0.018
Cr	0.011	0.001	0.031	0.002	0.035	0.012	0.071	0.003	0.107	0.002	0.089	0.004
Fe	0.037	0.001	0.053	0.004	0.112	0.005	0.071	0.003	0.063	0.001	0.063	0.004
Mn	0.002	0.000	0.002	0.001	0.007	0.001	0.002	0.000	0.002	0.000	0.004	0.001
Ni	0.002	0.001	0.002	0.001	0.000	0.000	0.001	0.000	0.002	0.000	0.001	0.001
Mg	0.897	0.012	0.781	0.013	1.007	0.026	0.874	0.011	0.811	0.002	0.913	0.025
Ca	0.889	0.001	0.798	0.010	0.744	0.008	0.735	0.023	0.719	0.005	0.739	0.029
Na	0.074	0.003	0.172	0.004	0.069	0.015	0.198	0.017	0.236	0.001	0.168	0.034
Total	4.007	0.003	4.018	0.007	4.018	0.002	4.036	0.002	4.034	0.002	4.027	0.002

Mg/(Mg+Fe)	0.961	0.002	0.936	0.005	0.900	0.004	0.925	0.004	0.928	0.001	0.935	0.002
Ca/(Ca+Mg)	0.498	0.004	0.505	0.005	0.425	0.007	0.457	0.005	0.470	0.001	0.447	0.003

Sample no. Rocktype n	JSL306 Lc 3		JSL107 P 7		JSL118 P 3		JSL171 P 3		JSL202 P 4		JSL209 P 4	
SiO2	54.66	0.07	52.58	0.33	52.50	0.15	54.46	0.13	54.52	0.27	54.11	0.08
TiO2	0.26	0.01	0.24	0.04	0.26	0.02	0.17	0.01	0.68	0.02	0.56	0.04
Al2O3	1.79	0.02	2.47	0.15	4.97	0.05	2.59	0.02	7.15	0.43	4.59	0.13
Cr2O3	1.81	0.12	0.52	0.06	0.77	0.01	0.49	0.03	0.30	0.02	0.62	0.05
FeO	2.61	0.05	2.83	0.10	2.02	0.26	2.07	0.01	2.72	0.05	1.26	0.02
MnO	0.10	0.02	0.08	0.01	0.10	0.01	0.05	0.03	0.06	0.01	0.03	0.01
NiO	0.03	0.02	0.04	0.02	0.09	0.02	0.01	0.01	0.06	0.01	0.02	0.01
MgO	16.52	0.07	16.61	0.10	16.15	0.95	16.37	0.03	13.19	0.34	15.42	0.18
CaO	19.50	0.27	23.92	0.23	21.76	1.14	22.91	0.07	17.81	0.40	21.01	0.15
Na2O	2.25	0.04	0.53	0.02	1.36	0.10	1.52	0.02	4.09	0.17	2.40	0.03
Total	99.53	0.30	99.82	0.39	99.98	0.55	100.63	0.11	100.56	0.19	100.03	0.35

Cations (recalculated to 6 oxygens)

Si	1.988	0.006	1.925	0.008	1.902	0.004	1.962	0.003	1.946	0.004	1.946	0.004
Ti	0.007	0.000	0.007	0.001	0.007	0.001	0.004	0.000	0.018	0.000	0.015	0.001
Al	0.077	0.001	0.106	0.006	0.212	0.003	0.110	0.001	0.301	0.017	0.194	0.005
Cr	0.052	0.003	0.015	0.002	0.022	0.000	0.014	0.001	0.008	0.000	0.017	0.001
Fe	0.063	0.001	0.087	0.003	0.061	0.008	0.062	0.000	0.081	0.001	0.038	0.001
Mn	0.003	0.000	0.003	0.000	0.003	0.000	0.002	0.001	0.002	0.000	0.001	0.000
Ni	0.001	0.000	0.001	0.000	0.003	0.000	0.000	0.000	0.002	0.000	0.001	0.000
Mg	0.895	0.003	0.907	0.007	0.872	0.049	0.879	0.002	0.702	0.020	0.827	0.007
Ca	0.760	0.009	0.938	0.006	0.844	0.045	0.884	0.004	0.681	0.018	0.810	0.007
Na	0.159	0.002	0.038	0.002	0.096	0.007	0.106	0.001	0.283	0.011	0.168	0.001
Total	4.020	0.007	4.026	0.005	4.022	0.005	4.024	0.002	4.023	0.006	4.017	0.003

Mg/(Mg+Fe)	0.919	0.001	0.913	0.003	0.935	0.004	0.934	0.000	0.896	0.003	0.956	0.000
Ca/(Ca+Mg)	0.459	0.003	0.509	0.003	0.492	0.027	0.502	0.000	0.493	0.005	0.495	0.004

Sample no. Rocktype n	JSL296 P 3	JSL-/91 GPP 10	JSL111 GPP 6	JSL142 GPP 6	JSL143 GPP 2	JSL151 GPP 1					
SiO2	52.45	3.42	53.73	0.21	54.56	0.09	54.79	0.26	54.49	0.09	55.27
TiO2	0.75	0.54	0.32	0.02	0.33	0.02	0.29	0.01	0.30	0.00	0.09
Al2O3	5.95	3.40	3.04	0.13	3.24	0.20	3.39	0.06	2.93	0.01	0.85
Cr2O3	0.92	0.28	3.44	0.44	3.63	0.09	1.52	0.06	3.73	0.18	0.91
FeO	3.13	0.67	2.29	0.07	2.55	0.06	2.15	0.07	1.85	0.05	2.02
MnO	0.16	0.05	0.05	0.01	0.07	0.01	0.08	0.01	0.06	0.01	0.05
NiO	0.07	0.02	0.04	0.03	0.05	0.01	0.04	0.01	0.06	0.01	0.06
MgO	15.41	1.09	15.07	0.29	15.01	0.27	16.42	0.11	15.53	0.07	19.24
CaO	18.92	0.57	18.46	0.40	17.65	0.20	18.19	0.16	17.49	0.05	21.70
Na2O	2.39	0.64	3.39	0.22	3.50	0.18	2.78	0.05	3.36	0.08	0.58
Total	100.16	0.28	99.83	0.39	100.58	0.12	99.64	0.38	99.79	0.20	100.77

Cations (recalculated to 6 oxygens)

Si	1.895	0.108	1.955	0.003	1.966	0.002	1.976	0.003	1.972	0.000	1.980
Ti	0.021	0.015	0.009	0.001	0.009	0.000	0.008	0.000	0.008	0.000	0.002
Al	0.255	0.148	0.130	0.005	0.137	0.009	0.144	0.003	0.125	0.000	0.036
Cr	0.026	0.008	0.099	0.013	0.103	0.003	0.043	0.001	0.107	0.005	0.026
Fe	0.095	0.021	0.070	0.002	0.077	0.002	0.065	0.002	0.056	0.002	0.061
Mn	0.005	0.002	0.002	0.000	0.002	0.000	0.002	0.000	0.002	0.000	0.001
Ni	0.002	0.000	0.001	0.001	0.001	0.000	0.001	0.000	0.002	0.000	0.002
Mg	0.830	0.052	0.817	0.017	0.806	0.014	0.882	0.003	0.837	0.005	1.027
Ca	0.733	0.028	0.720	0.016	0.681	0.008	0.703	0.008	0.678	0.003	0.833
Na	0.167	0.044	0.239	0.015	0.245	0.013	0.194	0.004	0.236	0.005	0.040
Total	4.028	0.002	4.041	0.003	4.027	0.004	4.020	0.005	4.022	0.000	4.007
Mg/(Mg+Fe)	0.897	0.027	0.921	0.001	0.913	0.002	0.932	0.002	0.937	0.001	0.944
Ca/(Ca+Mg)	0.469	0.026	0.468	0.004	0.458	0.005	0.443	0.003	0.447	0.000	0.448

Sample no. Rocktype n	JSL-/177 GPP 14	JSL278 GPP 5	JSL504 GPP 6	JSL533 GPP 6	JSL572 GPP 2	JSL572 GPP 5 intergrowth					
SiO2	54.70	0.32	53.67	0.08	54.29	0.27	54.54	0.11	54.33	0.12	55.11
TiO2	0.32	0.02	0.17	0.01	0.28	0.01	0.28	0.01	0.31	0.02	0.28
Al2O3	2.94	0.10	3.11	0.04	2.72	0.13	3.52	0.08	2.84	0.09	2.05
Cr2O3	3.52	0.36	1.61	0.02	3.02	0.04	4.32	0.22	3.65	0.23	2.58
FeO	2.26	0.05	2.07	0.15	2.14	0.06	2.25	0.04	2.10	0.17	2.64
MnO	0.10	0.02	0.06	0.01	0.08	0.01	0.07	0.01	0.09	0.02	0.09
NiO	0.03	0.02	0.05	0.02	0.06	0.01	0.00	0.01	0.07	0.02	0.05
MgO	15.07	0.17	15.75	0.07	15.71	0.14	14.73	0.21	15.14	0.24	19.60
CaO	18.00	0.26	20.54	0.07	18.43	0.27	16.77	0.09	18.25	0.13	15.44
Na2O	3.30	0.14	2.35	0.03	2.95	0.08	3.99	0.11	3.26	0.08	2.19
Total	100.25	0.53	99.38	0.17	99.70	0.31	100.47	0.29	100.02	0.01	100.04

Cations (recalculated to 6 oxygens)

Si	1.975	0.004	1.956	0.001	1.970	0.005	1.965	0.005	1.968	0.003	1.974	0.009
Ti	0.009	0.001	0.005	0.000	0.008	0.000	0.007	0.000	0.008	0.000	0.008	0.002
Al	0.125	0.004	0.134	0.002	0.116	0.006	0.150	0.003	0.121	0.004	0.087	0.040
Cr	0.100	0.010	0.047	0.000	0.087	0.001	0.123	0.006	0.105	0.006	0.074	0.033
Fe	0.068	0.002	0.063	0.005	0.065	0.002	0.068	0.001	0.064	0.005	0.079	0.025
Mn	0.003	0.001	0.002	0.000	0.003	0.000	0.002	0.000	0.003	0.001	0.003	0.001
Ni	0.001	0.001	0.002	0.000	0.002	0.000	0.000	0.000	0.002	0.000	0.002	0.001
Mg	0.811	0.010	0.856	0.004	0.849	0.006	0.791	0.011	0.817	0.014	1.038	0.384
Ca	0.696	0.009	0.802	0.003	0.717	0.011	0.647	0.003	0.708	0.006	0.599	0.294
Na	0.231	0.010	0.166	0.002	0.208	0.006	0.279	0.007	0.229	0.005	0.153	0.081
Total	4.020	0.006	4.032	0.001	4.024	0.006	4.031	0.005	4.025	0.006	4.015	0.012
Mg/(Mg+Fe)	0.922	0.002	0.931	0.005	0.929	0.002	0.921	0.001	0.928	0.004	0.929	0.004
Ca/(Ca+Mg)	0.462	0.003	0.484	0.002	0.458	0.003	0.450	0.004	0.464	0.002	0.376	0.183

Sample no. Rocktype n	JSL-/93 PP 3		JSL273 PP 3		JSL303 PP 3		JSL304 PP 3		JSL500A PP 8 symplectite		JSL500B PP 8 anhedral & vein	
SiO2	54.12	0.33	54.58	0.23	54.75	0.17	54.59	0.02	54.47	0.26	54.30	0.21
TiO2	0.32	0.02	0.34	0.01	0.26	0.00	0.10	0.01	0.30	0.03	0.31	0.01
Al2O3	1.66	0.04	2.99	0.08	1.21	0.02	2.82	0.03	1.34	0.22	1.50	0.05
Cr2O3	4.69	0.38	3.55	0.55	2.72	0.09	3.82	0.11	1.75	0.54	2.86	0.43
FeO	2.17	0.08	2.17	0.08	2.85	0.01	1.98	0.04	3.46	0.15	3.45	0.16
MnO	0.05	0.01	0.03	0.02	0.09	0.01	0.09	0.02	0.08	0.02	0.11	0.02
NiO	0.08	0.02	0.04	0.01	0.05	0.01	0.06	0.02	0.04	0.01	0.03	0.02
MgO	14.99	0.21	15.17	0.36	15.69	0.05	15.15	0.16	16.06	0.43	15.22	0.18
CaO	18.30	0.32	17.45	0.07	20.12	0.15	18.35	0.03	20.60	0.84	19.47	0.22
Na2O	3.28	0.21	3.36	0.14	2.32	0.04	3.23	0.03	2.08	0.45	2.78	0.11
Total	99.65	0.39	99.69	0.05	100.05	0.05	100.15	0.05	100.18	0.52	100.04	0.30

Cations (recalculated to 6 oxygens)

Si	1.977	0.005	1.977	0.003	1.992	0.004	1.973	0.001	1.983	0.006	1.982	0.003
Ti	0.009	0.000	0.009	0.000	0.007	0.000	0.003	0.000	0.008	0.001	0.009	0.000
Al	0.071	0.002	0.128	0.003	0.052	0.001	0.120	0.001	0.058	0.010	0.064	0.002
Cr	0.135	0.011	0.102	0.016	0.078	0.003	0.109	0.003	0.050	0.016	0.083	0.012
Fe	0.066	0.002	0.066	0.002	0.087	0.000	0.060	0.001	0.105	0.004	0.105	0.005
Mn	0.001	0.000	0.001	0.001	0.003	0.000	0.003	0.001	0.002	0.001	0.003	0.001
Ni	0.002	0.000	0.001	0.000	0.001	0.000	0.002	0.001	0.001	0.000	0.001	0.001
Mg	0.816	0.014	0.819	0.017	0.850	0.002	0.816	0.008	0.871	0.022	0.828	0.008
Ca	0.716	0.014	0.678	0.004	0.784	0.006	0.711	0.001	0.803	0.033	0.762	0.008
Na	0.232	0.014	0.236	0.010	0.164	0.003	0.226	0.002	0.147	0.031	0.197	0.008
Total	4.027	0.002	4.017	0.002	4.018	0.006	4.022	0.002	4.029	0.006	4.034	0.002

Mg/(Mg+Fe)	0.925	0.004	0.926	0.002	0.908	0.000	0.932	0.002	0.892	0.005	0.887	0.004
Ca/(Ca+Mg)	0.467	0.001	0.453	0.006	0.480	0.002	0.466	0.002	0.480	0.005	0.479	0.002

Sample no. Rocktype n	JSL516 PP 5		JSL520 PP 6		JSL520A PP 4		JSL520B PP 4		JSL532 PP 5		JSL547 PP 6	
SiO2	54.60	0.13	54.65	0.18	54.55	0.12	54.34	0.31	54.29	0.19	54.03	0.15
TiO2	0.32	0.01	0.32	0.01	0.34	0.01	0.34	0.01	0.15	0.02	0.35	0.01
Al2O3	2.39	0.28	1.84	0.18	1.79	0.01	1.79	0.02	0.85	0.14	2.48	0.02
Cr2O3	3.86	0.43	3.53	0.06	3.65	0.04	3.56	0.03	3.44	0.10	3.79	0.07
FeO	2.11	0.10	2.12	0.04	2.09	0.04	2.30	0.04	2.01	0.19	1.74	0.10
MnO	0.04	0.01	0.06	0.01	0.03	0.02	0.06	0.01	0.06	0.01	0.07	0.01
NiO	0.07	0.01	0.07	0.02	0.06	0.01	0.04	0.01	0.08	0.01	0.05	0.02
MgO	15.52	0.45	15.68	0.15	15.74	0.08	15.96	0.20	16.06	0.11	15.47	0.09
CaO	18.14	0.39	18.63	0.33	18.69	0.21	19.51	0.12	20.82	0.11	18.42	0.16
Na2O	3.30	0.26	2.76	0.04	2.75	0.05	2.83	0.07	2.31	0.05	3.15	0.08
Total	100.34	0.40	99.66	0.46	99.69	0.29	100.72	0.73	100.08	0.31	99.54	0.21

Cations (recalculated to 6 oxygens)

Si	1.972	0.004	1.986	0.006	1.983	0.003	1.964	0.003	1.978	0.005	1.966	0.003
Ti	0.009	0.000	0.009	0.000	0.009	0.000	0.009	0.000	0.004	0.001	0.010	0.000
Al	0.102	0.012	0.079	0.008	0.077	0.001	0.076	0.001	0.037	0.006	0.106	0.001
Cr	0.110	0.012	0.101	0.002	0.105	0.001	0.102	0.001	0.099	0.003	0.109	0.002
Fe	0.064	0.003	0.064	0.001	0.064	0.001	0.070	0.001	0.061	0.006	0.053	0.003
Mn	0.001	0.000	0.002	0.000	0.001	0.000	0.002	0.000	0.002	0.000	0.002	0.000
Ni	0.002	0.000	0.002	0.001	0.002	0.000	0.001	0.000	0.002	0.000	0.001	0.001
Mg	0.836	0.024	0.849	0.008	0.852	0.005	0.860	0.005	0.872	0.004	0.839	0.006
Ca	0.702	0.015	0.725	0.011	0.728	0.007	0.756	0.001	0.813	0.004	0.718	0.006
Na	0.231	0.018	0.195	0.002	0.194	0.003	0.198	0.004	0.163	0.004	0.222	0.005
Total	4.028	0.005	4.013	0.006	4.014	0.004	4.037	0.004	4.031	0.004	4.027	0.003

Mg/(Mg+Fe)	0.929	0.001	0.929	0.001	0.931	0.001	0.925	0.001	0.934	0.006	0.941	0.003
Ca/(Ca+Mg)	0.457	0.003	0.461	0.004	0.461	0.003	0.468	0.002	0.482	0.002	0.461	0.002

Sample no. Rocktype n	JSL565 PP 6		JSL565A PP 3		JSL565B PP 2		JSL75 MP 4		JSL110 MP 4		JSL180 MP 6	
SiO2	54.57	0.19	54.05	0.31	54.00	0.04	53.49	0.19	53.96	0.36	54.18	0.45
TiO2	0.36	0.01	0.31	0.06	0.39	0.01	1.02	0.05	0.25	0.02	0.08	0.01
Al2O3	2.57	0.10	1.91	0.48	2.61	0.07	6.47	0.17	3.19	0.32	1.85	0.05
Cr2O3	3.24	0.22	3.42	0.17	3.59	0.03	0.12	0.02	1.02	0.10	0.26	0.01
FeO	2.22	0.05	2.17	0.22	2.19	0.01	1.65	0.04	2.12	0.03	2.65	0.11
MnO	0.07	0.01	0.07	0.00	0.08	0.01	0.03	0.02	0.05	0.02	0.07	0.03
NiO	0.04	0.01	0.01	0.01	0.04	0.00	0.01	0.02	0.01	0.01	0.06	0.01
MgO	15.22	0.16	15.37	0.50	14.98	0.03	14.47	0.04	15.79	0.16	16.98	0.19
CaO	18.34	0.26	19.37	0.95	18.45	0.03	20.21	0.11	21.98	0.25	23.02	0.13
Na2O	3.23	0.07	2.78	0.53	3.30	0.13	3.00	0.06	1.97	0.13	1.16	0.04
Total	99.85	0.41	99.45	0.31	99.61	0.25	100.47	0.28	100.33	0.36	100.32	0.38
Cations (recalculated to 6 oxygens)												
Si	1.979	0.003	1.975	0.004	1.968	0.003	1.915	0.005	1.951	0.007	1.964	0.008
Ti	0.010	0.000	0.008	0.002	0.011	0.000	0.027	0.001	0.007	0.000	0.002	0.000
Al	0.110	0.004	0.082	0.021	0.112	0.003	0.273	0.007	0.136	0.014	0.079	0.002
Cr	0.093	0.007	0.099	0.004	0.103	0.001	0.003	0.001	0.029	0.003	0.007	0.000
Fe	0.067	0.001	0.066	0.006	0.067	0.000	0.049	0.001	0.064	0.001	0.080	0.003
Mn	0.002	0.000	0.002	0.000	0.002	0.000	0.001	0.000	0.002	0.001	0.002	0.001
Ni	0.001	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.002	0.000
Mg	0.822	0.006	0.837	0.031	0.813	0.000	0.772	0.004	0.851	0.010	0.918	0.014
Ca	0.713	0.008	0.758	0.040	0.720	0.000	0.775	0.002	0.851	0.010	0.894	0.007
Na	0.227	0.005	0.197	0.037	0.233	0.009	0.208	0.004	0.138	0.009	0.081	0.003
Total	4.024	0.006	4.025	0.002	4.031	0.006	4.024	0.002	4.029	0.006	4.031	0.008
Mg/(Mg + Fe)	0.924	0.002	0.926	0.009	0.924	0.000	0.940	0.001	0.930	0.001	0.919	0.004
Ca/(Ca + Mg)	0.464	0.002	0.475	0.004	0.470	0.000	0.501	0.002	0.500	0.003	0.493	0.003

Sample no. Rocktype n	JSL252 MP 2		JSL298 MP 4	
SiO2	53.25	0.22	54.33	0.06
TiO2	0.44	0.00	0.09	0.02
Al2O3	4.43	0.06	2.14	0.02
Cr2O3	0.48	0.01	0.45	0.02
FeO	1.22	0.10	1.75	0.07
MnO	0.01	0.01	0.03	0.02
NiO	0.03	0.00	0.08	0.01
MgO	15.95	0.05	17.02	0.10
CaO	22.23	0.33	23.06	0.11
Na2O	1.69	0.03	1.22	0.04
Total	99.74	0.25	100.18	0.26
Cations (recalculated to 6 oxygens)				
Si	1.926	0.009	1.965	0.003
Ti	0.012	0.000	0.003	0.001
Al	0.189	0.002	0.091	0.001
Cr	0.014	0.000	0.013	0.001
Fe	0.037	0.003	0.053	0.002
Mn	0.000	0.000	0.001	0.001
Ni	0.001	0.000	0.002	0.000
Mg	0.860	0.003	0.917	0.005
Ca	0.862	0.013	0.893	0.003
Na	0.119	0.002	0.086	0.003
Total	4.020	0.009	4.024	0.004
Mg/(Mg + Fe)	0.959	0.003	0.945	0.002
Ca/(Ca + Mg)	0.500	0.005	0.493	0.001

