# Mineral Provinces

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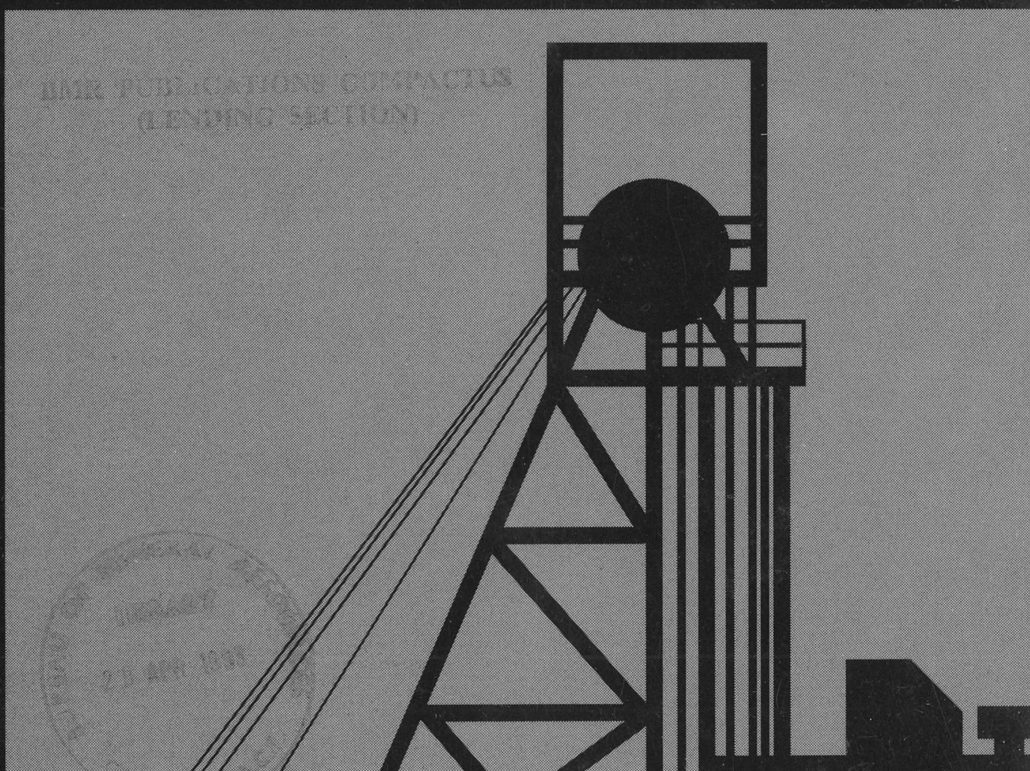
## Petrology of the layered mafic/ultramafic Giles Complex Western Musgrave Block, Western Australia:

**igneous stratigraphy, mineralogy and petrogenesis of the Jameson Range, Murray Range, Blackstone Range, Hinckley Range, Bell Rock Range, south Mt. West and Latitude Hill intrusions**

AUSTRALIA





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**Record 1992/73**
**by Christian G. Ballhaus***



MINERALS AND LAND USE PROGRAM
BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

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AUSTRALIAN GEOLOGICAL
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## SUMMARY

The middle to upper Proterozoic Giles Complex in central Australia comprises about twenty major layered mafic and ultramafic intrusions. All were emplaced in predominantly felsic granulite to amphibolite-facies gneisses of the middle Proterozoic Musgrave Block. On the basis of olivine-plagioclase relationships in the cumulates, a distinction is made between ultramafic intrusions (plagioclase-poor cumulate sequences that crystallized from olivine-saturated plagioclase-undersaturated melt), gabbroic intrusions (cumulates derived from olivine-clinopyroxene-plagioclase-saturated melt), and highly fractionated troctolitic intrusions (cumulate sequences that crystallized from olivine-plagioclase ± magnetite-saturated but pyroxene-undersaturated highly evolved parental melts). This report describes the magmatic stratigraphies of two ultramafic (Murray Range, South Mt. West), two gabbroic (Hinckley, Latitude Hill), and three troctolitic intrusions (Bell Rock, Blackstone, Jameson). The aim of the work was to (1) document fractionation patterns in the Giles Complex, (2) clarify possible stratigraphic and genetic relationships among individual intrusions, and (3) identify possible parental magma compositions to the Giles Complex.

Crystallization sequences and chemical fractionation patterns permit the identification of at least three discrete parental melt compositions. All these melt compositions can be derived from one primitive basaltic precursor liquid that originated in the upper mantle. The ultramafic intrusions of the Giles Complex (Gosse Pile, Kalka, Ewarara, Claude Hills, Wingellina Hills, Mt. West, and Murray Range) crystallized from unfractionated mantle-derived primitive basaltic magmas that were only saturated with olivine ± spinel at the time of emplacement. The gabbroic intrusions (Mt. Davies, Hinckley, Cavenagh, and Latitude Hill) were derived from moderately fractionated olivine-(orthopyroxene)-clinopyroxene-plagioclase-saturated gabbroic liquids. The troctolitic intrusions (Bell Rock, Blackstone, and Jameson) crystallized from highly evolved $SiO_2$-deficient liquids that were multiply saturated with Fe-rich olivine, sodic plagioclase, clinopyroxene, and minor Ti-magnetite.

The study will show that it is physically and chemically impossible to derive all intrusions from one continuously differentiating, episodically replenished body of parental melt, by simply fractionating the proportions of cumulus minerals present in the layered sequences. It is unlikely that the ultramafic olivine-rich intrusions represent the basal units and the most evolved troctolitic intrusions the uppermost fractionated units of one large formerly continuous Bushveld-type magma chamber. Fractionation trends within intrusions are all directed toward iron, alkali, and silica enrichment, regardless of the initial fractionation degree of the parent melt at the time of magma emplacement. However, among the intrusions, the olivine-melt peritectic evolves to progressively more iron-rich olivine compositions from the ultramafic to the troctolitic intrusions ($Fo_{78}$ in the Murray Range sequence, $Fo_{68}$ at Latitude Hill, $Fo_{57}$ at Hinckley, and below $Fo_{50}$ in Bell Rock and Jameson intrusions). This is difficult to achieve by in-situ fractionation. Phase equilibrium constraints clearly demand that once olivine is replaced on the liquidus by orthopyroxene, the magma cannot revert to olivine crystallization yet at the same time maintain its normal fractionation path with respect to iron, alkali, and silica enrichment. The range in parent magma compositions can be produced only by polybaric orthopyroxene-clinopyroxene-olivine fractionation of a primitive mantle-derived basaltic melt. Fractionation must have taken place at high pressure, before the melts were emplaced in their crustal reservoirs.

In addition to the layered suite, the Tomkinson Ranges host an extensive series of co-magmatic

marginal dykes and sills. These are partly intrusive to the cumulates. The dyke suite includes: (1) a primitive basaltic generation with olivine and aluminous spinel as phenocryst phases; (2) several common generations of variably fractionated olivine-plagioclase and olivine-clinpyroxene-plagioclase-phyric dykes and sills; and (3) a rare orthopyroxene-phyric dyke generation whose orthopyroxene phenocrysts may have been derived by high pressure crystallization. The olivine-spinel-phyric ultramafic dyke suite is primitive enough to be mantle-derived. It may qualify as the parental melt composition to all the derivative melts identified in the Giles Complex. The olivine-plagioclase-phyric and olivine-clinopyroxene-plagioclase-phyric dyke suites reflect more fractionated parental liquid compositions that are related to the primitive parent melt by high-pressure pyroxene fractionation. Variably fractionated examples of these liquids gave rise to the troctolitic and gabbroic cumulate sequences. The orthopyroxene-phyric dykes may provide direct physical evidence that high-pressure pyroxene fractionation has indeed taken place.

Most Giles intrusions feature all structural transitions between (1) rapidly quenched dykes cross-cutting the layered series, (2) fine-grained sill equivalents that intruded the cumulates along interfaces of cumulate layers, (3) stratabound pods and stratiform layers of microgabbro with the coarser-grained cumulates, and (4) coarse-grained mature cumulates of the layered sequences proper. These gradations illustrate the close genetic links between some of the dykes and the layered cumulates of the Giles Complex. They also imply that the Giles intrusions are the stacked sill equivalents of the dyke suite in the Musgrave block. This has important implications for the potential of the Complex for stratiform Merensky reef-type platinum-group element (PGE) mineralization. As the individual intrusions do not appear to represent fragments of an originally contiguous layered complex, any stratiform magmatic PGE mineralization that may be identified in the future would have a principally local significance – although relevant to similar occurrences in other intrusions of the Giles Complex.

Magmatism and thermal metamorphism in the western Musgrave Block may have been caused by a thermal anomaly in the upper mantle below the Musgrave Block. Magma emplacement must have taken place at a period of crustal extension as a result of mantle doming above a 'hot-spot'. Within the granulite terrain, intrusions of contrasting degrees of fractionation and parent magma characteristics are not randomly distributed. Cumulates with similar magma parentages and fractionation degrees are concentrated in discrete belts approximately parallel to the regional compositional layering ($S_0$) in the granulites of the Musgrave Block; the ultramafic intrusions in a belt extending from Gosse Pile to the Murray Range, the gabbroic intrusions from Mt. Davies to at least the Morgan Range, and the troctolitic intrusions in a belt from the Bell Rock Range to the Jameson Range. These belts are interpreted to reflect intrusive depths levels within the middle Proterozoic continental crust of the Musgrave Block, primarily controlled by magma densities. The most primitive melts must have been the least buoyant as they did not experience phase fractionation prior to emplacement; consequently they intruded in the deepest levels of the crust. The most fractionated troctolitic melts, on the other hand, had undergone extensive high-pressure pyroxene±olivine fractionation prior to emplacement; as a result, they were comparatively buoyant and thus able to intrude shallow crustal levels in the Musgrave Block. This interpretation implies that crustal levels as presently exposed in the western Musgrave Block progressively shallow from northeast to southwest.

## LOGISTICS AND METHODOLOGY

This report is based on systematic collections through selected intrusions of the layered mafic/ultramafic Giles Complex in Western Australia, conducted during July-September, 1987 and July-September, 1988, as a part of BMR/AGSO's Giles Project - redefined in 1990 as a part of the National Geoscience Mapping Accord. Eight intrusions were sampled by C.G. Ballhaus and A.Y. Glikson, including Jameson Range, Murray Range, Blackstone Range, Bell Rock Range, Latitude Hill, south Mount West (The Wart), Hinckley Range, and Wingellina Hills (for the latter see Ballhaus and Glikson, 1989). Samples were collected at regular intervals or where lithological variations were evident. Several other sections sampled through the layered intrusions were not included in this study due to limitations on cost and time. Layered intrusions of the South Australian part of the Tomkinson Ranges, studied in detail by staff and students of the University of Adelaide but not subjected to detailed electron probe work, were not included in the present study due to limitations on access into the Aboriginal reserve. Field work was assisted by J. Vickers and E.H. Feeken. Thin sections and polished thin sections were prepared by J. Duggan (Australian Petrographics Ltd.). Geochemical analyses of the material reported here were conducted at BMR laboratories using the X-ray fluorescence and Atomic Absorption techniques (analyst: J. Pyke) and will be reported separately. Electron microprobe analyses were carried out by C.G. Ballhaus at the Department of Geology, University of Tasmania, using a Cameca electron probe microanalyzer (technical advice: Wieslav Jablonsky). Part of the Murray Range suite was probed by A.Y. Glikson at the Research School of Earth Sciences, Australian National University, using a Cameca electron probe microanalyzer (supervisor: N. Ware). This Record was edited by A.Y. Glikson and prepared for production by J. Haldane. For further reference to the geology of the Tomkinson Ranges refer to the 1:100 000 geological map of the Tomkinson Ranges (Glikson and Stewart, in preparation) and references given in this report.

# 1 INTRODUCTION

The middle to upper Proterozoic Giles Complex comprises one of the most extensive suites of layered mafic/ultramafic intrusions in the world. It consists of about twenty major intrusions and numerous smaller bodies of layered gabbroic, anorthositic, troctolitic, pyroxenitic, and dunitic cumulates. All these intrusions were emplaced in middle Proterozoic predominantly felsic granulite to upper amphibolite-facies gneisses of the western Musgrave Block in central Australia (Nesbitt et al., 1970). From east to west, the major intrusions of the Giles Complex are Teizi Hill, Gosse Pile, Mt. Davies, Kalka, Ewarara, Claude Hills, Michael Hills, Hinckley, Wingellina Hills, Latitude Hill, South Mt. West (The Wart), Bell Rock, Blackstone, Murray, Morgan, Cavenagh, and finally Jameson. In addition, there are extensive but poorly documented mafic/ultramafic intrusions in the Musgrave Ranges near Mt. Woodroffe which may or may not belong to the same magmatic event that gave rise to the Giles Complex in the Tomkinson Ranges. The regional distribution of the Giles intrusions is illustrated in Fig. 1. The Figure is based on a more detailed structural map compiled by Pharaoh (1990).

The early view that the intrusions of the Giles Complex represent fragments of a formerly continuous larger layered complex (Sprigg and Wilson, 1959) has subsequently been abandoned. Available evidence suggests that several parent magma compositions were involved in the origin of the Giles Complex. Nesbitt et al, (1970) suggested on the basis of slight differences in olivine-plagioclase covariation that the Giles intrusions had been derived from chemically distinct parent magma compositions. Many intrusions, particularly those with poorly fractionated olivine-rich cumulate sequences, experienced a multiple intrusive history. Ballhaus and Glikson (1989) and Gray and Goode (1989) demonstrated that the Wingellina Hills and Kalka intrusions were continuously replenished by pulses of fresh unfractionated olivine-saturated melt, emplaced into evolving multiply-saturated gabbroic resident liquid of the same parentage. Such replenishment activity is reflected by spectacular megascale layering, where partly discordant olivine-rich orthocumulate layers and lenses alternate with gabbroic adcumulate units. Based on field observations (Moore, 1971, Daniels, 1974, Goode and Moore, 1975, Goode, 1976, 1977), one can infer that most Giles intrusions with megascale layering and significant ultramafic component have experienced similar intrusive histories.

The genetic and temporal relationships between magma emplacement and the granulite-metamorphic event in the Musgrave Block pose one of the principal questions in the study of the Giles Complex. These intrusions constitute the best documented examples for emplacement of a basaltic magma at high pressure (Nesbitt et al., 1970, Moore, 1971, Goode and Moore, 1975, Ballhaus and Berry, 1991), suggesting that some link may exist between magmatism and metamorphism. High pressure features include:

- Magmatic olivine, chromite, and plagioclase are in metamorphic reaction relationship, giving rise to complex pyroxene-spinel and olivine-spinel symplectites at former magmatic olivine-plagioclase grain boundaries.
- Liquidus spinel grains in ultramafic cumulates are unusually aluminous compared with chromites in cumulates from other layered intrusions of comparable degree of fractionation. In accordance with phase equilibrium constraints (Jaques and Green, 1980), this is also indicative of high crystallization pressure as high crystallization pressure forces spinel to become more aluminous.
- Clinopyroxene and orthopyroxene in ultramafic cumulates are exceptionally rich in

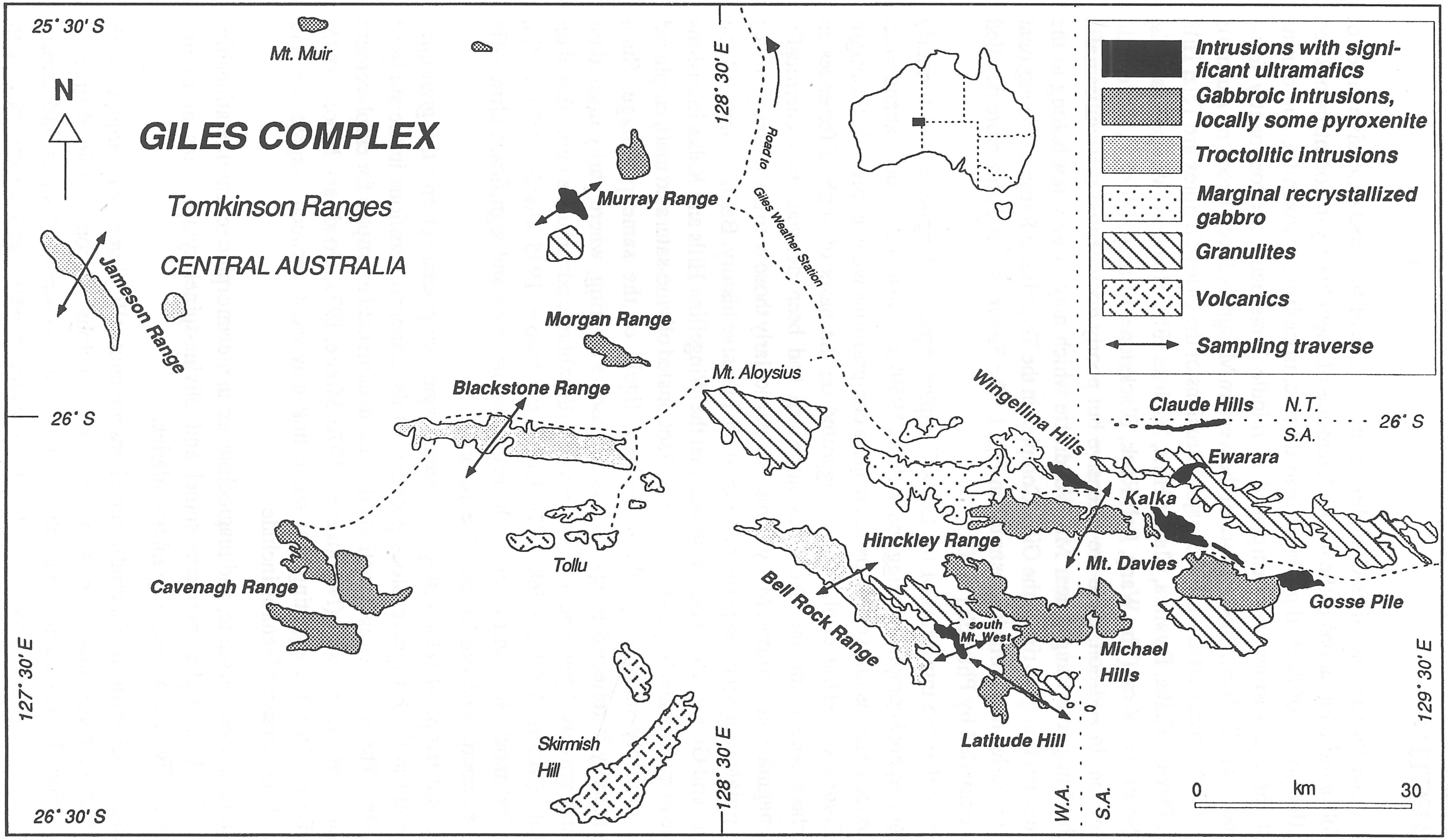



Figure 1. A geological sketch map of the Giles Complex, Tomkinson Ranges, western Musgrave Block, central Australia. Ultramafic intrusions: olivine-spinel-saturated parental melts; gabbroic intrusions with local pyroxenite layers: olivine-pyroxene± plagioclase-saturated parent melts; troctolitic intrusions: olivine-plagioclase-saturated parental melts; marginal gabbroic facies: deformed and recrystallized gabbro affected by granulite-facies metamorphism, in the Hinckley Ranges intruded by felsic veins.

Tschermak's component that has exsolved upon cooling as brownish chromiferous spinel rodlets.

- Primitive pyroxenitic cumulates of the Giles Complex commonly feature the most calcic and potassic antiperthites ever reported for terrestrial rocks.

The latter two points are not primarily due to high pressure but rather indicative of unusually high crystallization temperature due to elevated confining pressure.

Based on early experimental studies (Green and Ringwood, 1967a,b, Green and Hibberson, 1970), Goode and Moore (1975) suggested that the magmas were emplaced at lower crustal levels corresponding to 10 to 12 kbar or at least 35 km emplacement depth. That estimate was later revised by Ballhaus and Berry (1991) to around 6 ± 1 kbar using modern thermodynamic techniques. This new pressure range is in excellent agreement with pressures derived from the granulites immediately adjacent to the Complex (Clarke and Powell, 1991). Many structural and textural observations (e.g. chilled margins oblique to isoclinal F2 folds, preservation of delicate magmatic exsolution textures and high-temperature phase compositions) suggest that most of the Giles intrusions are unaffected by the granulite-facies peak metamorphic event, perhaps with the exception of some parts of the Hinckley Range (Clarke, 1992). Consequently, the pressure range calculated from reaction textures in cumulates must reflect emplacement conditions.

The economic potential of the Giles Complex has not been fully explored. There are some Ni laterites above olivine-rich ultramafic cumulates that have been mined in the past for gemstone-quality chrysoprase. The Jameson Range intrusion hosts vanadium-rich massive magnetite layers which contain up to 2% $V_2O_5$ in solid solution (Daniels, 1974). Of potentially more importance is the prospect of the layered suite for yet unidentified Merensky-type platinum-group element (PGE) mineralization or basal PGE-bearing platreef-type sulphide segregations. An important aim of the study therefore was to document similarities and differences of the Giles intrusions with the major platiniferous layered intrusions of the world, in order to evaluate the PGE potential of the complex. This in turn required documentation of the magmatic stratigraphies and fractionation patterns within the Giles intrusion, and the identification of parental magma compositions.

The present report describes results of a systematic investigation of the Hinckley Range, the Latitude Hill, the South Mt. West (The Wart), the Bell Rock Range, the Murray Range, the Blackstone Range, and the Jameson Range intrusions, and will:

- document in detail the crystallization sequences of the intrusions listed above, based on approximately 500 cumulate and dyke samples that were taken along 17 sampling traverses through the intrusions. Magmatic sequences are presented as a series of stratigraphic columns that are based on field observations and detailed thin section microscopy. Types of cumulates, deformation styles, and subsolidus re-equilibration textures are illustrated in representative photomicrographs. Fractionation degrees and trends are evaluated by plotting chemical compositions of cumulus and intercumulus phases against the magmatic stratigraphy and the measured stratigraphic height.

- characterize the possible parent magma compositions of the Giles intrusions. This aim will be achieved by comparing crystallization sequences in the layered suite with phenocryst populations in spatially associated basaltic dykes. In addition to the layered cumulate sequences, the granulite- metamorphic terrane of the Tomkinson Ranges hosts an extensive suite of basaltic dykes that are partly coeval with the layered cumulates and may include rapidly quenched samples of the parent magmas to the Giles intrusions.

- Attempt to reconstruct the original geographic and stratigraphic context among the intrusions, in order to test whether the Giles intrusions may be part of a formerly larger continuous layered complex (Sprigg and Wilson, 1959) that was disrupted by post-granulite-metamorphic thrusting activity (c.f. Harley, 1990), or whether some bodies are genetically separate entities (Nesbitt et al., 1970, Daniels, 1974). The latter point is particularly important when it comes to assessing the potential of the Giles Complex for stratiform Merensky Reef-type PGE-Cu-Ni mineralization and the possible lateral extent of such mineralization.

This report is primarily concerned with the petrology of the layered intrusions, whereas aspects of field relationships, contacts with country rocks and relationships with dykes are discussed elsewhere (Glikson et al., in preparation). The cumulate terminology adopted in this report follows the terminology suggested by Irvine (1982). Thin section descriptions are given in Appendix A and microprobe analyses are stored on 3.5" flexible disc included in the pocket of this report.

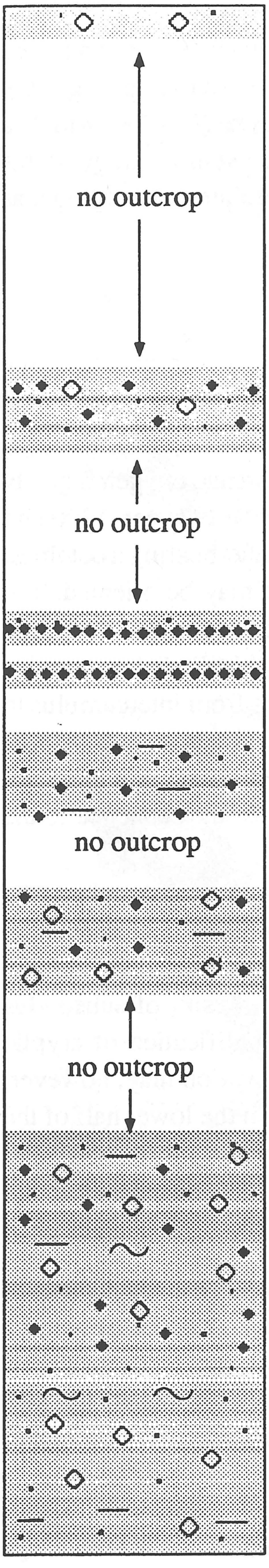
# 2 THE JAMESON RANGE INTRUSION

## 2.1 Magmatic sequence

The stratigraphic sequence of the Jameson Range intrusion is illustrated in Fig. 2. The intrusion consists of roughly 2500 m of well layered olivine-plagioclase cumulates, sampled along two consecutive traverses perpendicular to the magmatic layering. The Jameson Range sequence includes some of the most fractionated cumulates of the Giles Complex. The sequence is composed of variably well layered and partly deformed troctolites, gabbroic troctolites, and anorthosite adcumulates. Extreme chemical differentiation in the upper part of the sequence led to the formation of several massive titaniferous and vanadiferous magnetite layers. Exposure at Jameson is comparatively poor. About two thirds of the magmatic sequence is covered by alluvium. The bottom and top contacts of the intrusion are not exposed and the nature of the contacts with the granulites is unknown.

## 2.2 Rock Types

Typical types of cumulates are illustrated in Fig. 3A to E. Lithological variations are controlled by variations in the olivine/plagioclase modal ratio, mostly on a centimetre to metre scale (Fig. 3A to C). The major rock types include troctolites, anorthosites, gabbroic troctolites and anorthosites, and several massive magnetite layers. Plagioclase and Fe-rich olivine are the dominant cumulus phases. Clinopyroxene with opaque exsolution lamellae (Fig. 3D) is usually a minor phase and poikilitic or interstitial relative to olivine and plagioclase. Orthopyroxene is accessory and present as narrow moats around olivine. Magnetite is a common accessory intercumulus phase, grading into cumulus in the stratigraphic vicinity of massive magnetite layers. Post-magmatic accessory minerals include red (Ti-rich) biotite (Fig 3E.) and thin brownish amphibole rims, both preferentially attached to magnetite grains. Recrystallized samples contain secondary olivine, clinopyroxene, and orthopyroxene neoblasts, in addition to imperfectly preserved cumulus phases of the same composition. These neoblasts commonly




| | | |
|---|---|---|
| *2500* | 90980042<br>43 | coarse-grained gabbroic anorthosite with minor olivine only - strongly recrystallized |
| *2000* | | |
| | 044, 045 | olivine-bearing anorthosite with abundant interstitial oxides; locally some troctolitic and gabbroic layers |
| *1500* | 046, 047<br>048 | several massive Fe-Ti oxide layers within anorthositic to troctolitic matrix |
| | 049, 050 | recrystallized anorthositic troctolite, locally troctolitic layers and interstitial oxides |
| *1000* | 051, 052 | recrystallized anorthositic to gabbroic troctolite some interstitial oxides |
| | | no outcrop |
| | 039 | troctolite alternating with anorthosite and locally gabbroic |
| | 037, 038 | cumulates - some interstitial magmatic oxides |
| | 036 | coarse-grained deformed gabbro |
| *500* | 035 | recrystallized deformed troctoliti c anorthosite |
| | 034 | troctolite with some interstitial magmatic Fe-Ti oxides |
| | 033 | recrystallized troctolitic anorthosite |
| | 031, 032 | mainly anorthosite with some troctolite |
| | 030 | |
| | 029<br>026 to 028 | mainly troctolitic cumulates with some gabbroic material - some deformation |
| | 025 | recrystallized troctolitic anorthosite |
| | | recrystallized leucotroctolite alternating with troctolitic and |
| | 023 | anorthositic units - some diffuse lamination |
| | 021, 022 | |
| *metres* | 90980019 | recrystallized leucotroctolite, some lamination |

**Fig. 2. Stratigraphic sequence of the Jameson Range intrusion. Variations in olivine-plagioclase ratios are illustrated by variable gray shades. The presence of oxides is denoted by filled diamonds, clinopyroxene by open diamonds. Stratigraphic elevations are corrected for dip angles averaging 30°. For the positions of the sampling traverses compare Fig. 1. Numbers to the left of the text are sample numbers according to the AGSO catalogue system.**

coexist with rounded post-magmatic opaque oxides (Ti-magnetite) that have probably resulted from granule exsolution of oxide lamellae in primary magmatic clinopyroxene (e.g. Fig. 3D). The sampling traverse also intersected a thin plagioclase-olivine-phyric dyke (Fig. 3F), which is one of many in the environs of the Jameson Range sequence. The phenocryst mineralogy of this dyke resembles the crystallization sequence inferred for the gabbroic cumulates, qualifying it as a reasonable parent liquid of the Jameson Range intrusion.

## 2.3 Cryptic and modal layering

Stratigraphic variation plots of mineral compositions are shown in Fig. 4 and 5. The Jameson Range sequence is almost devoid of abrupt changes in modal mineralogy. Most mineralogic variations are gradational. Phase layering is most prominent where magnetite layers occur, i.e. at stratigraphic levels where the magma was sufficiently enriched in iron and had oxygen fugacity high enough to trigger magnetite supersaturation. The stratigraphic interval between 1200 and 1700 m includes several massive magnetite layers within a zone of magnetite-bearing troctolites. There is no clear field or geochemical evidence as to how the sequence may be oriented. The orientation adopted in Fig. 2 is based largely on the distribution of disseminated magnetite within the troctolites. In the stratigraphic units considered to be situated stratigraphically below massive oxide layers, magnetite tends to increase in modal abundance and changes from intercumulus to predominantly cumulus toward magnetite layers. This is taken to indicate a period of normal upward fractionation until magnetite supersaturation. In addition to this stratigraphic criterion, the shallow dip of the magmatic layers southwestward render younging of the sequence to the southwest very likely.

The cumulates in the Jameson Range intrusion are amongst the most fractionated rocks of the Giles Complex. Mg/(Mg+Fe) ratios of olivine range from about 0.65 to 0.51, and coexisting orthopyroxenes from 0.72 to 0.52. Anorthite content in plagioclase varies from 0.75 to 0.49, sometimes with a 20 percent variability within single thin sections as a result of subsolidus equilibration. Unfortunately, outcrop is too limited to allow reliable identification of cryptic variation patterns. The two highly fractionated samples at the 1000 m elevation may, however, represent the endmembers of an extended period of normal fractionation in the lower half of the sequence, subsequently terminated by a new pulse of less fractionated melt.

## 2.4 Subsolidus deformation

Nowhere along the sampling traverse are primary cumulate textures found. Nearly all samples taken are deformed to some degree (c.f. Fig. 3C). In the troctolites, ferromagnesian phases define centimetre-thick laterally impersistent laminae in which olivine is partly to wholly recrystallized to small neoblasts. As a general rule, the more fractionated a sample is, i.e. the higher the iron content of olivine, the more deformed it is. This may possibly indicate that samples with higher total iron were more susceptible to ductile flow. It is unclear whether this style of layering is primary-magmatic or entirely due to subsolidus differentiation, or whether it originated under supersolidus conditions and was only accentuated by subsolidus deformation.

## 2.5 Parent magma composition and magmatic evolution

The parent magma to the Jameson Range cumulates was highly fractionated and saturated with olivine, plagioclase, and perhaps clinopyroxene. As a result, there is no evidence for megascale

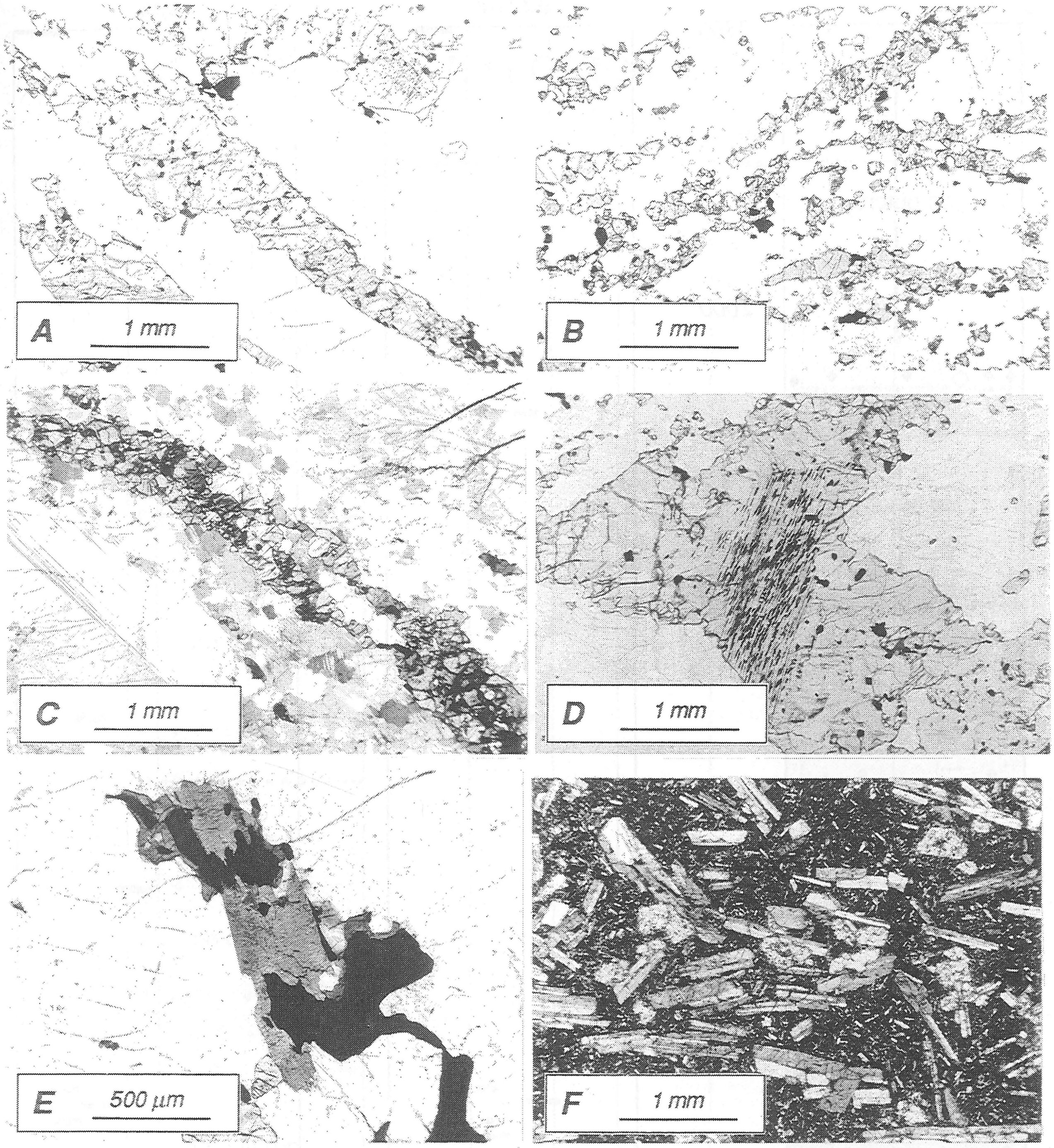



**Fig.3A. Types of cumulate textures in the Jameson Range Intrusion. Laminated troctolitic anorthosite. Small olivine and cpx grains arranged to layers and lenses within a plagioclase-dominated matrix. A few rounded oxide grains are due to granule exsolution of oxide lamellae within magmatic cpx. One magmatic cpx grain with opaque oxide exsolutions to the upper right of the photograph. Sample 90980023.**
**B. Finely banded recrystallized leucotroctolite to anorthosite. Small olivine and cpx neoblasts within matrix of highly deformed plagioclase granules. Sample 90980019.**
**C. Olivine-rich layer in a strongly deformed and recrystallized troctolitic anorthosite. A few large deformed plag relics within a neoblastic matric of plag. Partly crossed polarizers to accentuate the degree of deformation within plagioclase. Sample 90980022.**
**D. Large magmatic cpx relic with abundant opaque oxide exsolutions within its grain center. Along the peripheries the grain recrystallized to cpx-opaque oxide neoblasts. Recrystallized gabbroic troctolite. Sample 90980039.**
**E. Interstitial magnetite within coarse-grained anorthosite. A reddish biotite flake attached to a late-magmatic intercumulus oxide grain. Sample 90980042.**
**F. Olivine-plag-phyric dykelet crosscutting the layered sequence. Elongate plagioclase and euhedral olivine are phenocrysts, in a fine-grained plagioclase-oxide-bearing groundmass. Such compositions have phenocryst populations that resemble the cumulus phases in the troctolitic intrusions. They could qualify as derivative parental melts to the Jameson intrusion. Sample 90980032.**