Clinopyroxene

Sample no. Rocktype n	JSL67 1 5	JSL83 1 5	JSL106 1 8	JSL200 1 7	JSL201 1 7	JSL203 1 4						
SiO ₂	55.18	0.09	55.10	0.28	54.81	0.12	55.19	0.06	54.81	0.22	52.56	0.86
TiO ₂	0.27	0.01	0.27	0.02	0.29	0.01	0.30	0.01	0.36	0.01	0.89	0.12
Al ₂ O ₃	9.51	0.09	9.09	0.07	8.66	0.08	11.90	0.06	9.92	0.13	6.95	1.08
Cr ₂ O ₃	0.05	0.00	0.25	0.01	0.01	0.01	0.07	0.00	0.18	0.02	0.14	0.06
FeO	3.39	0.06	2.29	0.10	5.05	0.15	2.00	0.03	2.48	0.13	5.88	0.32
MnO	0.01	0.02	0.02	0.02	0.08	0.01	0.02	0.01	0.02	0.01	0.08	0.03
NiO	0.01	0.01	0.10	0.02	0.01	0.02	0.04	0.02	0.06	0.02	0.03	0.02
MgO	10.81	0.08	11.30	0.19	10.36	0.10	9.73	0.11	10.74	0.14	13.60	0.86
CaO	15.89	0.06	16.29	0.15	16.08	0.16	14.81	0.11	15.71	0.12	16.12	1.39
Na ₂ O	4.77	0.02	5.35	0.10	4.66	0.05	6.15	0.03	5.62	0.08	3.19	0.86
Total	99.91	0.33	100.05	0.40	100.01	0.29	100.22	0.21	99.90	0.42	99.45	0.16
Cations (recalculated to 6 oxygens)												
Si	1.968	0.003	1.962	0.004	1.971	0.003	1.948	0.003	1.954	0.004	1.916	0.016
Ti	0.007	0.000	0.008	0.001	0.008	0.000	0.008	0.000	0.010	0.000	0.024	0.003
Al	0.400	0.003	0.381	0.004	0.367	0.003	0.495	0.002	0.417	0.004	0.298	0.044
Cr	0.001	0.000	0.008	0.001	0.000	0.000	0.002	0.000	0.005	0.001	0.004	0.002
Fe	0.101	0.002	0.068	0.003	0.152	0.005	0.059	0.001	0.074	0.004	0.179	0.011
Mn	0.000	0.001	0.000	0.000	0.002	0.000	0.000	0.000	0.001	0.000	0.003	0.001
Ni	0.000	0.000	0.002	0.001	0.000	0.001	0.001	0.001	0.002	0.000	0.001	0.001
Mg	0.575	0.003	0.601	0.010	0.555	0.004	0.512	0.005	0.571	0.005	0.739	0.052
Ca	0.607	0.002	0.623	0.003	0.619	0.008	0.560	0.004	0.600	0.005	0.630	0.059
Na	0.329	0.001	0.369	0.008	0.325	0.003	0.421	0.002	0.388	0.004	0.225	0.060
Total	3.989	0.002	4.020	0.004	4.000	0.003	4.006	0.004	4.020	0.004	4.021	0.005
Jd	27.256	15.609	36.980	0.480	34.285	0.204	44.788	0.170	39.424	0.319	23.561	12.327
Wo	22.652	12.990	30.370	0.239	30.654	0.246	27.324	0.173	29.184	0.216	25.095	11.333
Hy	25.230	14.465	32.650	0.343	35.061	0.211	27.888	0.192	31.392	0.125	34.787	16.339
Mg/(Mg+Fe)	0.650	0.002	0.899	0.005	0.785	0.006	0.897	0.002	0.885	0.007	0.805	0.007
Ca/(Ca+Mg)	0.514	0.001	0.509	0.004	0.527	0.004	0.522	0.003	0.512	0.002	0.460	0.006
Fe/Mg.gt	0.746	0.006	0.348	0.013	1.254	0.069	0.520	0.005	0.499	0.003	1.589	0.024
X _{ca.gt}	0.277	0.005	0.212	0.005	0.287	0.019	0.349	0.003	0.306	0.005	0.240	0.012
Fe/Mg.cpx	0.176	0.003	0.114	0.006	0.273	0.009	0.115	0.002	0.129	0.008	0.243	0.010
Kd	4.237	0.033	3.062	0.090	4.592	0.313	4.517	0.079	3.874	0.261	6.550	0.262
Ellis and Green (1979) thermometer												
T (C) at 45kb	1034.8	2.8	1109.3	15.7	1014.5	21.9	1076.3	7.4	1100.5	26.1	854.7	17.1
T (C) at 50kb	1051.0	2.8	1127.3	15.9	1030.4	22.2	1092.2	7.5	1117.2	26.4	869.1	17.2

Sample no. Rocktype n	JSL204 1 5	JSL205 1 7	JSL206 1 6	JSL207 1 1	JSL208 1 7	JSL211 1 6						
SiO ₂	55.28	0.25	53.63	2.22	55.60	0.05	55.16	54.81	0.15	54.55	0.31	
TiO ₂	0.34	0.02	0.37	0.19	0.28	0.02	0.30	0.27	0.02	0.28	0.05	
Al ₂ O ₃	11.81	0.23	7.29	1.47	9.63	0.15	9.77	3.62	0.11	2.55	0.10	
Cr ₂ O ₃	0.02	0.01	0.08	0.04	0.13	0.01	0.02	0.58	0.03	0.32	0.28	
FeO	4.15	0.17	5.00	0.50	2.32	0.05	4.84	2.25	0.06	3.07	0.16	
MnO	0.03	0.01	0.07	0.04	0.02	0.01	0.04	0.09	0.02	0.12	0.03	
NiO	0.02	0.01	0.02	0.02	0.09	0.02	0.01	0.01	0.01	0.07	0.01	
MgO	8.42	0.12	12.31	1.46	11.39	0.08	9.70	16.08	0.09	17.30	0.21	
CaO	12.79	0.06	17.76	1.76	15.42	0.18	13.86	20.04	0.14	20.02	0.29	
Na ₂ O	6.49	0.07	3.52	1.36	5.72	0.10	6.41	2.50	0.09	1.88	0.09	
Total	99.36	0.27	100.04	0.37	100.59	0.22	100.10	100.25	0.19	100.16	0.42	
Cations (recalculated to 6 oxygens)												
Si	1.974	0.003	1.940	0.058	1.964	0.004	1.974	1.970	0.003	1.970	0.004	
Ti	0.009	0.001	0.010	0.005	0.007	0.001	0.008	0.007	0.001	0.007	0.001	
Al	0.497	0.009	0.310	0.062	0.401	0.006	0.412	0.153	0.005	0.108	0.004	
Cr	0.001	0.000	0.002	0.001	0.004	0.000	0.000	0.016	0.001	0.009	0.008	
Fe	0.124	0.005	0.152	0.017	0.069	0.002	0.145	0.068	0.002	0.093	0.005	
Mn	0.001	0.000	0.002	0.001	0.000	0.000	0.001	0.003	0.001	0.004	0.001	
Ni	0.001	0.000	0.000	0.001	0.003	0.001	0.000	0.000	0.000	0.002	0.000	
Mg	0.448	0.007	0.665	0.088	0.600	0.004	0.517	0.862	0.004	0.931	0.009	
Ca	0.489	0.002	0.689	0.078	0.583	0.006	0.532	0.772	0.006	0.774	0.009	
Na	0.449	0.006	0.246	0.093	0.391	0.007	0.444	0.174	0.006	0.131	0.006	
Total	3.993	0.007	4.017	0.014	4.022	0.003	4.034	4.025	0.003	4.030	0.006	
Jd	41.321	12.976	27.174	7.081	38.854	0.505	41.762	16.805	0.461	12.132	0.695	
Wo	22.178	4.851	33.299	2.935	28.486	0.316	25.908	37.681	0.291	37.764	0.348	
Hy	26.501	4.569	39.526	4.151	32.661	0.255	32.329	45.514	0.246	50.104	0.453	
Mg/(Mg+Fe)	0.783	0.006	0.814	0.005	0.897	0.002	0.781	0.927	0.002	0.909	0.005	
Ca/(Ca+Mg)	0.522	0.004	0.510	0.005	0.493	0.002	0.507	0.472	0.002	0.454	0.001	
Fe/Mg.gt	1.063	0.009	0.923	0.012	0.394	0.015	1.058	0.205	0.005	0.671	0.185	
X _{ca.gt}	0.240	0.010	0.234	0.002	0.226	0.005	0.217	0.100	0.001	0.170	0.018	
Fe/Mg.cpx	0.277	0.009	0.228	0.007	0.114	0.003	0.280	0.078	0.002	0.100	0.006	
Kd	3.847	0.146	4.045	0.135	3.443	0.152	3.782	2.617	0.091	6.841	2.102	
Ellis and Green (1979) thermometer												
T (C) at 45kb	1038.9	8.6	1013.2	12.9	1071.5	14.6	1023.2	1064.2	15.8	816.2	120.6	
T (C) at 50kb	1055.6	8.7	1029.6	13.0	1088.8	14.8	1040.0	1083.2	16.1	830.8	122.5	

Sample no. Rocktype n	JSL212 5	JSL214 4	JSL254 3	JSL54 	JSL57 	JSL70 	JSL72 	JSL73 	JSL74 			
	grainmounts==>											
SiO2	54.38	0.17	54.67	0.07	54.61	0.18	55.30	54.49	54.80	54.84	54.50	55.11
TiO2	0.28	0.02	0.50	0.01	0.53	0.01	0.18	0.37	0.41	0.30	0.39	0.41
Al2O3	3.00	0.01	5.56	0.12	7.14	0.08	2.90	3.57	8.62	3.48	3.38	3.43
Cr2O3	0.33	0.02	0.11	0.01	0.15	0.00	0.39	0.97	0.15	0.63	0.43	0.14
FeO	2.32	0.11	4.53	0.07	5.37	0.02	4.89	3.26	4.56	2.98	4.26	3.18
MnO	0.09	0.01	0.05	0.01	0.10	0.01	0.13	0.04	0.07	0.05	0.06	0.09
NiO	0.05	0.02	0.05	0.02	0.04	0.02	0.09	0.02	0.05	0.06	0.07	0.06
MgO	16.69	0.09	13.64	0.15	11.36	0.03	21.25	15.41	10.62	16.15	15.76	16.28
CaO	20.79	0.21	16.96	0.17	15.35	0.08	12.87	18.25	14.70	19.04	18.29	19.18
Na2O	2.07	0.08	4.04	0.10	5.19	0.03	1.90	2.78	5.59	2.54	2.61	2.41
Total	99.99	0.23	100.11	0.03	99.85	0.30	99.91	99.15	99.57	100.09	99.75	100.30
Cations (recalculated to 6 oxygens)												
Si	1.965	0.002	1.972	0.002	1.978	0.001	1.974	1.982	1.974	1.976	1.978	1.980
Ti	0.008	0.000	0.014	0.000	0.014	0.000	0.005	0.010	0.011	0.008	0.011	0.011
Al	0.128	0.001	0.236	0.005	0.304	0.003	0.122	0.153	0.366	0.148	0.145	0.145
Cr	0.010	0.001	0.003	0.000	0.004	0.000	0.011	0.028	0.004	0.018	0.012	0.004
Fe	0.070	0.003	0.137	0.002	0.163	0.001	0.146	0.099	0.137	0.090	0.129	0.095
Mn	0.003	0.000	0.001	0.000	0.003	0.000	0.004	0.001	0.002	0.002	0.002	0.003
Ni	0.001	0.001	0.002	0.000	0.001	0.001	0.003	0.000	0.002	0.002	0.002	0.002
Mg	0.899	0.004	0.733	0.008	0.813	0.001	1.131	0.835	0.570	0.867	0.852	0.872
Ca	0.805	0.009	0.655	0.007	0.595	0.002	0.492	0.711	0.568	0.735	0.711	0.738
Na	0.145	0.006	0.283	0.007	0.364	0.002	0.131	0.196	0.390	0.177	0.184	0.168
Total	4.032	0.003	4.036	0.000	4.038	0.002	4.020	4.016	4.025	4.022	4.025	4.018
Jd	11.533	4.854	21.407	6.605	32.877	0.158	12.977	18.630	37.309	16.852	16.749	15.658
Wo	32.641	14.447	27.444	9.217	29.082	0.146	24.165	35.142	27.852	36.083	34.940	36.456
Hy	39.409	17.422	36.278	12.130	38.041	0.061	62.859	46.228	34.839	47.065	48.311	47.886
Mg/(Mg+Fe)	0.928	0.003	0.843	0.003	0.790	0.001	0.886	0.894	0.806	0.906	0.868	0.901
Ca/(Ca+Mg)	0.472	0.003	0.472	0.002	0.493	0.001	0.303	0.460	0.499	0.459	0.455	0.459
Fe/Mg.gt	0.645	0.171	0.474	0.008	0.687	0.007	0.220	0.277	0.717	0.220	0.300	0.230
Xca.gt	0.172	0.011	0.141	0.006	0.142	0.001	0.100	0.105	0.185	0.101	0.100	0.094
Fe/Mg.cpx	0.078	0.004	0.186	0.004	0.265	0.002	0.129	0.119	0.241	0.103	0.152	0.109
Kd	8.332	2.344	2.546	0.046	2.591	0.043	1.703	2.339	2.977	2.124	1.976	2.104
Ellis and Green (1979) thermometer												
T (C) at 45kb	752.8	83.2	1121.7	12.9	1113.8	8.6	1298.5	1123.1	1094.3	1169.5	1208.9	1166.2
T (C) at 50kb	766.6	84.4	1140.9	13.0	1132.8	8.7	1320.8	1142.8	1112.5	1190.0	1229.9	1186.7

Sample no. Rocktype n	JSL80 	JSL85 	JSL92 	JSL93 	JSL99 	JSL102 	JSL216 	JSL217 	JSL218 	JSL219 	JSL220 	JSL221
SiO2	54.39	54.91	54.48	55.20	55.10	54.49	52.61	54.33	53.27	55.62	54.90	55.19
TiO2	0.36	0.26	0.22	0.26	0.23	0.38	0.41	0.28	0.47	0.26	0.29	0.26
Al2O3	2.96	3.57	3.10	2.42	2.38	3.36	6.29	2.76	6.26	7.75	5.60	7.87
Cr2O3	0.64	1.37	0.99	0.86	0.63	3.63	0.11	0.22	0.07	0.07	0.13	0.09
FeO	3.55	2.07	2.62	2.65	2.60	2.05	4.60	3.34	4.96	4.43	3.93	4.59
MnO	0.10	0.09	0.04	0.06	0.07	0.07	0.01	0.03	0.04	0.06	0.03	0.04
NiO	0.05	0.03	0.00	0.01	0.02	0.01	0.02	0.05	0.00	0.00	0.00	0.00
MgO	16.10	15.70	16.13	17.73	17.94	14.72	13.04	15.87	12.73	10.97	12.97	10.99
CaO	18.89	19.42	19.66	19.18	19.26	17.29	19.68	20.70	18.62	16.42	18.32	16.29
Na2O	2.25	2.62	2.44	2.08	1.96	3.66	2.97	1.99	3.30	4.32	3.66	4.52
Total	99.29	100.03	99.67	100.46	100.19	99.65	99.71	99.58	99.72	99.90	99.83	99.84
Cations (recalculated to 6 oxygens)												
Si	1.980	1.976	1.973	1.979	1.979	1.975	1.921	1.978	1.941	1.995	1.983	1.984
Ti	0.010	0.007	0.006	0.007	0.008	0.010	0.011	0.008	0.013	0.007	0.008	0.007
Al	0.127	0.151	0.132	0.102	0.101	0.143	0.271	0.118	0.269	0.327	0.238	0.334
Cr	0.018	0.039	0.028	0.024	0.018	0.104	0.003	0.006	0.002	0.002	0.004	0.003
Fe	0.108	0.062	0.079	0.080	0.078	0.062	0.140	0.102	0.151	0.133	0.119	0.138
Mn	0.003	0.003	0.001	0.002	0.002	0.002	0.000	0.001	0.001	0.002	0.001	0.001
Ni	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000
Mg	0.874	0.842	0.871	0.948	0.961	0.795	0.710	0.861	0.691	0.586	0.698	0.589
Ca	0.737	0.749	0.763	0.737	0.741	0.671	0.769	0.807	0.727	0.631	0.709	0.627
Na	0.159	0.183	0.171	0.145	0.136	0.257	0.210	0.140	0.233	0.300	0.256	0.315
Total	4.017	4.013	4.026	4.023	4.023	4.020	4.036	4.023	4.028	3.983	4.016	3.998
Jd	15.021	18.391	16.218	13.327	12.514	24.774	23.015	13.017	24.275	31.769	24.597	32.444
Wo	36.365	36.906	37.294	36.162	36.390	32.993	36.566	39.654	35.036	31.844	35.007	31.266
Hy	48.614	44.703	46.487	50.511	51.096	42.233	40.419	47.328	40.688	36.388	40.396	36.290
Mg/(Mg+Fe)	0.890	0.931	0.917	0.923	0.925	0.928	0.835	0.894	0.821	0.815	0.855	0.810
Ca/(Ca+Mg)	0.457	0.471	0.467	0.437	0.436	0.458	0.520	0.484	0.512	0.518	0.504	0.516
Fe/Mg.gt	0.251	0.189	0.210	0.181	0.178	0.185	0.842	0.346	0.893	0.860	0.627	0.858
Xca.gt	0.102	0.105	0.100	0.106	0.101	0.119	0.281	0.138	0.229	0.249	0.231	0.227
Fe/Mg.cpx	0.124	0.074	0.091	0.084	0.081	0.078	0.198	0.118	0.219	0.227	0.170	0.235
Kd	2.026	2.559	2.313	2.156	2.193	2.365	4.257	2.932	4.082	3.789	3.683	3.659
Ellis and Green (1979) thermometer												
T (C) at 45kb	1196.6	1079.2	1123.1	1167.0	1152.5	1134.0	1036.7	1051.6	1004.8	1053.0	1048.0	1047.0
T (C) at 50kb	1217.4	1098.3	1142.9	1187.3	1172.7	1153.7	1052.9	1069.8	1021.2	1069.8	1064.9	1064.0

Sample no. Rocktype n	JSL222 I	JSL224 I	JSL225 I	JSL226 I	JSL227 I	JSL231 I	JSL235 I	JSL238 I	JSL241 I	JSL243 I	JSL245 I
SiO2	55.78	55.56	56.67	55.05	52.68	53.94	55.72	55.21	54.80	55.02	55.15
TiO2	0.40	0.46	0.48	0.25	0.36	0.48	0.41	0.30	0.30	0.29	0.34
Al2O3	9.90	10.15	11.36	7.48	4.93	8.84	4.55	3.18	3.60	2.46	2.63
Cr2O3	0.08	0.05	0.08	0.07	0.07	0.09	0.17	0.61	0.83	0.72	0.48
FeO	4.81	5.14	4.65	3.86	5.94	4.05	4.15	3.13	2.63	3.22	2.89
MnO	0.06	0.04	0.03	0.03	0.03	0.01	0.07	0.09	0.03	0.11	0.12
NiO	0.00	0.00	0.02	0.04	0.06	0.02	0.06	0.08	0.04	0.00	0.00
MgO	9.52	8.72	8.77	11.67	13.79	10.85	14.58	15.79	14.99	16.48	16.36
CaO	12.77	12.94	11.14	17.11	19.97	15.39	17.47	19.55	20.12	19.60	19.90
Na2O	6.70	6.63	7.56	3.93	2.07	5.68	3.21	2.30	2.66	1.87	1.84
Total	100.02	99.69	100.76	99.50	99.90	99.34	100.38	100.23	100.01	99.77	99.70

Cations (recalculated to 6 oxygens)

Si	1.990	1.991	1.994	1.982	1.931	1.951	1.997	1.988	1.979	1.991	1.993
Ti	0.011	0.012	0.013	0.007	0.010	0.013	0.011	0.008	0.008	0.008	0.009
Al	0.416	0.429	0.471	0.318	0.213	0.377	0.192	0.135	0.153	0.105	0.112
Cr	0.002	0.001	0.002	0.002	0.002	0.003	0.005	0.017	0.024	0.021	0.014
Fe	0.144	0.154	0.137	0.116	0.182	0.122	0.124	0.094	0.079	0.097	0.087
Mn	0.002	0.001	0.001	0.001	0.001	0.000	0.002	0.003	0.001	0.004	0.004
Ni	0.000	0.000	0.001	0.001	0.002	0.001	0.002	0.002	0.001	0.000	0.000
Mg	0.506	0.466	0.460	0.626	0.753	0.585	0.779	0.847	0.807	0.889	0.881
Ca	0.488	0.497	0.420	0.660	0.784	0.597	0.671	0.754	0.778	0.760	0.770
Na	0.464	0.461	0.515	0.274	0.147	0.397	0.223	0.161	0.186	0.131	0.129
Total	4.022	4.012	4.014	3.988	4.025	4.045	4.005	4.009	4.017	4.004	3.999

Jd	43.622	44.364	49.273	29.732	17.364	37.309	21.046	15.548	17.917	12.797	12.738
Wo	24.138	24.728	20.939	33.045	37.669	28.676	33.611	37.492	38.366	37.874	38.579
Hy	32.239	30.909	29.788	37.223	44.967	34.015	45.343	46.960	43.717	49.328	48.682

Mg/(Mg+Fe)	0.779	0.752	0.770	0.843	0.805	0.827	0.862	0.900	0.910	0.901	0.910
Ca/(Ca+Mg)	0.491	0.516	0.477	0.513	0.510	0.505	0.463	0.471	0.491	0.461	0.466
Fe/Mg.gt	0.820	1.045	0.761	0.722	1.013	0.798	0.323	0.276	0.276	0.264	0.263
Xca.gt	0.153	0.220	0.120	0.211	0.245	0.226	0.105	0.122	0.142	0.126	0.110
Fe/Mg.cpx	0.284	0.331	0.298	0.186	0.242	0.209	0.160	0.111	0.098	0.110	0.099
Kd	2.890	3.160	2.554	3.886	4.192	3.815	2.024	2.477	2.803	2.410	2.656

Ellis and Green (1979) thermometer

T (C) at 45kb	1074.0	1102.8	1096.5	1006.7	1009.6	1028.4	1201.1	1114.2	1076.7	1131.4	1067.3
T (C) at 50kb	1092.3	1120.6	1115.6	1023.4	1025.9	1045.1	1221.9	1133.5	1095.2	1150.9	1086.1

Sample no. Rocktype n	JSL246 I	JSL247 I	JSL59 II 5	JSL60 II 8	JSL61 II 4	JSL62 II 5	JSL63 II 7					
<= grainmounts												
SiO2	55.14	55.12	54.26	0.10	52.90	0.21	55.28	0.12	53.97	0.11	53.87	0.43
TiO2	0.28	0.29	0.07	0.01	0.64	0.04	0.20	0.02	0.30	0.01	0.40	0.08
Al2O3	3.44	3.44	2.40	0.05	4.29	0.11	5.55	0.05	3.53	0.06	9.36	2.49
Cr2O3	0.07	0.07	0.43	0.01	0.85	0.03	0.09	0.01	0.14	0.01	0.11	0.10
FeO	3.42	3.34	1.49	0.12	1.33	0.04	3.12	0.05	2.50	0.05	2.71	0.69
MnO	0.10	0.10	0.06	0.02	0.03	0.02	0.05	0.02	0.02	0.02	0.02	0.02
NiO	0.04	0.05	0.02	0.01	0.03	0.01	0.04	0.02	0.03	0.02	0.08	0.02
MgO	16.88	16.84	17.08	0.19	15.42	0.13	14.04	0.13	16.16	0.11	11.47	1.72
CaO	18.62	18.60	22.28	0.06	22.75	0.15	18.75	0.17	20.37	0.16	17.28	0.48
Na2O	1.89	1.86	1.37	0.02	1.81	0.05	3.35	0.04	2.15	0.04	4.25	0.54
Total	99.87	99.92	99.46	0.28	100.04	0.37	100.48	0.19	99.17	0.12	99.55	0.41

Cations (recalculated to 6 oxygens)

Si	1.984	1.982	1.969	0.006	1.916	0.004	1.977	0.005	1.963	0.002	1.934	0.020
Ti	0.008	0.008	0.002	0.000	0.017	0.001	0.005	0.001	0.008	0.000	0.011	0.002
Al	0.146	0.146	0.103	0.002	0.183	0.004	0.234	0.002	0.151	0.003	0.396	0.105
Cr	0.002	0.002	0.012	0.000	0.024	0.001	0.002	0.000	0.004	0.000	0.003	0.003
Fe	0.103	0.101	0.045	0.003	0.040	0.001	0.093	0.001	0.076	0.001	0.081	0.021
Mn	0.003	0.003	0.002	0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.001
Ni	0.001	0.002	0.001	0.000	0.001	0.000	0.001	0.001	0.001	0.001	0.002	0.001
Mg	0.905	0.903	0.924	0.009	0.833	0.005	0.749	0.007	0.876	0.007	0.614	0.095
Ca	0.718	0.725	0.866	0.001	0.883	0.005	0.718	0.006	0.794	0.005	0.665	0.020
Na	0.132	0.130	0.096	0.001	0.127	0.004	0.232	0.003	0.151	0.003	0.296	0.037
Total	4.001	4.001	4.020	0.005	4.026	0.003	4.015	0.007	4.026	0.003	4.003	0.015

Jd	13.922	13.827	10.295	0.163	16.058	0.134	23.082	0.136	14.941	0.217	33.257	7.865
Wo	35.745	36.073	42.304	0.244	42.179	0.200	35.377	0.241	38.652	0.313	32.321	1.176
Hy	50.334	50.100	47.401	0.318	41.763	0.203	41.541	0.158	46.407	0.268	34.423	6.692

Mg/(Mg+Fe)	0.898	0.900	0.954	0.003	0.954	0.001	0.889	0.002	0.920	0.002	0.884	0.010
Ca/(Ca+Mg)	0.442	0.445	0.484	0.002	0.515	0.003	0.490	0.003	0.475	0.003	0.522	0.027
Fe/Mg.gt	0.221	0.424	0.219	0.000	0.185	0.001	0.429	0.008	0.251	0.003	0.678	0.015
Xca.gt	0.148	0.188	0.109	0.002	0.125	0.002	0.098	0.001	0.100	0.001	0.206	0.003
Fe/Mg.cpx	0.114	0.111	0.049	0.003	0.048	0.001	0.125	0.002	0.087	0.002	0.131	0.013
Kd	1.950	3.804	4.504	0.313	3.817	0.106	3.437	0.130	2.886	0.051	5.230	0.481

Ellis and Green (1979) thermometer

T (C) at 45kb	1274.1	993.7	860.3	23.4	932.3	11.1	946.2	13.6	1019.6	8.0	897.9	32.1
T (C) at 50kb	1295.2	1010.4	876.2	23.7	949.1	11.3	963.5	13.8	1037.9	8.1	913.1	32.6

Sample no. Rocktype n	JSL65 II 6	JSL69 II 8	JSL77 II 6	JSL86 II 5	JSL91 II 7	JSL95 II 5						
SiO ₂	54.59	0.16	53.89	0.15	54.08	0.20	54.92	0.18	54.85	0.09	54.28	0.11
TiO ₂	0.30	0.02	0.18	0.01	0.20	0.01	0.28	0.01	0.26	0.02	0.32	0.01
Al ₂ O ₃	3.15	0.11	2.33	0.06	3.36	0.06	3.65	0.06	3.58	0.04	3.52	0.16
Cr ₂ O ₃	0.32	0.02	0.08	0.02	0.11	0.02	1.12	0.05	1.45	0.09	1.64	0.02
FeO	3.68	0.09	2.06	0.11	3.01	0.07	2.12	0.02	1.99	0.04	2.54	0.03
MnO	0.09	0.02	0.05	0.02	0.05	0.01	0.09	0.02	0.08	0.02	0.09	0.02
NiO	0.04	0.01	0.05	0.02	0.04	0.02	0.01	0.01	0.06	0.03	0.02	0.02
MgO	16.15	0.14	16.92	0.12	15.66	0.10	16.20	0.09	15.68	0.08	15.81	0.04
CaO	19.10	0.14	22.47	0.10	21.67	0.12	19.30	0.09	19.34	0.11	18.98	0.20
Na ₂ O	2.46	0.05	1.23	0.06	2.01	0.03	2.74	0.05	2.75	0.05	3.06	0.13
Total	99.89	0.28	99.27	0.21	100.20	0.18	100.44	0.21	100.03	0.20	100.28	0.22
Cations (recalculated to 6 oxygens)												
Si	1.977	0.002	1.965	0.004	1.959	0.004	1.969	0.003	1.974	0.002	1.958	0.006
Ti	0.008	0.001	0.005	0.000	0.006	0.002	0.008	0.000	0.007	0.001	0.009	0.000
Al	0.135	0.005	0.100	0.003	0.144	0.003	0.154	0.002	0.152	0.002	0.150	0.007
Cr	0.009	0.001	0.002	0.001	0.003	0.001	0.032	0.001	0.041	0.003	0.047	0.001
Fe	0.111	0.003	0.063	0.003	0.091	0.002	0.064	0.001	0.060	0.001	0.077	0.001
Mn	0.003	0.001	0.002	0.001	0.001	0.001	0.003	0.001	0.002	0.001	0.003	0.000
Ni	0.001	0.000	0.001	0.001	0.001	0.001	0.000	0.000	0.002	0.001	0.001	0.001
Mg	0.872	0.006	0.919	0.006	0.845	0.006	0.866	0.004	0.841	0.004	0.850	0.003
Ca	0.741	0.004	0.878	0.003	0.842	0.005	0.741	0.004	0.746	0.004	0.734	0.007
Na	0.173	0.004	0.087	0.004	0.141	0.002	0.190	0.004	0.192	0.004	0.215	0.009
Total	4.029	0.005	4.023	0.005	4.033	0.004	4.026	0.004	4.018	0.003	4.043	0.007
Jd	15.344	0.221	9.279	0.278	13.908	0.185	18.364	0.123	18.878	0.325	19.841	0.608
Wo	36.321	0.154	42.716	0.234	40.774	0.285	36.157	0.105	36.666	0.201	35.362	0.411
Hy	48.336	0.176	48.006	0.174	45.316	0.220	45.479	0.193	44.455	0.153	44.797	0.361
Mg/(Mg+Fe)	0.887	0.002	0.936	0.003	0.903	0.002	0.931	0.001	0.933	0.001	0.917	0.001
Ca/(Ca+Mg)	0.460	0.001	0.488	0.002	0.498	0.003	0.461	0.002	0.470	0.001	0.463	0.003
Fe/Mg.gt	0.285	0.004	0.317	0.003	0.446	0.005	0.195	0.001	0.163	0.003	0.230	0.002
Xca.gt	0.098	0.001	0.130	0.002	0.113	0.002	0.100	0.001	0.107	0.003	0.108	0.001
Fe/Mg.cpx	0.128	0.003	0.068	0.004	0.107	0.003	0.074	0.001	0.071	0.002	0.090	0.001
Kd	2.231	0.071	4.649	0.287	4.162	0.093	2.657	0.030	2.287	0.046	2.546	0.043
Ellis and Green (1979) thermometer												
T (C) at 45kb	1140.9	16.1	868.3	19.8	889.3	7.2	1056.5	5.3	1137.8	10.3	1085.0	9.0
T (C) at 50kb	1161.0	16.3	884.1	20.0	905.6	7.3	1075.3	5.4	1157.7	10.4	1104.1	9.2

Sample no. Rocktype n	JSL98 II 3	JSL100 II 5	JSL104 II 8	JSL210 II 5	JSL213 II 4	JSL251 II no cpx						
SiO ₂	54.45	0.09	54.54	0.15	54.68	0.11	54.33	0.24	54.54	0.15		
TiO ₂	0.08	0.01	0.15	0.01	0.27	0.03	0.22	0.01	0.44	0.08		
Al ₂ O ₃	1.75	0.01	2.06	0.11	3.52	0.04	2.72	0.04	5.30	0.19		
Cr ₂ O ₃	0.39	0.01	2.59	0.04	0.59	0.03	0.40	0.03	0.16	0.06		
FeO	1.66	0.02	1.97	0.10	2.12	0.11	1.62	0.06	4.06	0.40		
MnO	0.06	0.02	0.07	0.01	0.04	0.02	0.04	0.01	0.05	0.01		
NiO	0.05	0.01	0.02	0.01	0.05	0.01	0.02	0.02	0.06	0.01		
MgO	17.48	0.09	16.68	0.14	15.88	0.06	16.95	0.06	14.17	0.18		
CaO	23.70	0.12	19.71	0.21	21.20	0.07	22.19	0.18	17.51	0.84		
Na ₂ O	0.93	0.04	2.39	0.08	2.21	0.04	1.54	0.03	3.78	0.19		
Total	100.55	0.17	100.18	0.16	100.57	0.14	100.04	0.60	100.07	0.17		
Cations (recalculated to 6 oxygens)												
Si	1.963	0.004	1.971	0.002	1.964	0.001	1.961	0.002	1.967	0.003		
Ti	0.002	0.000	0.004	0.000	0.007	0.001	0.006	0.000	0.012	0.002		
Al	0.075	0.000	0.088	0.004	0.149	0.002	0.116	0.001	0.225	0.009		
Cr	0.011	0.000	0.074	0.001	0.017	0.001	0.012	0.001	0.005	0.002		
Fe	0.050	0.001	0.060	0.003	0.064	0.003	0.049	0.001	0.123	0.012		
Mn	0.002	0.001	0.002	0.000	0.001	0.000	0.001	0.000	0.001	0.000		
Ni	0.001	0.000	0.001	0.000	0.001	0.000	0.001	0.001	0.002	0.000		
Mg	0.939	0.005	0.898	0.009	0.850	0.003	0.912	0.003	0.762	0.009		
Ca	0.916	0.004	0.763	0.009	0.816	0.003	0.858	0.003	0.677	0.023		
Na	0.065	0.003	0.167	0.005	0.154	0.002	0.108	0.002	0.264	0.013		
Total	4.024	0.005	4.028	0.003	4.023	0.001	4.023	0.001	4.038	0.003		
Jd	5.637	2.906	16.038	0.507	15.550	0.171	9.617	4.097	18.744	7.742		
Wo	33.484	19.095	37.193	0.386	39.790	0.129	34.842	15.452	29.788	6.921		
Hy	36.223	20.706	46.770	0.246	44.660	0.130	39.041	17.350	38.186	9.393		
Mg/(Mg+Fe)	0.949	0.001	0.938	0.003	0.930	0.004	0.949	0.002	0.862	0.013		
Ca/(Ca+Mg)	0.494	0.002	0.459	0.002	0.490	0.001	0.485	0.001	0.470	0.007		
Fe/Mg.gt	0.220	0.004	0.187	0.001	0.198	0.008	0.204	0.004	0.396	0.005		
Xca.gt	0.115	0.001	0.150	0.002	0.100	0.001	0.106	0.001	0.101	0.001		
Fe/Mg.cpx	0.053	0.001	0.066	0.004	0.075	0.004	0.054	0.002	0.161	0.017		
Kd	4.139	0.133	2.832	0.179	2.648	0.203	3.812	0.115	2.491	0.285		
Ellis and Green (1979) thermometer												
T (C) at 45kb	893.6	12.4	1081.7	27.9	1059.6	35.0	914.3	11.4	1092.7	51.3		
T (C) at 50kb	910.0	12.6	1100.1	28.3	1078.6	35.5	931.1	11.6	1112.0	52.0		

Sample no. Rocktype n	JSL600A II 8		JSL55 II	JSL56 II	JSL58 II	JSL64 II	JSL66 II	JSL68 II	JSL71 II	JSL76 II	JSL78 II	JSL79 II
	grainmounts ==>											
SiO2	54.68	0.18	54.75	54.65	54.45	54.46	54.17	54.39	53.98	54.64	54.68	54.56
TiO2	0.23	0.03	0.00	0.25	0.19	0.27	0.09	0.26	0.29	0.17	0.34	0.26
Al2O3	3.67	0.15	1.01	3.57	2.40	3.84	2.11	2.81	4.39	2.07	4.38	3.62
Cr2O3	1.37	0.33	0.28	0.37	0.34	0.31	0.23	0.58	0.46	0.11	0.10	0.26
FeO	2.45	0.03	2.33	2.20	2.02	2.65	3.66	2.32	2.77	1.81	2.42	2.06
MnO	0.08	0.02	0.12	0.07	0.04	0.03	0.09	0.03	0.03	0.04	0.01	0.07
NiO	0.04	0.01	0.05	0.07	0.03	0.04	0.09	0.10	0.08	0.09	0.00	0.03
MgO	15.43	0.27	18.28	15.82	16.66	15.57	16.24	16.68	14.73	17.08	15.26	15.85
CaO	19.25	0.57	22.54	20.91	22.37	20.43	21.99	20.61	21.24	23.17	20.43	20.85
Na2O	3.03	0.21	0.61	2.18	1.34	2.41	1.40	2.07	2.23	1.07	2.43	2.08
Total	100.22	0.36	99.98	100.07	99.85	100.02	100.06	99.84	100.20	100.23	100.04	99.63
Cations (recalculated to 6 oxygens)												
Si	1.970	0.004	1.982	1.970	1.972	1.966	1.972	1.968	1.951	1.972	1.968	1.972
Ti	0.006	0.001	0.000	0.007	0.005	0.007	0.002	0.007	0.008	0.005	0.009	0.007
Al	0.156	0.007	0.043	0.152	0.103	0.163	0.090	0.120	0.187	0.088	0.186	0.154
Cr	0.039	0.009	0.008	0.010	0.010	0.009	0.007	0.016	0.013	0.003	0.003	0.007
Fe	0.074	0.001	0.071	0.066	0.061	0.080	0.111	0.070	0.084	0.055	0.073	0.062
Mn	0.002	0.001	0.004	0.002	0.001	0.001	0.003	0.001	0.001	0.001	0.000	0.002
Ni	0.001	0.000	0.002	0.002	0.001	0.001	0.003	0.003	0.002	0.002	0.000	0.001
Mg	0.828	0.013	0.887	0.850	0.899	0.838	0.881	0.900	0.794	0.919	0.819	0.854
Ca	0.743	0.020	0.874	0.807	0.868	0.790	0.858	0.799	0.823	0.896	0.787	0.808
Na	0.212	0.015	0.043	0.152	0.094	0.169	0.099	0.145	0.156	0.075	0.169	0.148
Total	4.032	0.004	4.013	4.018	4.014	4.025	4.026	4.030	4.019	4.015	4.014	4.013
Jd	19.781	1.478	4.639	15.396	10.142	16.633	9.560	13.733	17.321	8.157	17.568	15.123
Wo	36.171	0.953	43.082	39.588	42.624	38.555	41.869	38.951	39.987	43.994	38.661	39.715
Hy	44.047	0.617	52.279	45.016	47.234	44.812	48.570	47.316	42.693	47.849	43.770	45.163
Mg/(Mg+Fe)	0.918	0.002	0.933	0.928	0.936	0.913	0.888	0.928	0.905	0.944	0.918	0.932
Ca/(Ca+Mg)	0.473	0.004	0.470	0.487	0.491	0.485	0.493	0.470	0.509	0.494	0.490	0.486
Fe/Mg.gt	0.191	0.006	0.222	0.269	0.268	0.286	0.485	0.212	0.391	0.252	0.273	0.198
Xca.gt	0.101	0.002	0.118	0.105	0.113	0.102	0.119	0.109	0.122	0.112	0.102	0.102
Fe/Mg.cpx	0.089	0.002	0.072	0.078	0.068	0.096	0.126	0.078	0.105	0.059	0.089	0.073
Kd	2.139	0.085	3.104	3.453	3.938	2.992	3.843	2.724	3.710	4.247	3.079	2.715
Ellis and Green (1979) thermometer												
T (C) at 45kb	1166.8	23.2	1006.9	950.0	908.4	1005.8	923.2	1054.0	939.6	881.6	993.9	1048.9
T (C) at 50kb	1187.2	23.5	1024.7	967.3	924.9	1023.9	939.9	1072.7	956.5	897.8	1011.9	1067.6

Sample no. Rocktype n	JSL81 II	JSL82 II	JSL87 II	JSL88 II	JSL89 II	JSL90 II	JSL94 II	JSL96 II	JSL97 II	JSL101 II	JSL228 II	JSL229 II
SiO2	54.24	54.45	53.83	54.02	54.21	54.04	54.25	53.48	54.35	54.64	53.43	55.44
TiO2	0.26	0.25	0.23	0.23	0.25	0.05	0.18	0.62	0.21	0.25	0.91	0.36
Al2O3	3.07	4.01	3.38	3.49	4.06	1.83	2.72	4.48	3.09	3.37	6.63	5.35
Cr2O3	0.49	0.34	1.17	1.33	2.19	0.44	0.43	0.92	1.28	0.63	0.15	0.06
FeO	2.11	2.49	2.09	2.05	2.31	1.84	1.59	1.61	2.40	2.21	1.31	3.11
MnO	0.05	0.02	0.10	0.06	0.11	0.04	0.03	0.01	0.05	0.03	0.03	0.05
NiO	0.08	0.08	0.05	0.00	0.03	0.03	0.02	0.00	0.04	0.03	0.05	0.03
MgO	15.87	15.16	16.18	15.93	14.74	17.20	16.73	15.32	15.65	15.83	14.01	14.19
CaO	21.90	21.11	19.72	19.35	17.75	22.97	22.79	21.54	20.58	21.10	20.30	18.39
Na2O	1.81	2.28	2.53	2.65	3.58	1.04	1.29	2.18	2.23	2.18	2.95	3.51
Total	99.99	100.19	99.26	99.11	99.23	99.47	100.04	100.15	99.88	100.27	99.77	100.49
Cations (recalculated to 6 oxygens)												
Si	1.965	1.964	1.958	1.965	1.970	1.968	1.960	1.930	1.969	1.968	1.922	1.982
Ti	0.007	0.007	0.006	0.006	0.007	0.001	0.005	0.017	0.006	0.007	0.025	0.010
Al	0.131	0.171	0.145	0.149	0.174	0.078	0.116	0.191	0.132	0.143	0.281	0.226
Cr	0.014	0.010	0.034	0.038	0.063	0.013	0.012	0.026	0.037	0.018	0.004	0.002
Fe	0.064	0.075	0.064	0.062	0.070	0.056	0.048	0.049	0.073	0.066	0.040	0.093
Mn	0.002	0.001	0.003	0.002	0.004	0.001	0.001	0.000	0.002	0.001	0.001	0.001
Ni	0.002	0.002	0.001	0.000	0.001	0.001	0.001	0.000	0.001	0.001	0.001	0.001
Mg	0.857	0.815	0.877	0.864	0.799	0.934	0.901	0.824	0.845	0.850	0.751	0.756
Ca	0.850	0.816	0.768	0.754	0.691	0.896	0.882	0.833	0.799	0.814	0.783	0.704
Na	0.127	0.159	0.178	0.187	0.252	0.073	0.090	0.152	0.157	0.152	0.206	0.243
Total	4.019	4.019	4.035	4.028	4.030	4.022	4.016	4.021	4.019	4.021	4.014	4.017
Jd	13.309	16.586	17.249	18.213	23.819	8.003	10.653	17.802	15.919	15.322	23.773	23.238
Wo	41.569	39.868	37.141	36.666	33.668	43.690	43.020	40.139	39.095	39.829	37.866	34.776
Hy	45.123	43.547	45.610	45.120	42.513	48.307	46.327	42.059	44.986	44.849	38.341	41.986
Mg/(Mg+Fe)	0.931	0.916	0.932	0.933	0.919	0.943	0.950	0.944	0.921	0.927	0.950	0.890
Ca/(Ca+Mg)	0.498	0.500	0.467	0.466	0.464	0.490	0.495	0.503	0.486	0.489	0.510	0.482
Fe/Mg.gt	0.272	0.326	0.208	0.188	0.185	0.236	0.269	0.225	0.322	0.279	0.277	0.369
Xca.gt	0.109	0.114	0.105	0.100	0.095	0.110	0.181	0.114	0.116	0.111	0.106	0.092
Fe/Mg.cpx	0.075	0.092	0.072	0.072	0.088	0.060	0.053	0.059	0.086	0.078	0.053	0.123
Kd	3.646	3.535	2.866	2.594	2.097	3.929	5.060	3.825	3.739	3.567	5.266	3.000
Ellis and Green (1979) thermometer												
T (C) at 45kb	933.4	950.5	1027.1	1067.2	1169.5	907.2	884.6	920.0	931.0	943.5	806.4	994.0
T (C) at 50kb	950.4	967.7	1045.5	1086.2	1190.0	923.7	900.0	936.8	947.8	960.6	821.6	1012.1

Sample no. Rocktype n	JSL230 II	JSL232 II	JSL233 II	JSL234 II	JSL236 II	JSL237 II	JSL239 II	JSL240 II	JSL242 II
								<= grainmounts	
SiO2	53.71	53.63	54.22	54.79	55.61	54.98	54.87	54.55	55.42
TiO2	0.57	0.08	0.14	0.27	0.21	0.14	0.12	0.12	0.27
Al2O3	4.46	2.15	2.30	5.04	6.63	2.60	2.12	1.99	3.59
Cr2O3	0.31	0.30	0.13	0.11	0.15	0.28	0.20	0.21	0.80
FeO	2.73	4.35	3.65	2.87	3.71	1.96	3.92	2.94	1.76
MnO	0.00	0.05	0.04	0.06	0.05	0.00	0.07	0.01	0.11
NiO	0.05	0.06	0.05	0.03	0.07	0.05	0.06	0.11	0.03
MgO	14.97	15.75	16.16	14.41	12.63	16.52	15.66	16.27	15.93
CaO	21.29	21.53	21.89	20.13	17.25	22.41	21.84	22.75	19.98
Na2O	2.20	1.54	1.41	2.85	4.07	1.47	1.39	1.19	2.38
Total	100.30	99.46	99.98	100.58	100.37	100.40	100.26	100.12	100.26

Cations (recalculated to 6 oxygens)

Si	1.940	1.970	1.973	1.965	1.987	1.977	1.991	1.979	1.984
Ti	0.015	0.002	0.004	0.007	0.006	0.004	0.003	0.003	0.007
Al	0.190	0.093	0.099	0.213	0.279	0.110	0.091	0.085	0.151
Cr	0.009	0.009	0.004	0.003	0.004	0.008	0.006	0.006	0.023
Fe	0.083	0.134	0.111	0.086	0.111	0.059	0.119	0.089	0.053
Mn	0.000	0.002	0.001	0.002	0.001	0.000	0.002	0.000	0.003
Ni	0.001	0.002	0.001	0.001	0.002	0.001	0.002	0.003	0.001
Mg	0.806	0.863	0.876	0.770	0.673	0.885	0.847	0.880	0.850
Ca	0.824	0.848	0.853	0.773	0.660	0.863	0.849	0.884	0.766
Na	0.154	0.110	0.099	0.198	0.282	0.102	0.098	0.083	0.165
Total	4.022	4.031	4.022	4.019	4.006	4.011	4.007	4.014	4.004

Jd	17.072	10.278	9.875	20.253	28.118	10.858	9.668	8.602	16.858
Wo	39.895	41.201	41.755	37.797	32.839	42.576	42.208	43.614	38.104
Hy	43.033	48.521	48.369	41.951	39.044	46.566	48.124	47.783	45.038

Mg/(Mg+Fe)	0.907	0.866	0.888	0.899	0.859	0.938	0.877	0.908	0.942
Ca/(Ca+Mg)	0.505	0.496	0.493	0.501	0.495	0.494	0.501	0.501	0.474
Fe/Mg.gt	0.351	0.431	0.499	0.468	0.575	0.264	0.596	0.423	0.188
Xca.gt	0.115	0.124	0.125	0.123	0.119	0.114	0.123	0.130	0.101
Fe/Mg.cpx	0.102	0.155	0.127	0.112	0.165	0.067	0.141	0.101	0.062
Kd	3.433	2.780	3.940	4.185	3.493	3.975	4.240	4.174	3.026