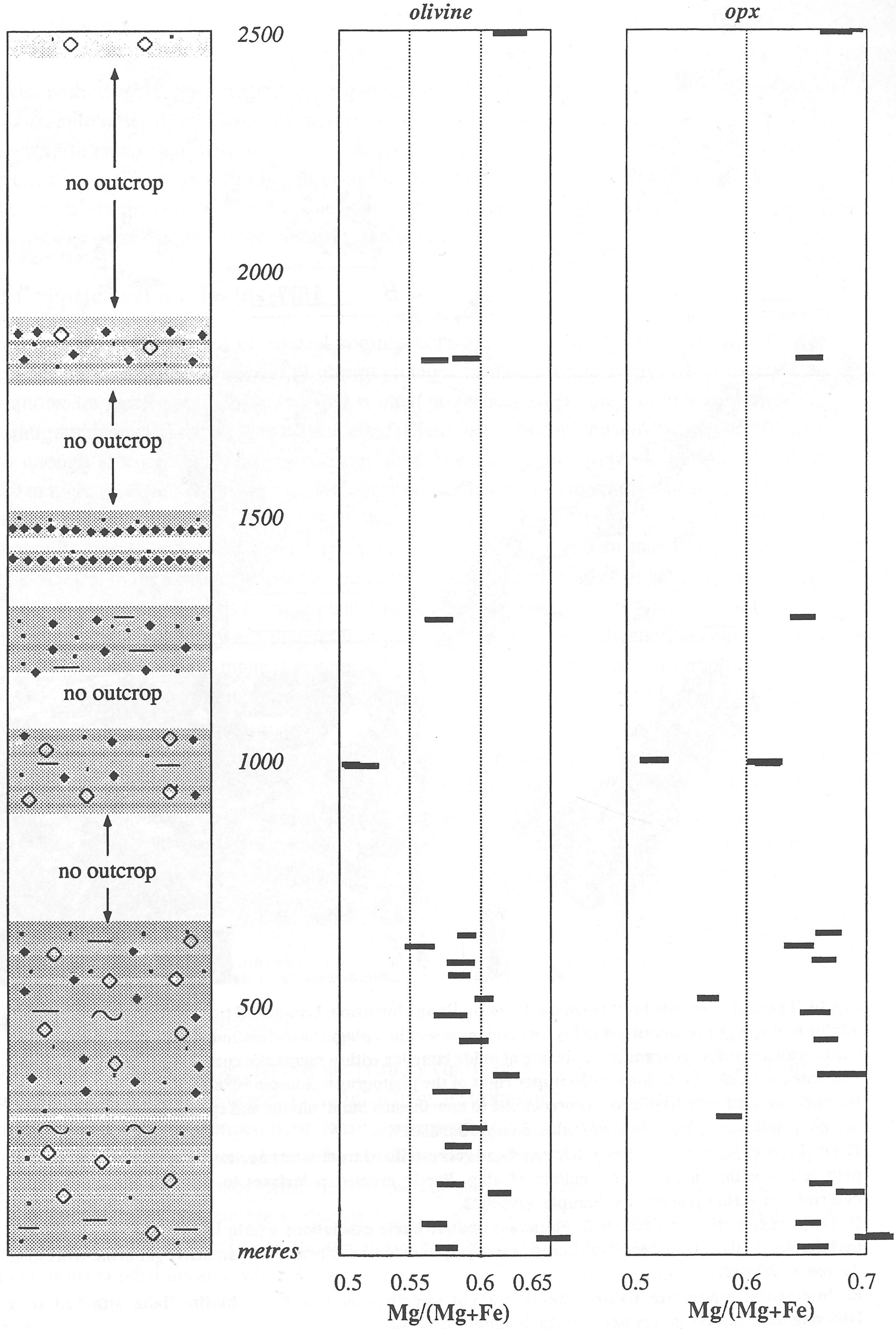
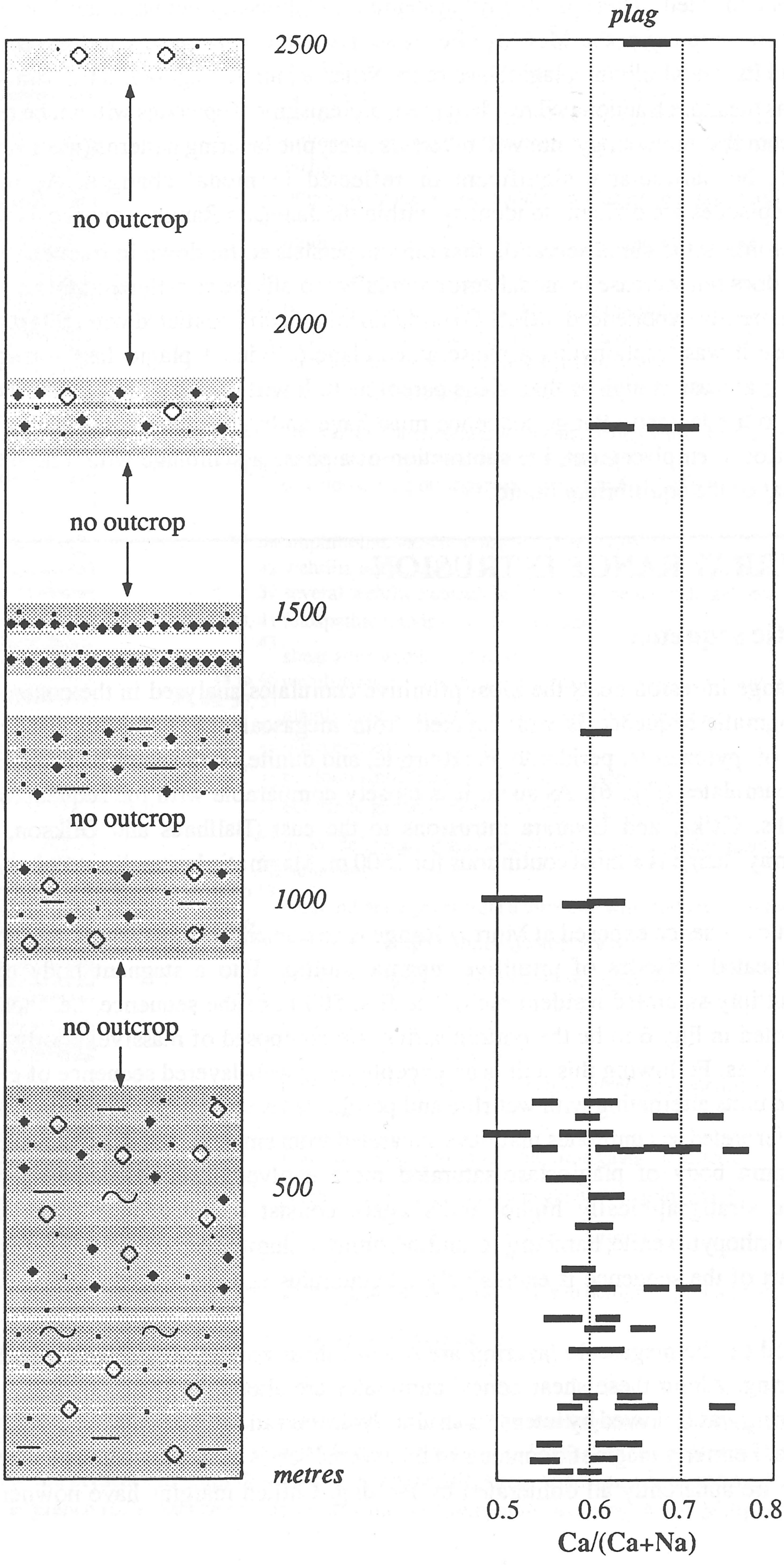



**Fig. 4 & 5. Cryptic layering within the Jameson Range sequence. Each symbol may represent several similar overlapping microprobe analyses. Shading denotes variations in the olivine/plagioclase ratio, open symbols the presence of clinopyroxene, heavy dots the presence of magnetite. For a more detailed description of rock types refer to fig. 2.**

# JAMESON RANGE SEQUENCE



phase layering that could be correlated with episodes of fresh magma addition into more fractionated resident melt. There is also no systematic relationship between the fractionation degree of a given sample, i.e. the Mg/(Mg+Fe) ratio in olivine or average anorthite content in plagioclase, and its modal olivine/plagioclase ratio. When a parent magma has the same phases on its liquidus as the more fractionated resident melt, replenishment episodes will not be reflected by changes in cumulus mineralogy, nor will reversals in cryptic layering patterns (more primitive magma added) be particularly significant or reflected in modal changes. As a result, replenishment episodes are difficult to identify within the Jameson Range sequence.

Of particular interest is the observation that olivine persists so far down in fractionation, but orthopyroxene does not increase in modal amount relative to olivine as differentiation advances. The magma apparently experienced little $SiO_2$ enrichment as it differentiated within its reservoir, possibly because it was fractionating a phase assemblage (olivine + plagioclase + magnetite) with a bulk $SiO_2$ at least as high as that of the parent melt. It will be shown in section 9 that the parent magma to the Jameson Range sequence must have undergone significant high-pressure fractionation prior to emplacement, i.e. subtraction of a phase assemblage with a higher silica content than that of the equilibrium liquid.

# 3 THE MURRAY RANGE INTRUSION

## 3.1 Magmatic sequence

The Murray Range intrusion hosts the most primitive cumulates analysed in the course of this study. The magmatic sequence is well layered from megascale to inch scale and consists predominantly of pyroxenite, peridotite, harzburgite, and dunite, with subordinate gabbroic to gabbronoritic cumulates (Fig. 6). As such, it is closely comparable with the sequences of the Wingellina Hills, Kalka, and Ewarara intrusions to the east (Ballhaus and Glikson, 1990). Outcrop at Murray Range is almost continuous for 2600 m. Magmatic layers dip steeply between 80 and 90°.

The magmatic sequence exposed at Murray Range is characteristic of a magma chamber that experienced repeated episodes of primitive magma addition into a stagnant body of more fractionated multiply-saturated resident melt. The first 500 m of the sequence, i.e. those units that are interpreted in Fig. 6 to be the bottom series, are composed of massive, poorly layered uniform pyroxenites. Following this unit is an exceptionally well-layered sequence of gabbroic to gabbronoritic units alternating with wehrlite and peridotite layers (ca. 600 to at least 1500 m). All these are interpreted as cumulates that have separated from small pulses of primitive magma fed into a magma body of plagioclase-saturated more evolved resident melt of the same parentage. The stratigraphically higher units again consist of ultramafic rocks, mostly coarse-grained orthopyroxenite, harzburgite, and subordinate dunite orthocumulates. Plagioclase in the upper part of the sequence is exclusively intercumulus and rarely exceeds five volume percent.

Superimposed on the megascale layering are several shear zones that are concordant to the magmatic layering. Along these shear zones, cumulates are altered and variably deformed to mylonite. Shearing was followed by intense cumulate hydration and in places intrusion of granitic and aplitic veins. Formerly magmatic contacts of the layered series of the Murray Range intrusion with granulites are apparently all obliterated by faulting. Chilled margins have nowhere been observed.

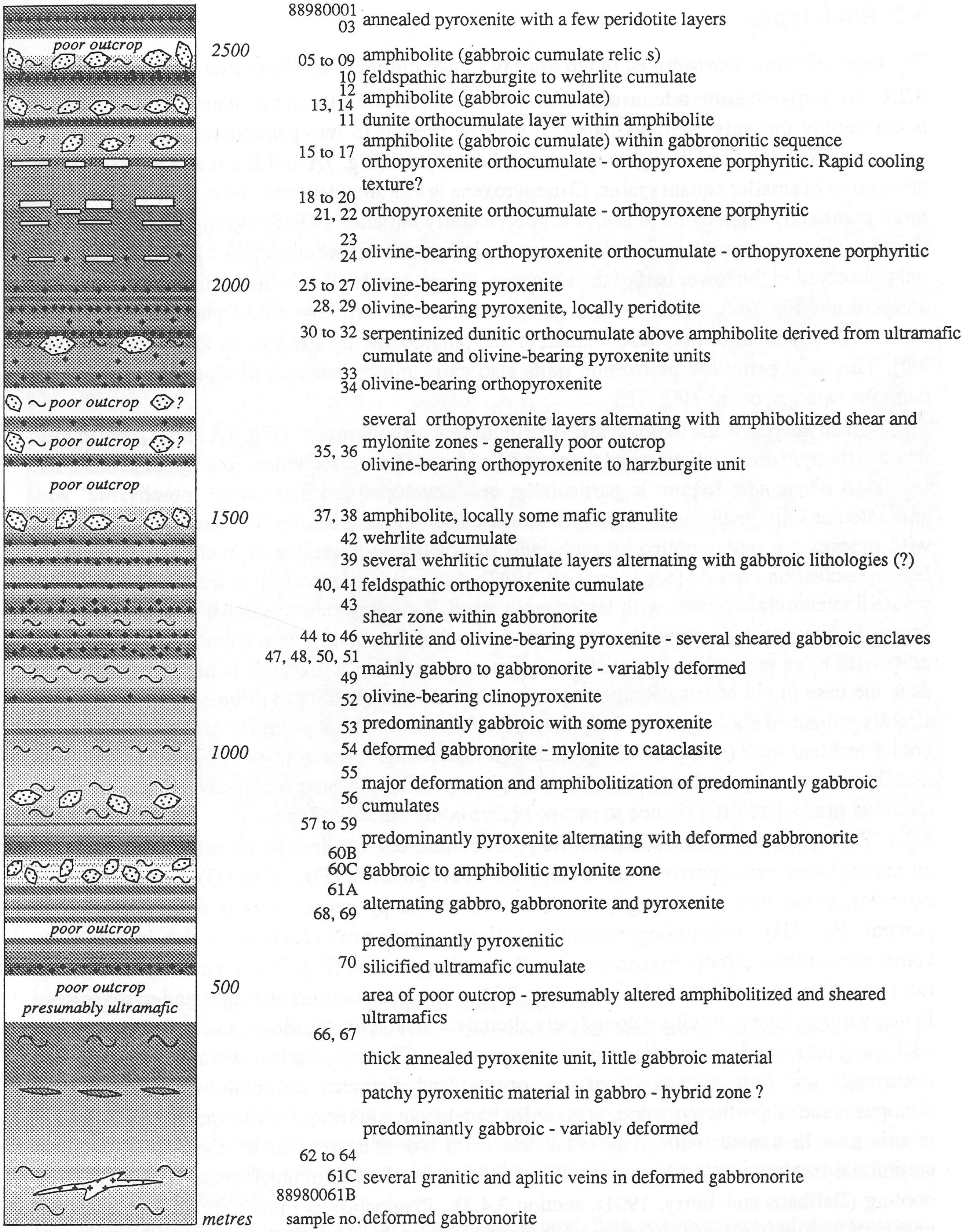



**Fig. 6. Stratigraphic sequence of the Murray Range intrusion. The shading illustrates variations in the mafic character of the cumulates (olivine/pyroxene to plagioclase ratio), black dots the presence of olivine, dotted 'phenocrysts' the presence of amphibolites and layer-parallel shear zones, and open rectangles in the upper part of the sequence the presence of (inferred) rapid crystallization textures. Average dip angles are 80 to 90°.**

## 3.2 Rock types

The types of cumulates sampled in the Murray Range intrusion are illustrated in Figures 7A-7J.

**3.2.1 Orthopyroxenite adcumulates to orthocumulates.** In these cumulates, orthopyroxene is commonly the only cumulus phase. It may be present in two generations, as an early (?) generation forming large elongate euhedral 'phenocrysts' (Fig. 7A and B), and as a second later generation of smaller equant grains. Clinopyroxene is less abundant and sometimes cumulus but more commonly a poikilitic phase. It is spectacularly enriched in brownish spinel exsolutions. Genuine clinopyroxenites where clinopyroxene is the predominating cumulus phase are rare and only observed in the lower half of the sequence. Plagioclase is always interstitial and commonly antiperthitic (Fig. 7C), notably in pyroxenite adcumulates with low modal plagioclase content. Some orthopyroxenites may also contain modal plagioclase in excess of 35 to 40 percent (Fig. 7D). The most primitive pyroxenite units also carry minor cumulus olivine coexisting with cumulus orthopyroxene (Fig. 7E).

Of much interest is the bimodal size distribution of orthopyroxene (Fig. 7A and B), especially in the orthopyroxenite units toward the top of the Murray Range sequence. Stratigraphic horizons in Fig. 6 where this feature is particularly well developed are marked as 'porphyritic' and annotated as units with 'rapid cooling features'. The rationale behind this interpretation is that with progressive undercooling, growth rates of crystalline phases reach their maximum well before nucleation rates do (e.g. Campbell, 1987). As a result, moderately undercooled melts will crystallize cumulate phases with larger grain sizes. If cooling rates diminish as crystallization proceeds, the resultant cumulate may show a bimodal size distribution (Marsh, 1988). Where units with these textural characteristics happen to coincide with reversals in mineral chemistry, as is the case in the Murray Range sequence, it seems reasonable to attribute these textures to slightly enhanced cooling rates. They may have formed when hot primitive magma mixed with cooler resident melt (intraplutonic quenching). Interestingly, horizons with bimodal grain size distributions usually have orthocumulate textures, possibly because the liquid trapped between cumulus grains had little chance to escape before complete solidification.

**3.2.2 Feldspathic peridotite and dunite orthocumulates.** Olivine and accessory chromite are cumulus phases, orthopyroxene and clinopyroxene are poikilitic (Fig. 7F and G). Pyroxenes may, however, grade into cumulus grains where total modal pyroxene exceeds approximately 25 percent (Fig. 7H). Both orthopyroxene and clinopyroxene are exceptionally rich in brownish spinel exsolutions, clinopyroxene more so than orthopyroxene (Fig. 7F). Transitions to dunites (all pyroxenes interstitial) are frequent (Fig. 7G), as are transitions to wehrlites and pyroxenites. In many dunite layers, olivine is completely altered to a characteristic mesh of silicified serpentine with magnetite and brown limonite impregnations. Chromite varies according to textural occurrence and host mineral; from near-opaque and distinctly euhedral when included in clinopyroxene and orthopyroxene, to greenish translucent and irregularly shaped when included in olivine. In contact with plagioclase, chromite has often reacted to complex pyroxene-amphibole-biotite symplectites, as a result of net transfer of Al from plagioclase to spinel during cooling (Ballhaus and Berry, 1991), section 3.4.3). Plagioclase is invariably an intercumulus phase, often highly altered and chemically zoned as a result of subsolidus equilibration.

**3.2.3 Gabbronorites.** Plagioclase and large orthopyroxene grains are the main cumulus phases. Clinopyroxene is rich in orthopyroxene and opaque oxide exsolutions and may range from cumulus to intercumulus (Fig. 7J). Gabbronorites are commonly strongly deformed, to an extent that formerly magmatic exsolved clinopyroxene grains are recrystallized to small clinopyroxene neoblasts coexisting with rounded opaque oxide grains (recrystallized opaque exsolutions).

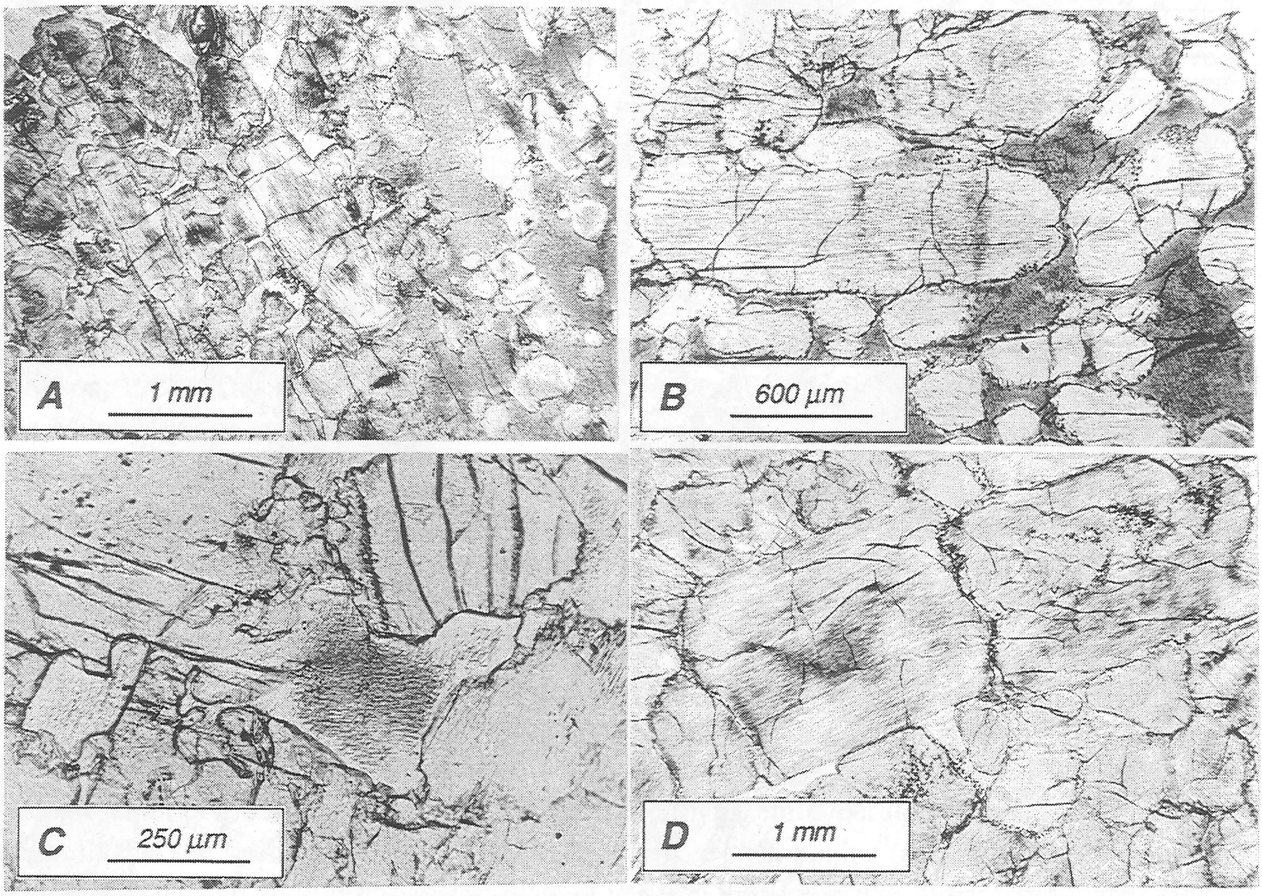



**Fig. 7. Types of cumulates observed in the Murray Range sequence.**

**A. Orthopyroxenite orthocumulate. Porphyritic orthopyroxene with some minor spinel exsolutions and a second generation of rounded smaller orthopyroxene grains. Brownish clinopyroxene is poikilitic and much richer in spinel exsolutions than orthopyroxene. Plagioclase is colourless and interstitial. Elongate grain shapes and bimodal size distributions are interpreted to reflect rapid cooling rates. Sample 88980012.**

**B. Porphyritic elongate orthopyroxene with some spinel exsolutions and spinel granules at their margins and a later generation of rounded orthopyroxene. All included in brownish poikilitic clinopyroxene rich in spinel exsolutions Sample 88980017.**

**C. Annealed pyroxene adcumulate with rare plagioclase (centre). Both orthopyroxene and clinopyroxene are cumulus here, plagioclase is antiperthitic and rich in K-feldspar exsolution rodlets that tend to concentrate in central parts of the grain. Sample 88983001.**

**D. Orthopyroxene orthocumulate. Euhedral slightly elongate porphyritic orthopyroxene in matrix of interstitial plagioclase. Note the high modal plagioclase content (around 40 volume percent), normally far too high to crystallize as an intercumulus phase. Sample 88980022.**

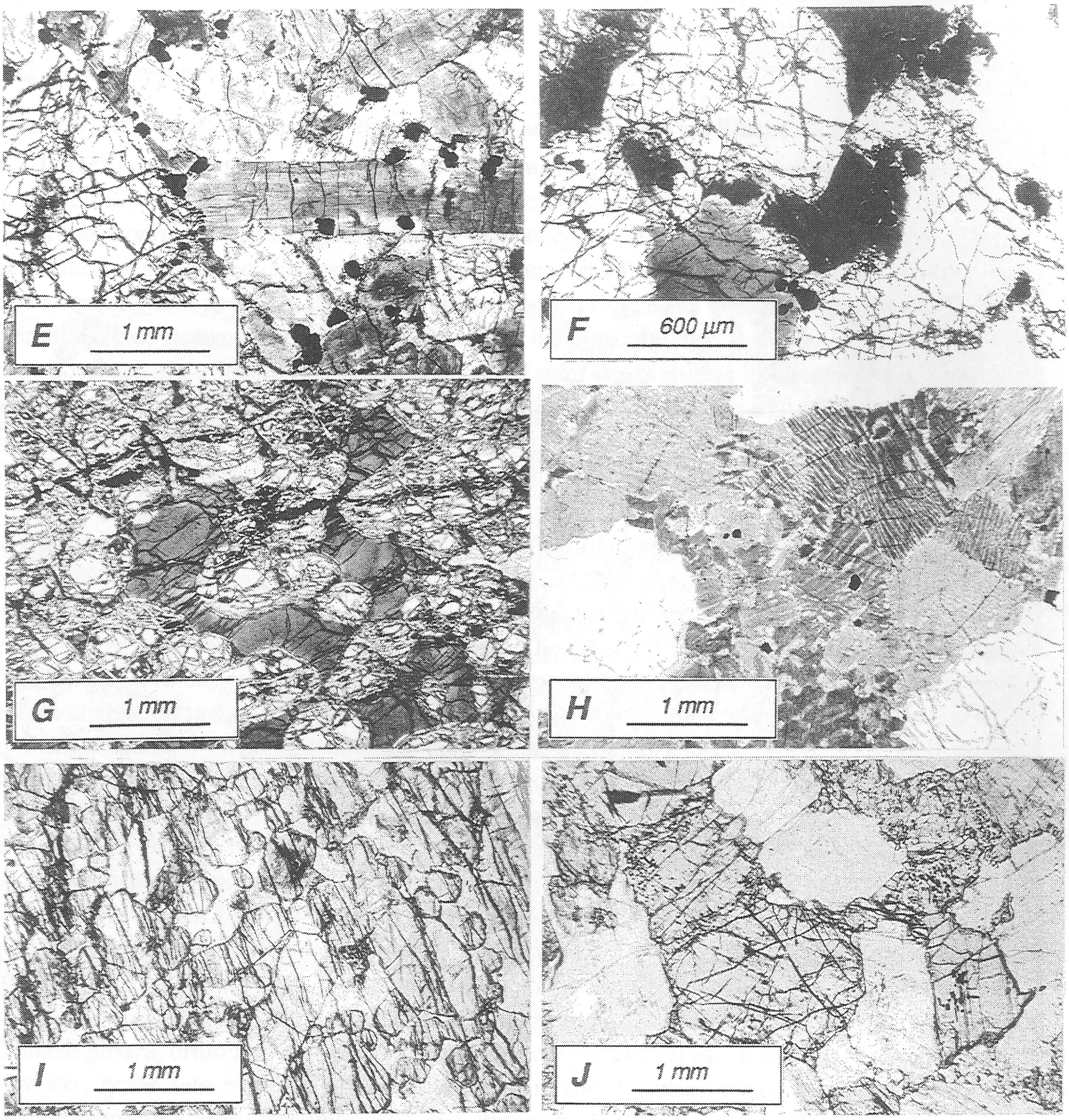



Fig. 7. cont'd. E. Olivine-bearing orthopyroxenite to harzburgite orthocumulate. Rounded cumulus olivine (clear cracked grains toward the left), porphyritic elongate orthopyroxene (brownish, spinel exsolutions), a second generation of rounded orthopyroxene with much less exsolved spinel, and opaque euhedral cumulus chromite grains. Rounded darkish grains are in part cumulus clinopyroxene. Clear plagioclase between rounded orthopyroxene grains is interstitial. Sample 88980010.

F. Peridotite orthocumulate. Rounded cracked olivine, poikilitic brownish orthopyroxene, poikilitic to interstitial dark brown clinopyroxene. Small rounded opaque cumulus chromite grains. Spinel exsolution in clinopyroxene in such a spectacular density that they mask birefringence colours. Such clinopyroxene grains contain in excess of 6.5 wt. percent $Al_2O_3$ and ~1 percent $Cr_2O_3$. Sample 88980002.

G. Dunite orthocumulate. Rounded olivine with characteristic serpentine mesh, poikilitic clinopyroxene rich in spinel exsolutions, some rare altered colourless plagioclase to the right of the photograph, and clear orthopyroxene overgrowth moats around some olivine grains. Sample 88980011.

H. Annealed wehrlite adcumulate. Rounded colourless olivine in matrix of annealed and exsolved clinopyroxene rich in fine-grained spinel exsolutions and vermicular orthpyroxene exsolution blebs. A few euhedral opaque chromite grains. Sample 88980036.

I. Fine-grained feldspathic orthopyroxene orthocumulate 'pocket' in a matrix of strongly annealed feldspar-free orthopyroxenite adcumulate. Patches of orthocumulate up to several cm across. Origin of texture and patchy distribution of orthocumulate pockets unceratin. Sample 88980004.

J. Typical gabbronorite adcumulate. Orthopyroxene (some ilmenite exsolution platelets), smaller clinopyroxene grains, and colourless plagioclase. Sample 88980005.

## 3.3 Cryptic layering patterns

The stratigraphic variation diagrams for the Murray Range sequence are illustrated in Fig. 8 to 10. The Murray Range intrusion is composed of poorly fractionated primitive cumulates with minor gabbro only. Mg/(Mg+Fe) ratios of olivine range from about 0.88 to about 0.77. Consequently, the most magnesian olivine is close to being in equilibrium with a primitive mantle-derived parent melt. Mg/(Mg+Fe) ratios of orthopyroxene range from about 0.88 to 0.67 and vary coherently with olivine. Orthopyroxene replaces olivine on the liquidus at an Mg/(Mg+Fe) ratio of about 0.77. The Cr/(Cr+Al) ratio in clinopyroxene is a very sensitive parameter for monitoring chemical fractionation trends because Cr partitions far more into pyroxene than does Al. This distribution coefficient is up to 0.25 in the most primitive peridotitic units and decreases to about 0.05 in the most fractionated gabbronorites. As expected, Cr/(Cr+Al) in cumulus spinel varies coherently with Cr/(Cr+Al) in coexisting clinopyroxene. Ca/(Ca+Na) ratios in plagioclase range from about 0.8 to 0.2. For a given Mg/(Mg+Fe) ratio of coexisting olivine or orthopyroxene, plagioclase is comparatively sodic, at least in comparison with other ultramafic intrusions of the Giles Complex such as the Wingellina Hills intrusion (Ballhaus and Glikson, 1988). This may in part be due to interstitial position of plagioclase in the majority of the Murray Range cumulates, but could alternatively reflect elevated crystallization pressure (Green and Hibberson, 1970).

The cryptic layering pattern at Murray Range is typical for a continuously differentiating layered intrusion that experienced repeated replenishment episodes. There are two major gradual reversals toward more primitive mineral compositions, one starting at the bottom contact of the intrusion and a second reversal commencing at an elevation of ~ 1100 m. Each reversal is followed by an extended period of normal upward fractionation. Reversals are best reflected in changes in the Mg/(Mg+Fe) ratio in orthopyroxene and Cr/(Cr+Al) ratio in clinopyroxene. As expected, chemical reversals are situated where the mineralogic composition of the sequence changes from predominantly gabbroic to ultramafic (pyroxenitic/peridotitic). This observation suggests that the fresh magma added was only saturated with olivine (and locally with spinel), with the result that addition of such a magma to a multiply-saturated more fractionated melt caused a change in liquidus relations. There is little evidence in the field to indicate in which direction the magmatic sequence may be facing. However, in multiply intrusive cumulate suites, it is commonly observed that new magma batches coincide with relatively sharp reversals. This is because a primitive magma that has only olivine on its liquidus is commonly denser than a derivative multiply-saturated melt, and therefore tends to pool on the magma chamber floor. Smooth and gradual changes in mineral composition, on the other hand, form during periods of normal fractionation, when the magma body gradually returns to chemically stagnant conditions. If that empirical rule is applied here, the Murray Range sequence may be facing north, as suggested in Fig. 8.

## 3.4 Deformation and subsolidus textures

A selection of deformation and subsolidus equilibration textures observed in the Murray Range sequence is illustrated in Fig. 11.