Ellis and Green (1979) thermometer

T (C) at 45kb	962.7	1061.1	920.0	896.4	959.7	906.5	892.5	904.0	999.5
T (C) at 50kb	980.0	1079.7	936.6	912.6	976.9	923.0	908.7	920.3	1017.5

Sample no. Rocktype n	JSL17 M 9	JSL19 M 17	JSL20 M 18	JSL22 M 11	JSL27 M 13	JSL28 CGI 21						
SiO2	54.69	0.26	54.47	0.24	55.03	0.14	54.49	0.24	54.88	0.32	54.99	0.25
TiO2	0.23	0.02	0.26	0.02	0.25	0.01	0.32	0.01	0.26	0.02	0.33	0.03
Al2O3	2.11	0.03	2.32	0.02	2.29	0.04	3.27	0.03	2.26	0.06	4.06	0.04
Cr2O3	0.82	0.03	0.38	0.02	0.47	0.02	0.38	0.01	0.41	0.02	0.16	0.01
FeO	4.02	0.11	4.79	0.18	4.80	0.12	4.53	0.22	4.45	0.15	6.99	0.19
MnO	0.13	0.02	0.13	0.02	0.13	0.03	0.12	0.02	0.12	0.02	0.11	0.02
NiO	0.08	0.02	0.06	0.03	0.08	0.03	0.08	0.02	0.07	0.03	0.06	0.02
MgO	21.36	0.09	21.34	0.18	21.21	0.17	19.42	0.11	21.64	0.15	18.29	0.14
CaO	15.17	0.09	14.79	0.15	14.49	0.28	14.85	0.11	14.72	0.07	12.77	0.17
Na2O	1.51	0.03	1.62	0.03	1.59	0.03	2.23	0.04	1.53	0.03	2.52	0.05
Total	100.11	0.51	100.16	0.35	100.34	0.40	99.69	0.45	100.33	0.30	100.28	0.32

Cations (recalculated to 6 oxygens)

Si	1.959	0.002	1.954	0.006	1.966	0.005	1.962	0.004	1.960	0.006	1.973	0.005
Ti	0.006	0.001	0.007	0.001	0.007	0.000	0.009	0.000	0.007	0.000	0.009	0.001
Al	0.089	0.001	0.098	0.001	0.096	0.002	0.139	0.001	0.095	0.003	0.172	0.001
Cr	0.023	0.001	0.011	0.001	0.013	0.001	0.011	0.000	0.011	0.001	0.004	0.000
Fe	0.120	0.003	0.144	0.006	0.144	0.003	0.136	0.006	0.133	0.005	0.210	0.006
Mn	0.004	0.001	0.004	0.001	0.004	0.001	0.004	0.000	0.004	0.001	0.003	0.001
Ni	0.002	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.002	0.001
Mg	1.140	0.003	1.141	0.009	1.130	0.008	1.042	0.003	1.152	0.008	0.978	0.007
Ca	0.582	0.002	0.568	0.005	0.555	0.010	0.573	0.005	0.563	0.003	0.491	0.007
Na	0.105	0.002	0.112	0.002	0.110	0.002	0.156	0.003	0.106	0.002	0.175	0.003
Total	4.031	0.002	4.041	0.006	4.027	0.004	4.033	0.004	4.033	0.006	4.017	0.006

Mg/(Mg+Fe)	0.904	0.002	0.888	0.003	0.887	0.002	0.884	0.005	0.897	0.003	0.823	0.004
Ca/(Ca+Mg)	0.338	0.001	0.333	0.003	0.329	0.005	0.355	0.002	0.328	0.002	0.334	0.004

Sample no. Rocktype n	JSL29 CGI 2		JSL18 GS 16		JSL323 GS 3		JSL3 CII 5		JSL32 CII 21		JSL36 CII 8	
SiO2	55.32	0.11	54.20	0.24	54.42	0.19	54.47	0.36	54.45	0.15	53.78	0.18
TiO2	0.29	0.02	0.16	0.04	0.29	0.00	0.58	0.02	0.49	0.04	0.44	0.02
Al2O3	2.32	0.01	2.14	0.25	2.42	0.04	3.25	0.06	2.77	0.04	2.76	0.05
Cr2O3	0.22	0.03	2.21	0.13	1.69	0.10	0.14	0.01	0.02	0.01	0.01	0.00
FeO	4.67	0.02	2.31	0.23	2.54	0.11	6.19	0.10	6.36	0.09	6.19	0.14
MnO	0.11	0.00	0.09	0.02	0.10	0.01	0.13	0.02	0.16	0.02	0.13	0.02
NiO	0.09	0.02	0.04	0.03	0.04	0.03	0.04	0.02	0.02	0.02	0.04	0.01
MgO	21.29	0.16	16.49	0.32	16.95	0.07	17.42	0.16	17.29	0.12	17.16	0.10
CaO	14.50	0.03	19.94	0.49	19.23	0.24	15.44	0.27	16.65	0.15	16.65	0.15
Na2O	1.40	0.00	2.33	0.19	2.24	0.07	2.42	0.04	2.24	0.06	2.29	0.04
Total	100.21	0.25	99.91	0.21	99.92	0.31	100.08	0.47	100.44	0.26	99.45	0.13

Cations (recalculated to 6 oxygens)

Si	1.974	0.001	1.967	0.007	1.969	0.001	1.970	0.004	1.970	0.003	1.967	0.004
Ti	0.008	0.001	0.004	0.001	0.008	0.000	0.016	0.000	0.013	0.001	0.012	0.000
Al	0.098	0.001	0.092	0.011	0.103	0.002	0.139	0.003	0.118	0.001	0.119	0.002
Cr	0.006	0.001	0.063	0.004	0.048	0.003	0.004	0.000	0.001	0.000	0.000	0.000
Fe	0.139	0.001	0.070	0.007	0.077	0.003	0.187	0.003	0.193	0.003	0.189	0.004
Mn	0.003	0.000	0.003	0.001	0.003	0.000	0.004	0.000	0.005	0.001	0.004	0.001
Ni	0.003	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.000	0.001	0.000
Mg	1.133	0.006	0.892	0.017	0.914	0.005	0.939	0.005	0.932	0.007	0.935	0.006
Ca	0.554	0.000	0.776	0.019	0.746	0.008	0.598	0.011	0.646	0.005	0.652	0.006
Na	0.097	0.000	0.164	0.014	0.157	0.005	0.170	0.003	0.157	0.004	0.162	0.003
Total	4.015	0.002	4.033	0.005	4.026	0.004	4.028	0.003	4.036	0.004	4.042	0.005
Mg/(Mg+Fe)	0.890	0.001	0.927	0.008	0.922	0.003	0.834	0.002	0.829	0.002	0.832	0.004
Ca/(Ca+Mg)	0.329	0.001	0.465	0.003	0.449	0.004	0.389	0.005	0.409	0.003	0.411	0.003

Sample no. Rocktype n	JSL44 CII 8		JSL47 CII 3		JSL315 CII 3		JSL46 OII 3		JSL160 OII 5		JSL51 MARID 2	
SiO2	53.90	0.41	52.72	0.29	54.49	0.08	53.31	0.05	54.57	0.58	54.25	0.15
TiO2	0.53	0.04	1.06	0.18	0.50	0.01	1.54	0.13	0.45	0.04	0.23	0.04
Al2O3	2.91	0.06	1.73	0.62	3.00	0.06	0.74	0.16	4.10	0.16	0.75	0.24
Cr2O3	0.11	0.01	0.13	0.01	0.09	0.01	1.67	0.27	2.90	0.24	2.61	0.49
FeO	6.25	0.08	5.78	0.39	5.68	0.07	4.17	0.15	3.83	0.11	3.45	0.06
MnO	0.16	0.02	0.07	0.01	0.19	0.01	0.12	0.01	0.09	0.03	0.06	0.02
NiO	0.02	0.02	0.02	0.01	0.05	0.01	0.06	0.01	0.03	0.03	0.05	0.00
MgO	17.60	0.13	16.64	0.02	17.50	0.02	18.15	0.21	13.75	0.30	15.86	0.22
CaO	16.27	0.06	20.48	0.83	15.94	0.08	18.72	0.69	15.81	0.63	20.21	0.06
Na2O	2.25	0.04	1.22	0.16	2.38	0.03	1.29	0.06	4.42	0.21	2.25	0.02
Total	100.00	0.29	99.84	0.23	99.84	0.21	99.77	0.32	99.93	0.73	99.74	0.15

Cations (recalculated to 6 oxygens)

Si	1.959	0.008	1.940	0.014	1.974	0.001	1.948	0.004	1.978	0.009	1.988	0.004
Ti	0.014	0.001	0.029	0.005	0.014	0.000	0.042	0.004	0.012	0.001	0.006	0.001
Al	0.125	0.003	0.075	0.027	0.128	0.002	0.032	0.007	0.175	0.008	0.033	0.011
Cr	0.003	0.000	0.004	0.000	0.003	0.000	0.048	0.008	0.083	0.007	0.076	0.014
Fe	0.190	0.003	0.178	0.012	0.172	0.002	0.127	0.005	0.116	0.004	0.106	0.002
Mn	0.005	0.001	0.002	0.000	0.006	0.000	0.004	0.000	0.003	0.001	0.002	0.000
Ni	0.001	0.001	0.001	0.000	0.002	0.000	0.002	0.000	0.001	0.001	0.001	0.000
Mg	0.953	0.010	0.912	0.003	0.945	0.000	0.988	0.012	0.743	0.014	0.866	0.012
Ca	0.634	0.003	0.808	0.034	0.619	0.003	0.733	0.026	0.614	0.022	0.794	0.002
Na	0.159	0.003	0.087	0.011	0.167	0.002	0.091	0.004	0.311	0.016	0.160	0.002
Total	4.042	0.008	4.035	0.002	4.030	0.001	4.016	0.004	4.036	0.009	4.032	0.004
Mg/(Mg+Fe)	0.834	0.001	0.837	0.009	0.846	0.002	0.886	0.003	0.865	0.005	0.891	0.000
Ca/(Ca+Mg)	0.399	0.003	0.469	0.010	0.396	0.001	0.426	0.011	0.452	0.008	0.478	0.004

APPENDIX 3d : ORTHOPYROXENE

Orthopyroxene

Sample numbers followed by a letter, eg. JSL 565A, indicate that more than one polished thin section of the particular sample was prepared.
Each average is followed by the standard deviation about the mean.

Sample no. Rocktype n	JSL108 GLd 5		JSL112 GLd 6		JSL119 GLd 6		JSL126 GLd 6		JSL140 GLd 3		JSL279 GLd 6	
SiO ₂	57.57	0.16	57.27	0.14	57.20	0.20	57.68	0.14	57.38	0.28	57.50	0.25
TiO ₂	0.14	0.02	0.14	0.01	0.07	0.02	0.01	0.01	0.16	0.01	0.01	0.01
Al ₂ O ₃	0.80	0.01	1.05	0.02	0.68	0.03	0.67	0.02	0.89	0.00	0.57	0.01
Cr ₂ O ₃	0.37	0.01	0.19	0.01	0.17	0.01	0.21	0.01	0.27	0.01	0.20	0.01
FeO	5.28	0.07	6.00	0.07	5.39	0.07	5.21	0.08	5.56	0.06	5.27	0.12
MnO	0.12	0.02	0.10	0.01	0.12	0.01	0.14	0.02	0.15	0.01	0.16	0.03
NiO	0.13	0.04	0.13	0.03	0.15	0.01	0.12	0.03	0.13	0.02	0.14	0.02
MgO	34.21	0.32	33.65	0.08	34.53	0.06	35.36	0.11	34.17	0.16	35.26	0.19
CaO	1.03	0.03	1.35	0.04	0.97	0.03	1.00	0.01	1.07	0.02	1.09	0.03
Na ₂ O	0.27	0.02	0.32	0.01	0.16	0.03	0.11	0.02	0.29	0.01	0.06	0.01
Total	99.92	0.46	100.19	0.23	99.43	0.25	100.49	0.17	100.07	0.40	100.26	0.51
Cations (recalculated to 6 oxygens)												
Si	1.983	0.005	1.975	0.002	1.980	0.002	1.975	0.002	1.977	0.002	1.975	0.003
Ti	0.004	0.000	0.004	0.000	0.002	0.001	0.000	0.000	0.004	0.000	0.000	0.000
Al	0.032	0.000	0.043	0.001	0.028	0.001	0.027	0.001	0.036	0.000	0.023	0.000
Cr	0.010	0.000	0.005	0.000	0.005	0.000	0.006	0.000	0.007	0.000	0.005	0.000
Fe	0.152	0.002	0.173	0.002	0.156	0.002	0.149	0.002	0.160	0.002	0.151	0.003
Mn	0.004	0.001	0.003	0.000	0.004	0.000	0.004	0.001	0.004	0.000	0.005	0.001
Ni	0.004	0.001	0.004	0.001	0.004	0.000	0.003	0.001	0.004	0.000	0.004	0.001
Mg	1.757	0.011	1.730	0.004	1.782	0.005	1.804	0.005	1.755	0.003	1.805	0.004
Ca	0.038	0.001	0.050	0.001	0.036	0.001	0.037	0.000	0.039	0.001	0.040	0.001
Na	0.018	0.001	0.021	0.001	0.011	0.002	0.007	0.001	0.019	0.001	0.004	0.001
Total	4.001	0.005	4.008	0.002	4.007	0.002	4.012	0.003	4.007	0.002	4.013	0.003
Mg/(Mg + Fe)	0.920	0.001	0.909	0.001	0.919	0.001	0.924	0.001	0.916	0.001	0.923	0.001
Ca/(Ca + Mg)	0.021	0.001	0.028	0.001	0.020	0.001	0.020	0.000	0.022	0.000	0.022	0.000

Sample no. Rocktype n	JSL280 GLd 6		JSL113 GHs 6		JSL262 GHs 3		JSL266 GHs 3		JSL267 GHs 3		JSL268 GHs 3	
SiO ₂	57.35	0.29	57.81	0.24	57.99	0.30	58.01	0.14	58.10	0.09	57.98	0.14
TiO ₂	0.15	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.04	0.01
Al ₂ O ₃	1.03	0.02	0.72	0.01	0.54	0.01	0.62	0.00	0.65	0.00	0.92	0.01
Cr ₂ O ₃	0.20	0.00	0.49	0.03	0.27	0.01	0.42	0.02	0.32	0.02	0.47	0.01
FeO	5.78	0.03	4.04	0.13	3.90	0.01	3.61	0.02	3.81	0.03	3.94	0.12
MnO	0.13	0.02	0.10	0.02	0.16	0.01	0.06	0.01	0.10	0.02	0.14	0.01
NiO	0.12	0.02	0.10	0.01	0.11	0.02	0.12	0.02	0.08	0.04	0.11	0.01
MgO	33.48	0.19	35.48	0.25	36.55	0.03	37.03	0.09	36.43	0.14	35.84	0.32
CaO	1.44	0.03	0.39	0.05	0.27	0.00	0.19	0.01	0.34	0.03	0.25	0.02
Na ₂ O	0.32	0.01	0.24	0.02	0.11	0.02	0.02	0.00	0.13	0.02	0.20	0.01
Total	100.02	0.20	99.38	0.22	99.91	0.34	100.09	0.25	99.95	0.17	99.89	0.55
Cations (recalculated to 6 oxygens)												
Si	1.980	0.006	1.987	0.008	1.981	0.003	1.975	0.000	1.982	0.002	1.981	0.006
Ti	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000
Al	0.042	0.001	0.029	0.001	0.022	0.000	0.025	0.000	0.026	0.000	0.037	0.000
Cr	0.005	0.000	0.013	0.001	0.007	0.000	0.011	0.001	0.009	0.001	0.013	0.000
Fe	0.167	0.001	0.116	0.004	0.111	0.001	0.103	0.000	0.109	0.001	0.113	0.003
Mn	0.004	0.001	0.003	0.001	0.005	0.000	0.002	0.000	0.003	0.001	0.004	0.000
Ni	0.003	0.001	0.003	0.000	0.003	0.000	0.003	0.000	0.002	0.001	0.003	0.000
Mg	1.723	0.012	1.818	0.013	1.861	0.007	1.879	0.001	1.853	0.005	1.825	0.009
Ca	0.053	0.001	0.015	0.002	0.010	0.000	0.007	0.000	0.012	0.001	0.009	0.001
Na	0.022	0.001	0.016	0.001	0.007	0.001	0.001	0.000	0.009	0.001	0.013	0.001
Total	4.003	0.006	3.999	0.007	4.008	0.002	4.007	0.000	4.005	0.002	3.999	0.006
Mg/(Mg + Fe)	0.912	0.001	0.940	0.002	0.944	0.000	0.948	0.000	0.945	0.000	0.942	0.001
Ca/(Ca + Mg)	0.030	0.001	0.008	0.001	0.005	0.000	0.004	0.000	0.007	0.001	0.005	0.000

Sample no. Rocktype n	JSL170 GH 4		JSL263 GH 7		JSL124 Sp 7		JSL153 Sp 7		JSL154 Sp 5		JSL156 Sp 7	
SiO2	57.49	0.10	57.36	0.21	56.45	0.23	57.20	0.28	56.85	0.24	57.34	0.31
TiO2	0.07	0.01	0.00	0.00	0.04	0.01	0.01	0.00	0.06	0.01	0.00	0.00
Al2O3	0.92	0.01	0.78	0.02	2.49	0.14	1.46	0.07	1.93	0.18	1.18	0.05
Cr2O3	0.27	0.01	0.45	0.01	0.39	0.04	0.31	0.02	0.31	0.06	0.23	0.02
FeO	4.88	0.05	4.88	0.08	4.98	0.06	4.29	0.02	4.13	0.07	4.83	0.06
MnO	0.13	0.01	0.14	0.02	0.14	0.01	0.11	0.02	0.10	0.02	0.13	0.03
NiO	0.07	0.03	0.15	0.01	0.08	0.02	0.07	0.02	0.03	0.01	0.06	0.02
MgO	35.78	0.10	34.71	0.20	35.26	0.28	35.73	0.14	35.81	0.18	35.67	0.13
CaO	0.24	0.02	1.44	0.03	0.16	0.03	0.24	0.05	0.19	0.02	0.17	0.02
Na2O	0.03	0.01	0.17	0.02	0.05	0.02	0.04	0.01	0.05	0.01	0.06	0.00
Total	99.87	0.25	100.09	0.41	100.05	0.40	99.46	0.26	99.45	0.28	99.67	0.38

Cations (recalculated to 6 oxygens)

Si	1.972	0.002	1.973	0.003	1.936	0.009	1.965	0.005	1.952	0.007	1.970	0.004
Ti	0.002	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.001	0.000	0.000	0.000
Al	0.037	0.000	0.032	0.001	0.100	0.006	0.059	0.003	0.078	0.007	0.048	0.002
Cr	0.007	0.000	0.012	0.000	0.011	0.001	0.008	0.001	0.008	0.002	0.006	0.001
Fe	0.140	0.001	0.140	0.002	0.143	0.002	0.123	0.001	0.119	0.002	0.139	0.002
Mn	0.004	0.000	0.004	0.001	0.004	0.000	0.003	0.000	0.003	0.000	0.004	0.001
Ni	0.002	0.001	0.004	0.000	0.002	0.000	0.002	0.000	0.001	0.000	0.002	0.001
Mg	1.830	0.002	1.780	0.007	1.802	0.011	1.830	0.008	1.833	0.006	1.826	0.005
Ca	0.009	0.001	0.053	0.001	0.006	0.001	0.009	0.002	0.007	0.001	0.006	0.001
Na	0.002	0.001	0.011	0.001	0.003	0.001	0.002	0.001	0.003	0.000	0.004	0.000
Total	4.005	0.002	4.010	0.003	4.009	0.007	4.002	0.005	4.005	0.003	4.005	0.004

Mg/(Mg+Fe)	0.929	0.001	0.927	0.001	0.927	0.001	0.937	0.000	0.939	0.001	0.929	0.001
Ca/(Ca+Mg)	0.005	0.000	0.029	0.001	0.003	0.001	0.005	0.001	0.004	0.000	0.003	0.000

Sample no. Rocktype n	JSL157 Sp 5		JSL158 Sp 6		JSL166 D 3		JSL116 GLc 3		JSL134 GLc 3		JSL-/193 Glc 3	
SiO2	56.45	0.15	56.50	0.07	57.79	0.14	58.09	0.29	57.61	0.21	57.62	0.12
TiO2	0.03	0.01	0.07	0.01	0.00	0.00	0.00	0.00	0.11	0.01	0.05	0.00
Al2O3	3.03	0.22	2.66	0.17	1.10	0.05	0.49	0.03	0.72	0.03	0.75	0.02
Cr2O3	0.18	0.03	0.27	0.02	0.27	0.04	0.24	0.00	0.37	0.01	0.46	0.01
FeO	4.76	0.08	5.40	0.05	5.16	0.01	4.55	0.03	4.74	0.07	4.39	0.02
MnO	0.12	0.01	0.13	0.01	0.17	0.01	0.10	0.03	0.12	0.01	0.08	0.00
NiO	0.07	0.01	0.05	0.02	0.08	0.02	0.09	0.02	0.11	0.02	0.10	0.02
MgO	35.71	0.11	34.74	0.15	35.66	0.17	35.88	0.42	35.79	0.15	35.74	0.25
CaO	0.26	0.06	0.20	0.03	0.23	0.02	0.48	0.03	0.40	0.00	0.37	0.02
Na2O	0.01	0.01	0.04	0.01	0.03	0.01	0.08	0.01	0.15	0.01	0.18	0.00
Total	100.62	0.20	100.05	0.13	100.48	0.21	100.01	0.74	100.12	0.26	99.73	0.14

Cations (recalculated to 6 oxygens)

Si	1.923	0.005	1.939	0.003	1.973	0.002	1.987	0.005	1.973	0.001	1.977	0.006
Ti	0.001	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.003	0.000	0.001	0.000
Al	0.121	0.009	0.107	0.007	0.044	0.002	0.020	0.001	0.029	0.001	0.030	0.001
Cr	0.005	0.001	0.007	0.001	0.007	0.001	0.007	0.000	0.010	0.000	0.012	0.000
Fe	0.136	0.002	0.155	0.002	0.147	0.001	0.130	0.000	0.136	0.002	0.126	0.001
Mn	0.004	0.000	0.004	0.000	0.005	0.000	0.003	0.001	0.004	0.000	0.002	0.000
Ni	0.002	0.000	0.001	0.001	0.002	0.001	0.003	0.001	0.003	0.000	0.003	0.000
Mg	1.813	0.009	1.777	0.009	1.814	0.005	1.829	0.008	1.827	0.003	1.828	0.011
Ca	0.010	0.002	0.007	0.001	0.008	0.001	0.018	0.001	0.015	0.000	0.014	0.001
Na	0.001	0.000	0.002	0.000	0.002	0.000	0.005	0.001	0.010	0.001	0.012	0.000
Total	4.014	0.003	4.003	0.002	4.003	0.002	4.002	0.005	4.009	0.002	4.006	0.005

Mg/(Mg+Fe)	0.930	0.001	0.920	0.001	0.925	0.000	0.934	0.000	0.931	0.001	0.936	0.001
Ca/(Ca+Mg)	0.005	0.001	0.004	0.001	0.005	0.000	0.009	0.001	0.008	0.000	0.007	0.000

Sample no. Rocktype n	JSL261 GLc 2		JSL306 Lc 3 intergrown		JSL107 P 7		JSL118 P 6		JSL171 P 3		JSL202 P 4	
SiO2	57.40	0.19	57.29	0.21	54.65	0.08	55.33	0.28	57.49	0.15	56.09	0.09
TiO2	0.10	0.01	0.13	0.01	0.04	0.01	0.04	0.01	0.03	0.01	0.07	0.01
Al2O3	0.61	0.01	0.69	0.06	2.37	0.15	3.87	0.15	0.82	0.01	1.20	0.02
Cr2O3	0.44	0.02	0.42	0.01	0.29	0.02	0.35	0.03	0.05	0.01	0.05	0.00
FeO	3.87	0.04	5.06	0.30	11.48	0.22	6.37	0.18	6.00	0.03	10.06	0.06
MnO	0.09	0.00	0.12	0.01	0.22	0.03	0.15	0.01	0.09	0.02	0.10	0.01
NiO	0.10	0.02	0.11	0.02	0.07	0.01	0.12	0.02	0.11	0.02	0.15	0.02
MgO	36.51	0.05	35.34	0.17	30.66	0.18	33.34	0.18	34.95	0.24	31.87	0.14
CaO	0.45	0.01	0.43	0.02	0.19	0.04	0.18	0.02	0.22	0.02	0.20	0.02
Na2O	0.19	0.03	0.18	0.01	0.00	0.01	0.02	0.01	0.03	0.01	0.07	0.01
Total	99.75	0.21	99.74	0.23	99.96	0.23	99.77	0.41	99.78	0.42	99.88	0.19
Cations (recalculated to 6 oxygens)												
Si	1.968	0.002	1.973	0.002	1.933	0.004	1.914	0.005	1.982	0.003	1.969	0.003
Ti	0.003	0.000	0.003	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.002	0.000
Al	0.025	0.000	0.028	0.002	0.099	0.006	0.158	0.006	0.033	0.000	0.050	0.001
Cr	0.012	0.000	0.011	0.000	0.008	0.001	0.010	0.001	0.001	0.000	0.001	0.000
Fe	0.111	0.001	0.146	0.009	0.339	0.007	0.184	0.005	0.173	0.001	0.295	0.001
Mn	0.003	0.000	0.003	0.000	0.006	0.001	0.004	0.000	0.003	0.000	0.003	0.000
Ni	0.003	0.000	0.003	0.000	0.002	0.000	0.003	0.001	0.003	0.001	0.004	0.000
Mg	1.866	0.007	1.814	0.004	1.617	0.008	1.719	0.007	1.796	0.006	1.668	0.006
Ca	0.017	0.000	0.016	0.001	0.007	0.001	0.007	0.001	0.008	0.001	0.008	0.001
Na	0.013	0.002	0.012	0.000	0.000	0.000	0.001	0.001	0.002	0.000	0.005	0.001
Total	4.018	0.002	4.010	0.003	4.013	0.002	4.001	0.004	4.001	0.003	4.005	0.003
Mg/(Mg+Fe)	0.944	0.001	0.926	0.004	0.826	0.003	0.903	0.003	0.912	0.001	0.850	0.001
Ca/(Ca+Mg)	0.009	0.000	0.009	0.001	0.004	0.001	0.004	0.000	0.004	0.000	0.005	0.000

Sample no. Rocktype n	JSL209 P 4		JSL296 P 3		JSL/91 GPP 1	JSL111 GPP 6		JSL142 GPP 6		JSL143 GPP 5	
SiO2	57.76	0.11	58.15	0.05	57.60	57.90	0.29	57.81	0.13	57.91	0.25
TiO2	0.08	0.01	0.11	0.01	0.08	0.09	0.01	0.05	0.03	0.07	0.02
Al2O3	1.42	0.06	0.70	0.00	0.70	0.74	0.01	0.66	0.02	0.68	0.02
Cr2O3	0.12	0.01	0.11	0.01	0.40	0.39	0.02	0.17	0.02	0.47	0.01
FeO	4.33	0.04	5.28	0.04	4.71	5.18	0.16	4.49	0.02	4.02	0.05
MnO	0.10	0.02	0.14	0.01	0.10	0.10	0.02	0.09	0.02	0.11	0.01
NiO	0.10	0.01	0.12	0.01	0.12	0.09	0.01	0.10	0.03	0.10	0.02
MgO	36.30	0.13	35.25	0.17	35.79	34.94	0.15	35.99	0.12	35.64	0.12
CaO	0.22	0.04	0.47	0.02	0.38	0.37	0.02	0.36	0.02	0.39	0.01
Na2O	0.04	0.01	0.16	0.00	0.15	0.19	0.01	0.16	0.01	0.19	0.03
Total	100.47	0.17	100.49	0.20	100.02	99.99	0.30	99.89	0.22	99.58	0.30
Cations (recalculated to 6 oxygens)											
Si	1.964	0.003	1.986	0.003	1.975	1.987	0.006	1.980	0.002	1.986	0.003
Ti	0.002	0.000	0.003	0.000	0.002	0.002	0.000	0.001	0.001	0.002	0.001
Al	0.057	0.002	0.028	0.000	0.028	0.030	0.000	0.027	0.001	0.028	0.001
Cr	0.003	0.000	0.003	0.000	0.011	0.011	0.000	0.005	0.000	0.013	0.000
Fe	0.123	0.001	0.151	0.001	0.135	0.149	0.004	0.129	0.001	0.115	0.001
Mn	0.003	0.000	0.004	0.000	0.003	0.003	0.001	0.003	0.001	0.003	0.000
Ni	0.003	0.000	0.003	0.000	0.003	0.003	0.000	0.003	0.001	0.003	0.001
Mg	1.840	0.007	1.795	0.006	1.828	1.787	0.010	1.837	0.004	1.822	0.007
Ca	0.008	0.002	0.017	0.001	0.014	0.013	0.001	0.013	0.001	0.014	0.000
Na	0.003	0.000	0.011	0.000	0.010	0.013	0.001	0.010	0.001	0.013	0.002
Total	4.005	0.003	4.001	0.003	4.009	3.997	0.006	4.008	0.002	3.998	0.005
Mg/(Mg+Fe)	0.937	0.001	0.922	0.000	0.931	0.923	0.002	0.935	0.000	0.941	0.001
Ca/(Ca+Mg)	0.004	0.001	0.010	0.000	0.007	0.007	0.000	0.007	0.000	0.008	0.000

Sample no. Rocktype n	JSL151 GPP 3	JSL151 GPP 5 intergrown		JSL-/177 GPP 3	JSL278 GPP 5		JSL504 GPP 6	JSL533 GPP 4				
SiO2	57.51	0.04	57.68	0.14	57.89	0.07	57.55	0.13	57.21	0.36	57.27	0.21
TiO2	0.04	0.01	0.08	0.00	0.05	0.00	0.06	0.01	0.07	0.01	0.07	0.01
Al2O3	0.58	0.02	0.54	0.02	0.64	0.00	0.82	0.01	0.66	0.02	0.72	0.01
Cr2O3	0.31	0.01	0.30	0.01	0.31	0.01	0.20	0.01	0.36	0.02	0.43	0.01
FeO	4.27	0.03	4.23	0.05	4.68	0.04	5.07	0.07	4.85	0.08	4.70	0.08
MnO	0.09	0.01	0.08	0.01	0.07	0.01	0.11	0.01	0.12	0.02	0.13	0.02
NiO	0.20	0.01	0.13	0.01	0.08	0.01	0.11	0.01	0.10	0.01	0.10	0.01
MgO	36.60	0.07	36.68	0.14	35.66	0.20	35.97	0.08	35.69	0.12	35.97	0.17
CaO	0.70	0.02	0.61	0.04	0.44	0.02	0.26	0.01	0.38	0.01	0.34	0.02
Na2O	0.06	0.00	0.07	0.01	0.16	0.01	0.07	0.01	0.12	0.01	0.17	0.01
Total	100.36	0.04	100.41	0.17	99.98	0.27	100.23	0.21	99.56	0.33	99.88	0.32
Cations (recalculated to 6 oxygens)												
Si	1.965	0.001	1.968	0.002	1.983	0.003	1.970	0.002	1.972	0.006	1.967	0.003
Ti	0.001	0.000	0.002	0.000	0.001	0.000	0.002	0.000	0.002	0.000	0.002	0.000
Al	0.023	0.001	0.022	0.001	0.026	0.000	0.033	0.000	0.027	0.001	0.029	0.001
Cr	0.008	0.000	0.008	0.000	0.008	0.000	0.005	0.000	0.010	0.001	0.012	0.000
Fe	0.122	0.001	0.121	0.002	0.134	0.001	0.145	0.002	0.140	0.002	0.135	0.002
Mn	0.003	0.000	0.002	0.000	0.002	0.000	0.003	0.000	0.003	0.001	0.004	0.001
Ni	0.006	0.000	0.004	0.000	0.002	0.000	0.003	0.000	0.003	0.000	0.003	0.000
Mg	1.863	0.003	1.865	0.005	1.821	0.006	1.836	0.003	1.834	0.009	1.842	0.007
Ca	0.026	0.001	0.022	0.001	0.016	0.001	0.010	0.000	0.014	0.000	0.013	0.001
Na	0.004	0.000	0.004	0.000	0.011	0.001	0.004	0.001	0.008	0.001	0.011	0.001
Total	4.021	0.001	4.018	0.002	4.004	0.003	4.011	0.002	4.012	0.005	4.016	0.003
Mg/(Mg+Fe)	0.939	0.000	0.939	0.001	0.931	0.000	0.927	0.001	0.929	0.001	0.932	0.001
Ca/(Ca+Mg)	0.014	0.000	0.012	0.001	0.009	0.000	0.005	0.000	0.008	0.000	0.007	0.000

Sample no. Rocktype n	JSL-/93 PP 4	JSL167 PP 3		JSL273 PP 2	JSL304 PP 2		JSL500A PP 16 large grain		JSL500A PP 7 neoblasts			
SiO2	57.83	0.22	58.30	0.23	57.42	0.02	57.25	0.20	57.81	0.19	57.70	0.33
TiO2	0.07	0.03	0.00	0.00	0.01	0.01	0.07	0.01	0.10	0.02	0.10	0.01
Al2O3	0.72	0.07	0.76	0.25	0.68	0.00	0.70	0.00	0.18	0.01	0.20	0.01
Cr2O3	0.45	0.03	0.26	0.02	0.39	0.01	0.32	0.01	0.12	0.03	0.16	0.02
FeO	4.40	0.11	4.00	0.03	4.27	0.02	5.13	0.02	6.59	0.12	6.52	0.10
MnO	0.10	0.00	0.13	0.02	0.14	0.01	0.11	0.01	0.15	0.02	0.15	0.03
NiO	0.12	0.01	0.08	0.01	0.11	0.01	0.11	0.01	0.06	0.02	0.06	0.03
MgO	36.02	0.18	36.39	0.06	35.96	0.11	35.68	0.04	34.81	0.27	34.95	0.11
CaO	0.38	0.01	0.20	0.00	0.36	0.02	0.36	0.01	0.40	0.03	0.37	0.02
Na2O	0.17	0.02	0.08	0.01	0.14	0.02	0.15	0.01	0.10	0.01	0.11	0.01
Total	100.25	0.39	100.21	0.12	99.48	0.15	99.87	0.28	100.34	0.35	100.33	0.30
Cations (recalculated to 6 oxygens)												
Si	1.975	0.004	1.984	0.006	1.975	0.002	1.970	0.001	1.990	0.005	1.986	0.004
Ti	0.002	0.001	0.000	0.000	0.000	0.000	0.002	0.000	0.003	0.001	0.003	0.000
Al	0.029	0.003	0.030	0.010	0.027	0.000	0.028	0.000	0.007	0.000	0.008	0.001
Cr	0.012	0.001	0.007	0.001	0.011	0.000	0.009	0.000	0.003	0.001	0.004	0.000
Fe	0.126	0.003	0.114	0.001	0.123	0.000	0.148	0.000	0.190	0.000	0.188	0.003
Mn	0.003	0.000	0.004	0.001	0.004	0.000	0.003	0.000	0.004	0.001	0.004	0.001
Ni	0.003	0.000	0.002	0.000	0.003	0.000	0.003	0.000	0.002	0.001	0.002	0.001
Mg	1.834	0.003	1.846	0.002	1.844	0.003	1.830	0.003	1.785	0.010	1.793	0.006
Ca	0.014	0.000	0.007	0.000	0.013	0.001	0.013	0.000	0.015	0.001	0.014	0.001
Na	0.011	0.001	0.005	0.001	0.009	0.001	0.010	0.001	0.007	0.001	0.007	0.001
Total	4.008	0.003	4.000	0.001	4.010	0.002	4.015	0.001	4.006	0.005	4.009	0.004
Mg/(Mg+Fe)	0.936	0.001	0.942	0.000	0.938	0.000	0.925	0.000	0.904	0.002	0.905	0.001
Ca/(Ca+Mg)	0.008	0.000	0.004	0.000	0.007	0.000	0.007	0.000	0.008	0.001	0.008	0.000

Sample no.	JSL511B		JSL516A		JSL516C		JSL520	JSL547	JSL565		
Rocktype	PP		PP		PP		PP	PP		PP	
n	3		8		5		1	6		3	
			band		above/below band						
SiO2	57.14	0.07	57.87	0.40	57.98	0.10	39.79	57.37	0.24	57.29	0.32
TiO2	0.17	0.05	0.00	0.00	0.01	0.01	0.03	0.11	0.01	0.10	0.01
Al2O3	0.42	0.11	0.73	0.01	0.73	0.01	0.01	0.54	0.03	0.67	0.02
Cr2O3	0.25	0.07	0.38	0.01	0.38	0.01	0.04	0.39	0.02	0.36	0.00
FeO	6.41	0.13	4.62	0.07	4.77	0.12	8.61	4.55	0.04	4.98	0.07
MnO	0.08	0.01	0.10	0.01	0.09	0.02	0.12	0.13	0.02	0.13	0.01
NiO	0.08	0.02	0.12	0.02	0.10	0.01	0.32	0.11	0.01	0.09	0.02
MgO	34.05	0.29	35.79	0.18	35.83	0.12	50.82	35.88	0.24	35.48	0.11
CaO	0.41	0.15	0.26	0.01	0.26	0.02	0.03	0.35	0.03	0.33	0.01
Na2O	0.16	0.04	0.17	0.01	0.17	0.00	0.01	0.14	0.03	0.17	0.03
Total	99.15	0.06	100.04	0.34	100.30	0.14	99.78	99.54	0.40	99.60	0.30

Cations (recalculated to 6 oxygens)

Si	1.989	0.001	1.981	0.007	1.980	0.002	1.464	1.975	0.003	1.975	0.005
Ti	0.004	0.001	0.000	0.000	0.000	0.000	0.001	0.003	0.000	0.003	0.000
Al	0.017	0.004	0.030	0.001	0.030	0.001	0.000	0.022	0.001	0.027	0.001
Cr	0.007	0.002	0.010	0.000	0.010	0.000	0.001	0.011	0.001	0.010	0.000
Fe	0.186	0.004	0.132	0.002	0.136	0.004	0.265	0.131	0.001	0.144	0.002
Mn	0.002	0.000	0.003	0.000	0.003	0.001	0.004	0.004	0.001	0.004	0.000
Ni	0.002	0.000	0.003	0.001	0.003	0.000	0.009	0.003	0.000	0.003	0.001
Mg	1.766	0.016	1.826	0.014	1.823	0.005	2.788	1.841	0.007	1.823	0.008
Ca	0.015	0.005	0.009	0.000	0.009	0.001	0.001	0.013	0.001	0.012	0.001
Na	0.011	0.003	0.011	0.001	0.011	0.000	0.001	0.009	0.002	0.012	0.002
Total	4.000	0.004	4.005	0.007	4.005	0.001	4.534	4.011	0.004	4.010	0.006
Mg/(Mg+Fe)	0.905	0.001	0.932	0.001	0.931	0.002	0.913	0.934	0.001	0.927	0.001
Ca/(Ca+Mg)	0.008	0.003	0.005	0.000	0.005	0.000	0.000	0.007	0.001	0.007	0.000

Sample no. Rocktype n	JSL565A PP 4	JSL565B PP 3	JSL25 MP 2	JSL75 MP 4	JSL110 MP 4	JSL252 MP 2						
SiO2	57.55	0.15	56.79	0.07	57.10	0.10	57.23	0.25	57.27	0.05	57.35	0.07
TiO2	0.11	0.00	0.09	0.01	0.07	0.01	0.08	0.01	0.04	0.00	0.07	0.01
Al2O3	0.63	0.06	0.69	0.02	0.71	0.02	1.57	0.06	0.86	0.01	1.89	0.01
Cr2O3	0.34	0.02	0.36	0.00	0.04	0.00	0.03	0.00	0.13	0.00	0.14	0.01
FeO	4.97	0.14	4.98	0.07	6.53	0.03	5.33	0.14	6.31	0.02	4.06	0.06
MnO	0.14	0.01	0.12	0.01	0.10	0.01	0.08	0.01	0.08	0.01	0.08	0.01
NiO	0.11	0.01	0.11	0.01	0.06	0.01	0.08	0.01	0.06	0.02	0.10	0.00
MgO	35.65	0.19	36.19	0.30	35.30	0.15	35.51	0.14	34.56	0.12	36.65	0.10
CaO	0.31	0.01	0.34	0.01	0.22	0.00	0.18	0.04	0.21	0.01	0.18	0.02
Na2O	0.15	0.01	0.16	0.01	0.03	0.00	0.02	0.00	0.04	0.00	0.01	0.00
Total	99.94	0.37	99.83	0.40	100.16	0.02	100.12	0.27	99.57	0.14	100.54	0.01

Cations (recalculated to 6 oxygens)

Si	1.976	0.001	1.956	0.005	1.968	0.003	1.961	0.004	1.981	0.002	1.948	0.003
Ti	0.003	0.000	0.002	0.000	0.002	0.000	0.002	0.000	0.001	0.000	0.002	0.000
Al	0.025	0.003	0.028	0.001	0.029	0.001	0.064	0.002	0.035	0.000	0.076	0.000
Cr	0.009	0.001	0.010	0.000	0.001	0.000	0.001	0.000	0.004	0.000	0.004	0.000
Fe	0.142	0.004	0.143	0.002	0.188	0.001	0.153	0.004	0.183	0.001	0.115	0.002
Mn	0.004	0.000	0.003	0.000	0.003	0.000	0.002	0.000	0.002	0.000	0.002	0.000
Ni	0.003	0.000	0.003	0.000	0.002	0.000	0.002	0.000	0.002	0.000	0.003	0.000
Mg	1.825	0.004	1.858	0.009	1.814	0.008	1.813	0.008	1.782	0.004	1.855	0.005
Ca	0.011	0.000	0.013	0.000	0.008	0.000	0.007	0.001	0.008	0.000	0.006	0.001
Na	0.010	0.001	0.011	0.001	0.002	0.000	0.002	0.000	0.002	0.000	0.001	0.000
Total	4.009	0.002	4.028	0.005	4.016	0.004	4.006	0.004	4.000	0.002	4.011	0.002
Mg/(Mg+Fe)	0.927	0.002	0.928	0.001	0.906	0.001	0.922	0.002	0.907	0.001	0.941	0.001
Ca/(Ca+Mg)	0.006	0.000	0.007	0.000	0.004	0.000	0.004	0.001	0.004	0.000	0.003	0.000

Sample no. Rocktype n	JSL298 MP 4	JSL600A+B+C II 22		JSL1 M 13	JSL2 M 10		JSL46 OII 4		JSL160 OII 4			
SiO2	57.69	0.10	57.85	0.40	56.88	0.28	55.95	0.42	56.29	0.36	57.08	0.13
TiO2	0.04	0.00	0.08	0.01	0.20	0.01	0.03	0.01	0.30	0.05	0.12	0.03
Al2O3	0.86	0.01	0.72	0.04	0.98	0.02	2.64	0.19	1.22	0.46	0.89	0.12
Cr2O3	0.07	0.02	0.11	0.03	0.13	0.01	0.43	0.04	0.36	0.10	0.38	0.04
FeO	5.01	0.10	4.74	0.16	7.02	0.08	4.85	0.08	7.46	0.16	6.94	0.15
MnO	0.11	0.02	0.12	0.02	0.14	0.03	0.14	0.02	0.14	0.01	0.14	0.02
NiO	0.10	0.01	0.10	0.03	0.11	0.02	0.09	0.02	0.06	0.03	0.08	0.04
MgO	35.73	0.19	35.98	0.29	32.61	0.35	35.20	0.26	33.01	0.11	33.33	0.15
CaO	0.28	0.07	0.35	0.02	1.24	0.03	0.31	0.18	0.50	0.02	0.37	0.09
Na2O	0.04	0.01	0.12	0.02	0.27	0.01	0.05	0.03	0.14	0.03	0.26	0.04
Total	99.93	0.34	100.17	0.51	99.58	0.29	99.70	0.51	99.49	0.47	99.59	0.11

Cations (recalculated to 6 oxygens)

Si	1.978	0.003	1.978	0.006	1.982	0.009	1.927	0.007	1.965	0.017	1.983	0.003
Ti	0.001	0.000	0.002	0.000	0.005	0.000	0.001	0.000	0.008	0.001	0.003	0.001
Al	0.035	0.001	0.029	0.002	0.040	0.001	0.107	0.008	0.050	0.019	0.036	0.005
Cr	0.002	0.001	0.003	0.001	0.004	0.000	0.012	0.001	0.010	0.003	0.011	0.001
Fe	0.144	0.002	0.135	0.004	0.205	0.002	0.140	0.002	0.218	0.004	0.202	0.004
Mn	0.003	0.001	0.003	0.001	0.004	0.001	0.004	0.001	0.004	0.000	0.004	0.000
Ni	0.003	0.000	0.003	0.001	0.003	0.000	0.003	0.001	0.002	0.001	0.002	0.001
Mg	1.826	0.005	1.834	0.014	1.693	0.017	1.807	0.011	1.717	0.003	1.726	0.006
Ca	0.010	0.003	0.013	0.001	0.046	0.001	0.012	0.007	0.019	0.001	0.014	0.003
Na	0.003	0.000	0.008	0.001	0.019	0.001	0.003	0.002	0.010	0.002	0.017	0.003
Total	4.004	0.003	4.008	0.006	4.001	0.009	4.015	0.003	4.002	0.006	3.999	0.003

Mg/(Mg+Fe)	0.927	0.001	0.931	0.002	0.892	0.001	0.928	0.001	0.887	0.002	0.895	0.002
Ca/(Ca+Mg)	0.006	0.001	0.007	0.000	0.027	0.001	0.006	0.004	0.011	0.001	0.008	0.002

Sample no. Rocktype n	JSL503 OII 7	
SiO2	56.23	0.36
TiO2	0.28	0.04
Al2O3	1.00	0.27
Cr2O3	0.44	0.11
FeO	7.24	0.12
MnO	0.14	0.01
NiO	0.09	0.01
MgO	33.82	0.34
CaO	0.50	0.03
Na2O	0.13	0.02
Total	99.85	0.34

Cations (recalculated to 6 oxygens)

Si	1.956	0.009
Ti	0.007	0.001
Al	0.041	0.011
Cr	0.012	0.003
Fe	0.211	0.003
Mn	0.004	0.000
Ni	0.002	0.000
Mg	1.754	0.014
Ca	0.019	0.001
Na	0.009	0.002
Total	4.014	0.004

Mg/(Mg+Fe)	0.893	0.002
Ca/(Ca+Mg)	0.010	0.001

APPENDIX 3f : PHLOGOPITE AND AMPHIBOLE

Phlogopite

Sample numbers followed by a letter, eg. JSL 565A, indicate that more than one polished thin section of the particular sample was prepared.