**3.4.1 Amphibolites.** The Murray Range sequence includes several stratabound layers and lenses of amphibolite. These rock units are derived from post-magmatic hydration. They are essentially confined to the environs of major shear zones and mylonite horizons, and are concordant with

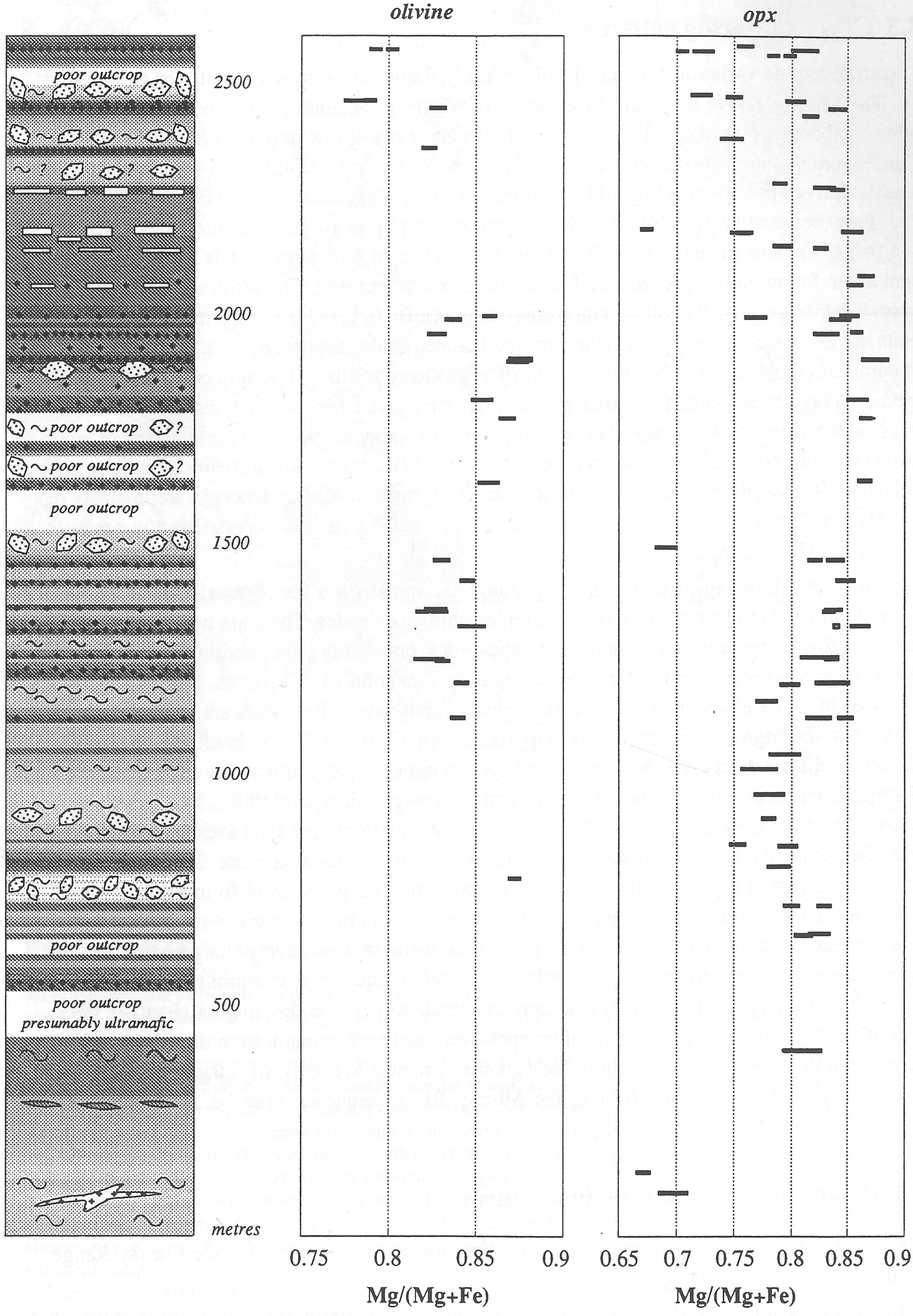



**Fig. 8 to 10. Cryptic layering in the Murray Range sequence.**

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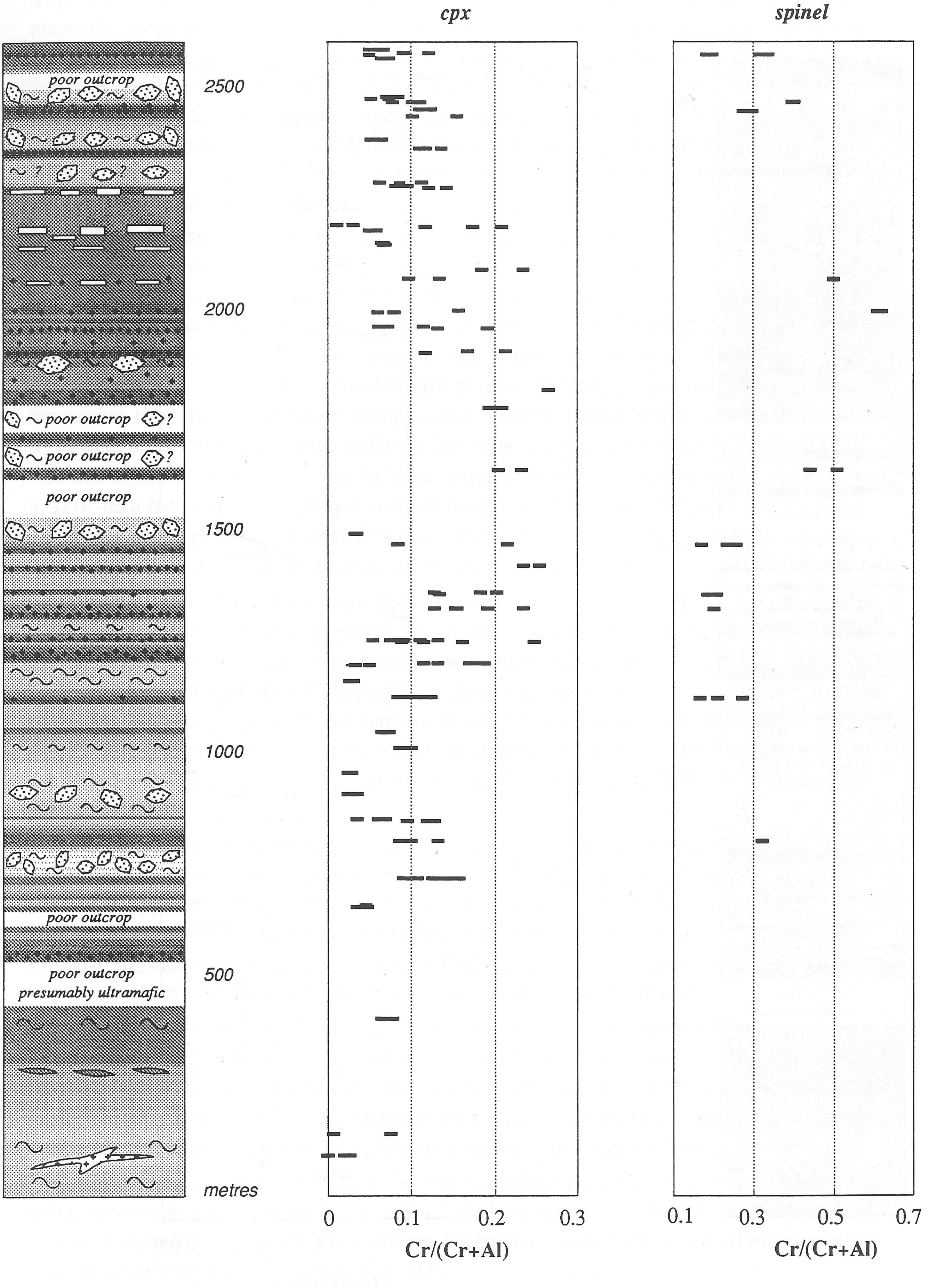

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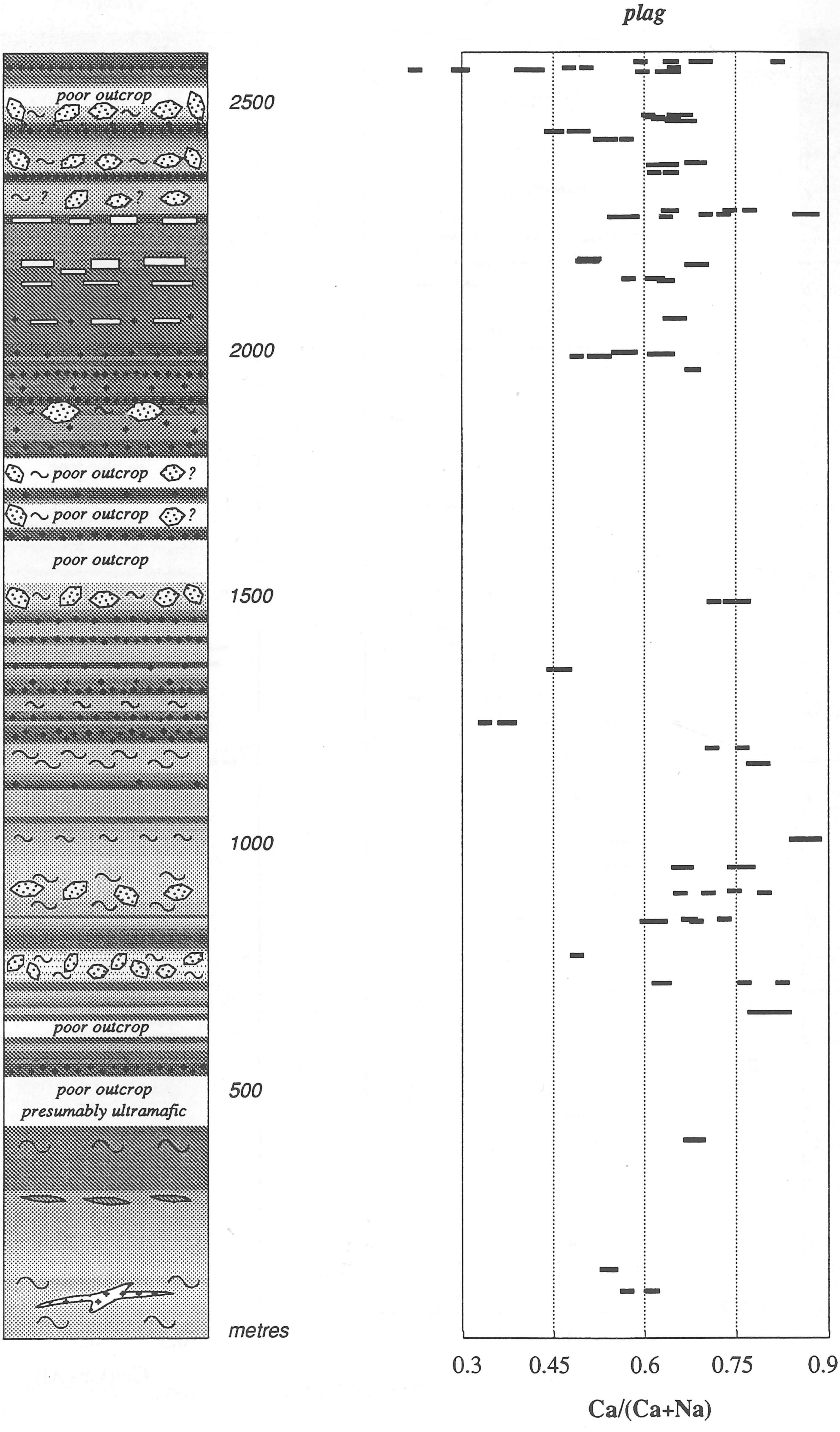


the megascale phase layering. The mineralogic composition of amphibolites, in particular their amphibole/plagioclase ratio, is controlled by the pyroxene + olivine/plagioclase ratio of their magmatic protoliths. The main phase is a greenish-blue (Na-bearing) euhedral coarse-grained post-magmatic amphibole (Fig. 11A). The next common phase is plagioclase, commonly only preserved as deformed magmatic cumulus relics. Clinopyroxene remnants are rare and partially replaced by amphibole. Olivine has not been observed. No deformation is evident in amphibolites except in the formerly magmatic plagioclase relics. Consequently, the amphibolites must have formed after deformation along the shear zones. They are attributed to episodes of post-deformational fluid infiltration.

**3.4.2 Mylonites and cataclasites.** Common deformation styles are illustrated in Fig. 11B to D. There are various stages of incipient mylonitization and cataclasis. Under the influence of strain, magmatic clinopyroxene tends to recrystallize to aggregates of equant neoblastic grains. Occasionally, these aggregates are intergrown with rounded opaque oxides, presumably recrystallized exsolved magnetite-ilmenite exsolution lamellae derived from magmatic clinopyroxene. More deformed cumulates show granulation along plagioclase/plagioclase grain boundaries in addition to advanced clinopyroxene recrystallization. Orthopyroxene apparently withstands considerable strain rates and is the last phase to break up under the influence of strain. Genuine mylonites are characterized by large 'porphyroclastic' kinked orthopyroxene relics in a 'flow-textured' matrix of hydrated and uralitized plagioclase and clinopyroxene. In places, proto-cataclasites predominate over proto-mylonites. This observation is tentatively attributed to variations in deformation temperature and/or subsolidus fluid regime.

**3.4.3 Symplectites around cumulus spinel relicts.** Cumulus spinel grains in contact with plagioclase are commonly overgrown by clinopyroxene-spinel symplectites (Fig. 11E). Similar reaction textures have been described from the Wingellina Hills ultramafics (Ballhaus and Berry, 1991). The newly formed spinel generation in the symplectite is light-green, in contrast to dark brownish colours retained by spinel cumulus relics that have escaped reaction. Plagioclase in contact with reacted spinel is optically zoned and depleted in anorthite. These clinopyroxene-spinel symplectites are attributed to net transfer of Al from plagioclase to spinel during high-pressure cooling.

In some samples, ferromagnesian silicates in contact with plagioclase are rimmed by poorly developed fine-grained spinel-amphibole-bearing (?) symplectites. There is apparently no rule as to what types of cumulates at what fractionation degrees are affected by this reaction. It appears, however, that symplectites of this kind are coarser-grained in samples where there is evidence for deformation and post-magmatic fluid infiltration. Evidently, fluid has played an important role in lowering kinetic barriers during subsolidus equilibration.

**3.4.4 Granule exsolution.** Plagioclase may contain micron-sized euhedral light-green clinopyroxene inclusions, especially in deformed cumulates. Compositionally, these inclusions resemble coarser-grained equilibrated clinopyroxene groundmass neoblasts. It is considered most likely that they formed when submicron-sized impurities in formerly magmatic plagioclase recrystallized. A similar feature occurs in cumulates from the Latitude Hill (see section 8).

Clinopyroxene and orthopyroxene in the most primitive cumulate units may be exceptionally rich in brown spinel exsolutions (e.g. Fig. 7F). Spinel exsolutions are commonly cleared toward rims of pyroxene grains by granule exsolution, but occurs as recrystallized small rounded blebs concentrated along grain boundaries (Fig. 11F).

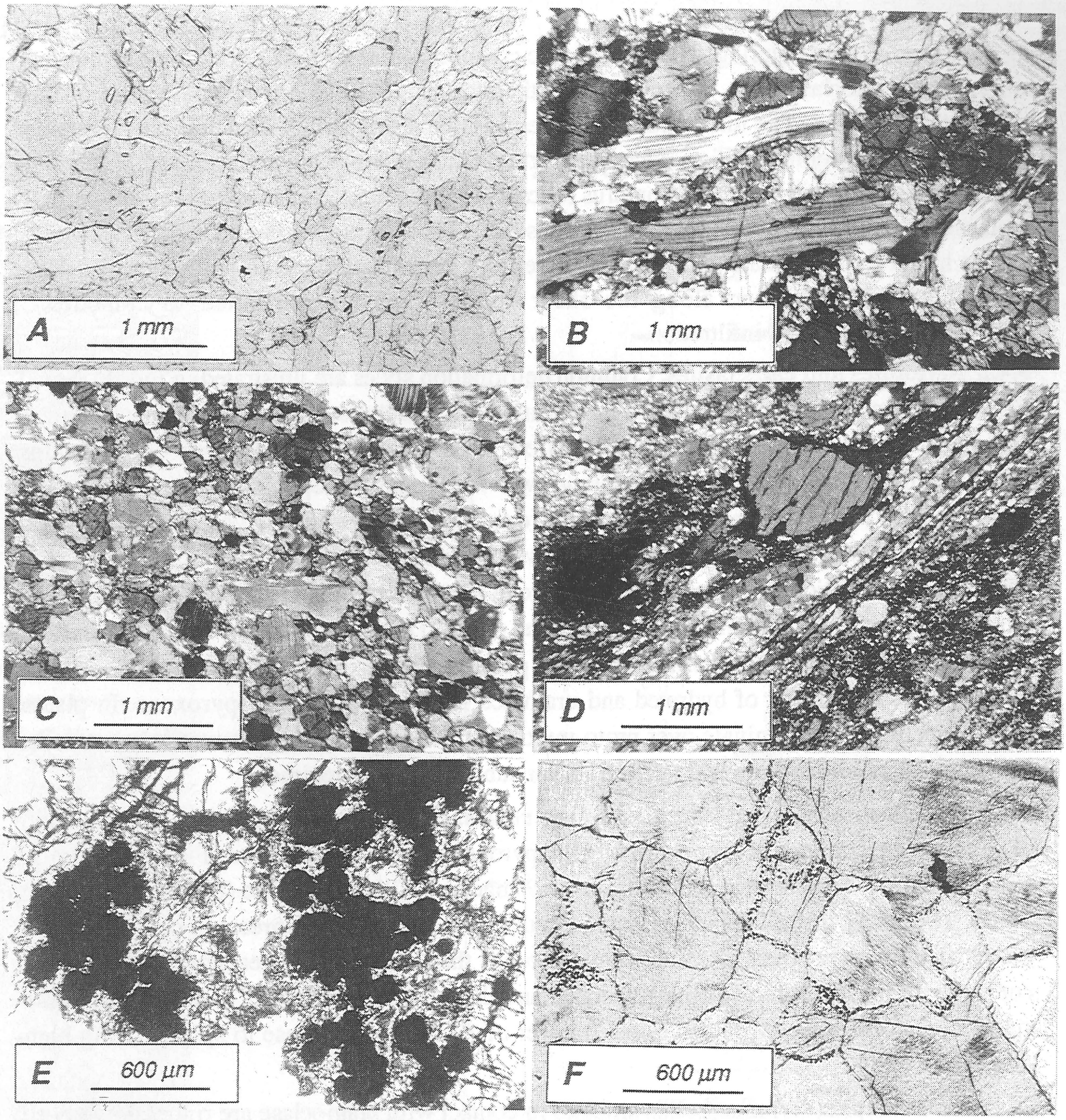



**Fig. 11. Deformation and subsolidus textures in rock types of the Murray Range sequence.**
**A. Amphibolite (uralitized pyroxenite or peridotite cumulate). Greenish actinolitic amphibole, no plagioclase preserved. Amphibolites are most undeformed but occur in close spatial relationship with mylonite zones and can replace entire cumulate sequences. Sample 88980037.**
**B. Strongly deformed gabbro to gabbronorite in proto-mylonite or proto-cataclasite texture. Rounded orthopyroxene cumulus relics and large deformed plagioclase laths in matrix of clinopyroxene, orthopyroxene, and plagioclase granules. Primary clinopyroxene not preserved. Sample 88980054.**
**C. Strongly sheared gabbronorite (cataclasite). Orthopyroxene and plagioclase fragments in fine-grained broken up matrix of plagioclase, clinopyroxene, and some hydrous phases. Sample 88980058.**
**D. Gabbroic uralitized mylonite to cataclasite. 'Augen' of relict magmatic clinopyroxene and coarse amphibole in fine-grained fragmented matrix of plagioclase and secondary amphibole. Occasionally cut by silicic veins (centre of photograph). Sample 88980060C.**
**E. Opaque cumulus chromite relics in contact with olivine (fragmented grains) and plagioclase (clear grains). Spinel relics are surrounded by coronas of clinopyroxene-spinel-amphibole symplectites. Sample 88980002.**
**F. Granule exsolution of spinel in an orthopyroxenite adcumulate. Spinel exsolutions within orthopyroxene cumulus grains are partly cleared toward the rims of grains, and concentrated as small brownish spinel granules around grain boundaries. Sample 88980023.**

### 3.5 Constraints on parent magma composition and magmatic evolution

The sequence of the Murray Range intrusion was derived from a near-primitive olivine-normative basaltic melt. Based on textural observations, the dominant crystallization sequence was (1) olivine + spinel, (2) olivine + orthopyroxene ± clinopyroxene, and (3) orthopyroxene + clinopyroxene + plagioclase. All these phase assemblages can be derived successively from one single parent melt composition.

The Murray Range sequence is a good example of a multiply intrusive suite with at least two major and presumably several smaller pulses of primitive olivine ± orthopyroxene ± spinel saturated melt. The batches of fresh melt were added to resident liquid that must have been a chemical derivative of the primitive parent melt. The multiply intrusive history is best illustrated in the central part of the sequence (1100 to 1500 m) where olivine-rich ultramafic cumulates (wehrlites and olivine-bearing pyroxenites) alternate with more fractionated gabbroic to gabbronoritic layers. With increasing stratigraphic height, the gabbroic units progressively diminish until plagioclase is interstitial, possibly reflecting progressive modification of the resident melt to more primitive compositions.

Of particular petrologic interest are three observations:

- Orthopyroxene and olivine coexist as cumulus phases in primitive cumulates with Mg/(Mg+Fe) phase ratios as high as 0.88. Textural relationships suggest that olivine and orthopyroxene crystallized along a cotectic phase boundary at the very early stages of chemical fractionation.
- Plagioclase is a minor phase only. Even where it crystallized in abundance, it is quite sodic compared with the primitive magnesian nature of coexisting olivine and orthopyroxene. Plagioclase also appears relatively late in the crystallization sequence, presumably because it had been suppressed as a stable phase relative to pyroxene.
- Clinopyroxene and orthopyroxene in the most primitive ultramafic cumulates are extremely aluminous with up to 6 and 4 wt. percent prior to spinel exsolution, respectively. To the author's knowledge, reintegrated bulk compositions of these pyroxenes are unrivalled by pyroxenes in any other mafic/ultramafic intrusive suite documented so far.

All these features can be attributed directly or indirectly to elevated crystallization pressure. High pressure will (1) stabilize a pyroxene phase relative to olivine on the liquidus of a basaltic magma; (2) shift the olivine-orthopyroxene peritectic into the olivine-normative field until olivine and orthopyroxene coprecipitate as cumulus phases; (3) favour sodic rather than calcic plagioclase compositions; and (4) indirectly cause non-quadrilateral components in pyroxenes to increase through an increase in liquidus temperature of the melt.

## 4 THE BLACKSTONE RANGE INTRUSION

### 4.1 Magmatic sequence

The Blackstone Range intrusion consists of a sequence of well layered highly fractionated troctolites, olivine gabbros, anorthosites, a few dunite layers, and some tens of centimetre-thick

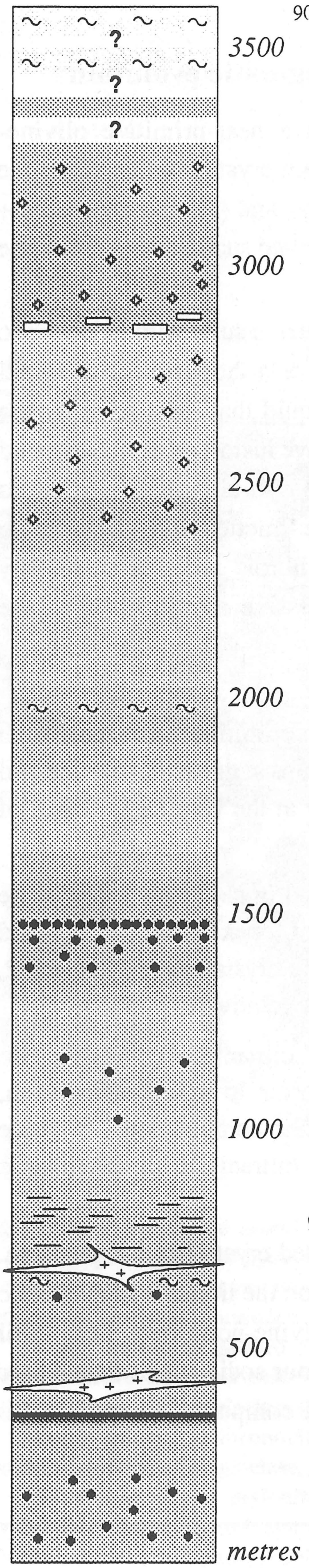



**Fig. 12. Schematic stratigraphic sequence of the Blackstone Range intrusion. Grey shades illustrate variable olivine/plagioclase modal ratios, heavy filled dots the presence of magmatic oxides, open dots the presence of clinopyroxene, and horizontal streaks the presence of inch-scale and graded layering. Some rapidly quenched rocks occur in the upper part of the sequence (open rectangles). Stratigraphic elevations corrected for a dip of 70°.**

monomineralic magnetite layers (Fig. 12). Exposure at Blackstone is continuous for almost 3600 m. Samples have been taken along two consecutive traverses across strike covering the entire intrusion.

Magmatic layers at Blackstone dip relatively steeply with average angles of 70° to the south. With the exception of one dunite layer and several thin magnetite layers, there is little evidence for megascale phase layering. Instead, the cumulates are well layered on a smaller scale, with 'inch-scale' and graded olivine/plagioclase layering being the most common styles. The Blackstone Range cumulates are largely undeformed except along the bottom and top contacts. The marginal cumulates, especially those along the northern contact (interpreted to be the top contact) are all recrystallized to fine-grained massive phlogopite-bearing mafic granulites. Intrusive contacts with granulites are nowhere exposed. Along its southern contact, the intrusion is faulted against the Bentley Group (c.f. Daniels, 1974).

## 4.2 Rock Types

The dominant rock types of the Blackstone Range sequence are troctolites and anorthosites with variable clinopyroxene and magnetite contents. Representative cumulates are illustrated in Fig. 13.

4 .2.1 **Troctolites, troctolitic gabbros, and gabbroic troctolites.** Olivine and plagioclase are the main cumulus phases, sometimes accompanied by minor cumulus clinopyroxene (Fig. 13A and B). Greenish clinopyroxene with opaque oxide exsolutions is a later poikilitic phase. Orthopyroxene forms narrow irregular moats around olivine, grading in places into larger irregular orthopyroxene-magnetite symplectites (Fig. 13A) and poikilitic orthopyroxene grains.

Opaque oxides include titaniferous magnetite and rounded green hercynite-pleonaste inclusions. In the vicinity of massive magnetite layers, magnetite gradually changes from intercumulus to cumulus and becomes more abundant. Accessory phases include post-magmatic biotite flakes attached to magmatic oxides, rare brownish amphibole moats around intercumulus magnetite (Fig. 13A), and occasionally greenish actinolitic amphibole. The primary-magmatic phases are usually fresh and undeformed, except in cumulates near shear zones and pseudotachylite veinlets.

4 .2.2 **Anorthosites.** Anorthosites are frequent in well-laminated portions of the magmatic sequence. Olivine-bearing anorthosites are cumulates where modal olivine is less than (estimated) 10 percent and where clinopyroxene is interstitial or entirely absent. At very low modal olivine content, olivine becomes interstitial (e.g. Fig. 13B). The sampling traverses also intersected a few genuine anorthosites where plagioclase is the only cumulus phase and where olivine and clinopyroxene are absent. Former interstitial phases in anorthosites (possibly clinopyroxene) are commonly replaced by actinolitic amphibole.

4 .2.3 **Dunites.** Dunites are rare in the Blackstone Range sequence. Rounded olivine grains are cumulus and tightly packed in an adcumulate to mesocumulate texture (Fig. 13E). Dunites and other near-monomineralic cumulates (anorthosites, massive magnetite layers) are commonly annealed to an extent that primary cumulus textures are replaced by granular mosaic fabrics with 120° triple grain boundaries. There is no primary interstitial phase preserved in dunites. Former intercumulus phases (plagioclase?) are replaced by greenish actinolitic amphibole. Interestingly, olivine is not affected by serpentinization or any hydrous alteration, suggesting that the replacement reaction must have taken place above the thermal stability of serpentine.

4 .2.4 **Quenched equivalents to the cumulates.** In addition to genuine cumulates, the

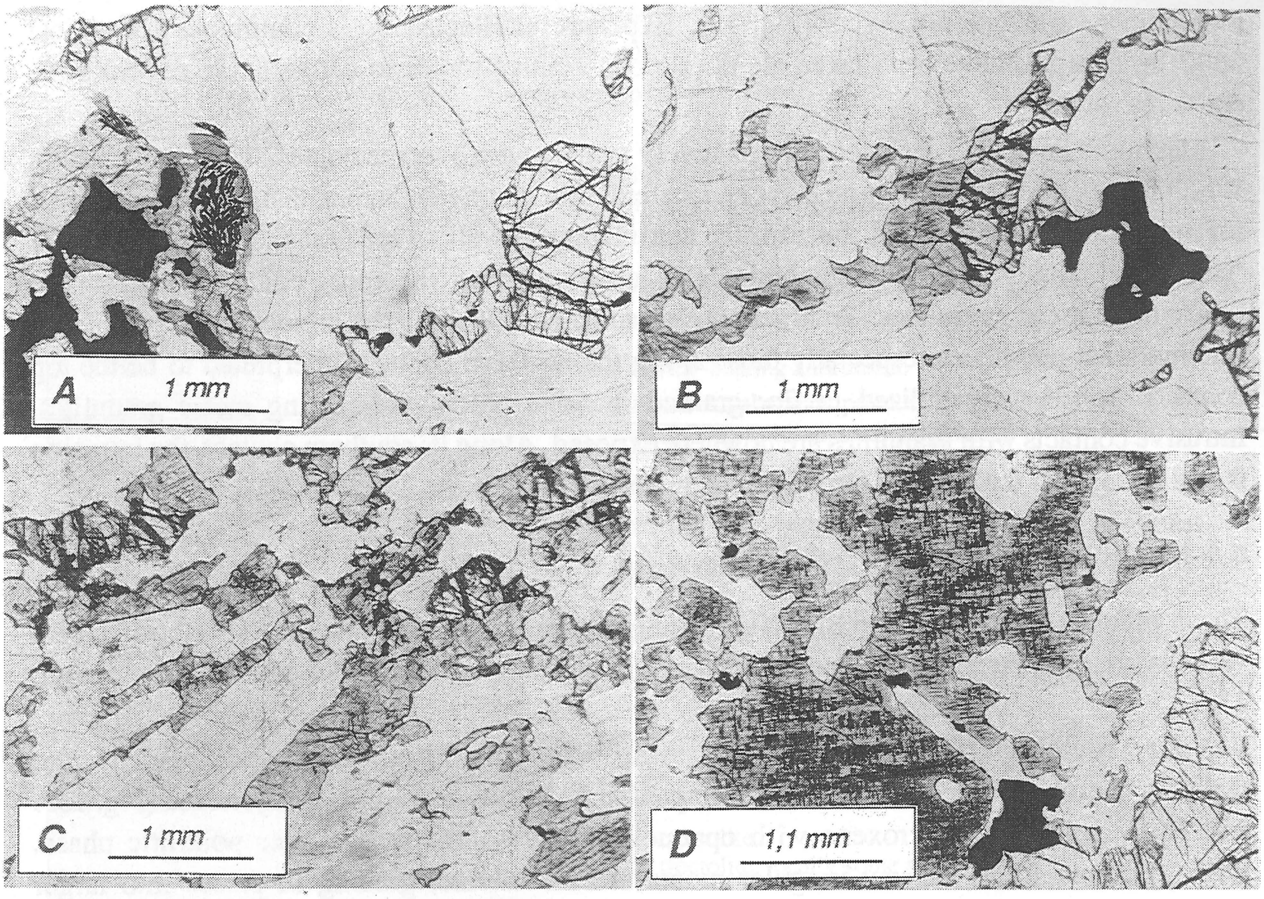



**Fig. 13. Types of cumulates in the Blackstone Range intrusion**
**A: Coarse-grained olivine gabbro to troctolite. Rounded, locally interstitial olivine grains (cracks), interstitial opaque oxides partly rimmed by amphibole, and one orthopyroxene-magnetite symplectite emanating from orthopyroxene rims around oxide grains. The colourless matrix is plagioclase. Sample 90987505.**
**B: Troctolite to troctolitic anorthosite. Irregular olivine (cracks), some clinopyroxene, and magnetite, in a matrix of cumulus plagioclase. Olivine may become interstitial in the most leucocratic troctolites. Sample 90980178.**
**C: Olivine gabbro (from the margin of the intrusion). Elongate euhedral plagioclase laths and irregular olivine are cumulus, clinopyroxene early intercumulus. Interpreted as a rapid crystallization texture, reminiscent of porphyritic dyke. Sample 90980148.**
**D: Exsolved poikilitic clinopyroxene with opaque oxide exsolutions in a gabbroic troctolite. To the lower right an olivine grain (cracks). Note euhedral plagioclase penetrating clinopyroxene (rapid cooling texture?). Sample 90980166.**

Range sequence includes rock types that are interpreted to be the rapidly chilled equivalents of the cumulates. In the upper part of the sequence, at about the 2850 m elevation, occurs a stratigraphic interval with several unusually fine-grained layers. These layers may be interpreted either as a series of basaltic sills that intruded after emplacement of the layered cumulates, or as a zone within the crystallizing magma chamber where fresh liquid quenched against much cooler resident melt or semi-solidified cumulates on the chamber floor. In fine-grained units, elongate euhedral plagioclase and near-opaque oxide accumulations (olivine pseudomorphs?) are phenocrystic phases. Granular clinopyroxene and oxides form interstitial aggregates 'squeezed' between the wedges of large plagioclase laths (Fig. 13F). Judging from phenocryst populations, these rock types may be reasonable parent melt equivalents to the Blackstone Range intrusion. Underlying and overlying this fine-grained zone and elsewhere in the sequence are several intervals where orthocumulates predominate (e.g. Fig. 13C and G). In these rock types,

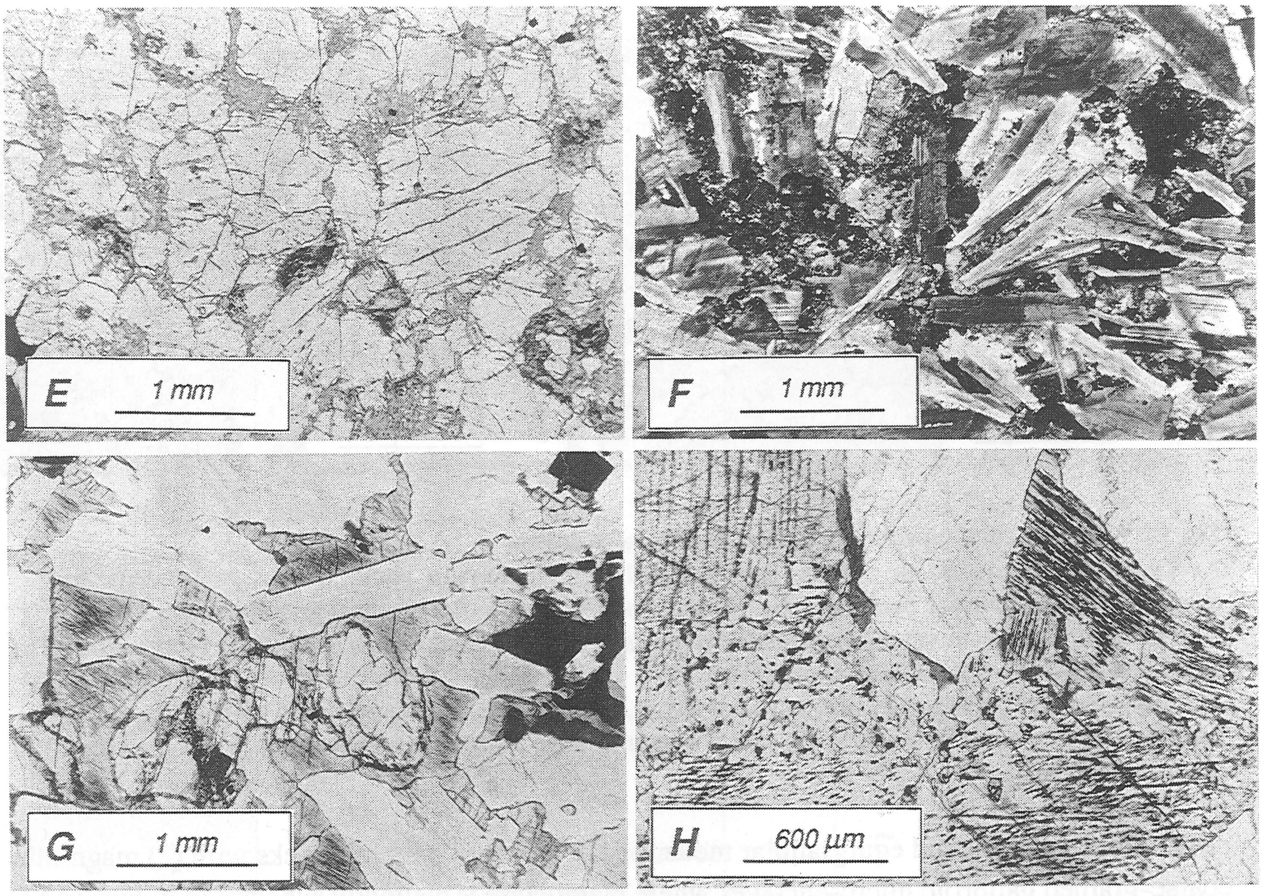



**Fig. 13 cont'd: Textures of cumulates and rapidly quenched equivalents in the Blackstone Range sequence**
**E: Dunitic adcumulate. Rounded olivine grains. Former interstitial phases (plagioclase and/or clinopyroxene?) replaced by actinolitic amphibole. Sample 90980167.**
**F: Coarse-grained plagioclase-phyric sill in the upper units of the Blackstone Range sequence (chilled margin?). Elongate plagioclase laths are phenocrysts, the accumulations of dark oxide-rich material may represent pseudomorphs after olivine. Groundmass contains oxides and clinopyroxene. Partly crossed polarizers. Sample 90980143.**
**G: Texture of troctolitic cumulate reminiscent of coarse-grained dyke. Cumulus olivine (clear rounded grains with cracks) and elongate plagioclase cumulus laths penetrating poikilitic clinopyroxene. Some euhedral and interstitial oxides. Sample from close to the southern margin of the intrusion Sample 90980166.**
**H: Poikilitic exsolution-rich clinopyroxene in a troctolitic anorthosite, partly recrystallized under the influence of some strain to smaller rounded clinopyroxene and opaque oxide neoblasts. Sample 90987505.**

plagioclase and olivine are cumulus phases but plagioclase is still distinctly elongate and euhedral. Formerly interstitial material (clinopyroxene and oxides) is better crystallized than in the fine-grained equivalents illustrated in Fig. 13F.

**4.2.5 Recrystallized cumulates.** Recrystallized gabbroic cumulates are common along the margins of the Blackstone Range intrusion. There are various stages of recrystallization where relict cumulate textures are partially preserved, and various doubtful textures where the origin is uncertain. In samples near the intrusion margins, primary clinopyroxene with oxide exsolutions tends to recrystallize to granoblastic aggregates consisting of clinopyroxene and rounded opaque oxide neoblasts (Fig. 13H). Interestingly, olivine is much less abundant in these recrystallized cumulates despite its common presence in the magmatic protoliths. Possibly, the transformation of cumulates to marginal granulites is an allochemical process and accompanied by fluid and silica addition. Marginal recrystallized cumulates also contain phlogopite, a phase that is missing in cumulates and may have formed as a result of K addition via fluid infiltration. There are several

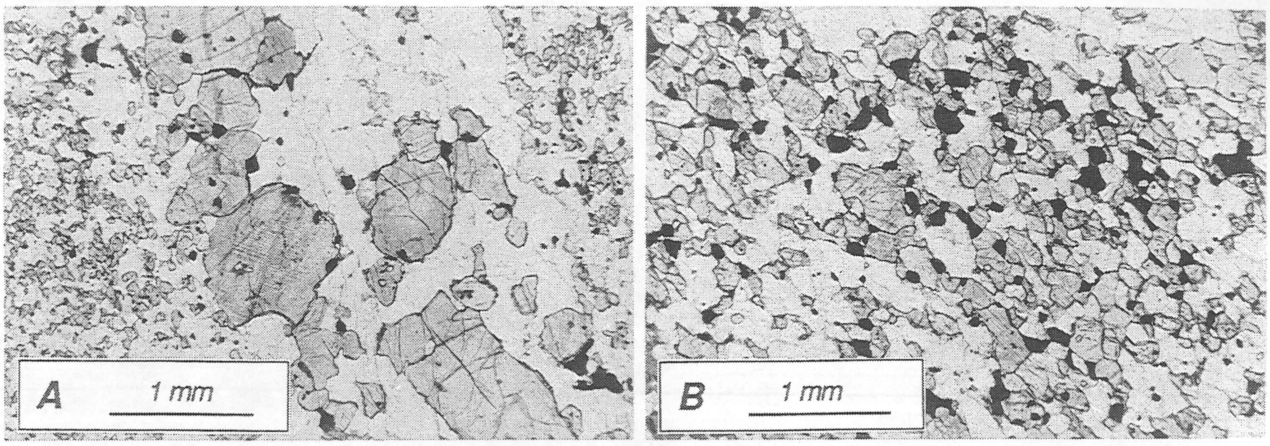



**Fig. 14: Marginal rock types of the Blackstone Range sequence**
**A: Gabbroic granulite or rapidly crystallized chilled margin rock. Coarse-grained gabbroic clinopyroxene-plagioclase enclaves with relict cumulus texture in fine-grained granular recrystallized (?) matrix of clinopyroxene-plagioclase-oxide neoblasts. Not clear whether this is a primary-magmatic or a secondary-metamorphic texture. Sample 90980151.**
**B: Fine-grained gabbroic granulite (marginal facies). Clinopyroxene, orthopyroxene, plagioclase, and oxide neoblasts, locally some phlogopite. Olivine is absent in these marginal recrystallized gabbroic granulites. Sample 90980147.**

problematic fine-grained equigranular metamorphic-textured gabbroic rocks with (?) magmatic coarse-grained gabbroic micro-enclaves where plagioclase is distinctly euhedral (e.g. Fig. 14A). Others are fully recrystallized to equigranular textures and lack any textural evidence for a previous magmatic history (Fig. 14B).