Each average is followed by the standard deviation about the mean.

Sample no. Rocktype n	JSL-91 GPP 4		JSL111 GPP 4		JSL111 GPP 1 secondary	JSL142 GPP 3		JSL142 GPP 2 secondary		JSL143 GPP 4	
SiO ₂	41.27	0.17	42.06	0.22	38.90	42.85	0.13	41.00	1.20	42.96	0.81
TiO ₂	0.75	0.02	0.97	0.02	3.19	0.92	0.04	3.67	0.69	0.87	0.03
Al ₂ O ₃	12.91	0.11	12.62	0.20	13.17	12.45	0.45	15.24	0.22	13.04	0.21
Cr ₂ O ₃	0.98	0.03	0.86	0.02	1.88	0.43	0.03	1.92	0.11	1.12	0.04
FeO	3.03	0.15	3.24	0.14	4.29	2.80	0.06	4.41	0.33	2.60	0.06
MnO	0.03	0.01	0.02	0.00	0.06	0.04	0.01	0.06	0.00	0.03	0.01
MgO	25.04	0.07	25.96	0.30	23.72	26.93	0.36	22.76	0.96	26.26	0.28
CaO	0.01	0.01	0.02	0.00	0.05	0.01	0.01	0.01	0.01	0.01	0.01
Na ₂ O	0.31	0.01	0.17	0.02	0.29	0.21	0.01	0.32	0.19	0.25	0.09
K ₂ O	10.29	0.24	9.64	0.18	8.58	9.84	0.54	8.71	0.43	9.59	0.51
Total	94.61	0.21	95.57	0.38	94.13	96.49	0.63	98.10	0.40	96.71	0.86
Cations (recalculated to 23 oxygens)											
Si	6.148	0.012	6.175	0.011	5.851	6.213	0.037	5.883	0.106	6.202	0.037
Ti	0.084	0.002	0.107	0.002	0.361	0.100	0.004	0.397	0.079	0.095	0.003
Al	2.266	0.021	2.184	0.028	2.334	2.128	0.070	2.577	0.066	2.218	0.019
Cr	0.116	0.004	0.100	0.003	0.224	0.050	0.003	0.218	0.010	0.128	0.003
Fe	0.377	0.018	0.398	0.017	0.540	0.339	0.006	0.529	0.045	0.314	0.006
Mn	0.004	0.001	0.002	0.001	0.007	0.005	0.001	0.007	0.001	0.003	0.001
Mg	5.560	0.015	5.679	0.070	5.317	5.821	0.096	4.868	0.151	5.651	0.037
Ca	0.001	0.001	0.003	0.001	0.008	0.002	0.001	0.002	0.001	0.001	0.001
Na	0.089	0.003	0.048	0.007	0.085	0.058	0.004	0.089	0.055	0.069	0.026
K	1.956	0.046	1.805	0.034	1.647	1.819	0.095	1.594	0.096	1.767	0.112
Total	16.600	0.024	16.502	0.017	16.375	16.536	0.046	16.164	0.075	16.448	0.110
100*Mg/(Mg+Fe)	93.643	0.276	93.453	0.201	90.777	94.490	0.177	90.195	1.031	94.743	0.098

Sample no. Rocktype n	JSL143 GPP 2 secondary		JSL151 GPP 2		JSL151 GPP 1 secondary	JSL-177 GPP 8		JSL504 GPP 2		JSL533 GPP 3	
SiO ₂	39.57	0.23	41.65	0.10	37.35	41.87	0.29	41.29	0.02	41.31	0.14
TiO ₂	2.25	0.04	0.63	0.01	3.90	0.91	0.03	0.79	0.00	0.66	0.01
Al ₂ O ₃	15.91	0.17	12.51	0.28	14.50	12.07	0.17	12.55	0.06	12.92	0.08
Cr ₂ O ₃	2.46	0.34	0.94	0.01	1.97	0.80	0.11	0.80	0.02	0.99	0.00
FeO	2.99	0.04	3.07	0.07	4.33	2.98	0.06	3.22	0.12	2.76	0.02
MnO	0.03	0.01	0.02	0.01	0.04	0.01	0.01	0.02	0.02	0.02	0.00
MgO	23.26	0.27	25.16	0.15	21.45	25.97	0.11	24.79	0.15	25.49	0.05
CaO	0.00	0.00	0.06	0.06	0.03	0.00	0.00	0.00	0.00	0.00	0.00
Na ₂ O	0.39	0.10	0.10	0.05	0.52	0.30	0.07	0.37	0.10	0.40	0.05
K ₂ O	9.69	0.20	10.41	0.25	8.97	10.26	0.17	10.40	0.14	10.10	0.05
Total	96.55	0.09	94.79	0.11	93.63	95.17	0.14	94.23	0.22	94.66	0.24
Cations (recalculated to 23 oxygens)											
Si	5.785	0.026	6.206	0.018	5.712	6.195	0.035	6.184	0.009	6.139	0.006
Ti	0.248	0.004	0.071	0.001	0.448	0.101	0.004	0.089	0.000	0.073	0.001
Al	2.741	0.033	2.196	0.048	2.613	2.105	0.032	2.216	0.015	2.262	0.008
Cr	0.284	0.039	0.111	0.002	0.238	0.094	0.013	0.095	0.002	0.117	0.001
Fe	0.365	0.005	0.383	0.009	0.554	0.369	0.007	0.403	0.014	0.342	0.002
Mn	0.004	0.001	0.003	0.001	0.005	0.001	0.001	0.002	0.002	0.002	0.001
Mg	5.070	0.052	5.588	0.037	4.888	5.728	0.019	5.535	0.023	5.646	0.020
Ca	0.000	0.000	0.009	0.009	0.004	0.000	0.000	0.001	0.001	0.001	0.001
Na	0.110	0.029	0.029	0.013	0.155	0.085	0.019	0.109	0.028	0.116	0.014
K	1.808	0.034	1.978	0.046	1.749	1.937	0.034	1.987	0.030	1.915	0.006
Total	16.414	0.008	16.574	0.009	16.367	16.615	0.025	16.619	0.015	16.614	0.010
100*Mg/(Mg+Fe)	93.282	0.157	93.590	0.100	89.821	93.942	0.114	93.207	0.193	94.281	0.045

Sample no. Rocktype n	JSL572 GPP 4 secondary		JSL-/93 PP 5		JSL167 PP 3		JSL273 PP 3		JSL304 PP 2		JSL500A PP 6	
SiO2	39.05	0.47	41.95	0.29	42.82	0.56	41.01	0.05	41.33	0.21	42.32	0.15
TiO2	2.78	0.12	0.84	0.03	0.06	0.00	0.26	0.00	0.88	0.01	0.86	0.04
Al2O3	14.10	0.19	11.99	0.12	12.30	0.62	12.88	0.18	12.60	0.11	11.31	0.37
Cr2O3	2.06	0.16	0.68	0.06	0.74	0.05	1.04	0.03	0.73	0.01	0.35	0.02
FeO	4.20	0.05	2.71	0.05	2.33	0.05	2.57	0.04	3.07	0.00	4.09	0.09
MnO	0.03	0.02	0.02	0.01	0.04	0.00	0.02	0.02	0.03	0.03	0.03	0.02
MgO	21.84	0.25	25.60	0.07	28.05	0.65	25.49	0.12	25.20	0.01	25.69	0.53
CaO	0.03	0.04	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01
Na2O	0.29	0.03	0.22	0.01	0.59	0.10	0.28	0.04	0.26	0.01	0.25	0.04
K2O	10.14	0.08	10.47	0.10	8.42	0.06	10.27	0.25	10.48	0.11	10.09	0.38
Total	94.50	0.44	94.48	0.20	95.34	1.02	93.83	0.53	94.58	0.07	95.00	0.60

Cations (recalculated to 23 oxygens)

Si	5.889	0.041	6.245	0.032	6.230	0.011	6.149	0.023	6.164	0.028	6.289	0.015
Ti	0.315	0.014	0.094	0.003	0.006	0.000	0.029	0.000	0.099	0.001	0.096	0.005
Al	2.506	0.040	2.103	0.024	2.109	0.094	2.276	0.024	2.215	0.020	1.981	0.058
Cr	0.246	0.020	0.080	0.007	0.085	0.006	0.124	0.003	0.086	0.001	0.041	0.003
Fe	0.529	0.009	0.337	0.006	0.283	0.005	0.322	0.005	0.383	0.000	0.508	0.009
Mn	0.004	0.002	0.003	0.001	0.004	0.000	0.003	0.002	0.003	0.003	0.004	0.002
Mg	4.910	0.040	5.681	0.017	6.084	0.153	5.696	0.011	5.603	0.005	5.691	0.127
Ca	0.004	0.007	0.000	0.000	0.000	0.001	0.002	0.001	0.000	0.000	0.002	0.002
Na	0.085	0.008	0.064	0.004	0.165	0.029	0.081	0.011	0.076	0.003	0.073	0.011
K	1.950	0.012	1.989	0.022	1.563	0.011	1.963	0.041	1.993	0.022	1.912	0.067
Total	16.438	0.025	16.596	0.025	16.531	0.076	16.644	0.035	16.622	0.028	16.597	0.017

100*Mg/(Mg+Fe)	90.264	0.205	94.399	0.088	95.555	0.052	94.651	0.093	93.606	0.009	91.794	0.227

Sample no. Rocktype n	JSL500B PP 2		JSL511 PP 6		JSL516 PP 4		JSL520 PP 5		JSL520A PP 3		JSL520B PP 3	
SiO2	42.66	0.10	41.03	0.17	41.87	0.10	41.17	0.13	40.93	0.20	41.27	0.12
TiO2	0.88	0.00	1.53	0.04	0.83	0.02	0.87	0.02	0.86	0.02	0.88	0.01
Al2O3	11.61	0.07	12.23	0.07	12.01	0.04	12.45	0.05	12.35	0.23	12.37	0.06
Cr2O3	0.35	0.01	0.78	0.03	0.39	0.01	0.77	0.02	0.75	0.03	0.74	0.01
FeO	4.17	0.08	3.99	0.05	2.84	0.06	3.02	0.03	3.08	0.03	3.05	0.05
MnO	0.03	0.00	0.02	0.01	0.02	0.01	0.03	0.01	0.03	0.00	0.02	0.01
MgO	25.24	0.00	24.47	0.07	25.99	0.04	25.64	0.10	25.76	0.12	25.76	0.08
CaO	0.01	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.00	0.00
Na2O	0.24	0.00	0.25	0.02	0.25	0.01	0.23	0.02	0.23	0.03	0.29	0.03
K2O	9.89	0.02	10.20	0.03	10.60	0.03	10.56	0.05	10.46	0.20	10.40	0.07
Total	95.09	0.08	94.51	0.24	94.79	0.16	94.75	0.17	94.47	0.33	94.78	0.09

Cations (recalculated to 23 oxygens)

Si	6.319	0.010	6.149	0.013	6.220	0.006	6.136	0.010	6.121	0.024	6.144	0.016
Ti	0.098	0.000	0.172	0.005	0.092	0.002	0.097	0.002	0.097	0.002	0.098	0.001
Al	2.027	0.014	2.160	0.012	2.103	0.005	2.188	0.010	2.177	0.038	2.171	0.010
Cr	0.041	0.001	0.093	0.003	0.046	0.001	0.091	0.002	0.089	0.004	0.087	0.001
Fe	0.516	0.010	0.500	0.005	0.352	0.008	0.377	0.004	0.386	0.003	0.379	0.007
Mn	0.004	0.000	0.002	0.002	0.002	0.001	0.003	0.001	0.004	0.001	0.003	0.002
Mg	5.572	0.004	5.465	0.016	5.756	0.009	5.697	0.022	5.742	0.023	5.717	0.021
Ca	0.001	0.001	0.000	0.000	0.001	0.001	0.000	0.000	0.002	0.002	0.000	0.000
Na	0.068	0.001	0.074	0.006	0.072	0.002	0.067	0.007	0.067	0.007	0.083	0.008
K	1.870	0.006	1.950	0.010	2.009	0.004	2.008	0.009	1.995	0.038	1.975	0.013
Total	16.517	0.005	16.565	0.011	16.654	0.009	16.665	0.017	16.680	0.025	16.657	0.012

100*Mg/(Mg+Fe)	91.517	0.149	91.612	0.085	94.234	0.111	93.797	0.076	93.706	0.030	93.778	0.102

Sample no.	JSL532		JSL547		JSL547	JSL565		JSL565A		JSL565B	
Rocktype	PP		PP		PP	PP		PP		PP	
n	4		3		1	4		5		4	
				secondary							
SiO2	42.00	0.06	41.44	0.27	39.41	41.71	0.27	42.10	0.40	40.84	0.19
TiO2	0.46	0.05	0.90	0.03	2.44	0.83	0.02	0.82	0.01	0.80	0.02
Al2O3	11.13	0.12	12.57	0.26	13.99	12.36	0.08	12.16	0.15	12.86	0.25
Cr2O3	0.35	0.02	0.92	0.05	2.29	0.82	0.03	0.70	0.02	0.79	0.03
FeO	3.47	0.24	2.74	0.04	2.99	2.92	0.02	3.00	0.11	2.81	0.05
MnO	0.01	0.01	0.01	0.01	0.00	0.03	0.01	0.01	0.01	0.03	0.01
MgO	26.30	0.22	25.23	0.29	22.71	25.53	0.08	25.27	0.31	25.59	0.24
CaO	0.05	0.06	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00
Na2O	0.23	0.03	0.33	0.01	0.26	0.36	0.00	0.33	0.02	0.44	0.02
K2O	10.27	0.30	10.27	0.10	10.35	10.19	0.03	10.06	0.10	10.13	0.16
Total	94.27	0.18	94.41	0.33	94.45	94.75	0.33	94.48	0.30	94.29	0.32

Cations (recalculated to 23 oxygens)

Si	6.284	0.010	6.176	0.021	5.918	6.195	0.014	6.259	0.036	6.102	0.017
Ti	0.051	0.006	0.100	0.004	0.275	0.092	0.002	0.092	0.001	0.089	0.002
Al	1.962	0.019	2.207	0.051	2.476	2.164	0.008	2.131	0.025	2.264	0.043
Cr	0.042	0.002	0.108	0.006	0.272	0.096	0.004	0.083	0.003	0.093	0.003
Fe	0.435	0.030	0.342	0.004	0.376	0.363	0.004	0.374	0.015	0.351	0.008
Mn	0.002	0.001	0.001	0.001	0.000	0.003	0.001	0.002	0.002	0.004	0.001
Mg	5.865	0.051	5.605	0.052	5.084	5.652	0.030	5.600	0.072	5.698	0.051
Ca	0.008	0.009	0.001	0.001	0.002	0.000	0.001	0.001	0.001	0.000	0.000
Na	0.067	0.009	0.096	0.004	0.076	0.103	0.001	0.095	0.006	0.127	0.004
K	1.961	0.056	1.953	0.014	1.983	1.931	0.012	1.908	0.023	1.931	0.029
Total	16.677	0.032	16.590	0.010	16.462	16.599	0.021	16.544	0.050	16.660	0.009

100*Mg/(Mg+Fe)	93.098	0.486	94.252	0.032	93.118	93.963	0.039	93.747	0.193	94.201	0.152

Sample no. Rocktype n	JSL25 MP 3 secondary	JSL75 MP 2 secondary	JSL252 MP 3 secondary	JSL203 I 4 secondary	JSL205 I 3 secondary	JSL211 I 3 secondary						
SiO2	41.29	1.14	41.31	1.12	39.86	1.11	39.26	1.27	38.84	0.94	40.09	0.73
TiO2	3.68	0.18	4.28	0.15	4.17	3.13	4.22	0.39	4.59	0.48	4.43	0.19
Al2O3	13.80	0.89	15.36	0.37	15.01	0.41	14.70	1.09	15.63	1.00	15.06	0.30
Cr2O3	0.40	0.06	0.09	0.00	0.53	0.03	0.72	0.48	0.07	0.00	0.80	0.24
FeO	5.98	0.25	3.31	0.03	2.11	0.10	7.29	2.35	8.80	0.25	5.89	0.41
MnO	0.06	0.02	0.03	0.00	0.04	0.01	0.03	0.01	0.04	0.01	0.01	0.02
MgO	22.63	1.36	24.02	0.34	24.78	0.63	20.98	1.92	19.74	0.15	21.84	0.23
CaO	0.00	0.00	0.00	0.00	0.04	0.02	0.02	0.02	0.02	0.01	0.01	0.01
Na2O	0.27	0.07	0.31	0.09	0.34	0.03	0.40	0.24	0.56	0.21	0.23	0.03
K2O	8.49	0.85	8.50	0.86	9.10	0.23	9.43	0.47	8.21	0.51	9.35	0.52
Total	96.59	0.26	97.22	1.00	95.97	0.80	97.04	0.52	96.52	0.52	97.72	0.75

Cations (recalculated to 23 oxygens)

Si	6.032	0.105	5.914	0.051	5.800	0.186	5.806	0.112	5.767	0.117	5.832	0.046
Ti	0.404	0.024	0.461	0.008	0.456	0.339	0.470	0.046	0.513	0.052	0.485	0.019
Al	2.376	0.176	2.592	0.015	2.574	0.081	2.562	0.219	2.734	0.177	2.582	0.040
Cr	0.046	0.007	0.010	0.000	0.061	0.003	0.084	0.055	0.008	0.000	0.092	0.029
Fe	0.730	0.037	0.396	0.012	0.257	0.013	0.901	0.304	1.093	0.027	0.717	0.044
Mn	0.008	0.002	0.004	0.001	0.004	0.001	0.004	0.001	0.005	0.001	0.001	0.002
Mg	4.928	0.244	5.126	0.023	5.375	0.161	4.625	0.371	4.369	0.057	4.736	0.060
Ca	0.000	0.000	0.000	0.001	0.006	0.003	0.002	0.003	0.003	0.002	0.002	0.002
Na	0.076	0.020	0.087	0.025	0.097	0.008	0.115	0.071	0.161	0.062	0.064	0.010
K	1.582	0.174	1.552	0.185	1.689	0.052	1.780	0.075	1.555	0.107	1.735	0.115
Total	16.182	0.090	16.143	0.172	16.319	0.139	16.349	0.032	16.208	0.165	16.246	0.099

100*Mg/(Mg+Fe)	87.090	1.102	92.829	0.164	95.444	0.100	83.694	5.774	79.990	0.573	86.859	0.705

Sample no.	JSL254	JSL62	JSL65	JSL86	JSL98	JSL98					
Rocktype	I	II	II	II	II	II					
n	5	2	10	5	2	1					
	secondary?	secondary				secondary					
SiO2	41.13	0.70	36.38	1.07	42.31	0.71	42.39	0.51	42.23	0.76	39.22
TiO2	1.82	0.11	6.30	0.40	0.96	0.03	0.84	0.06	0.56	0.00	3.24
Al2O3	13.41	0.25	16.79	0.38	12.63	0.27	13.42	0.21	14.52	0.21	15.11
Cr2O3	0.04	0.01	0.06	0.06	0.08	0.01	0.32	0.01	0.37	0.00	0.59
FeO	9.15	0.33	6.91	2.48	4.62	0.10	2.91	0.12	2.84	0.14	5.12
MnO	0.05	0.02	0.06	0.04	0.02	0.02	0.02	0.01	0.00	0.00	0.03
MgO	21.98	0.36	19.40	1.79	25.57	0.21	26.40	0.17	26.22	0.33	22.72
CaO	0.00	0.01	0.09	0.02	0.02	0.01	0.01	0.02	0.03	0.00	0.06
Na2O	0.24	0.04	0.81	0.21	0.16	0.03	0.20	0.02	0.52	0.12	0.64
K2O	9.22	0.99	7.58	0.65	9.54	0.41	9.43	0.45	7.97	0.48	8.45
Total	97.04	0.42	94.38	1.22	95.90	0.92	95.94	0.57	95.27	0.85	95.17

Cations (recalculated to 23 oxygens)

Si	6.091	0.050	5.488	0.038	6.209	0.028	6.164	0.020	6.129	0.030	5.821
Ti	0.203	0.011	0.715	0.062	0.105	0.003	0.092	0.005	0.061	0.000	0.362
Al	2.341	0.022	2.985	0.001	2.184	0.024	2.301	0.016	2.483	0.004	2.644
Cr	0.004	0.001	0.008	0.007	0.009	0.001	0.037	0.001	0.042	0.001	0.069
Fe	1.133	0.046	0.872	0.332	0.567	0.006	0.354	0.012	0.345	0.013	0.635
Mn	0.006	0.002	0.008	0.005	0.002	0.002	0.002	0.001	0.001	0.001	0.004
Mg	4.851	0.072	4.363	0.303	5.592	0.043	5.721	0.033	5.671	0.003	5.026
Ca	0.001	0.001	0.015	0.004	0.003	0.002	0.002	0.003	0.004	0.000	0.009
Na	0.070	0.012	0.236	0.056	0.047	0.008	0.057	0.006	0.147	0.036	0.184
K	1.741	0.196	1.458	0.092	1.786	0.092	1.748	0.097	1.476	0.108	1.600
Total	16.440	0.171	16.147	0.094	16.505	0.087	16.478	0.079	16.359	0.103	16.353

100*Mg/(Mg+Fe)	81.071	0.808	83.341	6.255	90.800	0.125	94.179	0.198	94.265	0.204	88.781

Sample no. Rocktype n	JSL251 II 4	JSL600A II 5	JSL600B II 4	JSL46 OII 4 secondary	JSL160 OII 5	JSL503 OII 2						
SiO2	40.75	0.35	41.69	0.18	40.51	1.32	41.02	0.50	41.72	0.23	41.79	0.49
TiO2	1.15	0.05	0.55	0.04	0.58	0.04	3.11	0.24	1.01	0.02	0.80	0.01
Al2O3	14.28	0.07	12.84	0.19	13.77	2.07	12.70	0.24	12.56	0.05	11.43	0.08
Cr2O3	0.37	0.02	0.52	0.05	0.65	0.21	0.76	0.09	0.75	0.03	0.20	0.03
FeO	3.17	0.22	2.97	0.06	3.23	0.74	4.86	0.05	4.37	0.11	4.85	0.02
MnO	0.02	0.00	0.03	0.02	0.01	0.02	0.02	0.01	0.01	0.01	0.02	0.02
MgO	25.60	0.24	26.12	0.62	24.68	1.40	23.55	0.23	24.62	0.16	25.01	0.22
CaO	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na2O	0.60	0.17	0.52	0.04	0.40	0.07	0.25	0.02	0.39	0.03	0.16	0.01
K2O	8.48	0.52	9.83	0.12	9.86	0.36	9.59	0.14	9.73	0.11	10.26	0.22
Total	94.43	0.68	95.06	0.77	93.69	0.65	95.86	0.30	95.16	0.21	94.49	0.38

Cations (recalculated to 23 oxygens)