## 4.3 Patterns of cryptic layering

The Blackstone Range sequence is as fractionated as the cumulates from the Jameson Range intrusion. Stratigraphic variation patterns of mineral compositions are shown in Fig. 15. Mg/(Mg+Fe) ratios of olivine range from 0.67 to 0.40 (Fo40 being the most fractionated olivine composition reported from the Giles Complex). Mg/(Mg+Fe) ratios of orthopyroxene vary from about 0.70 to 0.55 and are slightly compressed relative to those of coexisting olivine. Ca/(Ca+Na) ratios of plagioclase range from above 0.75 to about 0.5 and vary sympathetically with Mg/(Mg+Fe) ratios in olivine and orthopyroxene. Clinopyroxene is not plotted because Cr contents in clinopyroxene are close to the detection limit of the microprobe. The Mg/(Mg+Fe) ratio of clinopyroxene is generally not suitable for the illustration of primary-magmatic cryptic layering trends because it is shifted to higher values when magmatic clinopyroxene equilibrates at lower temperatures.

The cryptic layering pattern is conveniently explained with at least two major pulses of new magma or episodes of continuous magma addition, one starting at the assumed bottom contact of the intrusion and a second pulse above the 2500 m elevation. Magma addition must have occurred more in the form of a continuous outpour of magma into a well stirred magma chamber, rather than as discrete major pulses. The melt increments added were probably too small to be reflected by abrupt changes in mineral composition. There is no clear indication from the cryptic layering pattern as to which way chemical fractionation was directed and where the bottom and

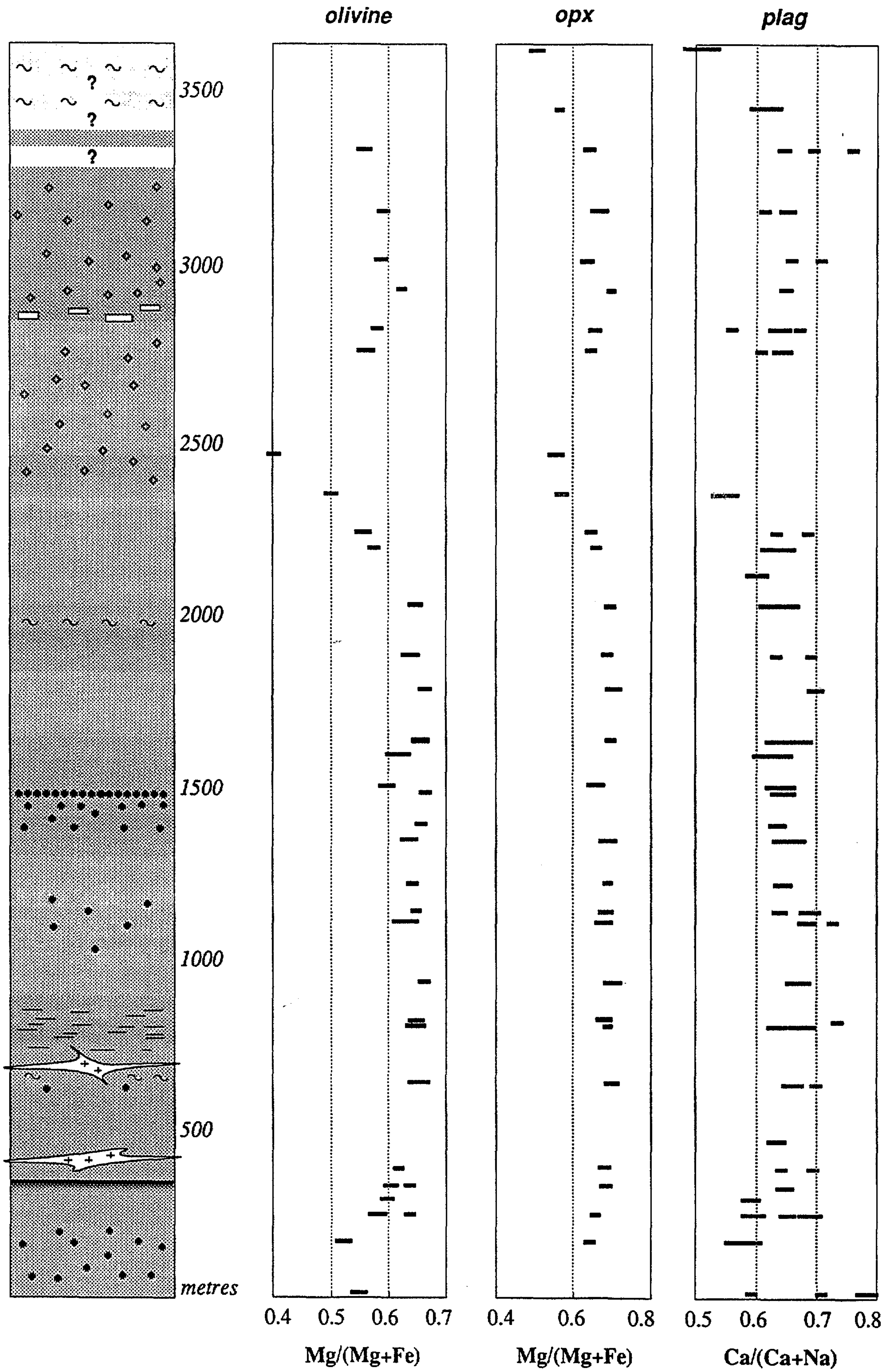



**Fig 15. Cryptic layering in the Blackstone Range sequence.**

top contacts may have been situated. However, if the Blackstone Range intrusion was originally continuous with the Bell Rock Range intrusion, as will be suggested in chapter 6, the sequence may be facing south.

## 4.4 Deformation and subsolidus reaction textures

The cumulates of the Blackstone Range intrusion are largely undeformed. The sequence includes a few mylonite horizons where deformation was accompanied by fluid infiltration and hydrous alteration of ferromagnesian phases. Shearing also involved intrusion of granitoid veins. In outcrop these veins have been interpreted as granophyres (e.g. sample 90980172), implying a genetic relationship with the layered sequence. Cumulates at the margin of the intrusion, especially those along the northern edge, are strongly recrystallized to fine-grained granular basic phlogopite-bearing granulites whose textures are shown in Fig. 14.

In some samples, olivine in contact with plagioclase is surrounded by fine-grained greenish symplectitic coronas. It is uncertain what phases are involved in these symplectites as grain sizes are generally below the resolution of the optical microscope and the microprobe. The textures are essentially confined to altered deformed cumulates that have suffered some fluid infiltration near mylonite zones, implying that the symplectite phases are dominated by hydrous minerals. Obviously, subsolidus reaction between olivine and plagioclase was only possible where a fluid phase was present to facilitate element transport and overcome kinetic barriers.

## 4.5 Constraints on parent magma composition

The parent magma to the Blackstone Range sequence must have been multiply saturated with olivine and plagioclase (and possibly clinopyroxene) at the time of emplacement. As a result, there is very little departure from olivine-plagioclase coprecipitation as a result of magma addition. The dunite layers near the assumed base of the intrusion are exceptional in this regard. Chemically, however, they are not the most primitive rock types in the Blackstone Range intrusion, nor do they coincide with a sharp reversal in the cryptic layering pattern. These dunite cumulates may have formed as a result of local plagioclase suppression (locally higher volatile contents or larger thermal gradients) rather than by addition of plagioclase-undersaturated melt. Their formation may also be diffusion controlled, i.e. linked to metastable fluctuations about the olivine/plagioclase cotectic, when a burst in plagioclase crystallization had temporarily shifted the magma off the olivine-plagioclase cotectic into the olivine stability field (c.f. Morse, 1986, Parsons, 1987). In any case, the presence of dunite layers in a dominantly troctolitic sequence cannot be taken as evidence that the parent magma to the Blackstone Range sequence was at times saturated only with olivine.

By analogy to the Jameson Range intrusion, the Blackstone Range magma was olivine-saturated throughout the entire differentiation history. There is no evidence that orthopyroxene replaced olivine on the liquidus, although with falling Mg/(Mg+Fe) ratio there is a slight trend of enrichment in modal orthopyroxene at the expense of olivine. Prior to emplacement, the parental magma must have experienced significant degrees of polybaric high-pressure pyroxene ± olivine fractionation to permit olivine crystallization to such low Mg/(Mg+Fe) ratios (see section 9).

# 5 THE HINCKLEY RANGE INTRUSION

## 5.1 Magmatic sequence

The Hinckley Range intrusion is one of the more deformed intrusions of the Giles Complex. Its northwestern units are affected by a metamorphic overprint, termed in Fig. 1 'recrystallized marginal facies' and identified by Clarke (1992) as mafic granulites (formerly magmatic gabbros) interleaved with older felsic and mafic granulites. In this part of the Hinckley Range, cumulate textures and magmatic layering are poorly preserved. The eastern extension of the intrusion has, however, largely escaped deformation and metamorphic overprint.

The most common rock types in the eastern part of the Hinckley Range include troctolites, olivine gabbros, gabbronorites, and anorthosites, as well as their deformed equivalents. Most interesting is a series of marginal finer-grained microgabbros, 'doleritic-textured' gabbros, and cross-cutting fine-grained basaltic dykes. These may locally grade into sills, conformable microgabbro units, and stratabound pods of microgabbro. The marginal rock types are most common along the southern (lower) contact of the intrusion. Since crystallization sequences in the marginal units are identical to the cumulus mineralogy of the coarser-grained layered sequence, they are interpreted as the more rapidly cooled equivalents to the cumulates.

The layered sequence is also cut by several generations of basaltic dykes. One olivine-spinel-phyric dyke generation is primitive enough to be mantle-derived. This composition probably qualifies as parental melt to the ultramafic olivine-rich units at Wingellina Hills, Murray Range, and the Kalka intrusion in South Australia. It may also represent the primary melt composition from which all derivative parental liquids to the Giles Complex have been derived.

Along the northern margin, the layered sequence is infiltrated and crosscut by very coarse-grained granitic material where quartz and K-feldspar occur in graphic intergrowth; possibly granophyric material was mobilized in the waning stages of magmatic differentiation. The granophyres intrude the most fractionated units of the layered sequence. In addition, there are several major mylonite zones near-parallel to the magmatic layering. The most prominent is the extension of the Hinckley thrust fault (Goode, 1978), a series of layer parallel splay faults and pseudotachylite veins within the Hinckley Range sequence. Nowhere in the Giles Complex are pseudotachylite veins more abundant and of greater thickness than in the Hinckley Range, where vein networks superimposed onto each other may reach several metres thickness (Glikson and Mernagh, 1990).

A schematic cross-section through the Hinckley Range intrusion is shown in Fig. 16. The magmatic sequence is approximately 5800 m thick and dips 70 to 80° northward. Cryptic layering patterns suggest that the top of the intrusion was toward the north. The sequence has been sampled along two consecutive traverses perpendicular to the magmatic layering.

## 5.2 Rock types

Representative types of cumulates of the Hinckley Range sequence are illustrated in Fig. 17.

**5.2.1 Troctolite and gabbroic troctolite.** Olivine and plagioclase are cumulus phases, followed in the crystallization sequence by subhedral poikilitic oxide-rich clinopyroxene and anhedral intercumulus (later) orthopyroxene (Fig. 17A to C). Orthopyroxene forms wide, optically continuous reaction rims around olivine and may have formed as a result of a peritectic olivine-melt reaction. In places, orthopyroxene grades into oikocrysts and irregular orthopyroxene-

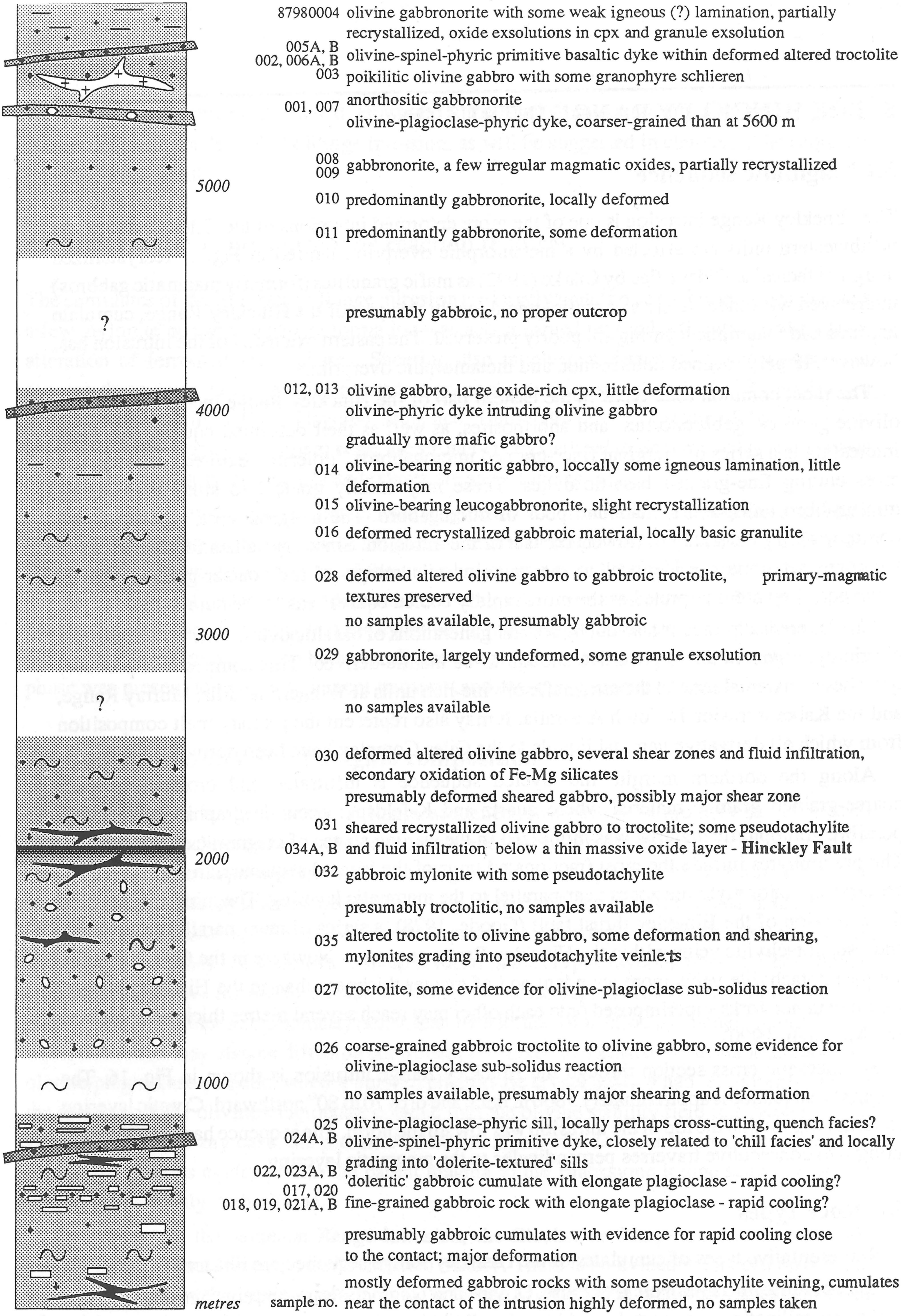



**Fig. 16. Stratigraphic sequence of the Hinckley Range intrusion. The sequence is predominantly troctolitic until about the 2000 m elevation, and above that level predominantly gabbroic. Rapidly crystallized units occur at the base of the intrusion (open rectangles). The layered sequence is cut by several olivine and olivine-plagioclase-phyric dykes. Major pseudotachylite veining (shown by schematic black veins) occurs near the Hinckley thrust fault and along the inferred bottom contact of the intrusion. Stratigraphic elevations have not been corrected for dip.**

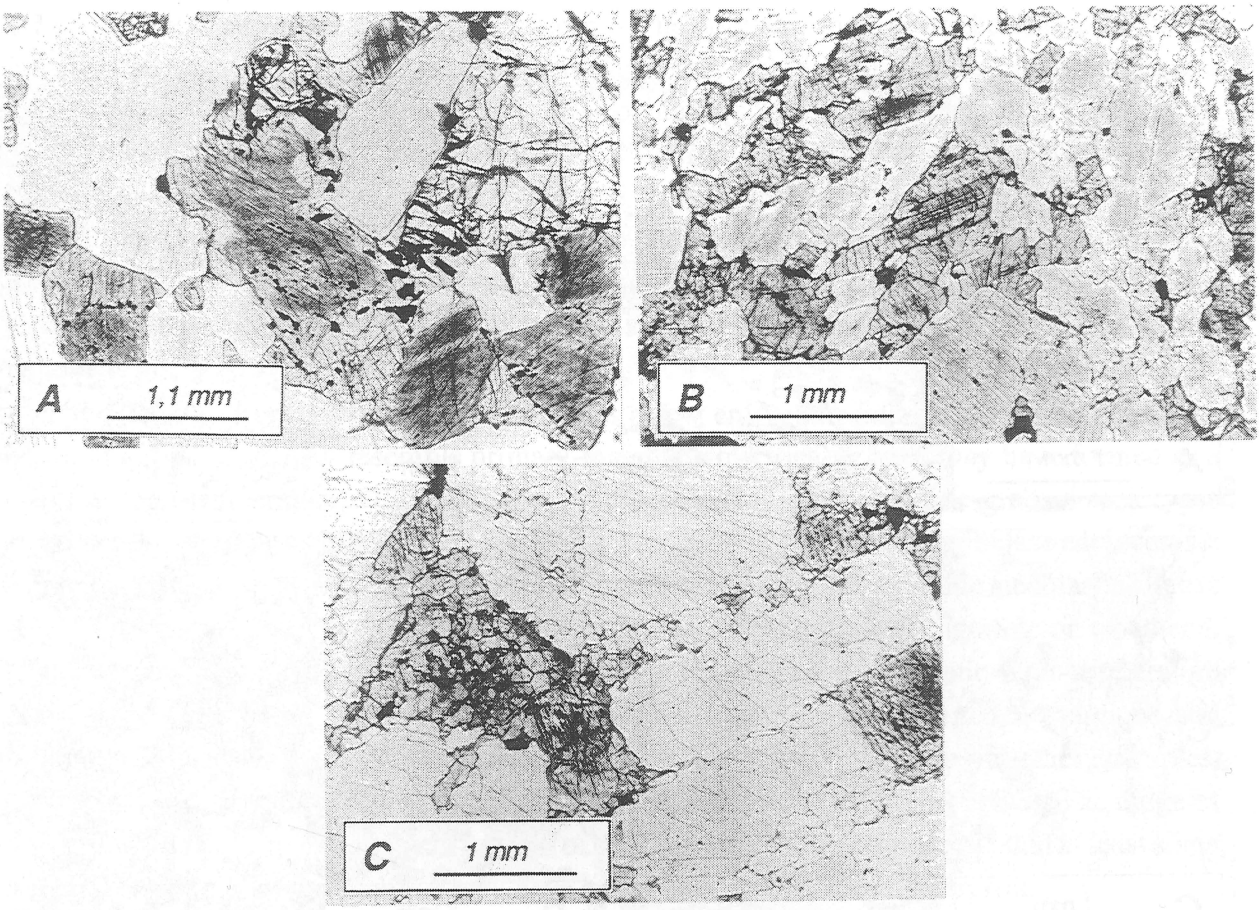



**Fig. 17: Types of cumulates observed within the eastern (magmatic) part of the Hinckley Range intrusion. A: Typical olivine-bearing gabbronorite. Olivine (clear grains with cracks), brownish clinopyroxene (oxide exsolutions), lighter orthopyroxene partly with magnetite symplectites, and euhedral plagioclase laths. The grey shading of plagioclase is due to minute dark particles, possibly originally Fe impurities in the lattice (rapid crystallization?) that exsolved upon cooling. Sample 87980003.**
**B: Gabbroic cumulate. Plagioclase laths, 'dusted' with small inclusions (grey shades), are the main cumulus phases, clinopyroxene is cumulus to intercumulus phase. Interpreted as an immature cumulate that may have formed by comparatively rapid crystallization. Sample 87980023B.**
**C: Anorthosite cumulate, possibly with some textural evidence for rapid crystallization. Large elongate euhedral plagioclase is cumulus, clinopyroxene largely intercumulus and recrystallized to small clinopyroxene-oxide neoblasts. Texture reminiscent of a holocrystalline 'doleritic-textured' sill or dyke with intergranular texture; plagioclase phenocrysts and groundmass clinopyroxene and oxides between the wedges of plagioclase laths. One of the most fractionated cumulates observed at Hinckley. Sample 87980001.**

magnetite symplectites. Plagioclase is commonly elongate and euhedral, and impregnated by submicroscopic opaque inclusions (Fig. 17B)—possibly exsolved ferric iron impurities that were incorporated in the plagioclase lattice at high temperature crystallization. Olivine in contact with plagioclase may be rimmed by a columnar orthopyroxene moat that is interpreted to have formed during the subsolidus stage (as opposed to the wider, optically continuous orthopyroxene rims that commonly grade into poikilitic grains). There are all stages of cumulate preservation and recrystallization, especially in the vicinity of shear zones. Under the influence of strain, clinopyroxene was the first phase to recrystallize to small anhedral granular-mosaic aggregates of clinopyroxene neoblasts and rounded opaque oxides (recrystallized oxide exsolutions; Fig. 17C).

**5.2.2 Olivine gabbro, gabbronorite and anorthosite.** All transitions exist between troctolitic rocks (clinopyroxene interstitial) and gabbroic rocks. Olivine gabbros contain plagioclase, large

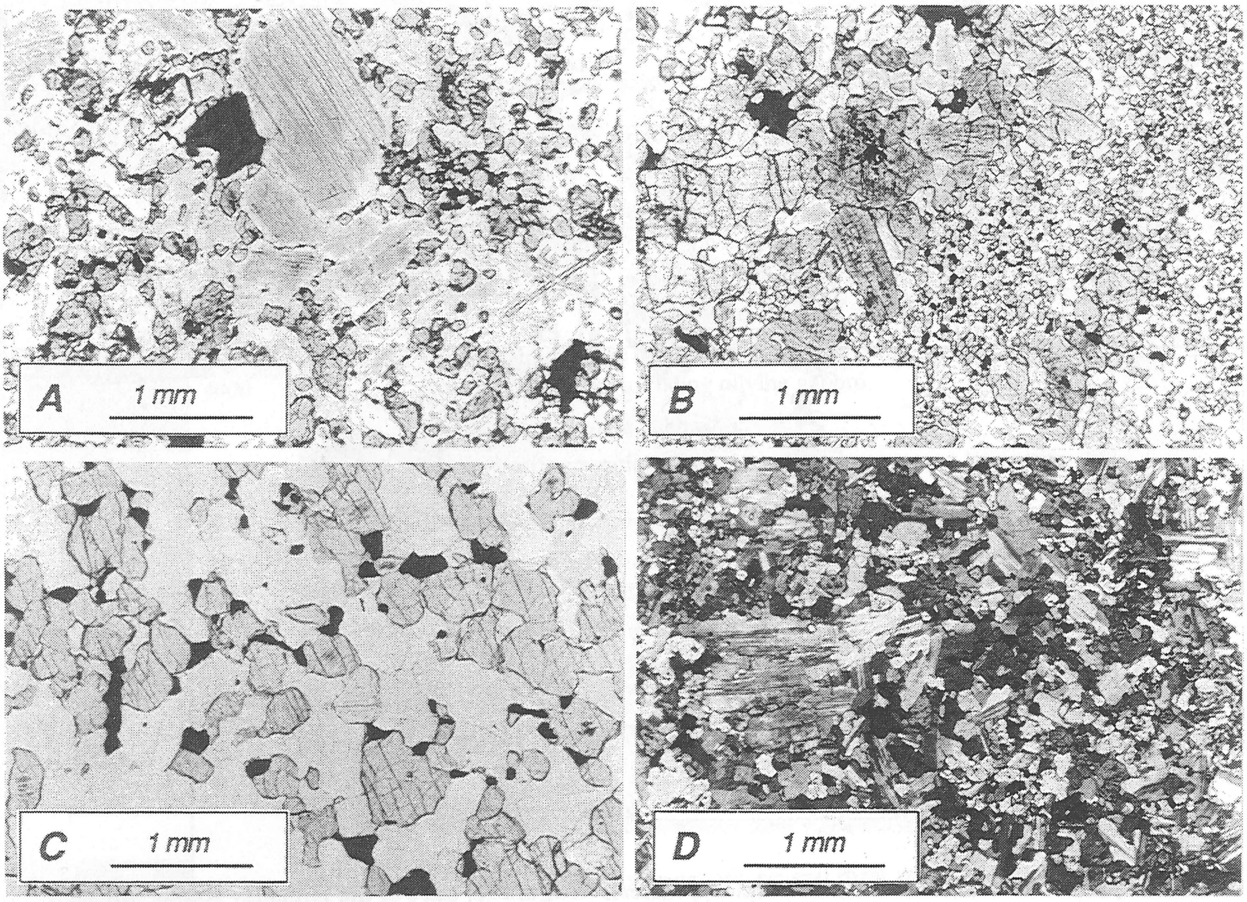



**Fig. 18: Fine-grained problematic rock types observed at the margins of the Hinckley layered sequence.**
**A: Fine-grained sample from the southern margin of the Hinckley intrusion. Possibly a rapidly quenched gabbroic rock that formed under highly variable cooling rates or may have lost a fluid phase during crystallization (rapid growth of fine-grained material because of fluid loss). Plagioclase typically impregnated by minute opaque impurities (rapid growth feature). Sample 87980017.**
**B: Fine-grained marginal gabbroic rock with coarse-grained cumulate-textured enclaves (similar to Fig. 5.5.). Unclear whether a primary-magmatic texture (chilled margin, highly variable cooling rates, variable fluid pressures) or secondary-metamorphic (high-temperature shearing followed by static high-temperature recrystallization. Sample 87980021A.**
**C: Gabbroic granulite. Equigranular plagioclase, clinopyroxene, oxides, and some orthopyroxene (olivine absent). Phlogopite is a common accessory phase. Modal ratio of clinopyroxene to oxide neoblasts approximately the same as in primary clinopyroxene with oxide exsolutions, suggesting a gabbroic precursor. Sample 87980016.**
**D: Fine-grained chilled margin (?) rock. Small euhedral to subhedral twinned plagioclase laths, some granular clinopyroxene and orthopyroxene. Based on plagioclase morphologies, this texture may be interpreted as primary-magmatic. Crossed polarizers to accentuate texture. Sample 87980021B.**

exsolved clinopyroxene grains rich in opaque oxide exsolutions, and sparse olivine as cumulus phases, while orthopyroxene forms later peritectic rims around olivine and clinopyroxene. In the most fractionated samples at the northern margin of the intrusion, olivine becomes progressively replaced by orthopyroxene (gabbronorites). Late-magmatic brown-green amphibole forms narrow moats around all ferromagnesian minerals. The most fractionated samples noted in the Hinckley Range sequence are anorthositic. Plagioclase is the only cumulus phase. Sparse clinopyroxene, magmatic opaque oxides, and some orthopyroxene are interstitial and occasionally recrystallized to neoblastic grains (Fig. 17C).

**5.2.3 Marginal cumulates.** Rock types close to the southern margin of the Hinckley Range intrusion are significantly finer-grained than cumulates within the layered suite, possibly as a result of larger thermal gradients close to the contacts of the magma chamber. All transitions exist from porphyritic fine-grained sills to 'doleritic-textured' cumulates. The latter are intermediate between genuine cumulates and rapidly chilled basaltic equivalents. Most 'doleritic-textured' cumulates are troctolitic to anorthositic. They carry euhedral elongate inclusion-rich zoned plagioclase and some rounded olivine as phenocryst phases, and clinopyroxene and opaque oxides as 'intergranular' material in the wedges between plagioclase laths (c.f. Fig. 17C).

The Hinckley Range sequence also includes a few enigmatic fine grained gabbroic rocks. Some marginal rocks may resemble primary-magmatic microgabbros or may have formed as a result of high-temperature recrystallization (gabbroic granulite). Some fine-grained rock types at the margin contain coarse-grained cumulate-textured clinopyroxene- plagioclase enclaves, set in a fine-grained granular clinopyroxene-orthopyroxene- plagioclase-oxide neoblastic matrix (Fig. 18A and B). It remains unclear whether that matrix is primary magmatic or whether it originated by very high-temperature plastic deformation followed by static high-temperature recrystallization. Other samples along the same margin are fine-grained throughout and predominantly granoblastic, with little evidence for a magmatic history. In yet other examples, plagioclase is distinctly euhedral, making a magmatic origin plausible (Fig. 18C). The range of doubtful textures along the southern margin of the Hinckley intrusion suggests that at least some primary magmatic chilled margins may have survived a post-intrusive overprint.

**5.2.4 Primitive olivine-spinel-phyric dykes.** The Hinckley Range intrusion features a number of cross-cutting basaltic dykes that are too primitive to be directly related to the layered sequence in which they occur. These dykes carry large olivine phenocrysts dusted with minute opaque impurities in a variably fine-grained 'reacted' (metamorphic) matrix of plagioclase, clinopyroxene, and some opaque oxides (Fig. 5.11.). Interestingly, the olivine phenocrysts host subhedral aluminous spinel inclusions which resemble in composition the equilibrated liquidus spinels observed in the ultramafic units of the Wingellina Hills intrusion (c.f. Ballhaus and Glikson, 1989). Olivine phenocrysts that are in contact with plagioclase or the former glassy (?) groundmass have marginally reacted to very fine-grained obscure greenish symplectites. These symplectites now comprise a major proportion of the groundmass. Temperatures calculated from olivine-spinel Fe-Mg exchange equilibria (Ballhaus et al., 1991) are around 600$^{o}$C. Evidently, these dykes have been emplaced at relatively high pressure (~ 6 to 7 kbar) when the country rocks were still comparatively hot, chilled rapidly down to around 850 to 900$^{o}$C (preservation of the primary-magmatic porphyritic texture), and then equilibrated slowly to around 600$^{o}$C in the course of general post-metamorphic cooling and uplift of the Hinckley Range intrusion (olivine-plagioclase reaction relationship, Fe-Mg exchange temperatures). Judging from their phenocryst mineralogy and composition, they represent a very reasonable parental melt to the primitive olivine-rich units of the Giles Complex, e.g. the ultramafic cumulates of the Wingellina Hills intrusion, the Murray Range, and most probably the Kalka intrusion. They may also represent the primitive mantle-derived parental liquid from which the derivative liquids to the Giles cumulates were derived (section 9).

In addition to primitive olivine-phyric dykes, the Hinckley Range also hosts the usual suite of olivine-plagioclase-phyric dykes and sills. Representative examples are illustrated in Fig. 19.

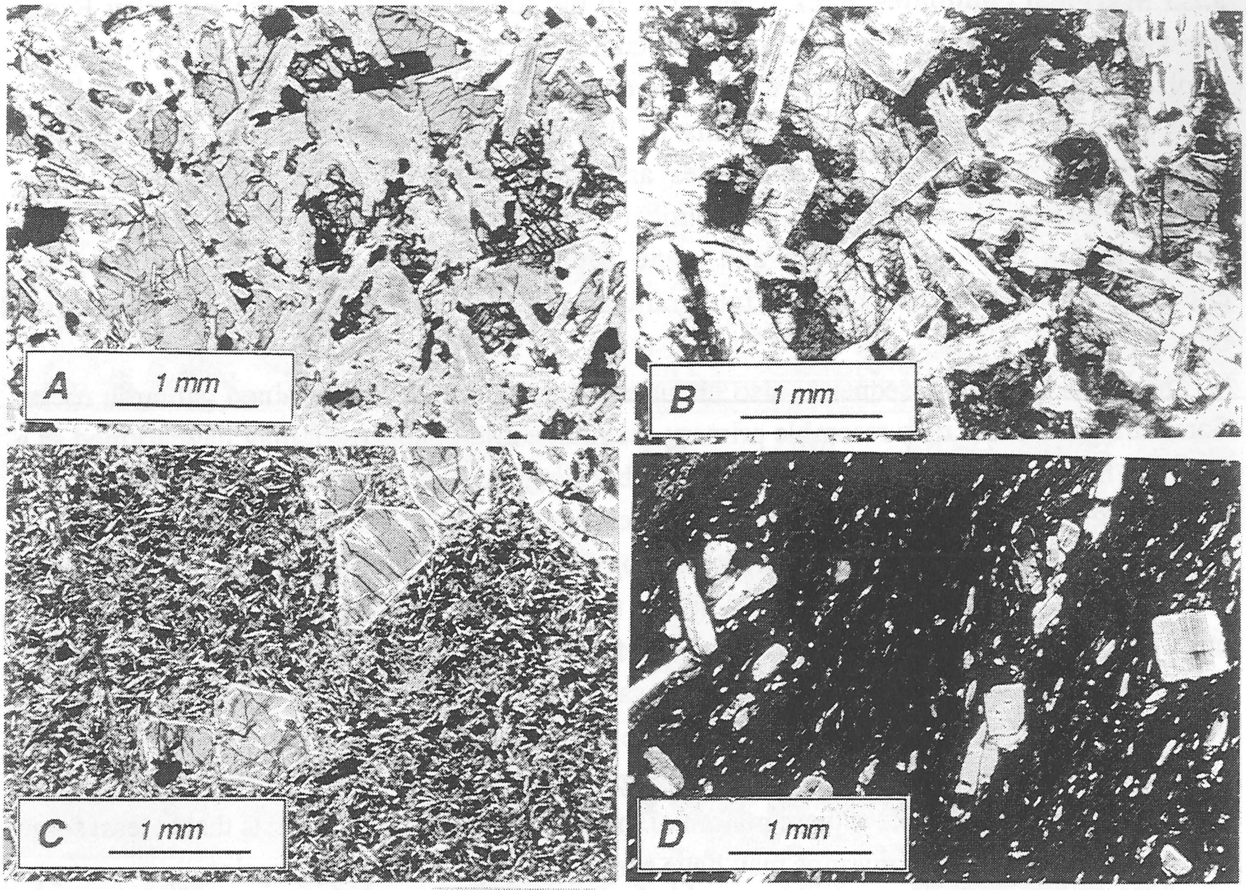



**Fig. 19: Sills and dykes in the Hinckley Range sequence, and their textural relationships with cumulates of the layered sequence.**
**A: Olivine-plagioclase-phyric dyke, quite coarse-grained. Close textural relations with immature 'doleritic-textured' cumulates (c.f. Fig. 17C). Elongate 'dusted' brownish plagioclase laths and rounded olivine are phenocrysts, clinopyroxene squeezed into 'interstitial' positions. Sample 87980007.**
**B: Plagioclase-olivine-phyric sill or chilled margin. Rounded olivine and plagioclase lath are phenocrysts, set in oxide-rich clinopyroxene-bearing 'dirty' groundmass. Olivine and plagioclase in reaction relationship - fine-grained spinel-bearing metamorphic symplectites in groundmass. Sample 87980019.**
**C: Primitive olivine-spinel-phyric dyke. Euhedral olivine 'dusted' with minute impurities and spinel inclusions in olivine (opaque grains) are phenocrysts. Plagioclase-oxide-clinopyroxene-rich groundmass. Parent magma to the Wingellina Hills/Murray Range ultramafic intrusions? Sample 87980024B.**
**D: Extremely fine-grained flow-textured dyke. Zoned plagioclase phenocrysts set in dark groundmass. Either a dyke or (more likely) a thick pseudotachylite vein. Sample 87980023A.**

## 5.3 Cryptic layering patterns

Stratigraphic variation plots of mineral compositions are shown in Fig. 20 and 21. The Hinckley Range sequence is comparatively fractionated. Mg/(Mg+Fe) ratios of cumulus olivine range from about 0.76 to 0.56 and steadily decrease within the sequence from south to north. Orthopyroxene Mg/(Mg+Fe) ratios vary sympathetically with olivine from about 0.8 to roughly 0.55. Orthopyroxene replaces olivine on the liquidus at an olivine Mg/(Mg+Fe) ratio of about 0.57, corresponding to an orthopyroxene Mg/(Mg+Fe) ratio of around 0.63. Ca/(Ca+Na) in plagioclase is more variable within single samples and ranges from 0.80 to about 0.55, also decreasing from south to north. The cryptic variation patterns and the presence of granophyre patches in cumulates along the northern margin are all consistent with an increasing fractionation degree from south to north.