Si	6.018	0.021	6.158	0.050	6.083	0.194	6.063	0.047	6.191	0.028	6.271	0.032
Ti	0.128	0.006	0.061	0.004	0.065	0.004	0.345	0.026	0.112	0.002	0.090	0.001
Al	2.485	0.008	2.235	0.030	2.436	0.363	2.213	0.049	2.197	0.010	2.021	0.026
Cr	0.044	0.002	0.061	0.006	0.077	0.025	0.089	0.010	0.088	0.003	0.024	0.004
Fe	0.391	0.027	0.366	0.005	0.405	0.092	0.601	0.007	0.542	0.013	0.608	0.007
Mn	0.002	0.000	0.003	0.003	0.002	0.002	0.002	0.001	0.001	0.001	0.002	0.002
Mg	5.636	0.080	5.749	0.094	5.524	0.320	5.189	0.061	5.446	0.032	5.595	0.013
Ca	0.003	0.002	0.000	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000
Na	0.171	0.050	0.148	0.010	0.116	0.020	0.072	0.005	0.111	0.010	0.047	0.003
K	1.597	0.091	1.853	0.031	1.889	0.071	1.808	0.035	1.842	0.026	1.964	0.054
Total	16.474	0.025	16.634	0.037	16.598	0.059	16.381	0.055	16.531	0.033	16.622	0.042

100*Mg/(Mg+Fe)	93.511	0.454	94.009	0.055	93.097	1.888	90.951	0.097	90.951	0.179	90.195	0.123

Sample no. Rocktype n	JSL503 OII 3 secondary	JSL51 MARID. 4	JSL-/181 GLM 5	JSL-/181 GLM 2 secondary				
SiO2	40.86	0.45	42.58	0.89	41.85	0.59	40.19	0.08
TiO2	2.50	0.50	0.79	0.03	0.83	0.23	2.66	0.08
Al2O3	12.34	0.24	11.10	0.15	10.29	1.68	12.62	0.10
Cr2O3	0.59	0.18	0.42	0.03	0.27	0.05	0.84	0.14
FeO	4.75	0.13	4.27	0.15	5.27	0.62	5.24	0.16
MnO	0.03	0.02	0.02	0.01	0.04	0.02	0.02	0.00
MgO	23.46	0.66	26.14	0.42	26.24	2.58	22.39	0.02
CaO	0.01	0.02	0.01	0.01	0.00	0.00	0.01	0.01
Na2O	0.23	0.02	0.22	0.05	0.19	0.03	0.25	0.03
K2O	10.04	0.16	9.74	0.31	9.04	1.37	10.13	0.09
Total	94.80	0.07	95.30	1.36	94.04	0.33	94.34	0.05
Cations (recalculated to 23 oxygens)								
Si	6.119	0.054	6.299	0.025	6.292	0.064	6.074	0.011
Ti	0.282	0.057	0.088	0.004	0.094	0.026	0.302	0.009
Al	2.178	0.047	1.936	0.009	1.824	0.303	2.248	0.018
Cr	0.069	0.021	0.049	0.004	0.033	0.006	0.101	0.016
Fe	0.595	0.017	0.529	0.013	0.663	0.080	0.662	0.020
Mn	0.004	0.003	0.003	0.001	0.005	0.003	0.003	0.000
Mg	5.235	0.136	5.764	0.005	5.878	0.547	5.044	0.006
Ca	0.002	0.003	0.002	0.002	0.001	0.001	0.002	0.002
Na	0.066	0.006	0.063	0.015	0.054	0.009	0.074	0.009
K	1.918	0.034	1.838	0.083	1.736	0.269	1.953	0.018
Total	16.468	0.034	16.571	0.063	16.580	0.027	16.463	0.014
100*Mg/(Mg+Fe)	89.792	0.500	91.595	0.188	89.777	1.515	88.392	0.316

Amphibole

Sample no. Rocktype n	JSL75 MP 1	JSL110 MP 2		JSL180 MP 2		JSL298 MP 1	JSL67 I 5 secondary		JSL200 I 3 secondary		JSL203 I 4 secondary	
SiO2	45.55	46.40	0.03	46.89	0.18	46.91	38.38	1.29	40.18	0.24	39.87	0.64
TiO2	2.40	0.90	0.01	0.45	0.00	0.52	3.54	1.78	1.67	0.30	4.42	0.70
Al2O3	13.62	11.15	0.05	10.71	0.10	11.58	17.84	0.42	17.98	0.49	15.31	0.99
Cr2O3	0.15	1.01	0.04	0.46	0.00	0.88	0.03	0.01	0.03	0.02	0.07	0.04
FeO	2.87	3.44	0.01	4.20	0.04	2.87	10.81	0.61	9.27	0.55	12.08	0.57
MnO	0.07	0.04	0.01	0.04	0.01	0.04	0.11	0.03	0.14	0.03	0.13	0.05
MgO	18.78	20.19	0.07	20.10	0.13	20.53	11.93	0.71	13.81	0.07	12.40	0.46
CaO	10.12	10.38	0.10	10.70	0.04	10.97	10.94	0.26	10.96	0.30	9.80	0.42
Na2O	2.88	4.21	0.03	3.55	0.02	3.66	2.82	0.11	2.79	0.22	3.39	0.14
K2O	1.12	0.20	0.06	1.07	0.00	0.58	1.50	0.19	1.30	0.16	1.09	0.06
Total	97.55	97.92	0.13	98.17	0.47	98.54	97.91	0.26	98.13	0.33	98.55	0.28

Cations (recalculated to 23 oxygens)

Si	6.397	6.531	0.009	6.615	0.006	6.546	5.659	0.173	5.833	0.042	5.852	0.077
Ti	0.254	0.095	0.001	0.048	0.000	0.054	0.393	0.199	0.183	0.032	0.488	0.079
Al	2.254	1.850	0.007	1.780	0.007	1.905	3.101	0.082	3.076	0.080	2.649	0.172
Cr	0.016	0.112	0.005	0.051	0.000	0.097	0.004	0.002	0.004	0.002	0.008	0.004
Fe	0.337	0.405	0.002	0.496	0.002	0.336	1.333	0.075	1.125	0.067	1.483	0.077
Mn	0.008	0.005	0.001	0.004	0.001	0.004	0.013	0.004	0.017	0.004	0.016	0.006
Mg	3.932	4.236	0.017	4.226	0.006	4.270	2.621	0.146	2.987	0.018	2.712	0.089
Ca	1.523	1.566	0.014	1.618	0.001	1.641	1.728	0.043	1.705	0.049	1.541	0.065
Na	0.785	1.149	0.009	0.970	0.009	0.990	0.806	0.030	0.785	0.062	0.966	0.042
K	0.201	0.036	0.011	0.193	0.001	0.103	0.282	0.037	0.241	0.031	0.204	0.011
Total	15.707	15.985	0.003	16.003	0.002	15.945	15.940	0.065	15.957	0.020	15.917	0.042

Sample no.	JSL204	JSL205	JSL206	JSL254	JSL59	JSL98					
Rocktype	I	I	I	I	II	II					
n	5	3	3	5	1	4					
	secondary	secondary	secondary	secondary							
SiO2	40.60	0.69	40.78	0.41	42.00	0.50	40.65	0.11	47.25	46.80	0.14
TiO2	4.28	0.89	2.15	0.20	0.56	0.15	4.20	0.38	0.36	0.47	0.01
Al2O3	16.13	0.67	16.60	0.79	17.97	0.91	14.77	0.42	10.90	11.05	0.02
Cr2O3	0.05	0.02	0.10	0.04	0.05	0.03	0.05	0.03	0.65	0.74	0.02
FeO	10.28	0.08	9.99	0.18	8.18	0.38	10.71	0.44	2.45	2.64	0.02
MnO	0.10	0.01	0.14	0.01	0.13	0.01	0.19	0.05	0.01	0.07	0.01
MgO	12.69	0.45	14.06	0.21	15.10	0.43	13.74	0.34	20.70	20.72	0.09
CaO	9.48	0.27	10.46	0.52	10.34	0.18	9.63	0.28	10.89	10.86	0.08
Na2O	3.55	0.10	3.27	0.21	3.47	0.02	3.25	0.12	3.67	3.41	0.02
K2O	1.23	0.22	0.98	0.15	0.90	0.07	1.07	0.12	1.13	1.12	0.03
Total	98.39	0.29	98.51	0.22	98.71	0.19	98.27	0.18	98.02	97.89	0.26

Cations (recalculated to 23 oxygens)

Si	5.903	0.091	5.911	0.060	5.994	0.074	5.934	0.033	6.629	6.582	0.012
Ti	0.468	0.097	0.234	0.022	0.060	0.016	0.461	0.041	0.038	0.050	0.001
Al	2.764	0.118	2.835	0.129	3.023	0.151	2.542	0.064	1.803	1.832	0.002
Cr	0.005	0.003	0.011	0.005	0.006	0.003	0.006	0.004	0.072	0.083	0.002
Fe	1.250	0.012	1.211	0.024	0.977	0.046	1.308	0.058	0.288	0.310	0.002
Mn	0.013	0.001	0.017	0.002	0.015	0.001	0.023	0.006	0.001	0.008	0.001
Mg	2.700	0.095	3.038	0.043	3.211	0.094	2.990	0.064	4.328	4.343	0.014
Ca	1.476	0.044	1.624	0.086	1.582	0.027	1.507	0.045	1.637	1.637	0.012
Na	1.001	0.028	0.918	0.056	0.961	0.005	0.920	0.033	0.998	0.930	0.004
K	0.229	0.041	0.182	0.028	0.164	0.012	0.200	0.022	0.202	0.201	0.005
Total	15.859	0.029	15.981	0.020	15.993	0.013	15.891	0.024	15.996	15.976	0.010

Sample no.	JSL251		JSL51	
Rocktype	II		MARID	
n	3		2	
	secondary			
SiO2	40.87	0.91	55.06	0.25
TiO2	4.34	0.67	0.56	0.01
Al2O3	15.50	0.33	1.60	0.07
Cr2O3	0.43	0.10	0.65	0.07
FeO	5.53	0.64	2.68	0.03
MnO	0.18	0.04	0.04	0.01
MgO	16.51	0.47	22.89	0.06
CaO	11.35	0.53	7.18	0.03
Na2O	2.44	0.52	4.10	0.03
K2O	1.50	0.32	3.78	0.03
Total	98.64	0.24	98.54	0.44

Cations (recalculated to 23 oxygens)

Si	5.837	0.110	7.674	0.001
Ti	0.466	0.073	0.058	0.001
Al	2.609	0.064	0.263	0.010
Cr	0.049	0.012	0.071	0.007
Fe	0.660	0.078	0.313	0.002
Mn	0.022	0.005	0.005	0.001
Mg	3.514	0.089	4.755	0.032
Ca	1.736	0.075	1.072	0.000
Na	0.676	0.146	1.106	0.002
K	0.273	0.057	0.673	0.002
Total	15.843	0.044	15.990	0.009

APPENDIX 3e : OPAQUE OXIDES

Sample numbers followed by a letter, eg. JSL 565A, indicate that more than one polished thin section of the particular sample was prepared.

Each average is followed by the standard deviation about the mean.

Sample no.	JSL500B		JSL511		JSL532	JSL25	JSL110		JSL254		JSL62
Rocktype	PP		PP		PP	MP	MP		I	II	
n	11		7		1	1	2		3		1
	vein										
TiO2	54.21	0.72	54.66	0.74	56.93	56.80	52.61	0.27	51.69	0.81	56.02
Al2O3	0.26	0.09	0.18	0.02	1.12	0.35	0.33	0.09	0.46	0.12	0.11
Cr2O3	3.34	0.38	4.35	0.14	2.43	0.44	4.60	0.13	0.12	0.01	0.17
FeO (probe)	28.42	1.29	26.76	0.68	20.79	29.12	30.37	0.31	38.69	1.10	27.86
FeO (calculated)	24.45	0.91	24.84	1.32	18.46	27.78	26.06	0.63	33.95	1.86	24.47
Fe2O3	4.41	1.99	2.13	1.36	2.59	1.50	4.80	0.36	6.38	1.62	3.77
MnO	0.26	0.04	0.19	0.04	0.22	0.40	0.22	0.00	0.36	0.13	0.29
NiO	0.17	0.02	0.20	0.03	0.11	0.10	0.18	0.01	0.04	0.00	0.37
MgO	13.39	0.45	13.42	0.61	18.18	12.79	11.70	0.49	6.80	0.87	14.17
Total	100.05	0.41	99.77	0.38	99.78	100.01	100.03	0.42	99.17	0.30	98.99
Total (calculated)	100.49	0.53	99.98	0.33	100.04	100.16	100.51	0.45	99.80	0.24	99.37

Cations (recalculated to 3 oxygens)

Elements (recalculated to 8 oxygens)	1	2	3	4	5	6	7	8	9	10
Ti	0.929	0.014	0.940	0.012	0.943	0.978	0.912	0.002	0.935	0.064
Al	0.007	0.002	0.005	0.001	0.029	0.009	0.009	0.002	0.013	0.003
Cr	0.060	0.007	0.079	0.003	0.042	0.008	0.084	0.003	0.002	0.003
Fe2+	0.399	0.143	0.475	0.027	0.340	0.532	0.502	0.016	0.683	0.042
Fe3+	0.143	0.156	0.037	0.023	0.043	0.026	0.083	0.006	0.115	0.029
Mn	0.005	0.001	0.004	0.001	0.004	0.008	0.004	0.000	0.007	0.003
Ni	0.003	0.000	0.004	0.001	0.002	0.002	0.003	0.000	0.001	0.006
Mg	0.455	0.014	0.457	0.019	0.597	0.437	0.402	0.014	0.244	0.007
Total	2.000	0.000	2.000	0.000	2.000	2.000	2.000	0.000	2.000	0.000

Sample no. Rocktype n	JSL4 M 5	JSL258 M 3	JSL3 CII 3	JSL32 CII 4	JSL36 CII 3	JSL44 CII 1	JSL 315 CII 1					
TiO2	50.01	0.27	50.58	0.20	49.69	0.22	48.06	0.72	49.78	0.37	49.46	49.61
Al2O3	0.75	0.06	0.81	0.03	0.59	0.12	0.77	0.22	0.76	0.03	0.94	0.81
Cr2O3	0.13	0.01	0.30	0.01	0.29	0.21	0.07	0.01	0.07	0.01	0.58	0.25
FeO (probe)	38.37	0.40	37.24	0.17	37.80	0.50	40.27	0.34	38.04	0.24	38.55	37.26
FeO (calculated)	27.60	0.32	26.95	0.15	26.68	0.17	26.56	0.54	27.10	0.44	27.32	26.63
Fe2O3	11.97	0.30	11.44	0.32	12.36	0.40	15.24	0.93	12.16	0.75	12.46	11.61
MnO	0.20	0.02	0.19	0.01	0.23	0.06	0.21	0.03	0.21	0.01	0.21	0.23
NiO	0.09	0.02	0.12	0.01	0.11	0.02	0.04	0.01	0.09	0.05	0.17	0.12
MgO	9.58	0.16	10.23	0.09	9.91	0.12	9.21	0.10	9.75	0.07	9.41	9.89
Total	99.13	0.48	99.46	0.08	98.61	0.27	98.62	0.77	98.69	0.06	98.32	98.18
Total (calculated)	100.33	0.48	100.61	0.08	99.85	0.28	100.15	0.69	99.91	0.04	100.57	99.36

Cations (recalculated to 3 oxygens)

[illegible]

Sample no. Rocktype n	JSL47 OII 3	JSL48 OII 3	JSL160 OII 3	JSL503 OII 6	JSL51 MARID 2	JSL-/181 GLM 5						
TiO2	51.05	0.18	53.43	0.26	53.50	0.19	54.92	0.41	54.87	0.17	51.71	1.01
Al2O3	0.76	0.10	0.15	0.01	0.21	0.07	0.26	0.14	0.06	0.02	0.43	0.05
Cr2O3	0.29	0.01	4.06	0.16	5.00	0.26	3.40	0.24	4.55	0.24	5.32	1.01
FeO (probe)	37.65	0.16	28.50	0.43	29.91	0.46	27.37	0.47	26.48	0.76	29.48	0.34
FeO (calculated)	28.64	0.09	24.65	0.16	27.41	0.27	25.33	0.91	25.91	0.66	24.53	0.93
Fe2O3	10.02	0.11	4.28	0.60	2.78	0.71	2.26	1.27	0.64	0.11	5.51	1.21
MnO	0.24	0.04	0.24	0.02	0.25	0.02	0.22	0.03	0.34	0.01	0.19	0.02
NiO	0.13	0.02	0.17	0.01	0.13	0.01	0.15	0.03	0.13	0.04	0.21	0.05
MgO	9.48	0.11	12.90	0.05	11.40	0.08	13.29	0.34	12.89	0.47	12.10	0.34
Total	99.60	0.25	99.45	0.36	100.40	0.15	99.60	0.42	99.31	0.06	99.45	0.14
Total (calculated)	100.60	0.26	99.88	0.37	100.68	0.21	99.83	0.50	99.38	0.05	100.00	0.12

Cations (recalculated to 3 oxygens)

[illegible]

Spinel

Sample no. Rocktype n	JSL113 GHs 1	JSL113 GHs 1	JSL113 GHs 1	JSL113 GHs 1	JSL113 GHs 1	JSL113 GHs 1	JSL113 GHs 1	JSL113 GHs 1	JSL170 GH 3		JSL124 Sp 5	
	primary	secondary	==>					<==secondary				
TiO2	0.68	1.03	1.25	1.57	1.74	1.75	2.90	1.69	0.67	0.01	0.06	0.02
Al2O3	6.92	28.35	28.18	25.88	21.99	21.62	14.84	16.11	16.25	0.12	43.02	0.97
Cr2O3	59.89	36.94	36.53	38.81	41.27	41.76	44.86	47.98	50.20	0.27	25.24	1.09
FeO (probe)	17.45	16.97	16.93	16.86	18.14	17.79	20.93	16.59	19.07	0.13	11.92	0.35
FeO (calculated)	12.50	11.75	11.68	12.11	12.81	12.71	14.11	11.24	15.54	0.04	9.31	0.76
Fe2O3	5.49	5.80	5.83	5.28	5.92	5.65	7.59	5.94	3.93	0.17	2.89	0.48
MnO	0.25	0.27	0.20	0.24	0.27	0.23	0.36	0.22	0.25	0.01	0.14	0.02
NiO	0.14	0.07	0.13	0.09	0.10	0.11	0.13	0.16	0.11	0.01	0.21	0.02
MgO	13.46	16.72	16.83	16.47	15.50	15.49	14.41	15.78	12.49	0.06	19.08	0.59
Total	98.78	100.35	100.06	99.93	99.02	98.75	98.44	98.53	99.04	0.22	99.68	0.29
Total (calculated)	99.33	100.93	100.64	100.46	99.81	99.32	99.20	99.13	99.43	0.22	99.97	0.32

Cations (recalculated to 32 oxygens)

Ti	0.135	0.180	0.220	0.280	0.319	0.322	0.553	0.318	0.128	0.002	0.011	0.003
Al	2.152	7.802	7.773	7.228	6.320	6.235	4.441	4.750	4.880	0.028	11.122	0.179
Cr	12.489	6.819	6.759	7.270	7.955	8.081	9.004	9.494	10.112	0.063	4.380	0.219
Fe2+	2.758	2.294	2.286	2.400	2.612	2.602	2.995	2.353	3.310	0.011	1.709	0.151
Fe3+	1.090	1.018	1.027	0.941	1.087	1.040	1.449	1.119	0.753	0.033	0.477	0.076
Mn	0.056	0.053	0.039	0.048	0.056	0.048	0.078	0.047	0.053	0.001	0.026	0.004
Ni	0.029	0.013	0.024	0.017	0.020	0.021	0.027	0.032	0.022	0.003	0.038	0.004
Mg	5.291	5.820	5.871	5.815	5.632	5.652	5.453	5.886	4.742	0.013	6.238	0.149
sum A	16.000	16.000	16.000	16.000	16.000	16.000	16.000	16.000	16.000	0.000	16.000	0.000
sum B	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	0.000	8.000	0.000

Sample no. Rocktype n	JSL153 Sp 3		JSL154 Sp 3		JSL156 Sp 5		JSL157 Sp 3		JSL158 Sp 2		JSL250 A 2	
TiO2	0.03	0.01	0.12	0.01	0.06	0.00	0.01	0.00	0.07	0.00	0.04	0.00
Al2O3	27.24	0.51	39.02	0.26	26.12	0.47	59.82	1.40	50.66	0.07	58.60	0.28
Cr2O3	41.85	0.53	30.14	0.09	42.98	0.48	9.11	1.54	16.88	0.03	7.37	0.05
FeO (probe)	14.55	0.07	11.50	0.13	15.33	0.40	8.22	0.31	12.19	0.05	12.49	0.03
FeO (calculated)	12.52	0.10	9.74	0.09	13.13	0.46	6.45	0.42	9.60	0.09	9.36	0.03
Fe2O3	2.26	0.10	1.96	0.05	2.44	0.11	1.96	0.14	2.88	0.15	3.47	0.00
MnO	0.24	0.00	0.16	0.02	0.25	0.01	0.10	0.02	0.12	0.01	0.06	0.00
NiO	0.11	0.02	0.10	0.01	0.08	0.01	0.38	0.05	0.25	0.01	0.49	0.01
MgO	15.25	0.15	18.43	0.05	14.85	0.33	22.70	0.40	19.72	0.09	20.48	0.15
Total	99.27	0.25	99.48	0.33	99.67	0.18	100.34	0.40	99.90	0.18	99.52	0.44
Total (calculated)	99.50	0.26	99.68	0.33	99.91	0.18	100.53	0.39	100.19	0.20	99.87	0.44

Cations (recalculated to 32 oxygens)

Ti	0.006	0.001	0.021	0.002	0.011	0.001	0.002	0.001	0.012	0.001	0.006	0.001
Al	7.672	0.124	10.294	0.031	7.384	0.110	14.241	0.238	12.682	0.010	14.248	0.001
Cr	7.909	0.120	5.333	0.032	8.153	0.118	1.456	0.256	2.835	0.011	1.202	0.002
Fe2+	2.502	0.030	1.823	0.011	2.635	0.100	1.090	0.078	1.706	0.019	1.616	0.013
Fe3+	0.406	0.017	0.330	0.008	0.441	0.019	0.299	0.020	0.460	0.022	0.539	0.003
Mn	0.049	0.001	0.030	0.004	0.050	0.003	0.017	0.003	0.021	0.002	0.011	0.001
Ni	0.021	0.004	0.018	0.001	0.016	0.002	0.062	0.007	0.043	0.002	0.082	0.002
Mg	5.434	0.033	6.150	0.012	5.309	0.101	6.834	0.073	6.241	0.014	6.297	0.016
sum A	16.000	0.000	16.000	0.000	16.000	0.000	16.000	0.000	16.000	0.000	16.000	0.000
sum B	8.000	0.000	8.000	0.000	8.000	0.000	8.000	0.000	8.000	0.000	8.000	0.000