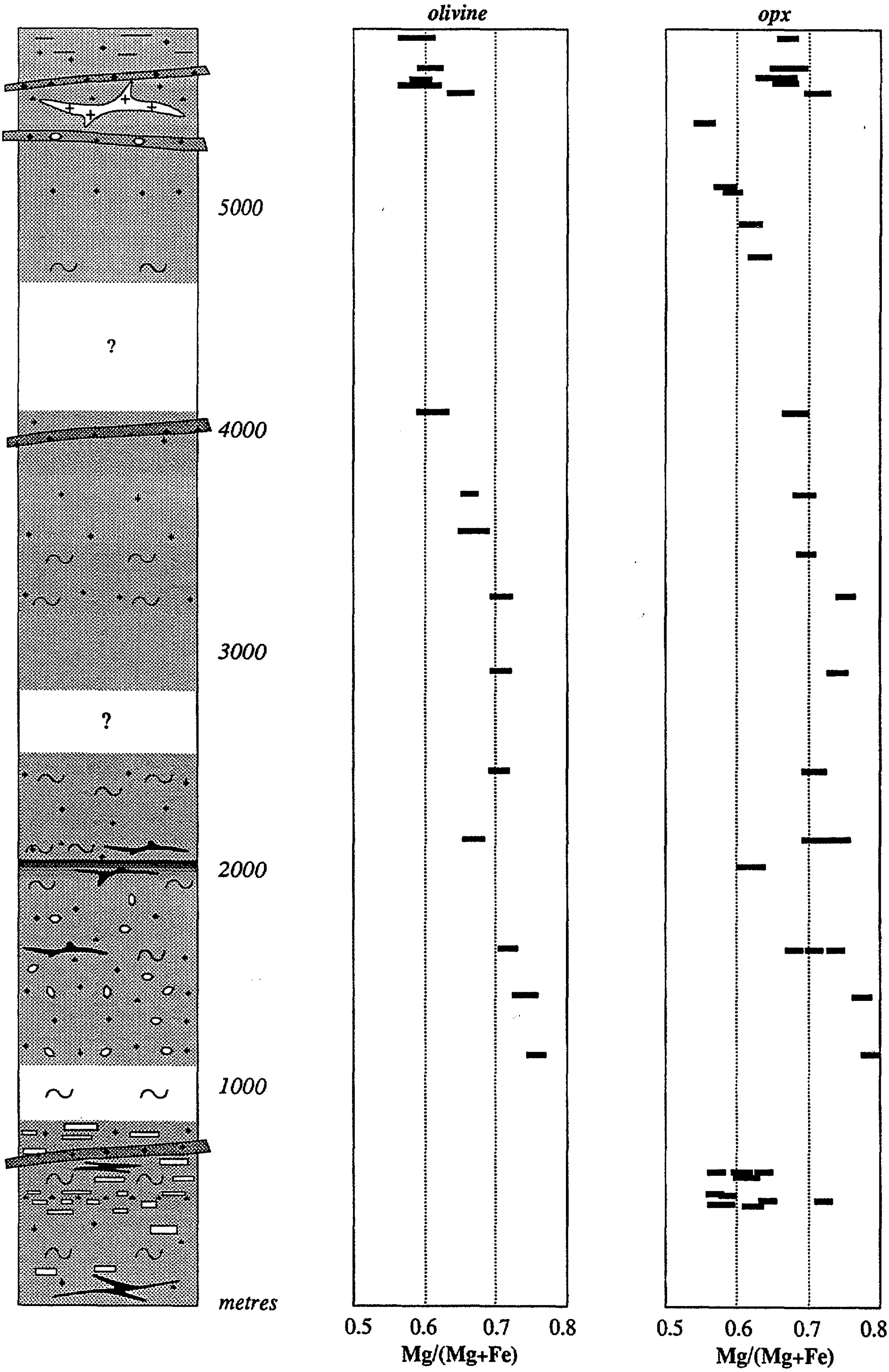
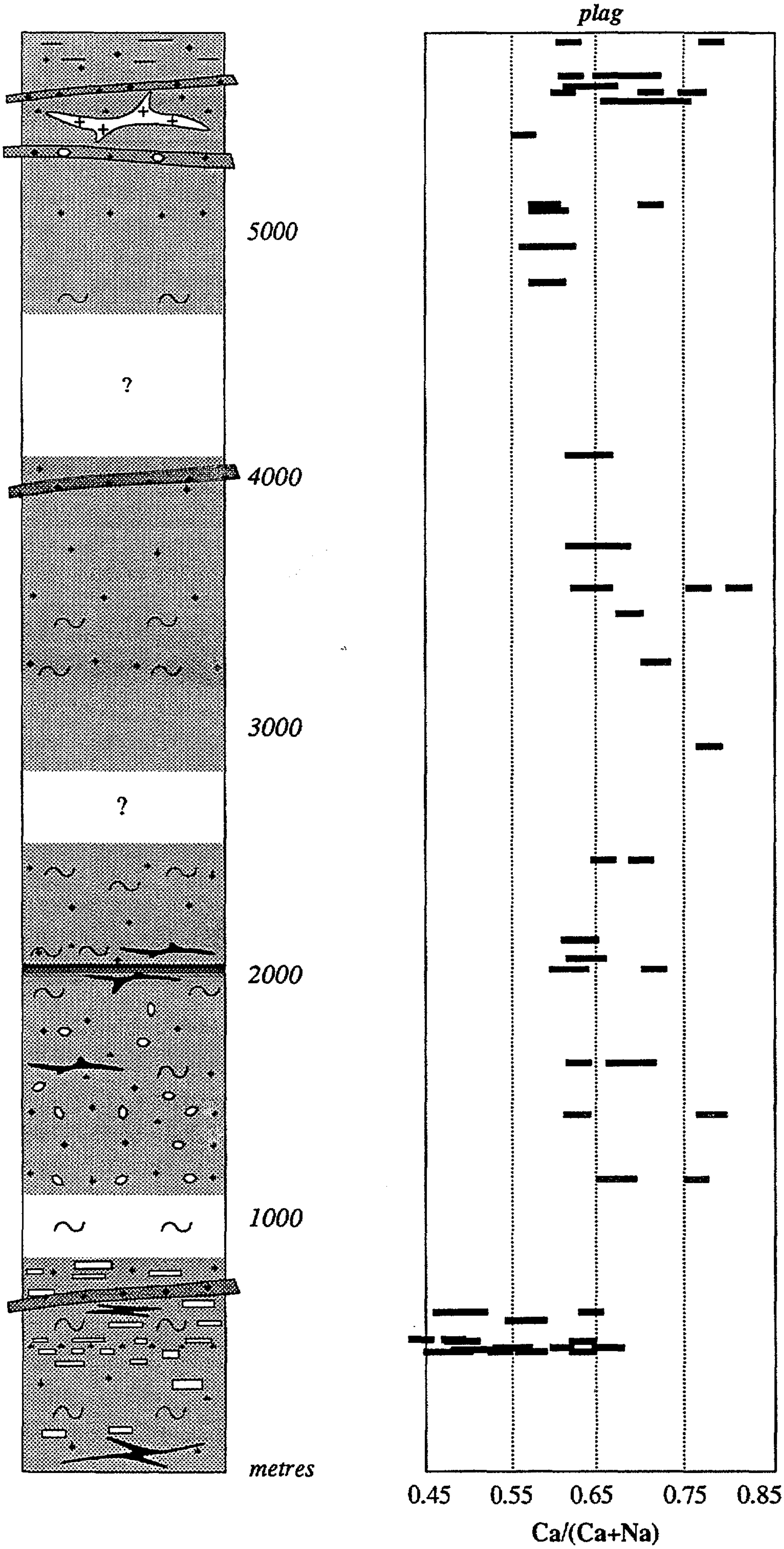



**Fig. 20 & 21. Cryptic layering in the Hinckley Range sequence.**

# HINCKLEY RANGE SEQUENCE



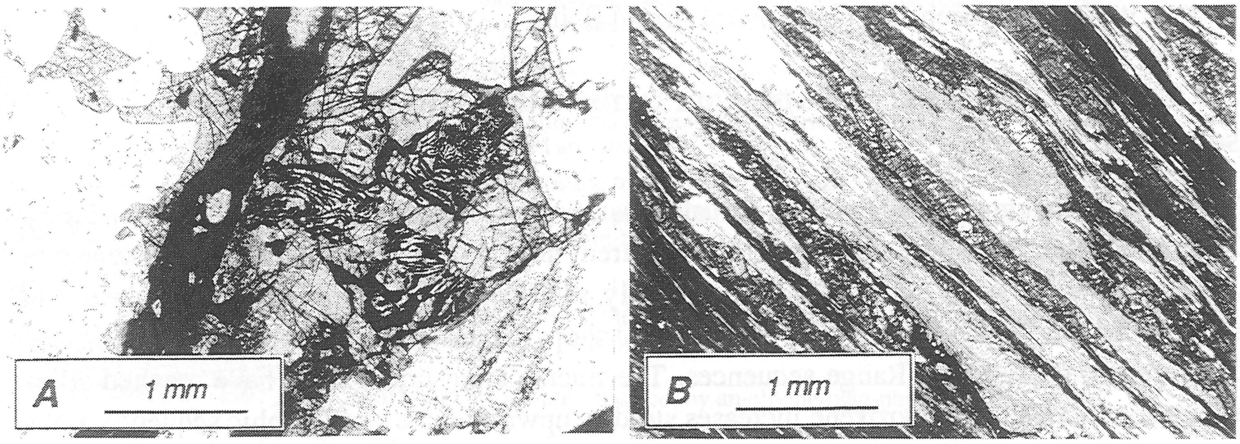



**Fig. 22: Deformation textures in cumulates of the Hinckley Range sequence.**
**A: Altered troctolite cut by opaque pseudotachylite veinlet. Olivine surrounded by a thin layer of greenish symplectites, orthopyroxene in symplectitic intergrowth with magnetite (oxidation reaction?) Sample 87980002.**
**B: Gabbroic mylonite. Deformed clinopyroxene relic s partly replaced by amphibole (medium-gray bands), altered plagioclase largely replaced by amphibole (light bands), and near opaque pseudotachylite. Sample from the environs of the Hinckley thrust fault. Sample 87980032.**

It is interesting to note that the lower half of the sequence, until about the 2500 m elevation, is dominated by troctolitic cumulates. This is in contrast to the predominantly gabbroic character of the higher stratigraphic levels. At an elevation of about 2500 m, a reversal in mineral compositions back to higher Mg/(Mg+Fe) ratios suggests a new influx of parent melt, possibly a magma with slightly higher normative pyroxene content than the parental melt that gave rise to the lower troctolitic sequence.

The marginal cumulates fall out of the large-scale fractionation trend. Mg/(Mg+Fe) ratios of ferromagnesian phases in the marginal suite are all intermediate relative to the range found in the cumulates proper. Ca/(Ca+Na) ratios in plagioclase in the marginal suite are more variable, probably because the early formed crystal fraction had the opportunity to equilibrate more thoroughly with derivative, more fractionated melt.

## 5.4 Deformation and subsolidus reaction textures

Within the Hinckley Range sequence, deformation was much more intense than in other intrusions of the Giles Complex. There are all stages of deformation from slightly deformed cumulates with incipient clinopyroxene recrystallization, fine-grained granoblastic two-pyroxene-plagioclase-oxide granulites (Fig. 18C), to genuine mylonites (Fig. 22B). A few marginal rock types where a metamorphic origin is doubtful have already been referred to in section 5.2.3. In addition, the sequence comprises several prominent mylonite zones with pseudotachylite veins (Fig. 22A and B) that run parallel to the magmatic layering. The most important of these zones is the Hinckley fault where superimposed pseudotachylite vein systems reach several metres in thickness (Glikson and Mernagh, 1990).

In some altered cumulates, olivine and other ferromagnesian phases are rimmed by very fine-grained greenish clinopyroxene-amphibole (?) symplectites, notably in contact with plagioclase. It is not clear whether spinel is involved in these reaction textures as grain sizes are near the limit of resolution of the optical microscope. Subsolidus reaction between olivine and plagioclase is absent in fresh unaltered and undeformed cumulates of the Hinckley Range intrusion. Where it occurs, it may have been facilitated by infiltrated fluids.

## 5.5 Constraints on parental magma composition and crystallization sequence.

The parental magma of the Hinckley intrusion was clearly more fractionated than of the Murray Range sequence, but more primitive than the parent melts that gave rise to the Blackstone and Jameson sequences. It must have been multiply saturated with olivine and plagioclase, but slightly undersaturated with clinopyroxene. Orthopyroxene is more abundant than in the Blackstone and Jameson Range sequences. The fractionating liquid must have reached silica saturation because orthopyroxene increases steadily upward in the stratigraphic sequence at the expense of olivine. In comparison, the magmas of the Blackstone and Jameson Ranges were so undersaturated with silica that olivine persisted to the most fractionated derivative liquids.

The sequence shows a relatively sudden increase in modal clinopyroxene above the 2500 m elevation. This change in modal mineralogy approximately coincides with a poorly defined reversal in cryptic layering patterns. It appears as if there was a slight change in parent magma composition toward a melt with higher normative clinopyroxene and higher silica activity. Such a change during the intrusive period of an intrusion is not unreasonable in view of the wide ranges of parental melt compositions identified in the Giles Complex intrusions and the dyke suites of the Tomkinson Ranges (see section 9).

# 6 THE BELL ROCK RANGE INTRUSION

## 6.1 Magmatic sequence

The Bell Rock Range intrusion consists of a fractionated well layered sequence of troctolites, gabbroic troctolites, anorthosites, some dunitic cumulates, and several thin massive oxide horizons. The first quarter of what is interpreted to be the lower units is composed of gabbroic troctolites and some olivine gabbro, gabbronorite, and microgabbro units. The remainder of the sequence is dominated by oxide-bearing troctolites, anorthosites, and thin dunite horizons. Eventually, magnetite changes from intercumulus to cumulus, culminating in the deposition of several decimetre-thick massive magnetite layers. Apart from these and a few dunite layers, monomineralic units are rare in the Bell Rock sequence, and there are few departures from cotectic crystallization relationships. Magmatic layering therefore is mainly developed on a small (centimetre to metre) scale (c.f. Boudreau, 1987). Megascale cyclicity such as in the Murray Range or Wingellina Hills intrusions is absent.

The Bell Rock Range intrusion is strikingly similar to the Blackstone Range intrusion in mineralogy, magmatic stratigraphy, styles of magmatic layering, and fractionation degree. Genetically, it is an interesting sequence in that it also comprises several fine-grained stratiform microgabbro units and crosscutting dykes whose phenocryst mineralogy resembles the cumulus mineralogy and crystallization sequence in the layered sequence.

The stratigraphic column as deduced from thin section microscopy and field observations is illustrated in Fig. 23. The sequence dips at approximately 70° toward the southwest. It has been sampled along two traverses at high angles to the magmatic layering. Outcrop is almost continuous for 3800 m.

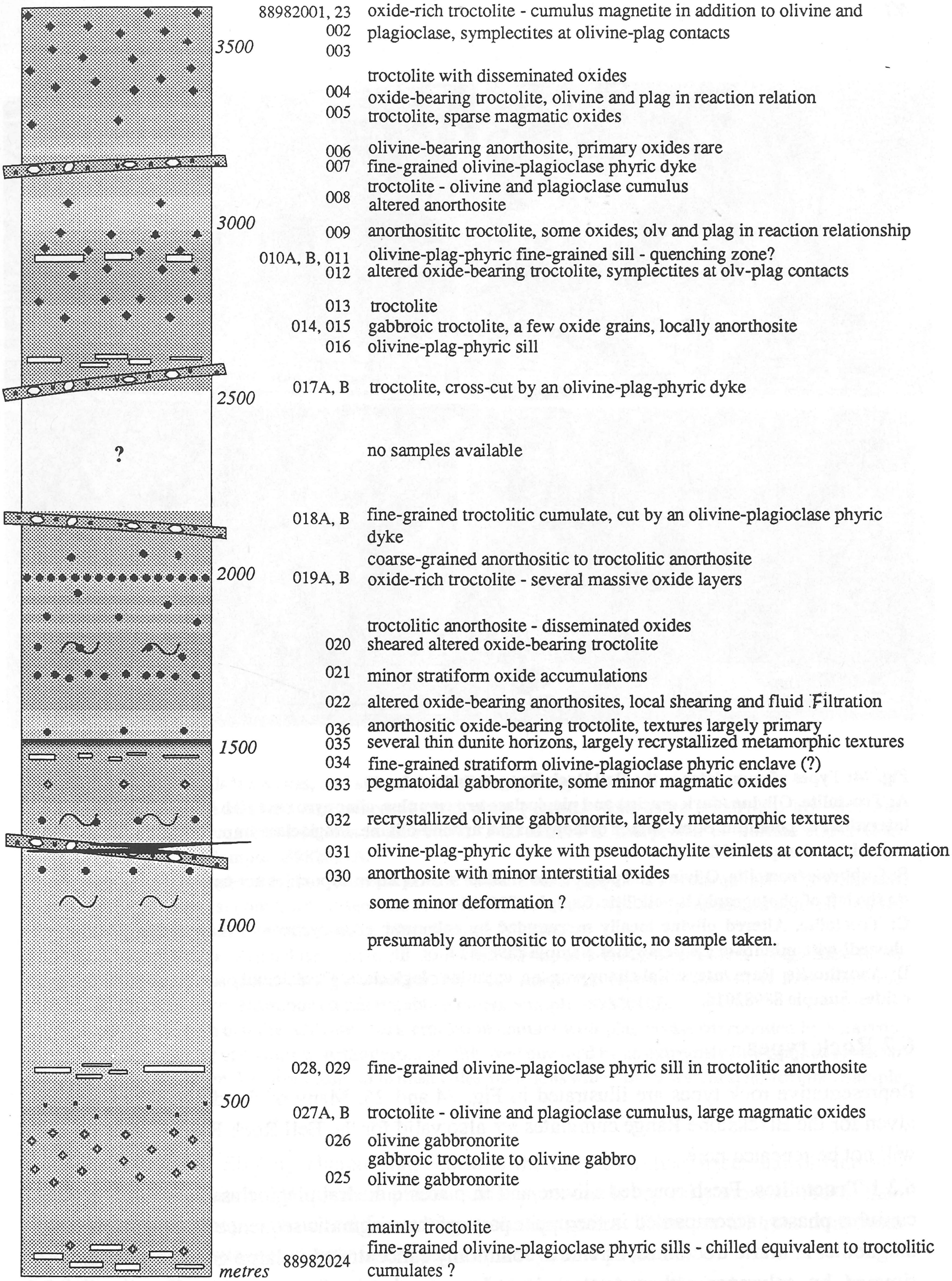



**Fig. 23: Stratigraphic sequence of the Bell Rock Range intrusion. Variable olivine/ plagioclase modal ratios are depicted by variable grey shades. The sequence includes several sills and intraplutonic quenching horizons (open rectangles). Disseminated oxides are signified by filled dots, the presence of clinopyroxene is illustrated by small open diamonds. The sequence is cut by numerous olivine-plagioclase-phyric dykes that are similar in mineralogy to the cumulates. Superimposed onto one dyke is a pseudotachylite veinlet. Stratigraphic elevations are corrected for average dip angles of 70°.**

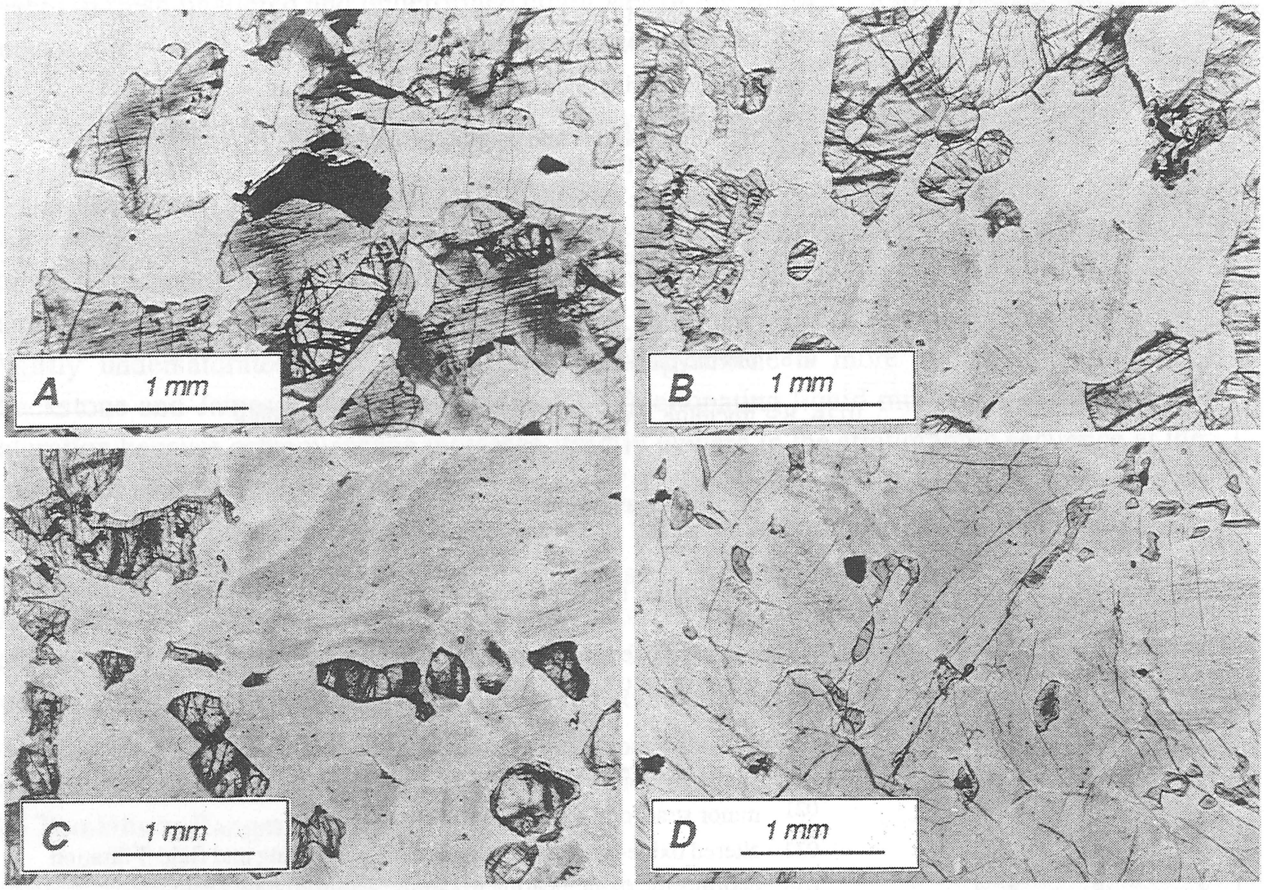



**Fig. 24: Types of cumulates in the Bell Rock Range intrusion**
**A: Troctolite. Olivine (dark cracks) and plagioclase are cumulus, clinopyroxene rich in oxide exsolutions is interstitial to poikilitic. Some minor orthopyroxene around olivine. Plagioclase impregnated with darkish impurities. Sample 88982012.**
**B: Gabbroic troctolite. Olivine and plagioclase 'dusted' with opaque impurities are cumulus, clinopyroxene (to the left of photograph) is poikilitic. Sample 88982014.**
**C: Troctolite. Altered olivine locally surrounded by columnar orthopyroxene overgrowths, plagioclase 'dusted' with minute oxide impurities. Sample 88982013.**
**D: Anorthosite. Rare interstitial clinopyroxene, cumulus plagioclase. Occasionally some euhedral opaque oxides. Sample 88982015.**

## 6.2 Rock types

Representative rock types are illustrated in Fig. 24 and 25. Many of the descriptions already given for the Blackstone Range cumulates are also valid for the Bell Rock Range intrusion and will not be repeated here.

**6.2.1 Troctolites.** Fresh rounded olivine and in places euhedral plagioclase laths are the main cumulus phases, accompanied in the upper parts of the magmatic sequence by sparse cumulus magnetite. In mafic troctolites, olivine is commonly concentrated in large grain aggregates and rimmed by columnar orthopyroxene rims. In more leucocratic troctolites (lower olivine/plagioclase modal ratios) orthopyroxene becomes volumetrically more important and may form large oikocrysts. Clinopyroxene is invariably later than olivine and plagioclase, and slightly later than orthopyroxene. Magmatic opaque oxides are intercumulus but tend to become cumulus phases near the massive magnetite layers at the 1970 m elevation. Post-magmatic biotite and rare amphibole are attached to oxide grains.

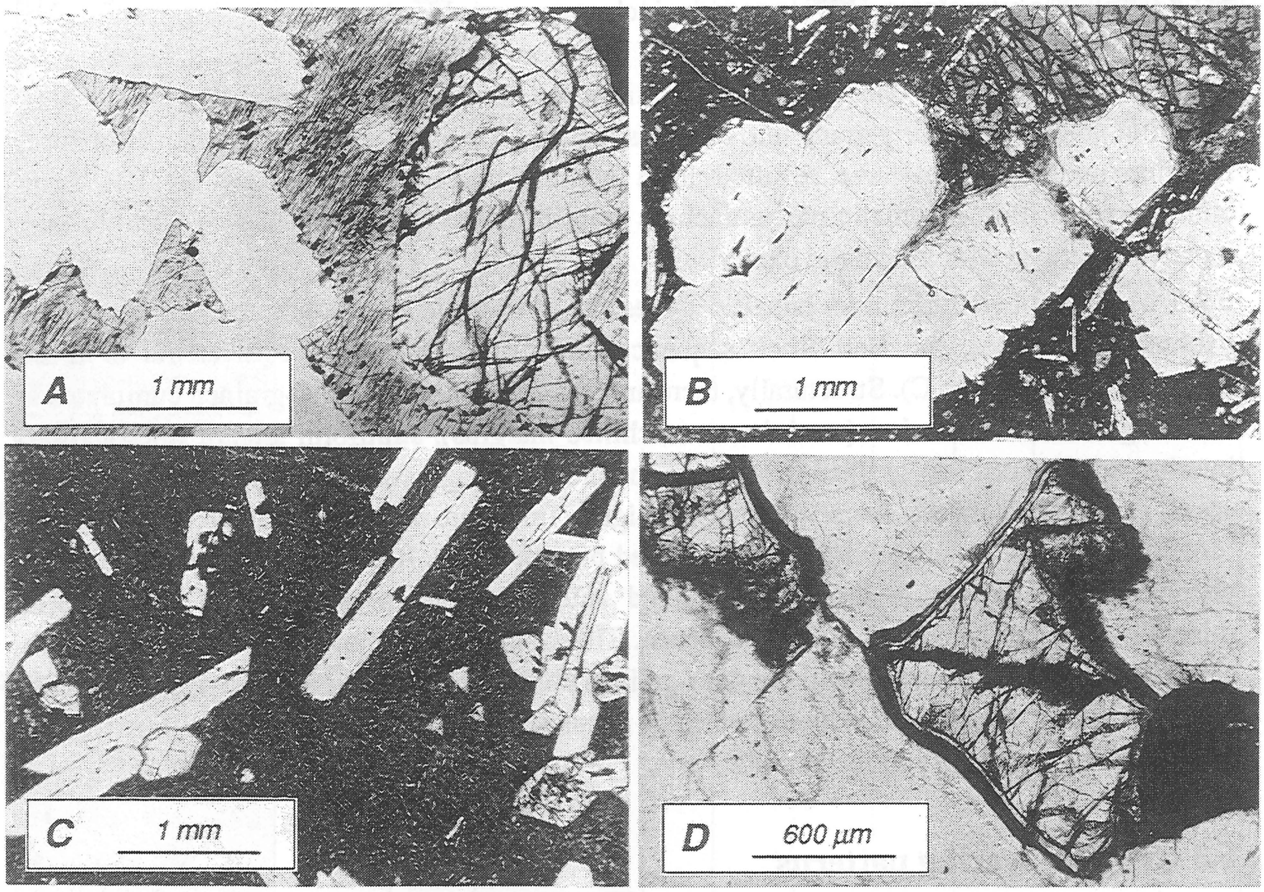



**Fig. 25. Types of cumulates, dykes, and sills of the Bell Rock Range intrusion**
**A: Gabbroic troctolite. Olivine and euhedral plagioclase ('dusted' with some impurities) are cumulus, clinopyroxene rich in oxide exsolutions is interstitial. This texture is interpreted to indicate higher than normal cooling rates. Sample 88982019A.**
**B: Olivine-plagioclase-phyric dyke. Rounded olivine and euhedral plagioclase set in quenched groundmass. Note that the phenocryst population resembles in all details the cumulus phases predominating in cumulates of the Bell Rock layered sequence (c.f. Fig. 25A). Sample 88982007.**
**C: Fine-grained olivine-plagioclase-phyric sill. Euhedral olivine and elongate euhedral plagioclase set in finest-grained groundmass. Although conformable with magmatic layering, the sill is later than the cumulates (in contrast to stratabound microgabbro units). Sample 88982010B.**
**D: Altered deformed troctolite. Olivine (dark cracks) in contact with plagioclase surrounded by a narrow inner clear bright moat of columnar orthopyroxene, followed outward by an extremely fine-grained greenish cloudy symplectite layer. Texture common to most Giles intrusions where there was fluid infiltration. Sample 88982010A.**

**6.2.2 Anorthosites.** Slightly altered plagioclase is the only cumulus phase, and olivine and clinopyroxene are minor intercumulus phases. Orthopyroxene is typically more abundant than both olivine and clinopyroxene and forms large poikilitic grains. There are all transitions from troctolite to anorthosite, commonly interlayered in a rhythmic pattern.

**6.2.3 Dunites.** Dunites are confined to a narrow, rhythmically layered stratigraphic interval at the 1580 m elevation where thin dunite layers alternate with troctolites and anorthosites. In dunites, olivine is the only cumulus phase and plagioclase a sparse intercumulus mineral, partly altered to greenish actinolitic amphibole (c.f. Fig. 13E, Blackstone sequence). Texturally, dunites are adcumulates where the original magmatic texture is commonly recrystallized to a well equilibrated equigranular fabric with triple grain boundaries.

**6.2.4 Gabbroic cumulates.** Olivine and plagioclase are cumulus phases in variable proportions, whereas orthopyroxene is interstitial and less common than in troctolitic cumulates. Clinopyroxene is rich in opaque oxide exsolutions and forms large subhedral to near-euhedral poikilitic grains that locally grade into cumulus textures. Opaque oxides are interstitial or form rounded neoblasts that have resulted from granule exsolution of oxide lamellae from clinopyroxene. Post-magmatic phases include reddish biotite and greenish-brown amphibole, mostly associated with magmatic oxides.

**6.2.5 Microgabbro units and basaltic dykes.** In addition to coarse-grained troctolitic and gabbroic cumulates, the Bell Rock sequence includes finer-grained equivalents to these cumulates (Fig. 25A to C). Structurally, there are all transitions from finer-grained cumulates at the margins of the intrusion (reminiscent of chilled margins), stratiform sills of microgabbro interleaved with coarser- grained cumulates, and cross-cutting basaltic dykes. Texturally, there are all gradations between coarse-grained but slightly immature cumulate textures, finer-grained 'doleritic-textured' microgabbros, and quenched basaltic melts. It is interesting to note that the phenocryst populations in these finer-grained units resemble in most details the cumulus mineralogy of the layered cumulate sequence. The structural relationships with the cumulate suite as noted above suggest that these finer-grained units resulted from parent magma injections into the magma chamber. Injections evidently occurred at all stages during the differentiation and solidification history of the cumulate pile.

## 6.3 Cryptic layering patterns

Stratigraphic variation patterns of mineral compositions are summarized in Fig. 26. With respect to cryptic layering and fractionation degrees, the Bell Rock Range sequence is similar to the Blackstone Range sequence. Mg/(Mg+Fe) ratios of olivine range from 0.68 to about 0.55, with no equivalent of the highly fractionated compositions observed at Blackstone Range. Orthopyroxene has slightly higher Mg/(Mg+Fe) ratios, ranging from 0.72 to 0.62. Ca/(Ca+Na) ratios of plagioclase are similarly variable between 0.85 and 0.55, but in contrast to olivine and orthopyroxene (and in contrast to the Blackstone Range intrusion) do not follow discrete stratigraphic fractionation trends. The stratigraphic orientation of the sequence remains ambiguous; in the field, however, there appears to be a weak increase in modal magnetite in the units now interpreted to underlie the massive magnetite layers, indicating that these units may have formed prior to magnetite supersaturation. One is tempted to conclude from the shape of the olivine-orthopyroxene cryptic layering patterns that the Bell Rock intrusion represents the southeastern extension of the Blackstone Range intrusion, an opinion already suggested by Daniels (1974). The detailed stratigraphic similarities between the Bell Rock and Blackstone Range sequences are indeed striking and stratigraphic overlap may be considerable:

- The series of dunite layers at Bell Rock in the lower half of sequence may be correlated with the dunites of the Blackstone Range sequence that occur at the 400 m elevation.
- As in the Blackstone sequence, the Bell Rock sequence also contains a few closely spaced massive magnetite layers some distance above the dunite horizons.
- The trend of normal fractionation from 2700 to 3600 m within the Bell Rock sequence resembles a similar trend in the Blackstone sequence from the 1800 to about 2500 m elevation.

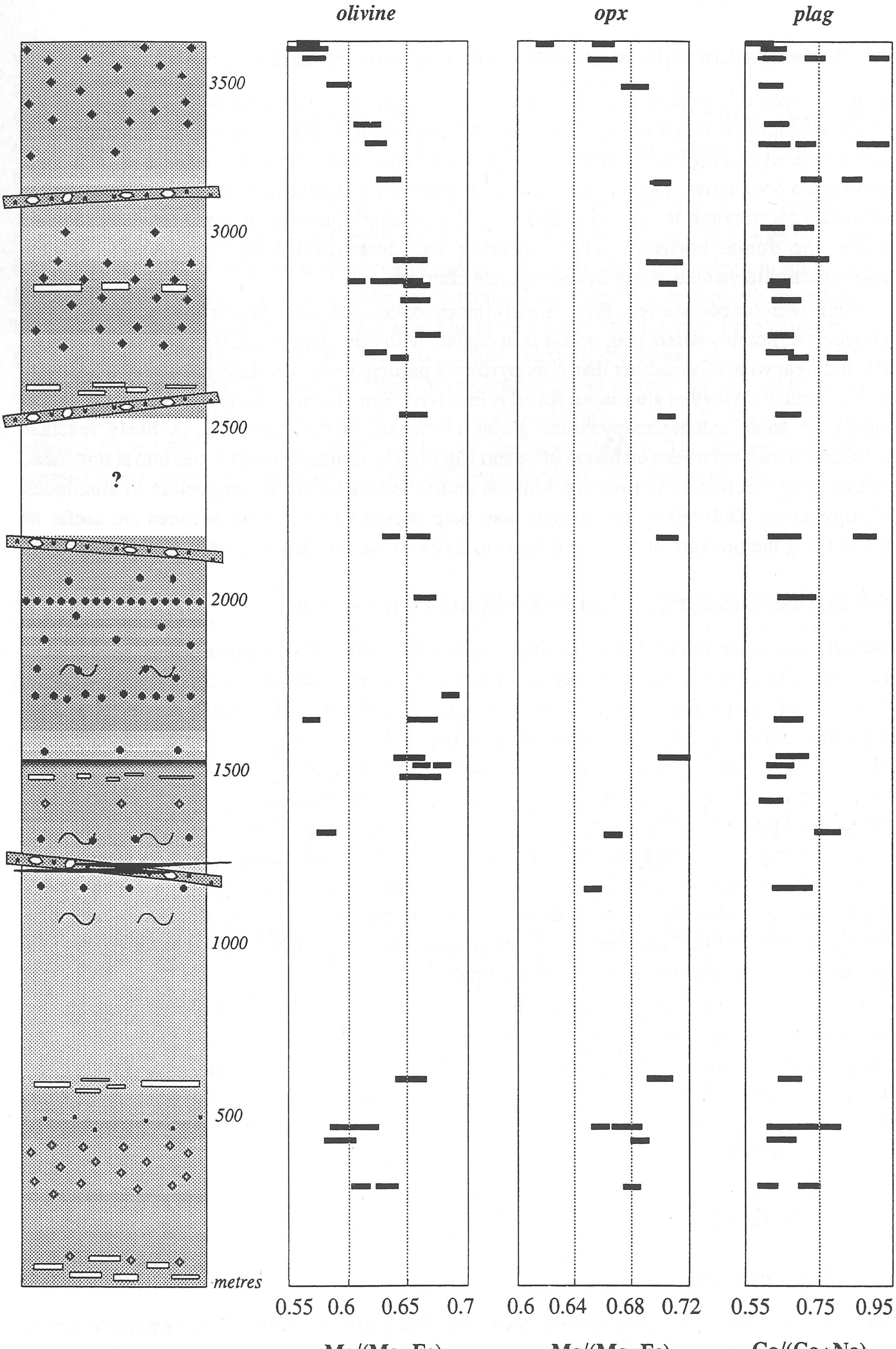



**Fig. 26: Cryptic layering in the Bell Rock magmatic sequence.**

### 6.4 Deformation and subsolidus equilibration textures

In most types of cumulates, primary magmatic textures are well preserved. Some advanced recrystallization is noted only in the near-monomineralic dunite, anorthosite, and magnetite layers where postmagmatic annealing has produced equilibrated granular-mosaic textures with triple grain boundaries. The sequence also comprises a few localized shear zones, with the usual cumulate deformation to mylonite. Shearing is particularly prominent along the basaltic dyke below the dunite horizons, where shearing was accompanied by emplacement of thin pseudotachylite veinlets along dyke-cumulate contacts.

Some samples contain very fine grained clinopyroxene-rich 'cauliflower' symplectites within plagioclase, notably where plagioclase is in contact with olivine (Fig. 25D) or a magmatic oxide. It is not clear what phases other than clinopyroxene participate in these fine-grained symplectites, and in particular whether aluminous spinel is involved. Symplectitic clinopyroxene is chemically similar to equilibrated clinopyroxene grains elsewhere in the cumulates. A likely reaction mechanism may have been diffusion of Fe and Mg from ferromagnesian silicates into plagioclase, followed by reaction of Fe and Mg with the anorthite component in plagioclase to aluminous clinopyroxene. Detailed probe analysis may help decide whether these textures are useful in quantifying the pressure under which the cumulates of the Bell Rock Range intrusion formed.

### 6.5 Intrusive history and parent magma composition

With the exception of the Hinckley Range and Latitude Hill intrusions (see below), nowhere in the Giles Complex are the relationships between the layered cumulates and the dyke swarms more evident than at Bell Rock (c.f. Fig. 25A to C). The Bell Rock Range intrusion experienced a multiply intrusive history. The parent magma is well documented by a series of rapidly cooled olivine-plagioclase-phyric dykes and sills, and the feeder dyke system to the magma chamber is well preserved. All structural transitions occur between cross-cutting fine-grained basaltic dykes, stratabound pods of microgabbro, genuine stratiform microgabbro units, and intraplutonic chill zones that may be entirely gradational with the coarser-grained mature cumulate layers. It seems reasonable to conclude on the basis of this field evidence, plus the observation that phenocryst populations in chilled dykes resemble the cumulus mineralogy and crystallization sequence in the cumulates, that the fine-grained olivine-plagioclase-phyric dykes at Bell Rock represent a parent magma composition to the Giles Complex.

Otherwise, most of the conclusions already reached for the Blackstone Range intrusion are also applicable to Bell Rock. The parent magma must have been multiply saturated with olivine and plagioclase, although it may have been slightly closer to clinopyroxene saturation than the parent melt to the Blackstone cumulate sequence. Magnetite saturation must have occurred in the course of chemical differentiation, as a result of Fe enrichment and an increase in oxygen fugacity in derivative liquids.

## 7 THE SOUTH MT. WEST (THE WART) INTRUSION

### 7.1 Magmatic sequence

The South Mt. West intrusion, recently renamed 'The Wart', is a small sliver of predominantly ultramafic pyroxenitic material with intrusive relationships to felsic granulites. It consists of an exceptionally well layered suite of clinopyroxenite cumulates, with numerous highly primitive wehrlite and locally peridotite intercalations and some olivine melagabbro, all overlying a sequence of gabbroic cumulates. Compared with pyroxenites of other mafic sequences of the Giles Complex, the Mt. West pyroxenites are very poor in plagioclase. The most fractionated units exposed are olivine-bearing melagabbros with less than 40 volume percent calcic plagioclase.

The Mt. West sequence also hosts a few stratiform microgabbro units and a number of cross-cutting basaltic dykes. Most significant in elucidating the evolution of the Giles Complex is one basaltic dyke population where orthopyroxene is the only phenocryst phase in addition to some plagioclase microphenocrysts in the groundmass. This dyke is, to the author's knowledge, the only direct evidence so far that some magmas to the Giles Complex may have experienced pre-emplacement high-pressure fractionation. Most other dykes noted at Mt. West carry phenocryst assemblages that disqualify them as reasonable parent melts to the layered sequence.

The Mt. West magmatic sequence is illustrated schematically in Fig. 27. Dip angles vary between 50 and 90°. Outcrop is almost continuous for about 1900 m. The sequence has been sampled along two partly overlapping traverses perpendicular to the magmatic layering.

## 7.2 Rock types

As a result of a relatively primitive undersaturated parent melt, the Mt. West intrusion is the most variable with respect to modal mineralogy, texture, and cumulate porosity. All transitions occur between pyroxenite, wehrlite, peridotite, and melagabbro, sometimes as multiple changes within several metres. Representative cumulate textures are illustrated in Fig. 28.

**7.2.1 Feldspathic clinopyroxenite orthocumulates.** Brown clinopyroxene, commonly spectacularly rich in spinel exsolutions, is the main cumulus phase. Occasionally, clinopyroxene is accompanied by rounded cumulus olivine, especially in primitive units near new magma pulses (Fig. 28A). Plagioclase is an intercumulus phase but sometimes so abundant that it is close to becoming a cumulus phase. Orthopyroxene is a minor phase and occurs as columnar rims around olivine, notably where olivine is in contact with plagioclase. Occasionally, orthopyroxene may grade into a late-magmatic intercumulus phase.

**7.2.2 Clinopyroxenite adcumulates.** In these rock types, clinopyroxene and in places minor olivine are closely packed cumulus phases, commonly annealed to an extent that primary-magmatic textures are obliterated. Grain boundaries between clinopyroxene grains are well equilibrated and occasionally traced by small brownish spinel neoblasts (Fig. 28B). Interestingly, orthopyroxene is extremely rare in almost all types of cumulates observed in the Mt. West sequence. Isolated occurrences of interstitial plagioclase are mostly antiperthitic, with minute exsolution rodlets of K-feldspar within a matrix of ~ An80 (c.f. Fig. 7C).

**7.2.3 Wehrlites and peridotites.** Olivine and clinopyroxene are cumulus phases, followed by abundant interstitial plagioclase (Fig. 28D and E). In peridotite orthocumulates, clinopyroxene may be poikilitic and very rich in spinel exsolutions, especially in the most primitive samples. Orthopyroxene is rare. The parental magma giving rise to these cumulates must have been saturated with olivine and in some instances in clinopyroxene. Unlike peridotite units of the Murray Range or Wingellina Hills sequences, cumulus spinel is not reported.

**7.2.4 Olivine melagabbros.** These rocks contain clinopyroxene, plagioclase, and olivine as cumulus phases (Fig. 28F). Plagioclase commonly grades from a cumulus phase to a nearly interstitial phase, especially in the melanocratic examples. All textural transitions exist between

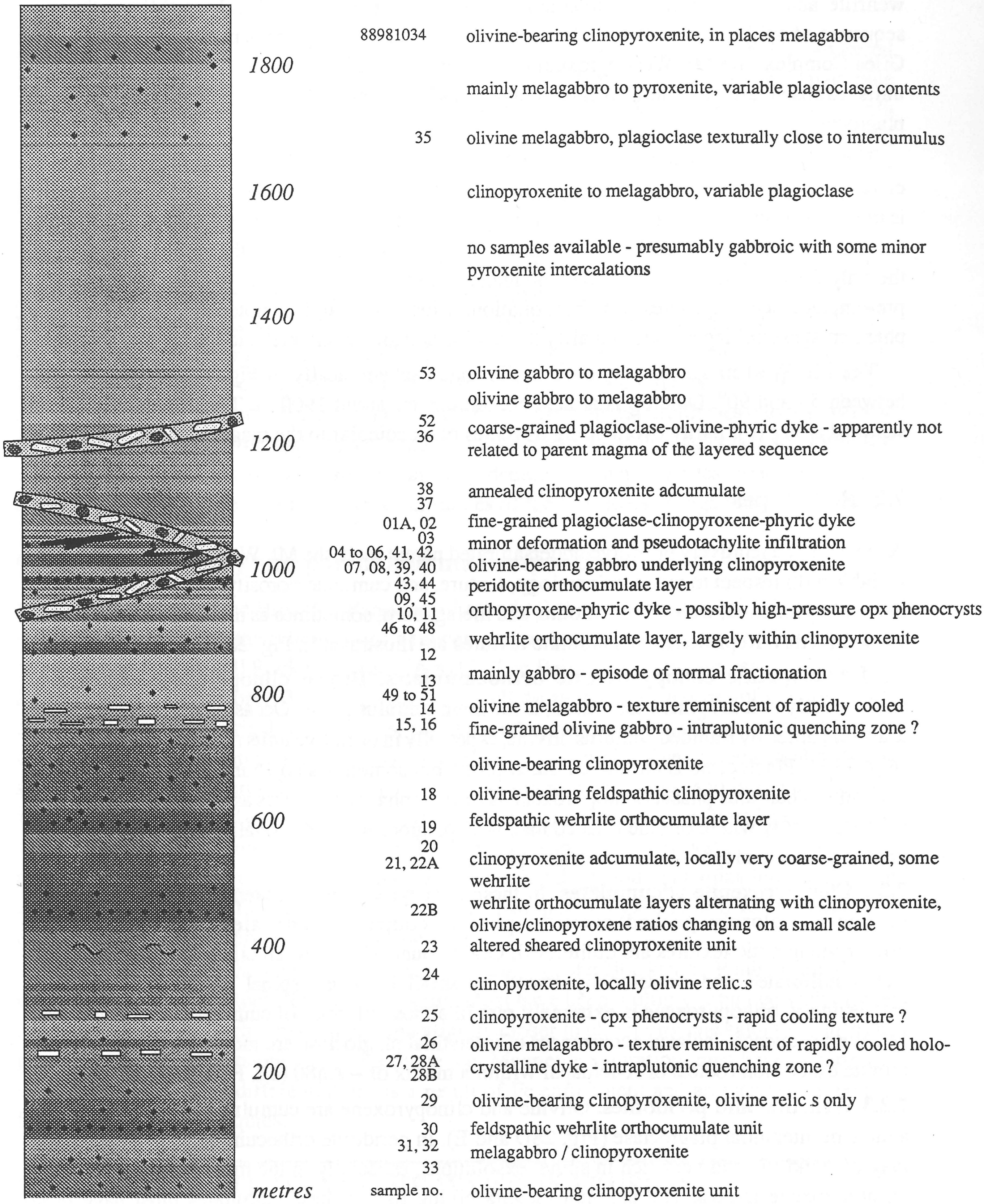



**Fig. 27. Stratigraphic sequence of the south Mt. West (The Wart) intrusion. The sequence is predominantly clinopyroxenitic with variable clinopyroxene/plagioclase ratios (illustrated by variable grey shades). The presence of olivine is denoted by black dots, inferred rapid cooling textures and stratigraphic positions where intraplutonic quenching may have occurred by open rectangles. The sampling traverse encountered several crosscutting dykes and some pseudotachylite veinlets. Stratigraphic elevations are not corrected for dip.**

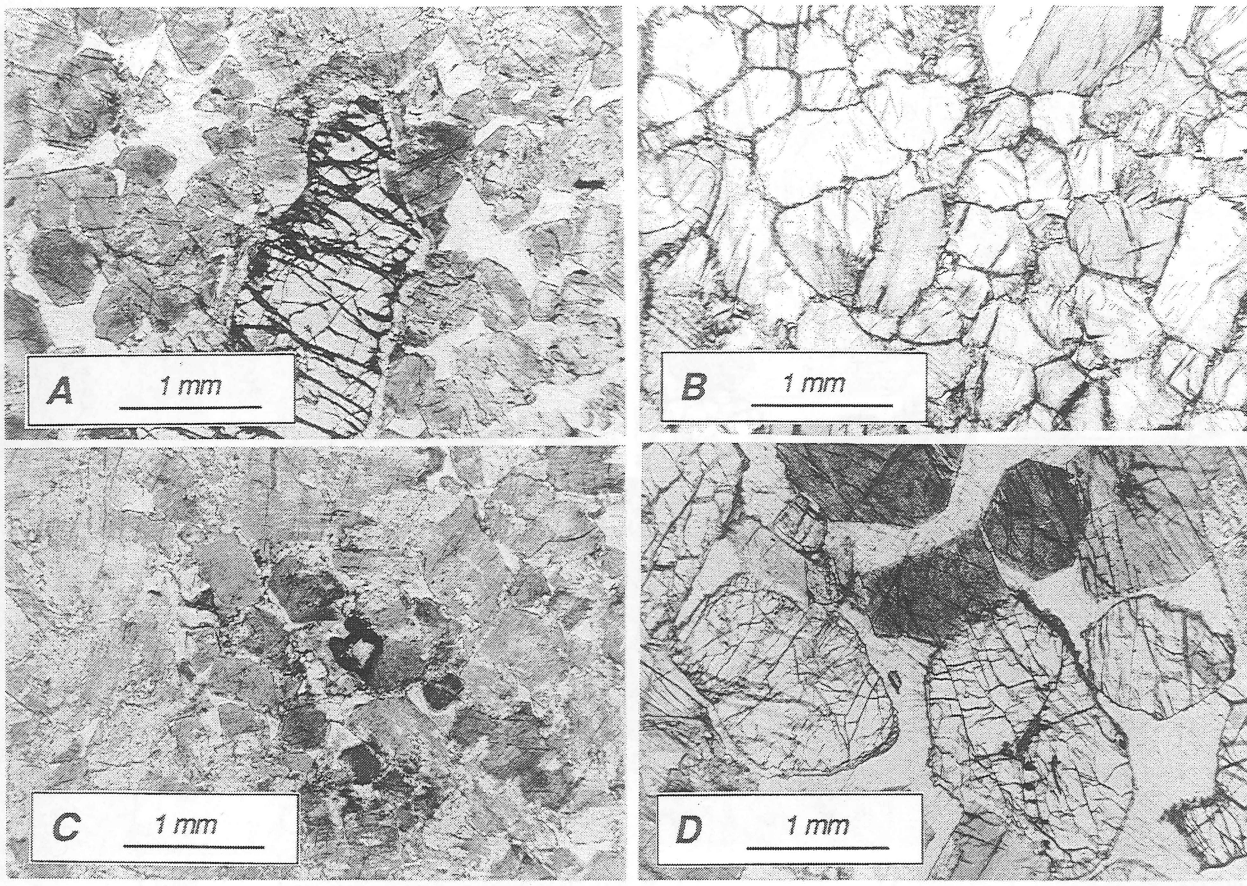



**Fig 28. Types of cumulates in the south Mt. West (The Wart) sequence.**
**A: Feldspathic olivine-bearing clinopyroxenite ortho-cumulate. Large rounded olivine, smaller roundish clinopyroxene rich in spinel exsolutions, colourless interstitial plagioclase. Olivine surrounded by a columnar orthopyroxene moat. Sample 88981033.**
**B: Annealed clinopyroxenite adcumulate. Clinopyroxene is free of spinel exsolutions. Traces of antiperthitic plagioclase. Sample 88981043.**
**C: Olivine-bearing clinopyroxenite mesocumulate. Altered olivine relic (dark), cumulus clinopyroxene with high density of spinel exsolutions, interstitial colourless plagioclase. Olivine relic partly reacted to columnar orthopyroxene. Sample 88981029.**
**D: Feldspathic wehrlite orthocumulate. Rounded olivine and subhedral brownish clinopyroxene rich in spinel exsolutions are cumulus phases, altered zoned plagioclase interstitial. Sample 88981030.**

clinopyroxenite orthocumulates and olivine melagabbros, particularly in units where textures suggest rapid cooling.

**7.2.5 Dykes.** The Mt. West sequence is cut by at least three generations of dykes with differing phenocryst populations (Fig. 29). The most common type carries subhedral clinopyroxene and elongate plagioclase laths as phenocrysts, embedded in a fine-grained oxide-rich groundmass (Fig. 29A). Another common 'troctolitic' generation carries rounded olivine and elongate plagioclase as phenocrysts, set in a hydrated biotite-rich groundmass (Fig. 29B). The troctolitic dyke generation cannot be related chemically to any of the cumulates observed in Mt. West sequence, but may represent a parent melt to the more fractionated troctolitic cumulates such as the Bell Rock and Blackstone Range intrusions. One dyke contains elongate euhedral, peripherally resorbed orthopyroxene as the only phenocryst generation, together with (later) plagioclase microphenocrysts and oxides in the groundmass. Orthopyroxene may be a high-pressure intratelluric phase (Fig. 29C). The dyke itself is regarded as an example of high-pressure orthopyroxene fractionation of a basaltic magma.

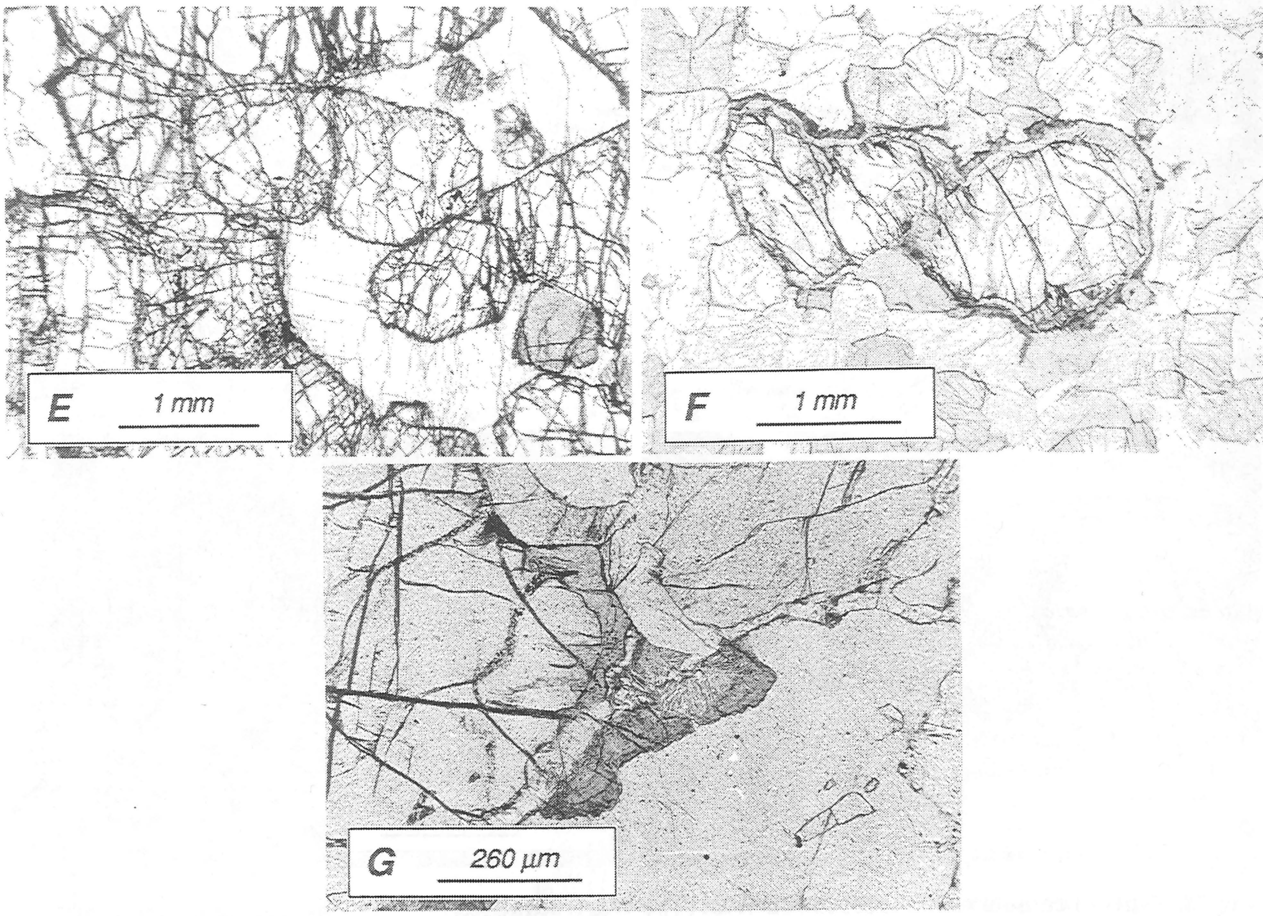



**Fig. 28 cont_d. Types of cumulates and subsolidus textures in the south Mt. West sequence.**
**E: Feldspathic peridotite orthocumulate. Rounded cracked olivine cumulus, clinopyroxene (brownish with spinel exsolutions) cumulus to poikilitic, zoned altered plagioclase interstitial. Sample 88981044.**
**F: Olivine gabbro to melagabbro. Rounded olivine surrounded by an inner moat of columnar clear orthopyroxene and an outer clinopyroxene-orthopyroxene-spinel symplectite layer. Clinopyroxene (free of spinel exsolutions) cumulus, colourless plagioclase cumulus to locally interstitial. Sample 88981049.**
**G: Subsolidus reequilibration textures at Mt. West. Cumulus olivine grains in olivine gabbro in contact with plagioclase are surrounded by an inner layer of columnar orthopyroxene and an outer discontinuous layer of 'cauliflower' orthopyroxene-clinopyroxene-spinel symplectites. Sample 88981039.**

## 7.3 Cryptic layering patterns

The cryptic layering patterns are illustrated in Fig. 30. and 31. The sampling density is not sufficient to define every modal change, but without doubt modal layering in the Mt. West sequence is due to several tens of small and medium-sized batches of primitive parent magma that were added to a continuously differentiating body of more fractionated melt.

Mg/(Mg+Fe) ratios of olivine range from 0.87 to 0.78 and are almost as primitive as in the Murray Range and Wingellina Hills sequences. Mg/(Mg+Fe) ratios of coexisting orthopyroxene are slightly higher. Clinopyroxene compositions, expressed in terms of Cr/(Cr+Al) ratios, are more fractionated than clinopyroxenes in analogous units of the Murray Range sequence. There is no evidence for cumulus chromite in the Mt. West sequence, probably because Cr was depleted by clinopyroxene fractionation. Plagioclase is extremely calcic with Ca/(Ca+Na) from 0.95 to about 0.55. The lower half of the sequence, until about the 1050 m level, signifies a period of multiple magma addition, while the upper half may indicate more stagnant conditions with less intrusive activity.

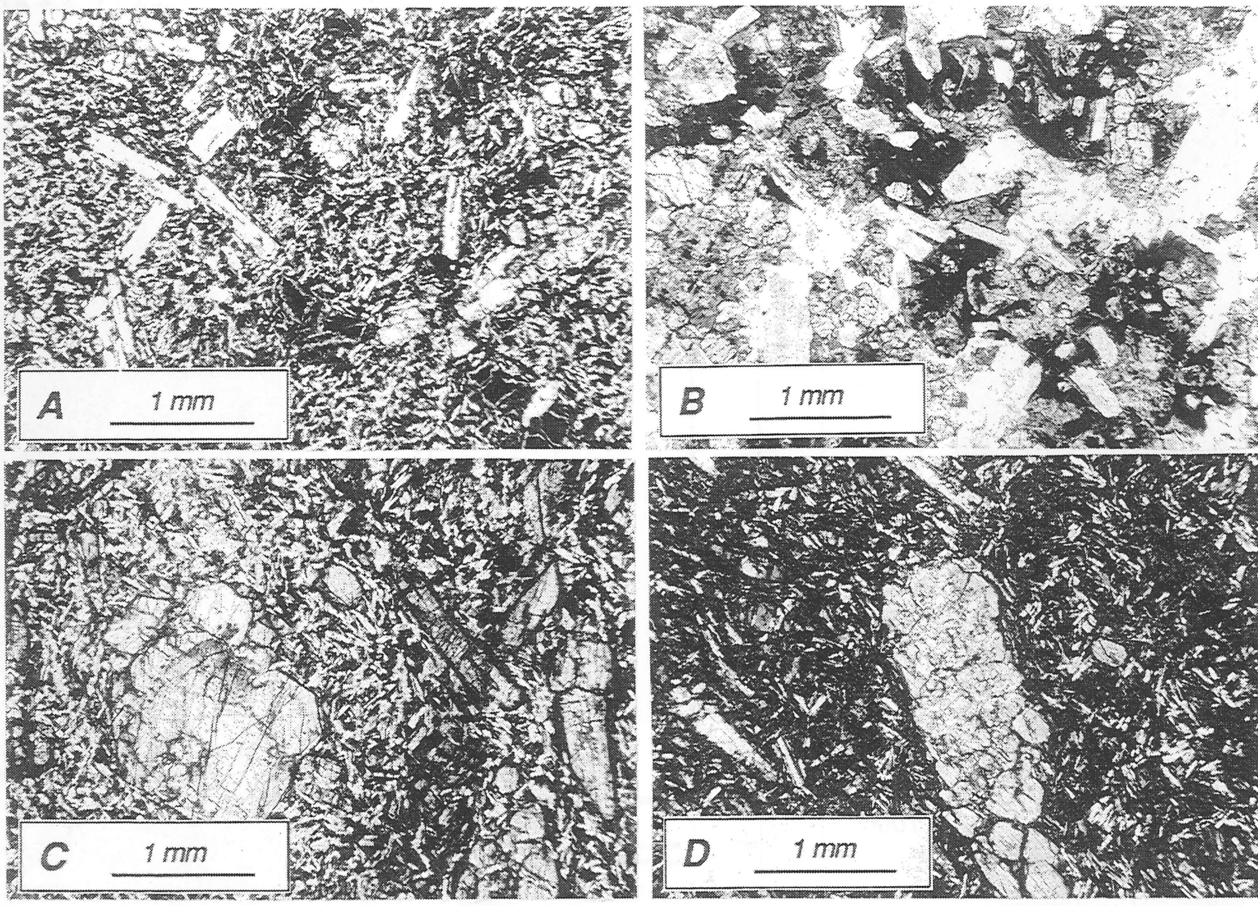



**Fig. 29. Dykes crosscutting the Mt. West layered sequence**
**A: Clinopyroxene-plagioclase-phyric fine-grained dyke. Elongate plagioclase and subhedral clinopyroxene are phenocrysts, set in an oxide-rich groundmass. Sample 88981037.**
**B: Coarse-grained olivine-plagioclase-phyric dyke. Large euhedral plagioclase laths and rounded smaller olivine grains (cracks) are phenocrysts, in brownish biotite-rich hydrated groundmass. This dyke composition is probably unrelated to the layered sequence. Sample 88981036.**
**C: Orthopyroxene-phyric high-pressure basaltic dyke. Intratelluric (?) orthopyroxene phenocrysts in groundmass rich in plagioclase and orthopyroxene microphenocrysts. Several generations of orthopyroxene; the equant grain in the centre is overgrown by a zoned rim, elongate orthopyroxene phenocrysts to the left. Sample 88981045.**

The stratigraphic orientation of the Mt. West sequence is not as ambiguous as in other intrusions of the Giles Complex. Pulses of new magma in the lower half have resulted in multiple cyclic units where sharp modal reversals to olivine-rich cumulates are followed by gradual changes back to pyroxenites and eventually melagabbros. The cyclicity is thought to result when dense olivine-rich liquid ponds on the magma chamber floor, where the first cumulates to form are peridotitic to wehrlitic. If this process is valid for the South Mt. West sequence, then sharp modal and cryptic reversals define the bottom of a new cyclic unit, whereas a gradual return in cryptic layering patterns to a periods of normal fractionation defines the upper part of a cycle.

## 7.4 Deformation and subsolidus equilibration textures

The Mt. West cumulates are largely undeformed, although many of the samples are strongly annealed (e.g. Fig. 28B). The sequence includes two very localized shear zones, one with some pseudotachylite veining. Cumulates in the vicinity of the shear zones are largely undeformed.

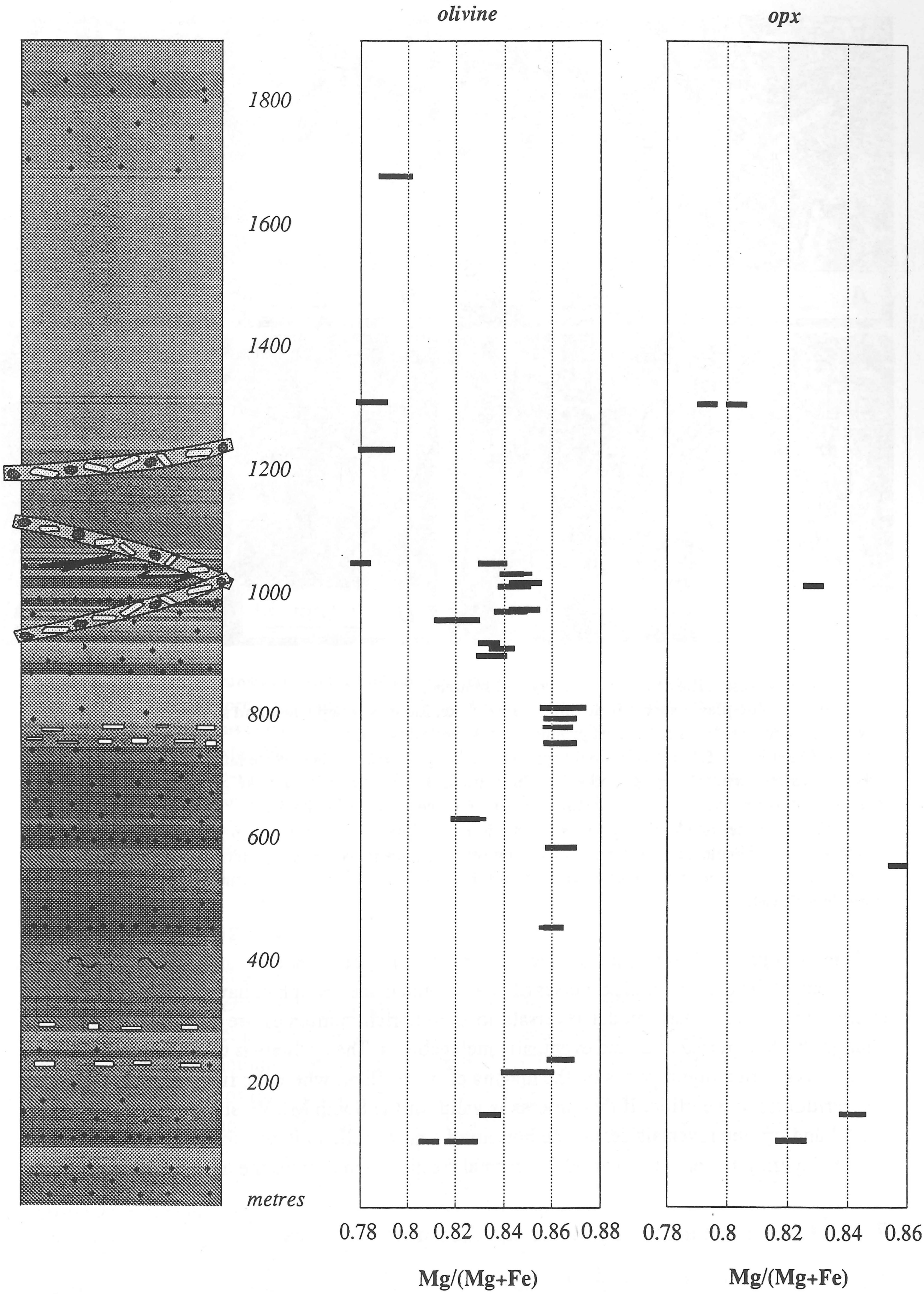
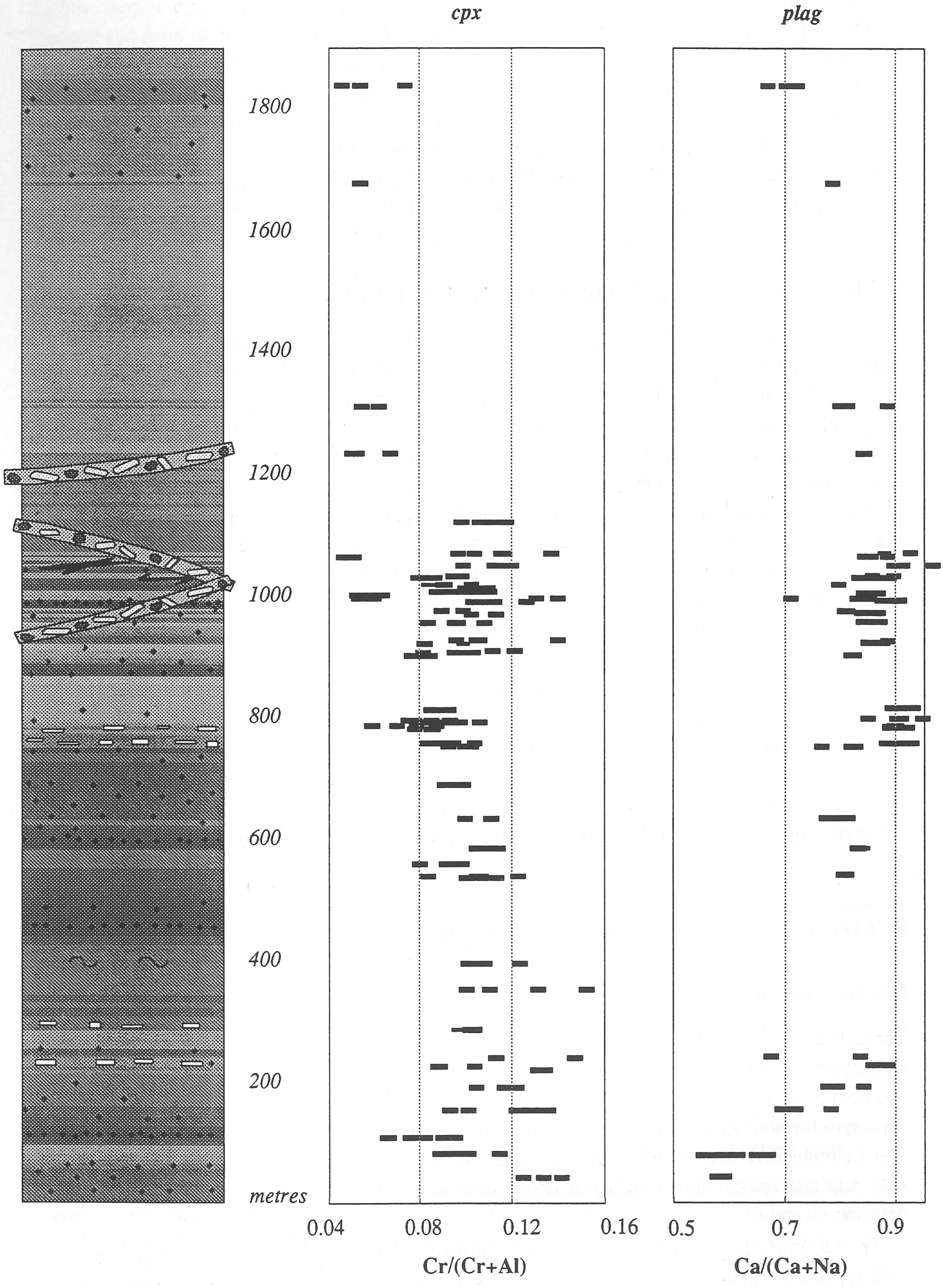



**Fig. 30 & 31. Cryptic layering in the south Mt West (The Wart) sequence.**

# MT. WEST (THE WART) INTRUSION SEQUENCE



Olivine is commonly surrounded by an inner rim of columnar orthopyroxene and an outer rim of fine-grained 'cauliflower' orthopyroxene-clinopyroxene± aluminous spinel symplectites, notably where olivine occurs in contact with plagioclase (Fig. 28G). Similar textures have been described from many medium-pressure olivine-plagioclase cumulates (Joesten, 1986; Ballhaus and Berry, 1991). Both the columnar orthopyroxene and the outer symplectite are believed to have formed by subsolidus equilibration. The columnar (spinel-free) orthopyroxene moat is thought to be a high temperature feature that formed when Al liberated by plagioclase breakdown was still able to migrate in the system by diffusion (>900°C). The outer symplectitic layer must have formed at a lower temperature when Al became largely immobile (<800°C) and precipitated in-situ at the reaction front as spinel.

## 7.5 Intrusive history and parent magma composition

The parent magma to the Mt. West intrusion is likely to have been a fairly primitive olivine-normative melt, although slightly more fractionated than the parent magma to the Murray Range intrusion and certainly not as primitive as the spinel-phyric dyke found to intrude the Hinckley Range intrusion. The most magnesian olivine in the South Mt. West sequence (Fo87) is slightly more fractionated than the most primitive olivine composition at Murray Range (Fo89). Clinopyroxene is also depleted in Cr compared with early-magmatic clinopyroxene at Murray Range, in good agreement with the observation that cumulus spinel is apparently absent. The magma may have experienced some limited pyroxene fractionation before it was emplaced in the magma chamber, and was very close to clinopyroxene saturation at the time of emplacement. Its crystallization sequence, best reflected in the most primitive orthocumulate units (Fig. 28E) is believed to have been (1) olivine + clinopyroxene, (2) clinopyroxene + olivine, (3) clinopyroxene + plagioclase + olivine. Chromite does not appear as a liquidus phase, possibly because Cr was depleted by early high-pressure pyroxene fractionation.

There is evidence in some horizons for rapid cooling, although textures are more ambiguous than in other intrusions of the Giles Complex (c.f. Bell Rock Range intrusion). In a number of cumulate layers, cumulus clinopyroxene is present in a distinctly bimodal grain size distribution. A similar observation was made in relation to orthopyroxene-rich cumulates of the Murray Range intrusion where the bimodal grain size distribution was attributed to rapid cooling (c.f. section 3.2.1.).

# 8 THE LATITUDE HILL INTRUSION

## 8.1 Magmatic sequence

The Latitude Hill intrusion is one of the thickest cumulate sequences of the entire Giles Complex. If there are no tectonic repetitions – a possibility that cannot be ruled out from field observations – it comprises almost 8000 m of layered gabbros and pyroxenites. Structurally, it appears to belong to the southern cumulate units of the Michael Hills gabbroic intrusion (Daniels, 1974). The Latitude Hills sequence has been sampled along three separate but consecutive traverses with minimal stratigraphic overlap or lateral displacement. Dips of the magmatic layers vary between 80 and 90°.