Sample no. Rocktype n	JSL-/91 GPP 3		JSL111(1) GPP 3		JSL111(2) GPP 2		JSL111(3) GPP 3		JSL143 GPP 1	JSL-/177 GPP 2		JSL-/177 GPP 1
												secondary
TiO2	1.95	0.03	1.66	0.51	2.11	0.57	0.93	0.37	1.74	3.24	0.45	0.46
Al2O3	8.21	0.07	16.52	1.59	25.77	2.91	42.83	5.34	7.51	9.45	0.04	46.28
Cr2O3	54.86	0.37	47.75	2.68	35.54	1.59	20.48	4.71	58.29	51.97	0.34	19.00
FeO (probe)	20.32	0.07	18.80	1.75	19.82	1.73	15.88	1.19	18.21	19.32	1.06	13.28
FeO (calculated)	14.58	0.22	14.25	0.64	13.74	1.72	10.28	0.98	13.81	13.12	0.69	8.36
Fe2O3	6.39	0.32	5.06	1.26	6.76	0.01	6.22	0.44	4.89	6.89	0.42	5.47
MnO	0.35	0.06	0.30	0.01	0.27	0.01	0.24	0.01	0.27	0.26	0.01	0.12
NiO	0.14	0.02	0.22	0.03	0.17	0.07	0.09	0.03	0.15	0.19	0.01	0.05
MgO	12.92	0.11	13.85	0.34	15.49	1.08	18.93	0.95	13.44	14.92	0.83	20.41
Total	98.75	0.23	99.11	0.45	99.16	0.16	99.37	0.17	99.61	99.35	0.61	99.59
Total (calculated)	99.39	0.20	99.62	0.36	99.84	0.16	99.99	0.15	100.10	100.04	0.56	100.14

Cations (recalculated to 32 oxygens)

Ti	0.385	0.006	0.314	0.098	0.382	0.111	0.155	0.066	0.342	0.626	0.080	0.075
Al	2.547	0.019	4.902	0.440	7.269	0.680	11.075	1.128	2.314	2.860	0.020	11.733
Cr	11.417	0.061	9.509	0.538	6.746	0.433	3.583	0.918	12.041	10.556	0.045	3.232
Fe2+	3.209	0.044	3.004	0.156	2.763	0.399	1.895	0.227	3.017	2.820	0.178	1.503
Fe3+	1.265	0.064	0.960	0.242	1.220	0.025	1.032	0.093	0.961	1.333	0.095	0.886
Mn	0.079	0.015	0.064	0.003	0.055	0.004	0.045	0.001	0.059	0.057	0.002	0.021
Ni	0.030	0.003	0.046	0.007	0.032	0.013	0.015	0.006	0.032	0.038	0.002	0.008
Mg	5.068	0.047	5.201	0.084	5.532	0.278	6.200	0.175	5.234	5.711	0.257	6.542
sum A	16.000	0.000	16.000	0.000	16.000	0.000	16.000	0.000	16.000	16.000	0.000	16.000
sum B	8.000	0.000	8.000	0.000	8.000	0.000	8.000	0.000	8.000	8.000	0.000	8.000

Sample no. Rocktype n	JSL533 GPP 3	JSL-93 PP 3	JSL273 PP 3	JSL304 PP 3	JSL532 PP 2	JSL547 PP 3	JSL565 PP 4							
								discrete						
TiO2	1.58	0.03	2.51	0.14	2.36	0.03	0.56	0.01	1.06	0.03	2.25	0.04	2.61	0.10
Al2O3	8.48	0.08	4.07	0.53	7.70	0.03	8.20	0.23	1.07	0.05	6.32	0.21	5.77	0.23
Cr2O3	56.46	0.23	59.36	1.10	54.70	0.05	58.45	0.41	63.08	0.03	59.06	0.71	55.33	0.71
FeO (probe)	19.68	0.75	20.26	1.04	21.14	0.03	18.44	0.07	24.26	0.01	17.85	1.08	23.55	0.20
FeO (calculated)	14.08	1.16	15.12	0.96	15.34	0.26	13.26	0.21	18.29	0.06	13.99	1.20	17.15	0.05
Fe2O3	6.22	0.55	5.72	0.11	6.45	0.25	5.75	0.20	6.64	0.07	4.28	0.16	7.11	0.21
MnO	0.30	0.02	0.27	0.03	0.26	0.00	0.28	0.01	0.34	0.01	0.29	0.03	0.29	0.02
NiO	0.15	0.03	0.08	0.03	0.20	0.01	0.13	0.00	0.20	0.01	0.18	0.02	0.18	0.02
MgO	13.34	0.77	12.65	0.49	12.69	0.22	13.09	0.06	9.33	0.06	13.40	0.77	11.50	0.07
Total	100.00	0.08	99.21	0.20	99.06	0.19	99.13	0.38	99.34	0.09	99.35	0.56	99.23	0.31
Total (calculated)	100.62	0.13	99.78	0.21	99.70	0.22	99.71	0.36	100.01	0.10	99.78	0.55	99.94	0.30

Cations (recalculated to 32 oxygens)

Ti	0.308	0.004	0.505	0.029	0.467	0.004	0.110	0.002	0.220	0.006	0.446	0.006	0.526	0.021
Al	2.592	0.029	1.264	0.166	2.391	0.007	2.532	0.066	0.349	0.018	1.962	0.076	1.818	0.072
Cr	11.577	0.096	12.554	0.244	11.396	0.049	12.113	0.064	13.826	0.007	12.297	0.085	11.699	0.152
Fe2+	3.055	0.268	3.381	0.213	3.380	0.068	2.907	0.037	4.240	0.018	3.063	0.275	3.835	0.005
Fe3+	1.214	0.101	1.151	0.022	1.279	0.046	1.134	0.044	1.386	0.013	0.849	0.036	1.432	0.042
Mn	0.065	0.005	0.062	0.007	0.058	0.001	0.062	0.003	0.081	0.002	0.065	0.007	0.066	0.006
Ni	0.032	0.007	0.017	0.006	0.042	0.002	0.027	0.000	0.044	0.003	0.038	0.003	0.039	0.005
Mg	5.155	0.269	5.045	0.199	4.986	0.070	5.114	0.037	3.855	0.019	5.260	0.284	4.586	0.023
sum A	16.000	0.000	16.000	0.000	16.000	0.000	16.000	0.000	16.000	0.000	16.000	0.000	16.000	0.000
sum B	8.000	0.000	8.000	0.000	8.000	0.000	8.000	0.000	8.000	0.000	8.000	0.000	8.000	0.000

Sample no.	JSL565	JSL565A		JSL565B		JSL252	JSL60	JSL61
Rocktype	PP	PP		PP		MP	II	II
n	3	3		3		1	1	1
	intergrown	discrete		discrete				secondary
TiO2	2.37	0.02	2.66	0.09	2.34	0.08	0.01	0.17
Al2O3	5.39	0.04	5.25	0.48	6.11	0.46	61.48	41.97
Cr2O3	56.47	0.42	55.91	0.28	55.42	1.04	6.44	26.57
FeO (probe)	22.88	0.38	23.52	0.21	22.31	0.42	7.14	10.27
FeO (calculated)	16.62	0.33	17.50	0.22	16.08	0.55	5.22	7.97
Fe2O3	6.96	0.18	6.69	0.14	6.92	0.35	2.14	2.56
MnO	0.28	0.01	0.25	0.01	0.32	0.00	0.00	0.08
NiO	0.17	0.02	0.21	0.01	0.19	0.01	0.42	0.19
MgO	11.68	0.27	11.20	0.10	11.91	0.27	23.42	19.84
Total	99.23	0.38	99.01	0.66	98.59	0.34	98.91	99.11
Total (calculated)	99.93	0.39	99.68	0.65	99.29	0.31	99.12	99.36

Cations (recalculated to 32 oxygens)

Ti	0.477	0.006	0.539	0.013	0.471	0.015	0.002	0.029	0.119
Al	1.899	0.021	1.665	0.137	1.928	0.144	14.642	10.892	14.890
Cr	11.946	0.048	11.901	0.141	11.736	0.223	1.029	4.626	0.073
Fe2+	3.719	0.090	3.941	0.016	3.602	0.120	0.882	1.467	1.458
Fe3+	1.402	0.034	1.356	0.036	1.394	0.071	0.325	0.425	0.799
Mn	0.063	0.002	0.058	0.004	0.073	0.001	0.000	0.015	0.023
Ni	0.037	0.004	0.045	0.002	0.040	0.003	0.068	0.034	0.015
Mg	4.658	0.085	4.496	0.005	4.755	0.113	7.052	6.513	6.622
sum A	16.000	0.000	16.000	0.000	16.000	0.000	16.000	16.000	16.000
sum B	8.000	0.000	8.000	0.000	8.000	0.000	8.000	8.000	8.000

Rutile

Sample no. Rocktype n	JSL75 MP 4		JSL110 MP 3		JSL106 I 2		JSL203 I 2		JSL203 I 1	JSL204 I 1	JSL207 I 2	
TiO2	99.33	0.58	95.87	1.55	97.65	1.22	98.98	0.10	94.14	99.32	97.54	0.32
Al2O3	0.06	0.03	0.07	0.02	0.28	0.22	0.14	0.05	0.18	0.20	0.28	0.02
Cr2O3	0.24	0.14	1.98	0.25	0.08	0.02	0.05	0.01	0.06	0.08	0.00	0.00
FeO	0.31	0.17	0.84	0.99	0.17	0.08	0.15	0.01	4.84	0.26	0.86	0.01
MnO	0.00	0.00	0.03	0.03	0.00	0.00	0.03	0.02	0.01	0.01	0.00	0.00
NiO	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	0.01	0.01	0.09	0.13	0.00	0.00	0.00	0.00	0.36	0.00	0.03	0.00
Total	99.96	0.48	98.87	0.41	98.18	0.94	99.36	0.17	99.58	99.89	98.71	0.27

Sample no. Rocktype n	JSL61 II 1	JSL62 II 2		JSL69 II 2		JSL251 II 3	
TiO2	99.41	99.32	0.05	94.41	1.06	93.54	1.20
Al2O3	0.43	0.14	0.05	0.39	0.00	0.28	0.01
Cr2O3	0.28	0.39	0.04	0.49	0.01	2.50	0.02
FeO	0.30	0.12	0.09	1.02	0.08	0.63	0.52
MnO	0.00	0.04	0.04	0.00	0.00	0.00	0.01
NiO	0.00	0.05	0.05	0.01	0.01	0.01	0.01
MgO	0.01	0.00	0.00	0.18	0.03	0.11	0.14
Total	100.43	100.07	0.12	96.51	0.95	97.06	1.52

APPENDIX 4: ANALYTICAL TECHNIQUES EMPLOYED DURING ISOTOPE ANALYSES

Isotope analyses were performed at the Bernard Price Institute for Geophysics (BPI) at the University of the Witwatersrand, Johannesburg. Detailed descriptions of the procedures set out below can be found in the unpublished BPI internal laboratory manual (A laboratory manual for radiogenic isotope analysis, by A.B. Moyes, 2nd ed. 1990). The following is a brief summary of the methods employed.

Peridotite xenoliths from the initial sample batch had been crushed to approximately 3-4 cm at Orapa and all parts of the xenoliths in contact with the kimberlite melt had therefore been removed. Larger xenoliths from a later sample batch were slabbed and material from the rims was not crushed to avoid any possible kimberlite contamination. The samples were wrapped in clean paper and broken by hammer. All implements were cleaned and dried with acetone after each successive sample to avoid contamination. Initial crushing took place with steel pliers and a steel mortar and pestle. The crush was then separated into size fractions of which the 250-500 micron fractions were eventually chosen for analysis.

Samples were then leached overnight in 6N HCl and for 30 minutes in 4% HF and cleaned several times with distilled water and ultrasonic agitation. The 250 micron fraction was then passed through a Frantz magnetic separator in order to preconcentrate garnet and clinopyroxene.

Samples were handpicked using a binocular microscope with fibre optic illumination. Only clear grains with clean cleavage planes or conchoidal fractures and no inclusions or milky fractures were selected. Any grains containing adhering calcite, zeolite or surface films were scrupulously avoided. Badly frosted or pitted grains were also rejected. All grains were examined from every side to avoid initially unseen contamination. In general, more than 50% of the initial sieved fraction was discarded. Once selection was completed, samples were again examined to ensure maximum purity. Sample masses of final fractions selected for isotope work varied between 26 and 102 mg.

The grains were then dissolved in a mixture of double-distilled HF and HNO₃ (5:1) in pre-cleaned 15 ml Savillex beakers. The samples were brought to the boil on a hot plate, covered and left for approximately 5 days. The excess liquid was then evaporated. Double-distilled 6N HCl was added and the sample was boiled until a clear yellow solution was obtained. The solution was then split into two aliquots for isotope dilution (spike) and isotope composition (natural) in the ratio 1/3:2/3. The isotope dilution aliquot was spiked with pre-weighed spikes of ⁸⁷Rb, ⁸⁴Sr, ¹⁴⁶Nd and ¹⁴⁹Sm and then heated to homogenize these spikes. Both aliquots of each sample were dried in separate air boxes under thermal lamps. Contact between isotope dilution and isotope composition aliquots was avoided at all costs to prevent contamination.

All ion-exchange chemistry was executed on small columns which are reserved for low-level isotope studies. Blank values are considerably less than on larger columns. Separate columns were used for natural and spiked samples. Rb, Sr and REE separations were carried out in columns with a diameter of 5mm and a resin length of 10 cm. The resin is known as Biorad AG50, 100-200 mesh. The samples were dissolved in 500 microlitres of 2.51N HCl, centrifuged in clean plastic test tubes and pipetted into pre-cleaned columns. Any precipitate that may form, particularly in the natural columns, should be redissolved, since it will contain most of the REE. The Sr, Rb and REE fractions were dried under thermal lamps in clean air boxes. REE exchange chemistry was completed on 5mm diameter columns (9cm resin length) containing teflon particles coated with a solution of bis (2-ethylhexyl) phosphoric acid (HDEHP). The REE fractions were once again dried under thermal lamps in clean air boxes.

The primary columns were calibrated by using the flame test. A mixture of Ca-Sr-K salts was used for Rb and Sr and a Ba salt for the REE. The flame test simply involves collecting a drop of the eluted liquid from the base of the column on a platinum wire loop and holding it in the flame of a Bunsen burner. Each element results in a different flame colour. The secondary (REE) column was calibrated with a Nd solution (natural) and Nd-Sm solution (spike). Since REE cannot be determined by the flame test, an indicator solution (Chlorophosphazone III) is used. The indicator colours vary from purple in the absence of REE, to

blue/green, depending on the concentration of REE.

All samples were loaded on previously prepared and outgassed filaments. Rb was loaded onto double Ta filaments with distilled water. H_3PO_4 was used to fix the sample to the filament. Rb concentrations were determined on a VG Micromass 30 mass spectrometer and values were found to be within blank levels. Sr was loaded onto single Ta filaments using a mixture of H_3PO_4 and 2% HNO_3 . Isotopic measurements were determined on a VG 354 mass spectrometer. Sm and Nd was loaded onto single Re filaments. A retarding agent of Pt-activated charcoal avoids too rapid burning of the sample at high temperatures and is added to a mixture of H_3PO_4 and 2.59N HCl. Nd isotopic ratios were determined on a VG 354 mass spectrometer and Sm and Nd concentrations on a VG 30 mass spectrometer. Nd is reported relative to $^{143}\text{Nd}/^{144}\text{Nd}=0.511850(30)$ for the La Jolla standard. Sr is reported relative to $^{87}\text{Sr}/^{86}\text{Sr}=0.708002(35)$ for the E&A standard. Ba concentrations in the minerals were found to be very low and no BaF interference during Nd determination was detected. Blank levels are <100 picogram for Sm, Nd and Rb.

APPENDIX 5



IAVCEI CANBERRA 1993

ABSTRACTS



GENERAL ASSEMBLY
SEPTEMBER 1993 - CANBERRA AUSTRALIA

**ANCIENT VOLCANISM
& MODERN ANALOGUES**

THE STRUCTURE OF THE ACTIVE RING FAULT AT RABAU CALDERA

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The active ring fault at Rabaul Caldera is defined by earthquake locations. The seismic image shows that the ring fault is elliptical in plan and has an outwards dip.

The detailed structure of the ring fault is obscured by the errors implicit in locating earthquakes. These produce scatter in the locations and so blur our image of the caldera. However, a technique has been devised that manipulates the earthquake locations within the limits of the errors in an attempt to "de-blur" the image.

Each earthquake hypocentre has an associated spatial error: an ellipsoidal normal distribution. We use this as a guide as to how far an earthquake location can be perturbed during computer analysis. The analysis consists of repeatedly perturbing individual earthquakes in order to simplify the overall structure. Our criterion here is that a small volume of dense seismicity is simpler than a large volume of diffuse seismicity: based on the physical premise that one earthquake fault slipping a number of times is a more acceptable mechanism than a number of faults slipping only once.

For the Rabaul Caldera earthquakes, the results of the analysis are striking.

- 1 The ring fault consists of two, superimposed, ring faults.
- 2 There is variation in the dip of the fault. Outward dip is still dominant, but there are some places where the fault is almost vertical and one segment where the dip is inwards.
- 3 There are similarities in the images of the E and W caldera walls which indicate the presence of a regional lineament.
- 4 The wall images contain structures which suggest the location of the magma chamber and, perhaps, conduits to the surface.

DISTINCTION BETWEEN CLINOPYROXENE IN METASOMATIZED AND NON-METASOMATIZED PERIDOTITES FROM THE LETLHAKANE DK1 AND DK2 KIMBERLITES, CENTRAL EASTERN BOTSWANA

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DK1 and DK2 form part of the famous Orapa kimberlite cluster and are rooted in rocks of the Zimbabwe craton. The following mantle xenoliths are present: garnet lherzolites (coarse and deformed), garnet harzburgites (calcic and subcalcic), spinel peridotites, dunites, pyroxenites, eclogites (including diamond- and graphite-bearing varieties), megacrysts and silicate intergrowths. The calculated pressures and temperatures obtained from some of these xenoliths plot on the 40mWm⁻² continental geotherm. It was found that clinopyroxene in metasomatized (i.e. phlogopite-bearing) peridotites are enriched in Na and Cr, compared to clinopyroxene in non-metasomatized samples. High-Cr, -Na clinopyroxenes may also contain higher Fe³⁺. Garnet peridotites exhibit higher temperatures and pressures of equilibration than the metasomatized peridotites. Although difficult to quantify, the between-grain variation of Cr in high-Cr, -Na clinopyroxene appears to be dependant on the degree of textural equilibration, i.e. the greater the state of textural equilibration, the smaller the variation of Cr in the clinopyroxene of a particular sample. High-Cr, -Na clinopyroxenes exhibit the following petrographic features, all of which may not be present simultaneously: an association with primary metasomatic, low-Ti phlogopite; an association with veins of low-Ti phlogopite and ilmenite; an association with the breakdown of garnet; an irregular habit and often smaller grain size (mainly in poorly equilibrated samples). Viljoen et al. (1991) also note the presence of high-Cr, -Na clinopyroxene in subcalcic garnet harzburgites from Roberts Victor. An isotopic study of several peridotites, including a subcalcic harzburgite, was undertaken. The peridotitic clinopyroxenes have both depleted and enriched Sr and Nd isotopic compositions, similar to the Kimberley peridotites, but exhibiting a greater range of values.

Magmatism on an Ordovician Plate Boundary

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The Caledonide volcanic rocks of SE Ireland provide a time-integrated model for the development and evolution of a volcanic arc situated above an active continental margin. By comparison with modern analogues, the Lower Palaeozoic rocks have the advantage that the whole evolution of architecture and magmatism of this continental margin terrane can be studied. The geological history of the region is dated by both palaeontological and radiometric methods, and provides evidence of a hundred million year orogenic cycle of sedimentation, magmatism and deformation, from the initiation of subduction to its termination with the docking of the colliding terranes and on to subsequent relaxation with accompanying batholithic granite emplacement.

Early submarine magmatism progressed from low-potash island arc tholeiites to calc-alkaline basalts, andesites and dacites. Some of these sequences are rather high in potassium. Later stage magmas, erupted in an extensional tectonic setting within a continental margin volcanic arc, were distinctly bimodal, with basalts indicating contributions from both subduction zone and enriched mantle sources, while the rhyolites occasionally evolved to peralkaline highly fractionated compositions strongly enriched in HFS elements. In one case at least such a rhyolite is associated with Kuroko-type copper mineralisation. Elsewhere there is evidence that base metals initially enriched in the earlier ocean-floor sediments associated with basaltic volcanism, have been remobilised and concentrated in fault zones during later Variscan movements. Granite batholith emplacement into regionally deformed low-grade metasediments and volcanics did not take place until more than 40 million years later and was associated with strike-slip deformation and the injection of basic magma which formed a swarm of dolerite dykes and a number of appinitic and lamprophyric minor intrusions.

ISOTOPIC EVIDENCE FOR OPEN-SYSTEM MAGMATISM AT CLEAR LAKE, CALIFORNIA

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Oxygen and strontium isotopic data on a wide range of rocks, inclusions, and mineral separates demonstrate that Pliocene to Quaternary volcanism at Clear Lake, California was strongly influenced by crustal assimilation and magma mixing. Volcanic rocks range from +6.6-11.2‰ in δ¹⁸O and 0.7031-0.7054 in ⁸⁷Sm/⁸⁶Sr. The most primitive mafic lavas have relatively high δ¹⁸O (+6.6-8.2‰) but low ⁸⁷Sm/⁸⁶Sr (0.7031-0.7034), reflecting a mantle source enriched in ¹⁸O and/or limited crustal assimilation. Most other mafic rocks are highly contaminated, as indicated by crustal debris and δ¹⁸O and ⁸⁷Sm/⁸⁶Sr ranging up to +11.2‰ and 0.7053. The most contaminated of these lavas approach bulk mixtures of crustal and mantle components. Graywackes from the bedrock Franciscan assemblage (FA) and Great Valley sequence (GVS) have O and Sr isotopic values from +11-16‰ and 0.705-0.710 respectively, encompassing the range of metasedimentary crustal xenoliths (+11.1-13.6‰ and 0.706-0.708) in the volcanic rocks. Rhyolites ranging from +8.7-10.5‰ and 0.7041-0.7054 could not be derived solely by anatexis of exposed, inferred, or included crustal material, since pure crustal melts of these rocks would be +12‰ and 0.706 or greater. We favor a model where rhyolites formed by multiple episodes of crustal contamination and fractionation of mantle-derived basaltic precursors at lower crustal levels. Voluminous dacitic lavas were derived mainly by mixing of this rhyolitic component with relatively primitive mafic magmas in upper crustal reservoirs.

KEY TO SYMBOLS USED IN THE PLOTS

PERIDOTITE-PYROXENITE SUITE

- hot, deformed peridotite
- coarse-textured garnet lherzolite
- ⊕ coarse-textured garnet wehrlite
- subcalcic garnet harzburgite
- garnet harzburgite
- ⊙ coarse-textured lherzolite
- ▼ pyroxenite
- ① dunite
- + alkremite
- × spinel lherzolite

METASOMATIZED PERIDOTITE-PYROXENITE SUITE

- ⊖ phlogopite-bearing garnet peridotite
- * phlogopite-bearing peridotite
- ▲ metasomatized pyroxenite

ECLOGITE SUITE

- ⬡ group I eclogite
- ⬢ group II eclogite
- ◆ diamond and graphite-bearing eclogite
- ⬤ graphite-bearing eclogite

MEGACRYST, INTERGROWTH AND MARID SUITE

- ⊕ clinopyroxene megacryst
- ⊗ garnet megacryst
- ilmenite megacryst
- ▣ orthopyroxene megacryst
- ⊖ clinopyroxene-garnet intergrowth
- ⊕ clinopyroxene-ilmenite intergrowth
- ▣ orthopyroxene-ilmenite intergrowth
- ⌘ MARID/glimmerite

GENERAL

- ★ single analyses taken from the literature
- ☆