The schematic sequence of the Latitude Hill intrusion is shown in Fig. 32. The most common rock types are gabbros and microgabbros with unusually immature cumulate textures, termed

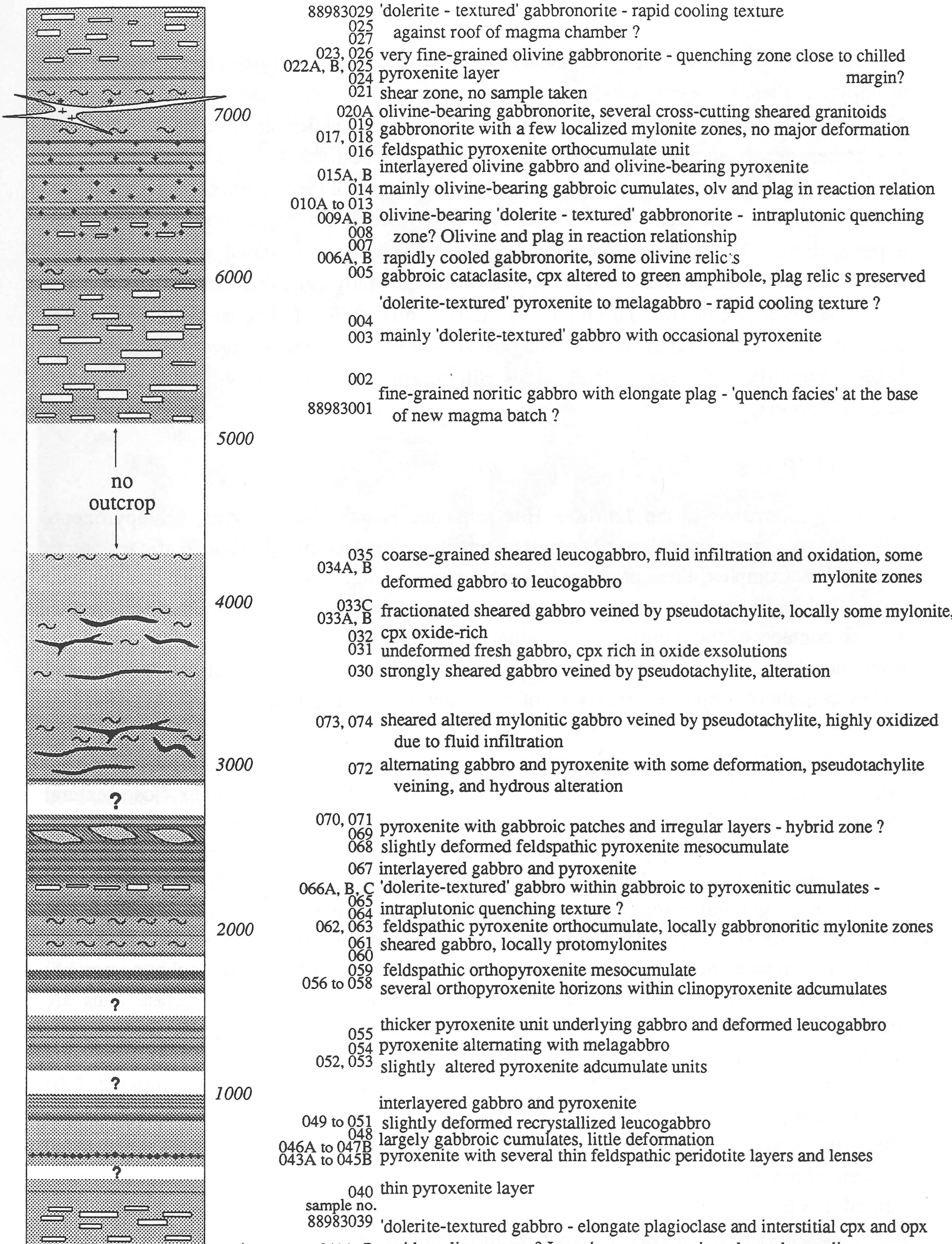



**Fig. 32. Magmatic stratigraphy of the Latitude Hill intrusion. The sequence is predominantly gabbroic with several pyroxenite intercalations (darker shading). Olivine (black dots) is most common in the upper part of the sequence, and 'doleritic-textured' gabbro (open rectangles) occurs at several elevations. The central units are highly deformed and veined by pseudotachylite (black veins). One crosscutting granitic vein was encountered at the 7000 m elevation.**

'doleritic-textured' in Fig. 32, along with 'normal' (cumulate-textured) gabbros, orthopyroxenites, and rarely olivine-bearing ultramafic cumulates. It is debatable whether the cumulates exposed at Latitude Hill represent one continuous and genetically coherent sequence, or whether the sequence is composite with up to three genetically and temporally different units superimposed onto each other. Rock types of the central part of the sequence (from about 2900 to at least 4250 m) are highly deformed and far more fractionated than cumulates of lower and upper sections. The underlying and overlying cumulates are undeformed except along some localized shear zones, significantly more mafic, and texturally quite different from the central deformed sliver (see below). This highly deformed central section (on aerial photo 34/125) has many macroscopic, textural, and mineralogical similarities with basic enclaves within outcrops of felsic granulite to the east of the Latitude Hill intrusion. As such it may predate the layered sequence proper.

## 8.2 Rock Types

A large proportion of the Latitude Hill sequence is gabbroic. Olivine, clinopyroxene, orthopyroxene, and plagioclase all coexist as cumulus phases. Unlike the more mafic sequences in the Giles Complex, there are very few monomineralic units. Most rock types observed are texturally highly immature compared with conventional cumulates, especially near the bottom and top contacts of the intrusion. Texturally, the Latitude Hill intrusion features all transitions from quenched dykes and sills, coarser-grained microgabbro enclaves and chilled margins, and mature cumulates. Representative types of cumulates and cooling textures are illustrated in Fig. 33.

**8.2.1 'Doleritic-textured' gabbronorites.** Included in this group are olivine-bearing gabbronorites where the prefix 'doleritic-textured' serves to emphasize their close textural resemblance with rapidly cooled basaltic dykes. Large elongate plagioclase laths make up approximately 50 volume percent. Clinopyroxene and occasionally olivine occur as much smaller rounded cumulus multi-grain aggregates interstitial to plagioclase laths. Texturally, these intercumulus aggregates appear to have been 'squeezed' by rapidly growing plagioclase into remaining interstitial positions. Orthopyroxene, where present, is slightly later in the crystallization sequence than clinopyroxene. It tends to form poikilitic grains that commonly emanate from cumulus olivine and clinopyroxene grain aggregates. Plagioclase laths are impregnated ('dusted') with submicroscopic brownish inclusions, commonly present in a spectacular density especially near the centres of plagioclase grains.

Fig. 33 illustrates a series of textural transitions from fine-grained 'doleritic-textured' cumulates close to the margins of the intrusion, to mature gabbroic and pyroxenitic cumulates. 'Doleritic-textured' gabbros (Fig. 33A to D) are most abundant toward the bottom and top contacts of the western and the eastern sections of the sequence. They are interpreted to have formed in a high thermal gradient as a result of heat loss to the cooler granulite-facies country rocks. Occasionally, 'doleritic- textured' gabbros also occur within the stratigraphic sequence, notably at levels where one can infer from reversals in the cryptic layering patterns that the magma chamber had experienced a replenishment episode (intraplutonic quenching). The doleritic textures illustrate well the locally exceptionally high cooling rates in some intrusions of the Giles Complex, already postulated for the Wingellina Hills intrusion (Ballhaus and Glikson, 1988) on the basis of much less convincing textural evidence.

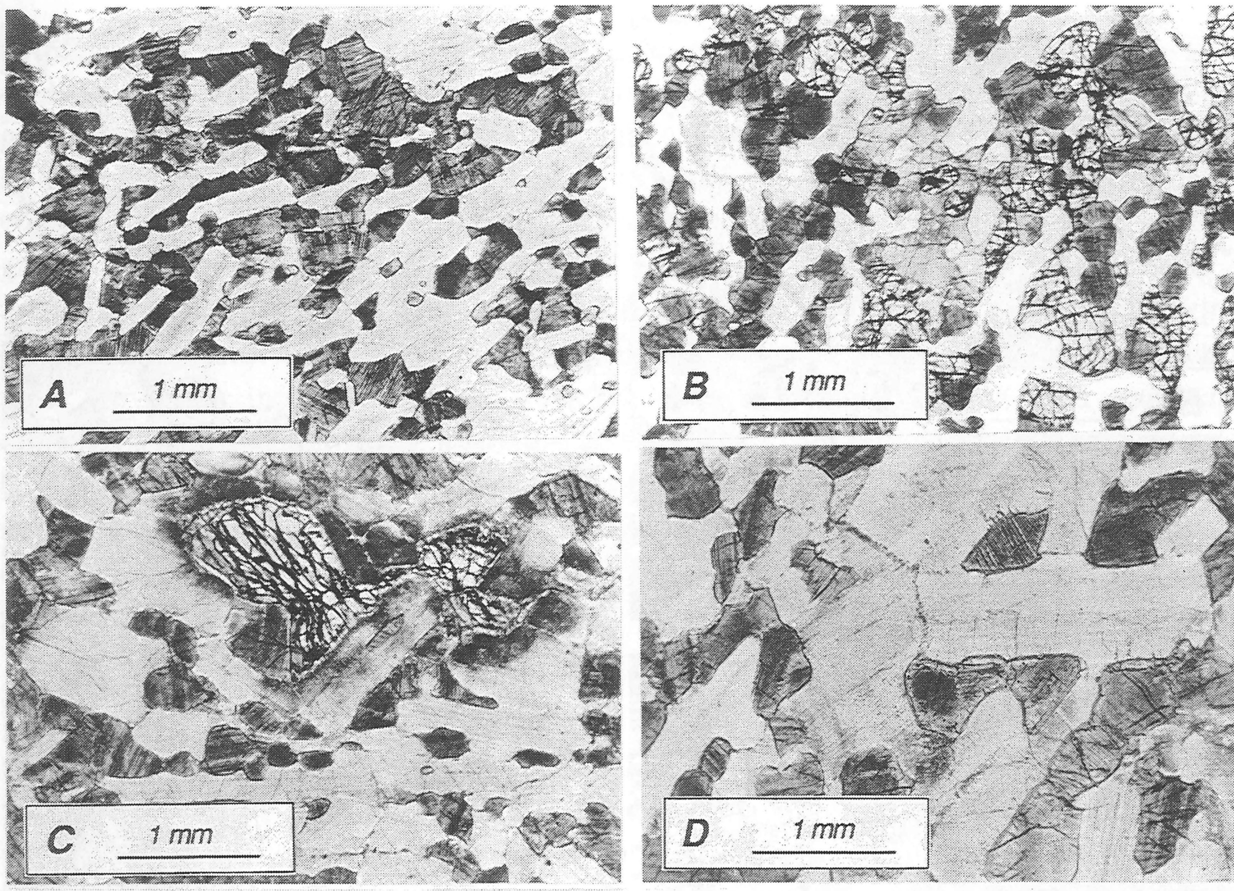



**Fig. 33: Cumulate and cooling textures of the Latitude Hill Intrusion**
**A: Fine-grained 'doleritic-textured' laminated olivine-bearing gabbronorite. Elongate plagioclase laths are impregnated with submicron-sized opaque inclusions, i.e. particles that may result from exsolution of 'foreign' material (Fe?) trapped in the lattice of rapidly growing plagioclase. Pyroxenes close to interstitial positions and also 'dusted' with finest-grained opaque inclusions and exsolutions. Sample 88983021.**
**B: 'Doleritic-textured' olivine gabbronorite. Olivine (dark cracks) and 'dusted' plagioclase are cumulus throughout, pyroxenes cumulus to poikilitic. Clinopyroxene much darker than orthopyroxene (richer in sub-microscopic impurities). Sample 88983023.**
**C: Coarser-grained 'doleritic-textured' olivine gabbro. Plagioclase impregnated by impurities, pyroxenes largely interstitial. Plagioclase in contact with olivine clouded with small greenish inclusions, probably clinopyroxene, as a result of Fe-Mg diffusion and reaction of Fe and Mg with anorthite in plagioclase. Sample 88983013.**
**D: Coarse-grained doleritic-textured gabbronorite. Euhedral plagioclase laths impregnated by impurities that recrystallize along grain boundaries as small clinopyroxene neoblasts. Primary-magmatic clinopyroxene and orthopyroxene largely 'squeezed' into interstitial positions, clinopyroxene darker than orthopyroxene (richer in opaque inclusions). Sample 88983008.**

**8.2.2 Pyroxenites.** Orthopyroxene and clinopyroxene are cumulus phases, occasionally accompanied by a few slightly altered olivine grains (Fig. 33E and F). Pyroxenes mostly occur in a distinctly bimodal size distribution (like ultramafic units within the Murray Range intrusion), with orthopyroxene forming elongate laths much coarser-grained than clinopyroxene. Occasionally, olivine may join as a minor cumulus phase, then coexisting with cumulus orthopyroxene grains. Plagioclase contents are highly variable from less than 2 (in pyroxenite adcumulates) up to 40 modal percent where feldspathic orthocumulates grade into melagabbros. On a centimetre scale pyroxenite adcumulates may contain finer-grained feldspathic orthocumulate pockets in which plagioclase is so abundant that it is close to becoming a cumulus phase. Like plagioclase, pyroxenes may also be impregnated by submicroscopic opaque inclusions, sometimes in such spectacular density that they mask birefringence colours.

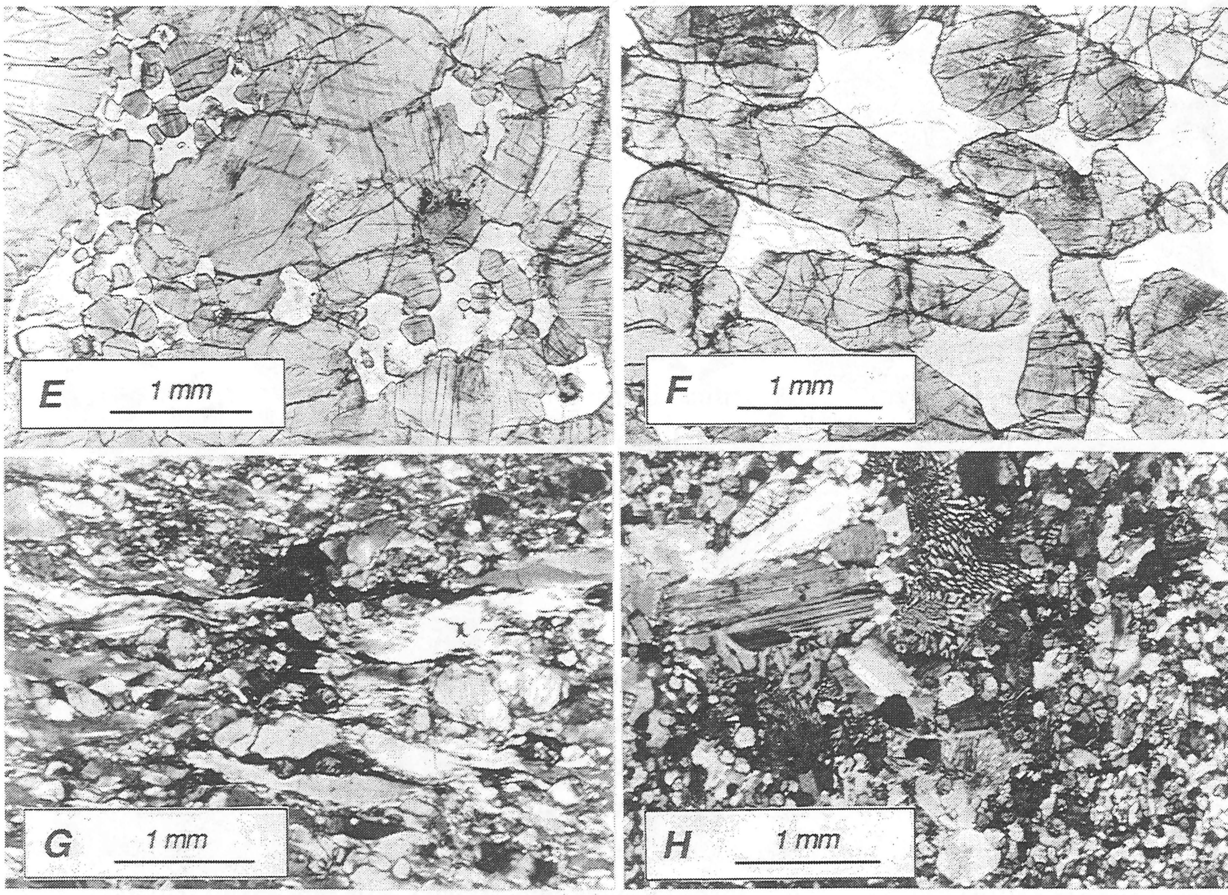



**Fig. 33 cont_d. Cumulate and deformation textures in samples of the Latitude Hill Intrusion**
**E: Mature pyroxenite adcumulate with feldspathic orthocumulate pockets (mottled appearance in the field). Both orthopyroxene and clinopyroxene cumulus. Sample 88983015B.**
**F: Feldspathic pyroxenite orthocumulate, locally olivine-bearing (olivine not shown). Orthopyroxene and clinopyroxene are cumulus, plagioclase is interstitial. The slightly porphyritic phase is orthopyroxene. In these mature cumulates, plagioclase is virtually free of impurities, probably because of slower cooling rates. Sample 88983051.**
**G: Gabbroic mylonite to proto-mylonite. Relict plagioclase and clinopyroxene porphyroclasts in altered matrix of plagioclase fragments. Infiltrated by pseudotachylite. Common texture in section 34/125. Sample 88983035.**
**H: Marginal microgabbro (chilled margin?). Euhedral small plagioclase, orthopyroxene, and clinopyroxene. Several quartz-K-feldspar myrmekites that may be due to contamination by acidic contact-metamorphic melts from heated acidic granulites. Sample 88983041A.**

**8.2.3 Feldspathic peridotites.** Peridotite cumulates are only observed at about the 600 m elevation. Olivine, orthopyroxene, clinopyroxene, and chromite are all cumulus phases, while highly altered zoned sodic plagioclase is interstitial. Peridotite cumulates are not nearly as mafic as in the primitive suites of the Murray Range or Wingellina Hills intrusions where olivine and chromite are commonly the only cumulus phases.

**8.2.4 Gabbros and anorthosites of the central section.** This section differs markedly from gabbros of the lower section and upper section . The major rock types are fractionated oxide-bearing gabbros and anorthosites, mostly highly deformed and veined by pseudotachylite (Fig. 33G and H). Plagioclase is the most abundant cumulus phase, followed by cumulus to intercumulus clinopyroxene and less commonly orthopyroxene. In samples where the original cumulus texture is preserved, clinopyroxene is commonly enriched in opaque oxide exsolutions and very iron-rich. The sequence also comprises several anorthositic units where the total pyroxene content is less than 10 volume percent, several formerly gabbroic horizons where all textural evidence for a magmatic history is obliterated, a number of stratabound enclaves of felsic granulites, and numerous occurrences of granitic to aplitic veins. The central section of the Latitude Hill sequence is tentatively interpreted to predate the deposition of cumulates from the other sections. It may be contemporaneous with gabbroic enclaves within the deformed granulites east of the Latitude Hill sequence.

**8.2.5 Marginal rock types.** The Latitude Hill intrusion is one of the few intrusions with demonstrably intrusive contacts with a small granulite occurrence to the east. The marginal rock types are fine-grained microgabbros where distinctly euhedral plagioclase laths, rounded clinopyroxene, and orthopyroxene are cumulus phases. In addition, they also contain coarser-grained enclaves with larger euhedral cumulus phases and myrmekitic quartz-orthoclase segregations (Fig. 33H). These segregations are either fractionated late-stage differentiates concentrated in larger pools prior to complete solidification, or granitic liquids that were derived from partial melting of felsic granulites.

## 8.3 Cryptic layering patterns

Stratigraphic variation plots of mineral compositions are shown in Fig. 34 and 35. The Latitude Hill sequence is significantly more fractionated than the primitive sequences at Murray Range or at Wingellina Hills. Olivine is present only in a series of thin peridotite layers at 610 m and in olivine gabbros and olivine-bearing pyroxenites of the central section. Mg/(Mg+Fe) ratios of olivine range from about 0.83 to 0.67. Mg/(Mg+Fe) ratios of orthopyroxene range from about 0.58 in the deformed gabbroic units of the central section, to up to 0.85 in the most primitive units of the central and eastern sections. Orthopyroxene Mg/(Mg+Fe) ratios are slightly higher than in coexisting olivines. Ca/(Ca+Na) of plagioclase ranges from about 0.5 to up to 0.9, and varies coherently with orthopyroxene. Cr/(Cr+Al) in clinopyroxene rarely exceeds 0.1, probably because the magma had experienced considerable Cr depletion by pre-emplacement pyroxene fractionation.

There are two major smooth reversals in orthopyroxene and plagioclase compositions that may coincide with prolonged episodes of magma addition and open-system crystallization. Each reversal is followed by a similarly extensive period of normal fractionation during which the intrusion reverted to magmatically stagnant conditions. It is not clear why olivine is so rare in the cumulates of the eastern section despite their comparatively mafic character. In fact, the average orthopyroxene in the lower units is slightly more magnesian than orthopyroxene that coexists with cumulus olivine in the upper part of the sequence. Abrupt changes in modal mineralogy and megascale layering are rare, even where there is evidence for magma replenishment.

In the Latitude Hill intrusion, the choice of the vertical orientation of the three traverses in Fig. 32 is entirely arbitrary. There is no textural indication as to where the bottom and where the top contact may be, nor do the symmetrical chemical fractionation patterns provide any clue as to which way chemical fractionation may have proceeded. The gabbroic units of the central section are significantly more fractionated than the 'underlying' and 'overlying' cumulate series of the other sections, corroborating the previous suggestion that these units may belong to an older gabbroic enclave within the granulite-facies terrane.

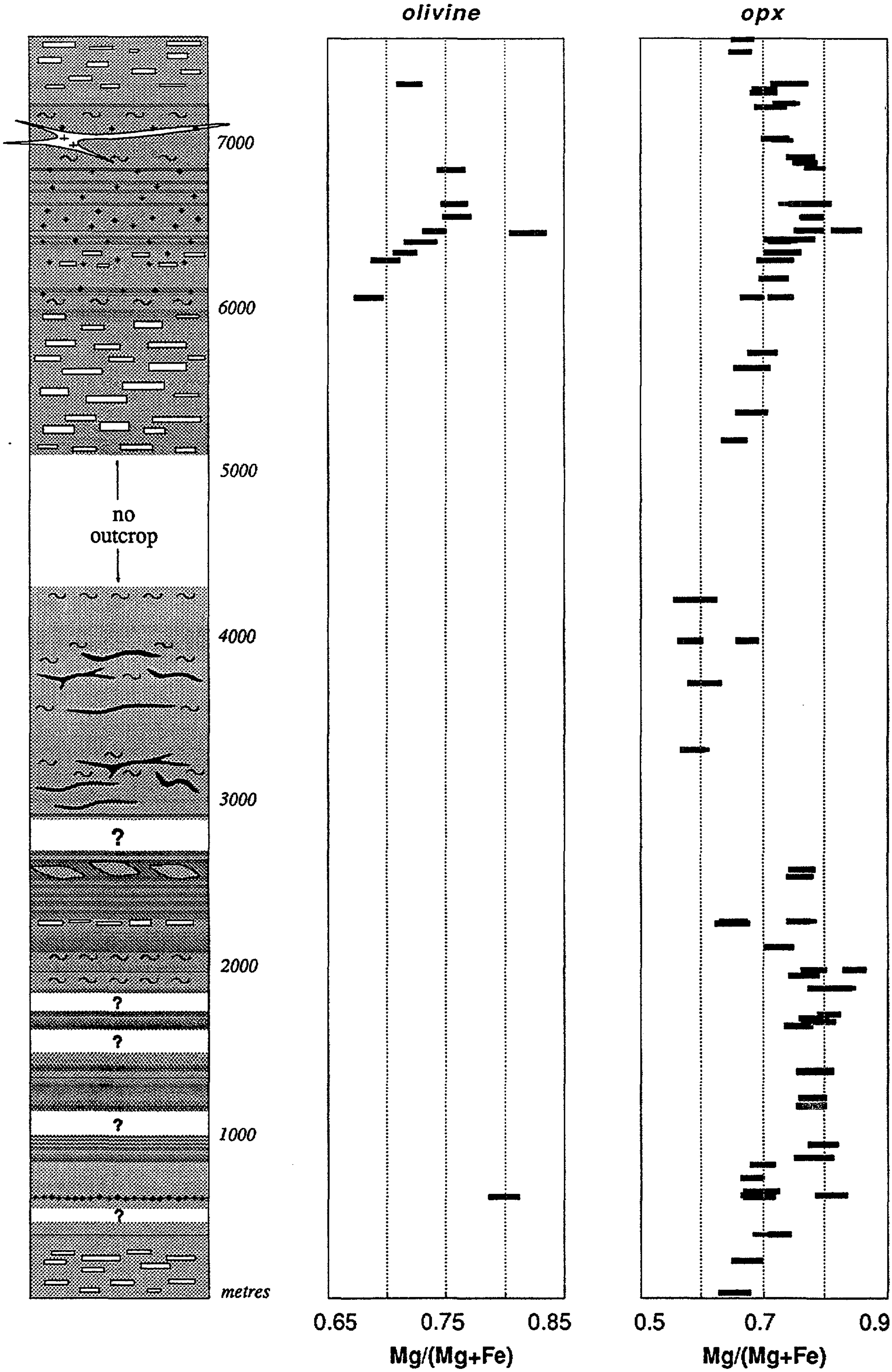
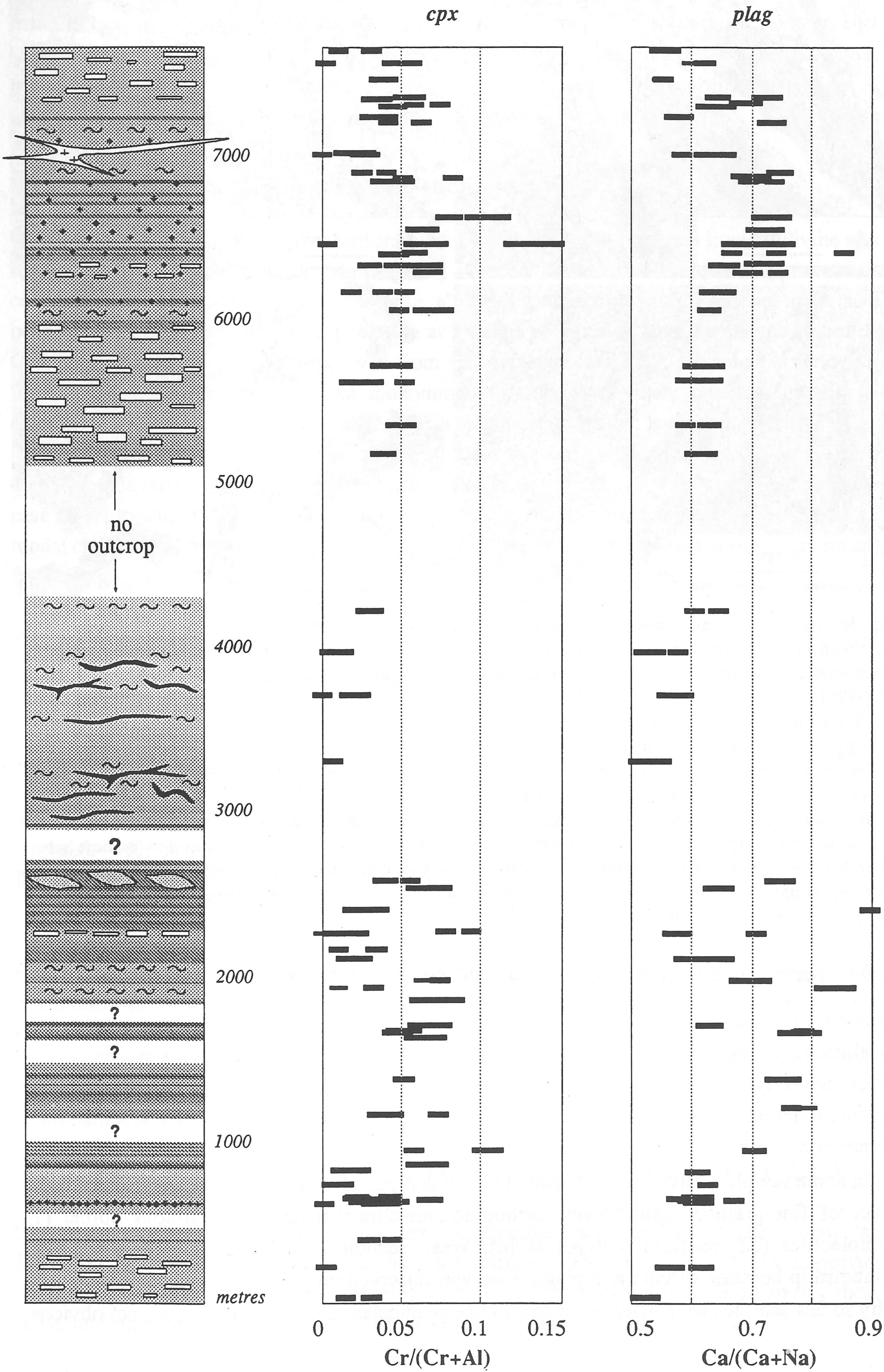



**Fig. 34 and 35: Cryptic layering patterns within the Latitude Hill intrusion.**

# LATITUDE HILL SEQUENCE



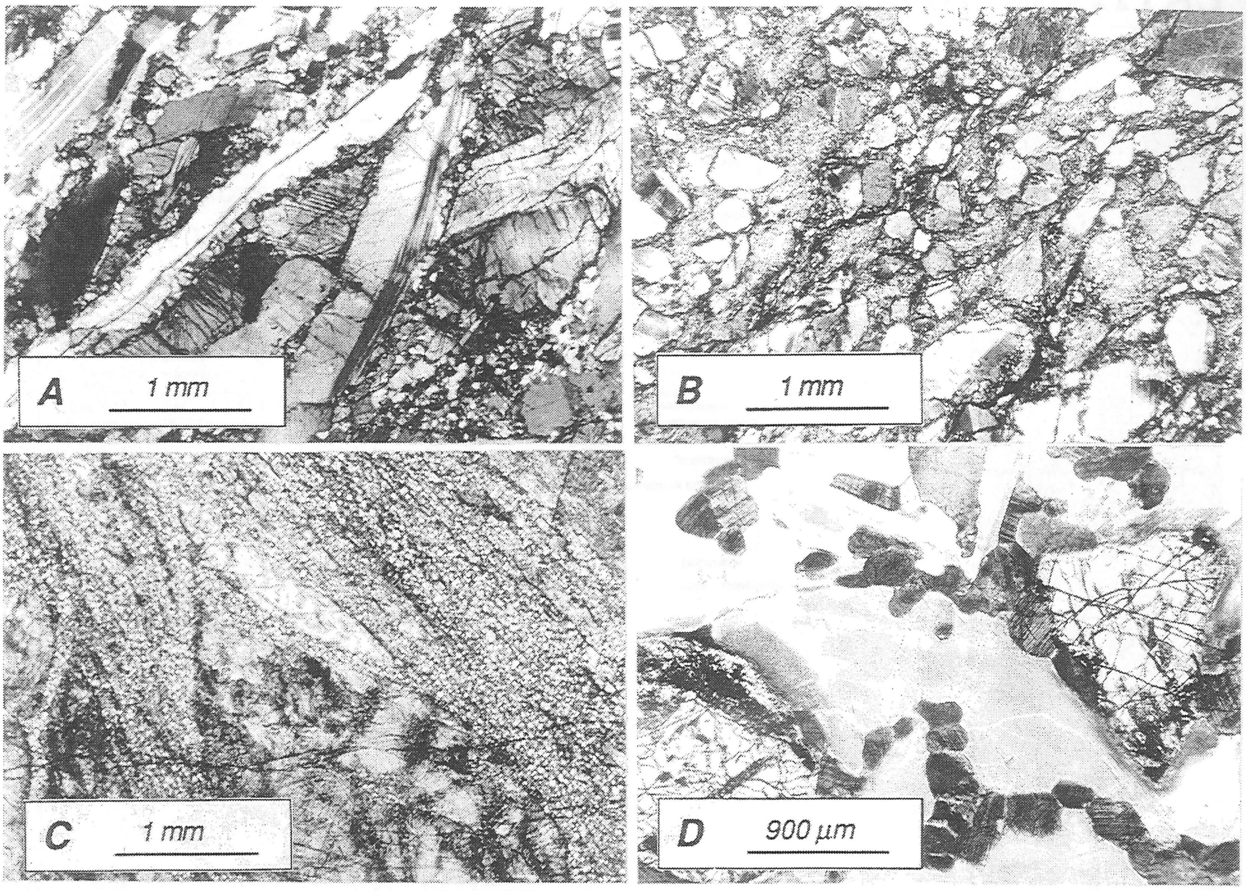



**Fig. 36. Deformation and subsolidus textures in the Latitude Hill cumulates.**
**A: Sheared gabbronorite in proto-mylonitic texture. Incipient granulation along plagioclase grain boundaries, clinopyroxene largely broken up to smaller fragments or recrystallized to neoblasts. Sample 88983061.**
**B: Gabbroic cataclasite. Angular fragments of plagioclase in matrix of actinolitic amphibole (replaced clinopyroxene fragments?). Sample 88983005.**
**C: Mylonite in pyroxenite. Porphyroclastic 'augen'-textured pyroxene cumulus relic s in matrix of small clinopyroxene neoblasts and fragments. Sample 88983066C.**
**D: Reaction texture between olivine and plagioclase in a 'doleritic-textured' immature olivine gabbronorite. Plagioclase in contact with olivine clouded by clinopyroxene inclusions that coarsen and become more abundant toward olivine (subsolidus Fe-Mg diffusion out of olivine and reaction with Ca in plagioclase?). Primary-magmatic clinopyroxene as rounded grains along grain boundaries between plagioclase, clouded by opaque inclusions. Sample 88983008.**

## 8.4 Deformation and subsolidus equilibration textures

In addition to the highly deformed central unit, the Latitude Hill sequence comprises a few localized shear zones (Fig. 36). In these zones, cataclastic deformation predominates over ductile deformation styles, suggesting that deformation temperatures may have been comparatively low. In cumulates affected by shearing, clinopyroxene is commonly replaced by greenish-blue amphibole.

In some samples, olivine is surrounded by a columnar orthopyroxene rim and then an outer layer of fine-grained 'cauliflower' orthopyroxene-clinopyroxene ± aluminous spinel (?) symplectites (c.f. reaction textures at Mt. West, section 7.4). However, such a reaction relationship between olivine and plagioclase was observed only in three samples. The reason why so few samples were affected by the olivine-plagioclase subsolidus reaction is not obvious.

In some cumulates, grain boundaries between plagioclase are traced by tiny clinopyroxene neoblasts, especially in 'doleritic-textured' cumulates. These neoblasts are tentatively interpreted to result from granule exsolution of impurities trapped in rapidly growing plagioclase. However, Fe-Mg diffusion along grain boundaries followed by reaction with the anorthite component of plagioclase to form clinopyroxene cannot be ruled out with certainty.

## 8.5 Parent magma composition and cooling history

The Latitude Hill sequence crystallized from a relatively fractionated parent liquid. Olivine was replaced on the liquidus at an Mg/(Mg+Fe) ratio of around 0.67, and orthopyroxene is comparatively abundant. The parent magma, although saturated only with olivine, must have been very close to multiple phase saturation at the time of intrusion into the magma chamber. Compositionally, it was not far removed from a clinopyroxene-plagioclase cotectic. Evidence for this comes from the scarcity of monomineralic units even where reversals in mineral composition suggest that major volumes of fresh magma where added to the sequence. A change in modal mineralogy during replenishment episodes can only be expected if the replenished component is far removed from a cotectic (e.g. well within the olivine saturation field as in the case of Wingellina Hills). In cases where the added melt is close to multiple phase saturation, a modal change will result only if the mass ratio of added (primitive) to resident (more fractionated) melt is high.

The Latitude Hill intrusion is yet another excellent example of a multiply intrusive suite. It features all textural transitions from rapidly quenched chilled margin rocks, holocrystalline thick basaltic ('doleritic-textured') sills, and mature cumulates. The 'doleritic-textured' gabbros close to the margins of the intrusion are interpreted as intermediate in terms of cooling rate. The presence of minute opaque impurities in plagioclase and occasionally in pyroxene (Fig. 33B) is related to rapid crystal growth. A phase that crystallizes in a high thermal gradient is less capable of excluding foreign components from its lattice than a phase that grows slowly under equilibrium conditions. In the sequence of textures illustrated in Fig. 33A to F, impurities in plagioclase diminish with progressive 'maturation' of cumulate texture, entirely consistent with a diminishing cooling rate.

The crystallization sequence inferred from cumulate textures and mineral compositions apparently was (1) olivine + orthopyroxene (olivine-bearing pyroxenites), (2) orthopyroxene + clinopyroxene (pyroxenites), and (3) orthopyroxene + clinopyroxene + plagioclase (gabbronorites). The observation that olivine and orthopyroxene coexist as cumulus phases – without evidence for a peritectic reaction relationship with melt – indicate elevated crystallization pressure (c.f. section 3.5.). However, there may have been significant departures from equilibrium crystallization because of high thermal gradients (see section 9.3.3.).

# 9 ASPECTS OF THE PETROGENESIS OF THE GILES COMPLEX

Chemical fractionation patterns within the stratigraphic sequences investigated allow the deduction of crystallization sequences for each intrusion. They also place a few important constraints on the parental melts to the Giles intrusions, on chemical relationships among these melts, and on the emplacement history of the Giles Complex.

## 9.1 A single magma chamber?

It has been an important question in the past whether the cumulate occurrences comprising the Giles Complex are segments of one formerly continuous larger single layered intrusion (c.f. Sprigg and Wilson, 1959), or whether they are individual intrusions that formed from separate, possibly unrelated magma batches (Nesbitt et al., 1970, Daniels, 1974). The results of this work clearly rule out the first option, for several reasons:

- With the exception of the Bell Rock and Blackstone Range intrusions, there are too few similarities among the magmatic sequences to justify a stratigraphic correlation of intrusions with similar fractionation degrees.
- Many intrusions are characterized by the development of distinct quench facies along their margins, either in the form of rapidly crystallized immature cumulates or as genuine chilled margin rocks. This even applies to intrusions where the original intrusive contacts have been faulted away by later tectonic activity or where they are covered by alluvium. The presence of a marginal quench facies indicates that the present-day margins of the layered intrusions of the Giles Complex roughly coincide with the dimensions of the magma chambers.
- All intrusions investigated crystallized from different parent magma compositions. Within individual sequences, chemical differentiation involved progressive iron, silica, and alkali enrichment until olivine was replaced by orthopyroxene. In a regional context, however, olivine persists among the sequences from Fo89 (Wingellina Hills and Murray Range intrusions) to at least Fo50 (Blackstone, Bell Rock, and Jameson Ranges), and in one instance (Blackstone Range) down to Fo40. This is only possible if the parent melt compositions to the Giles intrusions differed at any given Mg/(Mg+Fe) ratio in their silica activity.

On that basis, it appears that all intrusions investigated are separate entities that crystallized from different batches of chemically different parental magmas. The present-day sizes of the intrusions approximately reflect the sizes of individual magma chambers. The geographic distribution of intrusions probably resembles the vertical distribution of individual magma chambers within the Proterozoic middle crustal section exposed in the Musgrave Block (see section 9.4).

## 9.2 The parental magmas to the Giles intrusions

Certain compositional characteristics of the parental melts to the Giles intrusions can be inferred by comparing and evaluating the crystallization sequences and fractionation trends within the intrusions. Structural transitions between dykes, sills, and cumulate layers strongly suggest that the extensive dyke swarms in the Tomkinson Ranges include melt compositions that qualify as parent melts. However, so long as a systematic chemical investigation of the dyke swarms is not available, one can infer parent melt relationships only from crystallization sequences within the cumulates.

**9.2.1 The primitive parental melt.** The Wingellina Hills, Murray Range, and South Mt. West (and possibly the Kalka and Ewarara intrusions) were all derived from an unfractionated, near-primitive tholeiitic magma. This magma was saturated with olivine and locally (Murray Range and Wingellina Hills intrusions) with aluminous spinel. As it evolved in the respective magma chambers, orthopyroxene replaced olivine on the liquidus at a relatively high Mg/(Mg+Fe) ratio of 0.78 to 0.77, suggesting that the melt may have been just olivine-normative. The most primitive olivine composition observed is Fo88 - Fo89. The melt from which this olivine crystallized must have been in near- equilibrium with its upper mantle source. High Cr in cumulus clinopyroxene and orthopyroxene and Ni in olivine are also consistent with this magma not having experienced any significant olivine or pyroxene fractionation prior to emplacement in the crustal reservoirs.

**9.2.2 The gabbroic parental melt.** The gabbroic intrusions with little ultramafic components (Hinckley, Latitude Hill, and probably Michael Hills intrusions) apparently formed from multiply-saturated fractionated parental melts. With the exception of the Latitude Hill and possibly Michael Hills sequences, monomineralic cumulate layers are minor or absent. It appears that prior to emplacement, the parent magma to the gabbroic intrusions was saturated with olivine ± orthopyroxene and clinopyroxene, and very close to being saturated with plagioclase. A relatively primitive example of that melt may be represented by the Latitude Hill sequence where plagioclase-poor pyroxenites are relatively common rock types. By the time the Hinckley Range sequence formed, however, the parental melt had evolved further and was saturated also with plagioclase. Overall, the gabbroic parent magma had experienced appreciable fractionation relative to the primitive mantle melt. The most primitive olivine compositions are Fo83 (Latitude Hill) and Fo75 (Hinckley Range), to become replaced by orthopyroxene at Fo67 (Latitude Hill) and below Fo56 (Hinckley Ranges). Cr was also significantly depleted relative to the primitive mantle liquid in the gabbroic parental melt. Cr/(Cr+Al) in clinopyroxenes from the Latitude Hill sequence is highly variable up to 0.15, while in the Hinckley Range Cr in clinopyroxene is below the microprobe detection limit.

**9.2.3 The troctolitic parental melt.** The troctolitic intrusions (Bell Rock, Jameson, and Blackstone Range intrusions) were derived from highly fractionated olivine-plagioclase ± magnetite-saturated melts. That melt was so evolved that with progressive fractionation, olivine in the stratigraphic sequences showed no tendency to be replaced by orthopyroxene; in fact, orthopyroxene is as rare in the most Fe-rich cumulates as it is in the most primitive samples. The melt must have been sufficiently enriched in ferrous iron that olivine and orthopyroxene were in cotectic relationship (c.f. Bowen and Schairer, 1935). Bulk silica content of the fractionating phases must have been higher than the silica content of the melt, in order to prevent silica enrichment during differentiation. As a result, modal orthopyroxene did not increase relative to modal olivine with protracted fractionation, in contrast to all other intrusive suites of the Giles Complex. Interestingly, the magma must have been very low in normative clinopyroxene in comparison with the gabbroic parental melts, and this despite the observation that clinopyroxene increases in modal abundance with falling Mg/(Mg+Fe) ratio in the gabbroic intrusions (Hinckley Range or Latitude Hill).

## 9.3 Chemical relationships among the parent melts

Source heterogeneities or differences in the degree of melting of a common mantle source are obscured by both the high pressure fractionation and the shallower level fractionation of the magma. It is not possible to derive the range of parental melts of individual intrusions from one common precursor melt by fractionating the phases that occur as cumulus phases in the Giles intrusions. The principal argument against one large formerly continuous layered complex is that olivine persists as a phase from the ultramafic down to the troctolitic sequences, although within individual sequences olivine was replaced by orthopyroxene when Mg/(Mg+Fe) ratios became

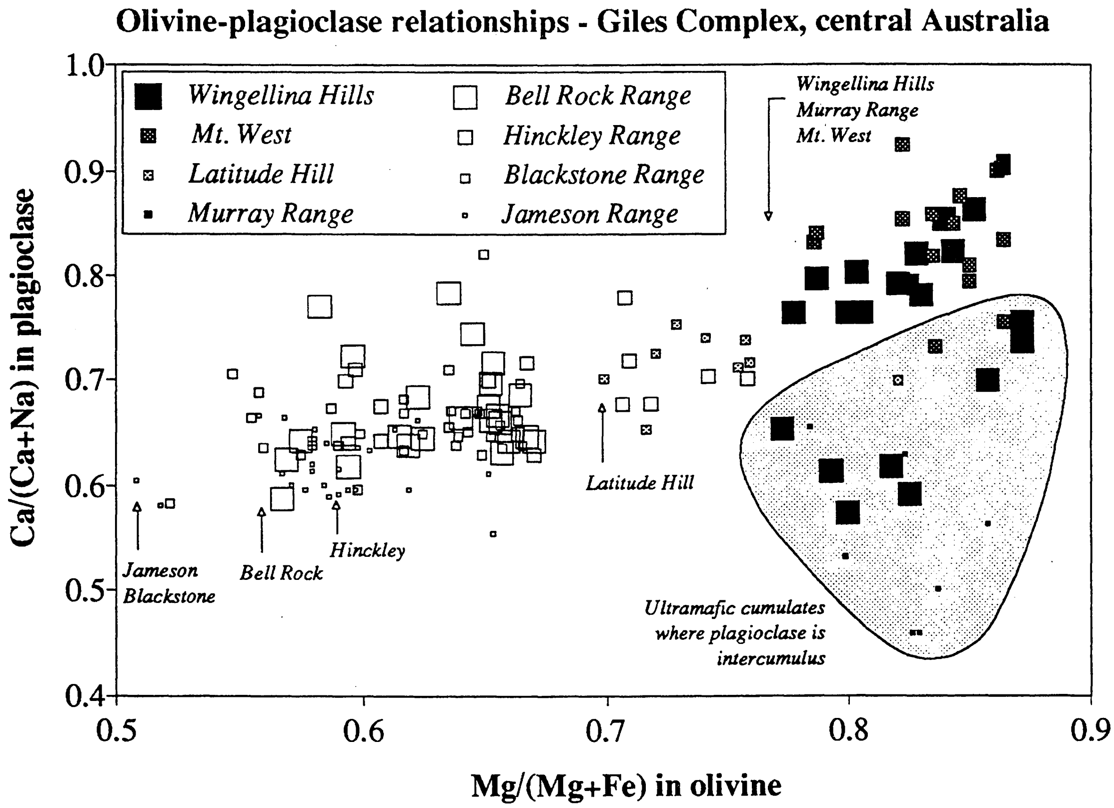



**Fig. 37. Chemical relationships between olivine and plagioclase in cumulates of the Giles Complex (olivine-plagioclase pairs are averages of several microprobe analyses). Marked by arrows are the approximate compositions of the most fractionated olivine compositions observed in each intrusion. These compositions coincide with the point in fractionation history where olivine became replaced by orthopyroxene from the liquidus. The trend, in particular the shift of the olivine-melt peritectic to progressively lower Mg/(Mg+Fe) ratios is consistent with high-pressure pyroxene fractionation of the parental melt to the Giles intrusions, before derivatives of that melt became squeezed off their high-pressure reservoirs and emplaced in shallower crustal reservoirs (see text for further explanations).**

sufficiently low. This replacement occurs when the melt is more silica-rich than at all positions along the olivine-orthopyroxene peritectic, and it is irreversible in a normal fractionating sequence. Once this stage is reached, there is no way to revert to olivine-normative compositions unless there is a major replenishment episode or a fundamental shift in crystallization pressure. A replenishment episode, however, would necessarily terminate the normal fractionation paths also with respect to the Mg/(Mg+Fe), Ca/(Ca+Na), and Cr/(Cr+Al) ratios in the fractionating phases.

**9.3.1 High pressure pyroxene fractionation?** Fig. 37 illustrates the chemical relationships among the Giles Complex intrusions with respect to the Mg/(Mg+Fe) and Ca/(Ca+Na) ratios of coexisting olivine and plagioclase. Also marked are the most Fe-rich olivine compositions recorded for each sequence, below which olivine is replaced by orthopyroxene. The diagram suggest on the one hand that all intrusions may have been derived from one magma, at least with respect to Mg/(Mg+Fe) and Ca/(Ca+Na), but on the other hand the behaviour of silica during fractionation excludes this possibility. Within single sequences, olivine became replaced by orthopyroxene when silica activities were sufficiently high; on a regional scale, however, olivine persists as a major phase throughout the entire range of Mg/(Mg+Fe) ratios down to the most fractionated cumulates, in Fig 37 reflected by the progression of the olivine-melt peritectic to lower Mg/(Mg+Fe) ratios. This apparent contradiction can only be resolved if the parent magmas to the individual intrusions were linked to each other by high-pressure fractionation of a mantle-derived parent melt, before they were emplaced into their shallower crustal reservoirs.

Consider an olivine-normative mantle-derived melt emplaced at middle crustal levels corresponding to a pressure of 6 to 7 kbar. At this pressure, the first silicate to crystallize will be olivine, which is then followed by clinopyroxene and later plagioclase. A typical intrusive cycle will commence with the deposition of dunite and peridotite orthocumulates, subsequently followed and overlain by pyroxenites and gabbros (cf. Ballhaus and Glikson, 1989). Mg/(Mg+Fe) and Ca/(Ca+Na) will fall and the silica activity of the melt will rise, since the fractionating phases have a lower bulk silica content than the magma from which they separate. When the silica content of the evolving melt is higher than the silica content permitted by the olivine- orthopyroxene peritectic, olivine becomes irreversibly replaced by orthopyroxene.

The scenario changes if fractionation takes place at higher pressure. An increase in the confining pressure causes the olivine-orthopyroxene peritectic to shift into the olivine-normative field and to become a cotectic phase boundary. At the same time, the stability fields of clinopyroxene and spinel will expand at the expense of the olivine and plagioclase stability fields until troctolitic mineral assemblages become unstable. A direct consequence of these changes in phase relations is that the silica content of melts along the olivine-orthopyroxene cotectic are lower than the silica content of the equilibrium orthopyroxene (compare the systems forsterite-anorthite-SiO2 and forsterite-diopside-SiO2 as simple analogues to most basaltic melts: Kushiro, 1969; Presnall et al., 1978, 1979). Crystal fractionation will cause the Mg/(Mg+Fe) and Ca/(Ca+Na) ratios in the melt to fall since pyroxenes will preferentially fractionate Mg and Ca over Fe and Na. The main difference from fractionation at low pressure, however, is that the silica content in the derivative melt will fall with protracted crystal fractionation, because the fractionating phases have a higher bulk silica content than their equilibrium melts.

A combination of high-pressure and low-pressure fractionation of a mantle-derived basaltic precursor melt will then produce the chemical trends inferred for the Giles Complex melts. High-pressure fractionation will produce the observed drop in silica activity in the parent melts with an increasing degree of fractionation. If derivative fractions of the high-pressure parental melt are periodically squeezed off to shallower pressure regimes in the crust, phase relations will shift such that such melt fractions will experience a relative compositional shift from an olivine-pyroxene cotectic into the olivine stability field or onto an olivine-plagioclase cotectic when decompression occurs. Further fractionation will now be dominated by olivine and later clinopyroxene-plagioclase, while the silica level in the melt is allowed to increase with further fractionation. Depending on the stage in the high-pressure fractionation history at which a derivative melt becomes removed from its high pressure reservoir, it may now crystallize gabbroic or troctolitic cumulates.

**9.3.2 Evidence in support of high-pressure crystallization.** There is ample evidence in support of high pressure fractionation, not just from this study but also from previous work (c.f. Goode and Moore, 1975).

- In all troctolitic intrusions, clinopyroxene is a very minor phase and appears late in the crystallization sequence. This is understandable only if the parental melts to the troctolitic intrusions were severely depleted in normative clinopyroxene through high-pressure pyroxene fractionation, before these magmas became emplaced in their shallow crustal reservoirs.

- In the Murray Range intrusion, olivine and orthopyroxene coexist as cumulus phases at Fo88. This suggests that both minerals crystallized along a cotectic phase boundary. If that is due to high pressure crystallization, the minimum pressure must have been 7 to 8 kb (cf. Green and Ringwood, 1967a), assuming the magma was primitive, i.e. in equilibrium with upper mantle material, and just olivine-normative.
- Plagioclase in the Murray Range sequence is more sodic at any given olivine composition than in other mafic sequences of the Giles Complex (Wingellina Hills or Mt West sequences). This may in part be attributed to the fact that plagioclase in the Murray Range sequence is predominantly interstitial and therefore later in the crystallization sequence than coexisting olivine and clinopyroxene. However, it is also known that elevated pressure will stabilize diopside and aluminous spinel relative to anorthite (Green and Ringwood, 1967b; Green and Hibberson, 1970; Presnall et al., 1979). Plagioclase crystallizing at elevated pressure will therefore be more sodic at any given magma composition than at low pressure.
- Pyroxenes are high in alumina and other non-quadrilateral components, notably in the ultramafic cumulates of the Murray Range sequence. Although the primary reason for high Al and Cr in pyroxenes must be high crystallization temperature (especially in the spinel stability field), it may indirectly be due to high pressure, since an increase in confining pressure displaces the liquidus of a dry basaltic melt to higher temperature.
- The single most important evidence in support of high-pressure fractionation may be the existence of orthopyroxene-phyric dykes in the Mt. West intrusion (Fig. 29C). These dykes may represent fractions of a basaltic melt tapped from greater depths, that managed to carry samples of the high- pressure fractionating phase as intratelluric phenocrysts to lower pressure regimes. Unfortunately, there is as yet no information available on whole-rock chemistry of this dyke suite, nor is it known how common this dyke generation is in the Tomkinson Ranges. It would be essential to test whether it is primitive enough to qualify as a mantle melt, in particular whether the orthopyroxene phenocrysts are sufficiently magnesian to be in chemical equilibrium with upper mantle material.

**9.3.3 Metastable crystallization?** Some of the features summarized above may be due to metastable rather than high-pressure crystallization. For example, if crystallization takes place under a high temperature gradient, crystal/melt element partitioning will change such that partition coefficients will approach unity. Pyroxenes will become enriched in Tschermak's components relative to equilibrium pyroxene compositions. Plagioclase will tend to incorporate components into its lattice (e.g. ferric iron) that would usually be rejected during equilibrium crystallization (c.f. dark plagioclase in 'doleritic-textured' cumulates; Fig. 33). Sufficiently high degrees of undercooling may also alter crystallization sequences. Undercooled basaltic melts may end up crystallizing a metastable liquidus phase with a polymerization degree close to that of the melt; in basaltic melts this will normally be a pyroxene. In turn, phases like olivine and plagioclase will be relatively suppressed and will appear later in the crystallization sequence. Metastable crystallization due to undercooling could therefore explain why occasionally orthopyroxene joins olivine as a cumulus phase. It has been demonstrated by Ballhaus and Glikson (1989) that magma crystallization in the Giles Complex had in places been affected by rapid cooling. The frequent structural and textural transitions between coarse-grained cumulates and rapidly quenched samples provide additional support for that hypothesis.

## 9.4 Toward an emplacement model for the Giles Complex

It is tentatively suggested that the magmatism associated with the Giles Complex and the high-temperature granulite-metamorphic event in the Tomkinson Ranges are related processes. Magmatism and metamorphism may have taken place above a thermal anomaly situated in the upper mantle below the Musgrave Block (see also Sun and Sheraton, 1992).

Melt emplacement into crustal reservoirs must have coincided with extension during the granulite-metamorphic event. Batches of the parental mantle-derived magma that formed as a consequence of mantle heating and decompression were emplaced directly into crustal reservoirs. Emplacement pressures for these liquids were low enough to allow extensive olivine fractionation followed by clinopyroxene and plagioclase fractionation, although in places pressures were high enough to allow orthopyroxene saturation (e.g. in the Murray Range intrusion). Examples of these magma batches are reflected in intrusions termed 'ultramafic' in Fig. 1, where olivine-pyroxene-rich cumulates alternate with gabbroic lithologies.

Significant amounts of the primitive mantle magma have also ponded at greater depths, possibly in the lower crust or in the shallow lithosphere. The higher confining pressure stabilized orthopyroxene-clinopyroxene+/-olivine assemblages on the liquidus. As a result, these higher pressure melt fractions evolved along an orthopyroxene-clinopyroxene+/-olivine control line and experienced silica depletion with progressive fractionation. The derivative melt compositions were fractionated with respect to Mg/(Mg+Fe) and Ca/(Ca+Na) just as their lower pressure counterparts.

Eventually, there must have been situations when derivatives of the high-pressure melt became squeezed off into shallower crustal (secondary) reservoirs. This decompressional stage must have caused an expansion of the olivine and plagioclase stability fields at the expense of the pyroxene and spinel stability fields. Accordingly, silica activities in the evolved melts rose as decompression occurred. Further differentiation was now completed within shallower crustal reservoirs at much lower pressure. That stage involved the crystallization of olivine and plagioclase, and subsequently produced the fractionated troctolitic Bell Rock, Jameson, and Blackstone Range sequences. The following implications arise from this model:

- The lower crust of the Musgrave Block may host several more pyroxene-dominated high-pressure intrusions than the present-day erosion level in the Tomkinson Ranges would suggest. These cumulates, if they indeed exist, will be characterized by high modal pyroxene/olivine ratios and high-temperature/high-pressure crystallization features such as high Cr and Al contents in pyroxenes and very aluminous spinels. Plagioclase (if present) will be minor and comparatively sodic. To the author's knowledge, the only intrusions exposed at present-day erosion levels in the Tomkinson Ranges that come close to these high-pressure criteria are the Murray Range intrusion described here, and possibly the Ewarara and Gosse Pile intrusions described by Goode (1967), Moore (1971), and Goode and Moore (1975).

- The dyke swarms will include samples of the high-pressure melt fractions that froze on their way to a shallower magma chamber. Many Giles intrusions (e.g. Bell Rock, Latitude Hill, Hinckley) show gradations between cross-cutting dykes, fine-grained sills and microgabbro units interleaved with mature cumulates, and genuine chilled margins. In terms of their phenocryst populations, all these rock types are essentially similar to the cumulates in the Giles intrusions. On that basis alone, it appears reasonable to assume that the fine-grained dyke suite in the Musgrave Block approximately reflects the range of derivative parent melt compositions to the Giles Complex intrusions, as postulated from phase equilibria in the cumulates.

- The geographic distribution of the Giles intrusions may have been controlled by magma densities and buoyancy differences between magmas and the surrounding crust. Fractionated derivative gabbroic and troctolitic melts will be less dense (more buoyant) than their primitive precursor liquids. As such, they will intrude shallower crustal levels in the granulite-metamorphic crust than the denser mantle-derived basaltic liquids. Interestingly, intrusions with similar magma parentages tend to occur in discrete belts that are oriented parallel to the regional compositional layering in the granulites of the Musgrave Block. (Fig. 1). For example, the ultramafic intrusions are concentrated in a belt along the northeastern margin of the Tomkinson Ranges, extending from Gosse Pile to the Murray Range. The most fractionated troctolitic intrusions (Bell Rock, Blackstone, Jameson), on the other hand, are concentrated in the southern regions of the mountain belt, while the gabbroic bodies (Hinckley, Mt. Davies, Latitude Hill, Michael Hills) take intermediate positions. This regional distribution pattern may reflect different depths within the middle to upper Proterozoic crust. This implies that the crustal section as exposed in the Tomkinson Ranges progressively shallows from northeast to southwest.

- With the prospect of more ultramafic high-temperature intrusions occurring at greater depth in the crust, one is tempted to conclude that the granulite-facies metamorphic event was in part related to heat conducted from the basic magmas associated with the Giles Complex. This view, however, could be too simplistic. Intrusive contacts of the Giles cumulates with granulites are all oblique to structures of the D2 deformation event and thus later than the pervasive deformation in the granulites, although Clarke (1992) suggests that D1 and D2 may have been pure shear events that may have predated the heating event. The new U/Pb single zircon dates of Sun and Sheraton (1992), on the other hand, seem to place an important time interval of 15 to 20 ma between the granulite-facies metamorphism and subsequent intrusion of felsic magmas.

## 9.5 Economic potential of the Giles Complex for platinum-group elements

Past exploration of the Giles Complex has been focussed on nickel in lateritic deposits above olivine- rich cumulates at Wingellina Hills, and on vanadium in magnetite layers of the Jameson Range intrusion (c.f. Daniels, 1974). Of more interest, however, is the potential of the Complex for stratiform Merensky Reef-type sulphide-PGE mineralization. The Giles intrusions comprise the largest concentration of layered mafic/ultramafic cumulates in Australia. As such, they are a potentially important exploration target for stratiform Merensky Reef-type PGE mineralization. Presently available results, however, suggest that the Giles Complex has little potential for stratiform sulphide-PGE mineralization.

- Three extensive field seasons have failed to identify cumulate horizons with disseminated sulphide enrichments. Chromitite layers, commonly spatially associated with stratiform sulphide accumulations, are conspicuously absent in the Giles Complex, probably because the parental melts to the Giles intrusions were severely depleted in Cr by way of early (high-pressure) clinopyroxene fractionation. Basal sulphide mineralization of the Sudbury or Platreef-type where sulphide unmixing is triggered by assimilation of crustal material, is also not observed.

- The intrusions comprising the Giles Complex are not the dismembered fragments of a layered complex. Textural comparisons between cumulates and dyke samples and structural gradations between the layered suites and rapidly quenched dykes suggest that the intrusions commonly referred to as 'the Giles Complex' are the voluminous sill equivalents of many of the associated dykes. As such, they are not genetically comparable with the shallower level Bushveld, Stillwater, or Great Dyke complexes.
- The cumulates of the Giles intrusions crystallized under far greater cooling rates than all PGE- rich intrusions documented so far. All Giles intrusions are characterized by cumulates with high proportions of intercumulus material, and presumably high proportions of trapped melt. Some cumulate textures closely resemble textures that are normally observed in dykes rather than layered intrusions. High cooling rates will create inefficient differentation conditions that are very unfavourable for the enrichment of trace elements in the course of chemical differentiation (c.f. Campbell, 1987). It seems unfeasible to reach PGE enrichment levels in sulphides such as those observed in disseminated Merensky-type sulphides (Naldrett et al., 1986), unless chemical fractionation is extremely efficient.
- A third point relates to the economic viability of stratiform sulphide-PGE mineralization, in the (unlikely) case that such mineralization will be identified in the future. All Giles intrusions investigated formed in separate magma chambers. There is little scope to correlate the major stratigraphic units among different intrusions, the Blackstone and Bell Rock sequences being a notable exception. Therefore, any promising stratiform sulphide-PGE mineralization will necessarily be of limited lateral extent and essentially restricted to single cumulate sequences.

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## REFERENCES

BALLHAUS C.G & GLIKSON A.Y. (1989). Magma mixing and intraplutonic quenching in the Wingellina Hills Intrusion, Giles Complex, central Australia. J. Petrol. 30, 1443-1469.

BALLHAUS C.G. & BERRY R.F. (1991). Crystallization pressure and cooling history of the Giles layered igneous complex, central Australia. J. Petrol. 32, 1-28.

BALLHAUS C.G., BERRY R.F. & GREEN D.H. (1991). High pressure experimental calibration of the olivine-orthopyroxene-spinel oxygen geobarometer: implications for the oxidation state of the upper mantle. Contr. Miner. Petrol. 107, 27-40.

BALLHAUS C.G. & GLIKSON A.Y. (1992). Magmatic and metamorphic evolution and economic potential of the mafic/ultramafic Giles Complex, western Musgrave Block, W.A. BMR Res. Newslett. 16, 6-9.

BOUDREAU A.E. (1987). Pattern formation during crystallization and the formation of fine-scale layering. In: Parsons I. (ed.) Origins of Igneous Layering. D. Reidel Publishing Company, Dordrecht, 453-471.

BOWEN N.L. & J.F. SCHAIRER (1935). The system MgO-FeO-SiO2. Amer. J. Sci. 29, 151-217.

CAMPBELL I.H. (1987). Distribution of orthocumulate textures in the Jimberlana intrusion. J. Geol. 95, 35-54.

CLARKE G.L. & POWELL R. (1991). Decompressional coronas and symplectites in granulites of the Musgrave Block, central Australia. J. Metam. Geol. 9, 441-450.

CLARKE G.L. & GLIKSON A.Y. (1992). Field relationships and tectonic history of the Hinckley gabbro felsic to mafic granulites and granitoids, West Hinckley Range and Champ de Mars areas, Tomkinson Ranges, Musgrave Block, W.A.. BMR Record 1992/33, Minerals and Land Use Program, 48 p.

DANIELS J.P. (1974). The geology of the Blackstone region, Western Australia. Geol. Surv. W.A. Bull. 123, 257 p.

GLIKSON A.Y. & MERNAGH T.P. (1990). Significance of pseudotachylite vein systems, Giles basic/ultrabasic complex, Tomkinson Ranges, western Musgrave Block, central Australia. BMR J. Aust. Geol. Geophys. 11, 509-519.

GLIKSON A.Y., STEWART, A.J., BALLHAUS, C.G., SUN, S.S. & SHERATON, J.W. (in preparation). The layered mafic/ultramafic Giles Complex and environs, western Musgrave Block, central Australia.

GOODE A.D.T. (1976). Small-scale primary cumulus igneous layering in the Kalka layered intrusion, Giles Complex, central Australia. J. Petrol. 17, 379-397.

GOODE A.D.T. (1977). Intercumulus igneous layering in the Kalka layered intrusion, central Australia. Geol. Mag. 114, 215-218.

GOODE A.D.T. (1978). High temperature, high strain rate deformation in the lower crustal Kalka Intrusion, central Australia. Contr. Miner. Petrol. 66, 137-148.

GOODE A.D.T. & KRIEG G.W. (1967). The geology of Ewarara intrusion, Giles Complex, central Australia. J. Geol. Soc. Aust. 14, 185-194.

GOODE A.D.T. & MOORE A.C. (1975). High-pressure crystallization of the Ewarara, Kalka and Gosse Pile intrusions, Giles Complex, central Australia. Contrib. Miner. Petrol. 51, 77-97.

GRAY C.M. & GOODE A.D.T (1989). The Kalka layered intrusion, central Australia. A strontium isotopic history of contamination and magma dynamics. Contr. Miner. Petrol. 103, 35-43.

GREEN D.H. & HIBBERSON W. (1970). The instability of plagioclase in peridotite at high pressure. Lithos 3, 209-221.

GREEN D.H. & RINGWOOD A.E. (1967a). The genesis of basaltic magmas. Contr. Miner. Petrol. 15, 103-190.

GREEN D.H. & RINGWOOD A.E. (1967b). An experimental investigation of the gabbro to eclogite transformation and its petrological application. Geochim. Cosmochim. Acta 31, 767-833.

HARLEY S.M. (1989). The origins of granulites: a metamorphic perspective. Geol. Mag. 126, 215-247.

IRVINE T.N. (1982). Terminology for layered intrusions. J. Petrol. 23, 127-162.

KUSHIRO I. (1969). The system forsterite-diopside-silica with and without water at high pressures. Amer. J. Sci. 267-A, 269-294.

JOESTEN R. (1986). The role of magmatic reaction, diffusion and annealing in the evolution of coronitic microstructures in troctolitic gabbro from Risor Norway. Miner. Mag. 50, 441-467.

MARSH B.D (1988). Crystal size distribution (CSD) in rocks and kinetics and dynamics of crystallization. Contr. Miner. Petrol. 99, 277-291.

MOORE A.C. (1971). Some aspects of the geology of the Gosse Pile ultramafic intrusion, central Australia. J. Geol. Soc. Aust. 18, 69-80.

MOORE A.C. (1971). The mineralogy of the Gosse Pile ultramafic intrusion, central Australia. II. Pyroxenes. Contr. Miner. Petrol. 18, 243-258.

MORSE S.A. (1986). Convection in aid of adcumulus growth. J. Petrol. 27, 1183-1214.

NALDRETT A.J., CAMERON G., VON GRUENEWALDT, G. & SHARPE M.R. (1986). The formation of stratiform PGE deposits in layered intrusions. In: Parsons I. (ed.) Origins of Igneous Layering. D. Reidel Publishing Company, Dordrecht, 313-397.

NESBITT R.W., GOODE A.D.T., MOORE A.C. & HOPWOOD T.P. (1970). The Giles Complex, central Australia: a stratified sequence of mafic and ultramafic intrusions. Geol. Soc. S. Afr. Spec. Publ. 1, 547-564.

PARSONS I. (1987). Origins of Igneous Layering. D. Reidel Publishing Company, Dordrecht, 666 p.

PHARAOH T.C. (1990). Aspects of structural geology of the Giles layered basic/ultrabasic complex and associated felsic granulites, Tomkinson Range, Musgrave Block, central Australia. BMR, Minerals and Land Use Program, Record 1990/5, 28 p.

PRESNALL D.C., DIXON S.A., DIXON J.R., O'DONNELL T.H., BRENNER N.L., SCHROCK R.L. & DYKUS D.W. (1978). Liquidus phase relations on the join diopside-forsterite-anorthite from 1 atm to 20 kbar: their bearing on the generation and crystallization of basaltic magma. Contr. Miner. Petrol. 66, 203-220.

PRESNALL D.C., DIXON J.R., O'DONNELL T.H. & DIXON S.A. (1979). Generation of mid-ocean ridge tholeiites. J. Petrol. 20, 3-36.

SPRIGG R.C. & WILSON R.B. (1959). The Musgrave mountain belt in South Australia. Geol. Rundsch. 47, 531-542.

SUN S.S. & SHERATON J. (1992). Zircon U/Pb chronology, tectono-thermal and crust-forming events in the Tomkinson Ranges, Musgrave Block, central Australia. AGSO Research Newslett. 17, 9-11.

# Appendix A: Description of samples investigated

Appendix_A.TXT has been omitted from the original copy of Record 1992/73.

Disc file name: **APPENDIX_A.TXT** (ASCII file)

This appendix summarizes the relevant petrographic characteristics of all samples investigated in the course of this study. The characterizations are based on thin section microscopy but also include field observations made by the author (field seasons 1987 and 1988) and A.Y. Glikson (field seasons 1987 through 1990). The samples are ordered according to field number and the corresponding AGSO numbers and stratigraphic elevations in metres. The nomenclature used here and in the preceding report follows essentially the terminology suggested by Irvine (1982). A few commonly used terms are defined below:

- cumulate – a rock that is composed of an early crystal fraction plus some interstitial liquid trapped between cumulus phases.
- cumulus – a term used here in a genetic sense to denote an origin of a particular mineral by early crystallization; cumulus phases are normally euhedral and crystallize at the liquidus of a melt
- intercumulus – (also postcumulus and interstitial) a phase that has crystallized in the interstices of cumulus crystals, partly from trapped liquid and partly as a result of diffusive material exchange between trapped liquid and overlying melt.
- poikilitic – an intercumulus phase that is optically continuous over significant areas and encloses a number of cumulus crystals. In the Giles cumulates, poikilitic phases (or 'oikocrysts') are most common in cumulates from intraplutonic mixing zones. They are believed to have formed by relatively rapid crystallization as a result of high degrees of oversaturation.
- adcumulate – less than 5 volume percent of intercumulus minerals
- mesocumulate – 5 to 20 volume percent of intercumulus minerals
- orthocumulate – 20 to 30 volume percent of intercumulus minerals.

All volume estimates inferred in the descriptions by using these terms are visual estimates. 30 percent interstitial material is rare because such concentrations usually cause the phase to crystallize as cumulus. Orthocumulates are most frequent in mixing zones of the intrusions and may be diagnostic of elevated cooling rates.

Prefixes to rock and cumulate types (e.g. feldspathic, olivine-bearing) are used to modify rock types and signify the presence of the respective phase or phase combination in minor proportions only, usually around 10 volume percent:

- feldspathic – used in conjunction with ultramafic mesocumulates and orthocumulates to signify the presence of some interstitial plagioclase.
- olivine-bearing cumulus – olivine present in amounts not exceeding visually estimated 10 volume percent.
- troctolitic – used in combination with a rock type to denote the presence of significant olivine and plagioclase in relative proportions typical for a troctolite.
- gabbroic – denotes the presence of significant clinopyroxene as a minor cumulus to poikilitic phase, in addition to other cumulus phases including plagioclase

- anorthositic – cumulus plagioclase is the predominating phase, present in amounts exceeding 70 volume percent
- noritic – denotes the presence of significant orthpyroxene as a minor cumulus to poikilitic phase, in addition to other cumulus phases including plagioclase

Specifications such as fine-grained, coarse-grained, and pegmatoidal are entirely subjective and used to specify deviations from some poorly defined 'average' grain size typical for the respective rock type. Please refer to photomicrographs in the preceding section.

The following abbreviations are used:

olv = olivine
opx = orthopyroxene
cpx = clinopyroxene
plag = plagioclase

## Appendix B: Electron probe analyses of investigated samples

Disc ASCII files Data has been made available as a separate download file.

**Clinopyroxene analyses:**

CPXBEL
CPXBLACK
CPXHINCK
CPXJAMES
CPXLATI
CPXMURRA
CPXWEST

**Plagioclase analyses**

PLAGBELL
PLAGBLAC
PLAGHINC
PLAGJAMES
PLAGLATI
PLAGMURR
PLAGWEST

**Orthopyroxene analyses:**

OPXBELL
OPXBLACK
OPXHINCK
OPXJAMES
OPXLATI
OPXMURRAY
OPXWEST

**Spinel analyses**

SPLMURRA

**Olivine analyses:**

OLBELL
OLBLACK
OLHINCK
OLJAMES
OLLATI
OLMURRAY
OLWEST

The data associated with this record have been compressed into two files: LOTUS.EXE and TEXT.EXE. LOTUS.EXE is in Lotus 123 format and TEXT.EXE is in ASCII format. The file README.TXT on the disk explains the procedure for uncompressing the files