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The petrology of layered mafic–ultramafic intrusions of the Giles Complex, western Musgrave Block, Western Australia

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The Musgrave Block hosts about twenty major layered intrusions and several generations of compositionally diverse sills and dykes collectively referred to as the Giles Igneous Complex. All were emplaced in middle Proterozoic intermediate to felsic granulites and amphibolites. On the basis of crystallisation sequences within the cumulates, we distinguish between (1) ultramafic olivine–clinopyroxene rich cumulate sequences, (2) mafic clinopyroxene–plagioclase-rich sequences, and (3) evolved troctolitic olivine–plagioclase ± magnetite-rich sequences. The layered igneous rocks are intruded by several generations of dykes, whose phenocryst assemblages resemble the crystallisation sequences in the cumulates. On this basis, at least three discrete parental melt compositions are identified, namely (1) a near-primitive olivine±clinopyroxene saturated melt, (2) a slightly fractionated olivine–(orthopyroxene)–clinopyroxene–plagioclase saturated melt, and (3) a strongly fractionated fayalitic olivine–plagioclase ± magnetite saturated melt. These magmas represent derivatives of a parental liquid that experienced various degrees of polybaric orthopyroxene–clinopyroxene ± olivine fractionation prior to emplacement, at depths significantly greater than the emplacement levels of the Giles intrusions and the dykes.

Introduction

The upper Proterozoic Giles Complex is one of the most extensive suites of layered mafic/ultramafic intrusions in the world. It comprises about twenty major intrusions, numerous smaller bodies of layered cumulates, and several swarms of dykes, all intruded into middle Proterozoic mafic to felsic granulite to upper amphibolite facies gneisses (Nesbitt et al. 1970). Age determinations (Sun & Sheraton 1992) suggest that the melts were emplaced about 1.18–1.2 Ga, whereas more recent data may suggest a younger age of ~1.08 Ga, coeval with volcanics of the Bentley Supergroup (Sun et al. in press). From east to west, the major intrusions include the Teizi Hill anorthosite; Gosse Pile pyroxenite intrusion; Mt Davies, Kalka, and Ewarara pyroxenite-rich intrusions and Claude Hills ultramafics; Michael Hills and Hinckley Range gabbros; Wingellina Hills ultramafic intrusion; Latitude Hill gabbro–pyroxenite (a segment of the Michael Hills intrusion); The Wart pyroxenite; Bell Rock and Blackstone Range troctolites; Murray Range ultramafic intrusion; Morgan and Cavenagh Range gabbros; and, finally, Jameson Range troctolite. In addition, there are several mafic intrusives in the eastern Musgrave Ranges in South Australia near Mt Woodroffe, which have a similar setting to the Giles intrusions in Western Australia.

The Giles Complex is an important target for petrological studies, for several reasons. It is one of the largest accumulations of layered mafic igneous rocks in Australia, and, therefore, of potential interest for exploration for platinum-group element (PGE) mineralisation. The Giles Complex represents a major thermal event in the crustal evolution of the Musgrave block, and its relationships with the granulite-metamorphic event or events need to be clarified. It is an example of the type of magmatic intrusive activity that can be expected at lower to middle crustal levels (Goode & Moore 1975; Ballhaus & Berry 1990), and is, therefore, relevant to the compositional evolution of the lower crust. To address these issues, the compositional relationships between the different intrusions need to be understood, i.e. are they tectonised segments of a formerly larger complex? (e.g. Sprigg & Wilson 1959) or individual intrusions derived from chemically distinct magmas (Nesbitt et al. 1970; Ballhaus & Glikson 1989; Gray & Goode 1989, Ballhaus 1993)

This paper documents the magmatic sequences of seven major intrusions of the Giles Complex in WA, i.e. the Murray Range, Hinckley Range, Latitude Hill, The Wart, Bell Rock, Blackstone Range, and Jameson Range intrusions. It presents geological maps and petrographic sections compiled from sampling traverses, thin-section petrography (Ballhaus 1993), systematic airphoto evaluation (Pharaoh 1990), and Landsat-5 TM satellite imagery (Glikson 1994). The nature and extent of chemical fractionation in each intrusion are illustrated by cryptic variation diagrams based on microprobe analysis of about 300 cumulate samples (Ballhaus 1993). The results suggest that the intrusions cannot be related by continuous in-situ fractionation of a single parental melt in a single magma chamber, and resulted from batches of chemically diverse parent melts derived from high-pressure fractionation of one common parental liquid.

Regional distribution of the Giles Complex

Figure 1 illustrates the generalised geology of the larger Giles intrusions. The intrusions are subdivided according to the principal cumulus phases. Ultramafic intrusions have an essential component of primitive (i.e. Mg-rich) olivine-rich orthocumulates in which plagioclase is a late poikilitic or intercumulus phase (for a cumulus terminology cf. Irvine 1982). The mafic gabbroic intrusions are composed of olivine–(orthopyroxene)–clinopyroxene–plagioclase adcumulates as well as subordinate pyroxenites. Intrusions termed troctolitic are dominated by fractionated (i.e. Fe-rich) olivine–plagioclase±magnetite adcumulates, locally containing magnetite seams. Most of the ultramafic intrusions (Murray Range, Wingellina Hills, Claude Hills, Ewarara, and Kalka) are concentrated along the northern periphery of the Giles Complex; most mafic gabbroic intrusions (Hinckley, Michael Hills Mt Davies, and Latitude Hill) occupy central parts of the complex; and the troctolitic intrusions (Jameson Range, Blackstone Range, and Bell Rock Range) define its southern margin. In so far as the Tollu volcanics of the Bentley Supergroup (1.08 Ga) are coeval with the Giles Complex (Sun et al. in press), they represent the highest level in a crustal section which becomes progressively shallower south of the Woodroffe Thrust (Glikson et al. 1995—this issue).

Murray Range intrusion

Figure 2 illustrates the generalised geology of the Murray Range intrusion. The stratigraphic succession is continuous for about 2600 m, with layering dipping steeply between 80 and 90°. The sequence is illustrated schematically in Figure 3 along a traverse from the southwestern to the northeastern contact (cf. Fig. 2). The magmatic sequence starts with about 500 m of poorly layered, uniform olivine-free feldspathic pyroxenite to melagabbro adcumulates with minor intercalations of peridotite orthocumulates. Following this unit to the 1800 m

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elevation is a well-layered gabbroic to gabbronoritic suite with olivine-bearing pyroxenite, wehrlite, and peridotite/dunite intercalations. The sequence then changes to predominantly ultramafic lithologies, where coarse-grained pyroxenites alternate with harzburgite, peridotite, and dunite orthocumulate layers. Superimposed on the magmatic layering are several layer-parallel mylonite zones, along which the cumulates are highly strained and locally hydrated to light-green amphibolite (tremolitic amphibole in a matrix of sodic plagioclase). The contacts of the magmatic series of the Murray Range sequence with the granulite country rocks are covered by alluvium, and their relationships are unclear.

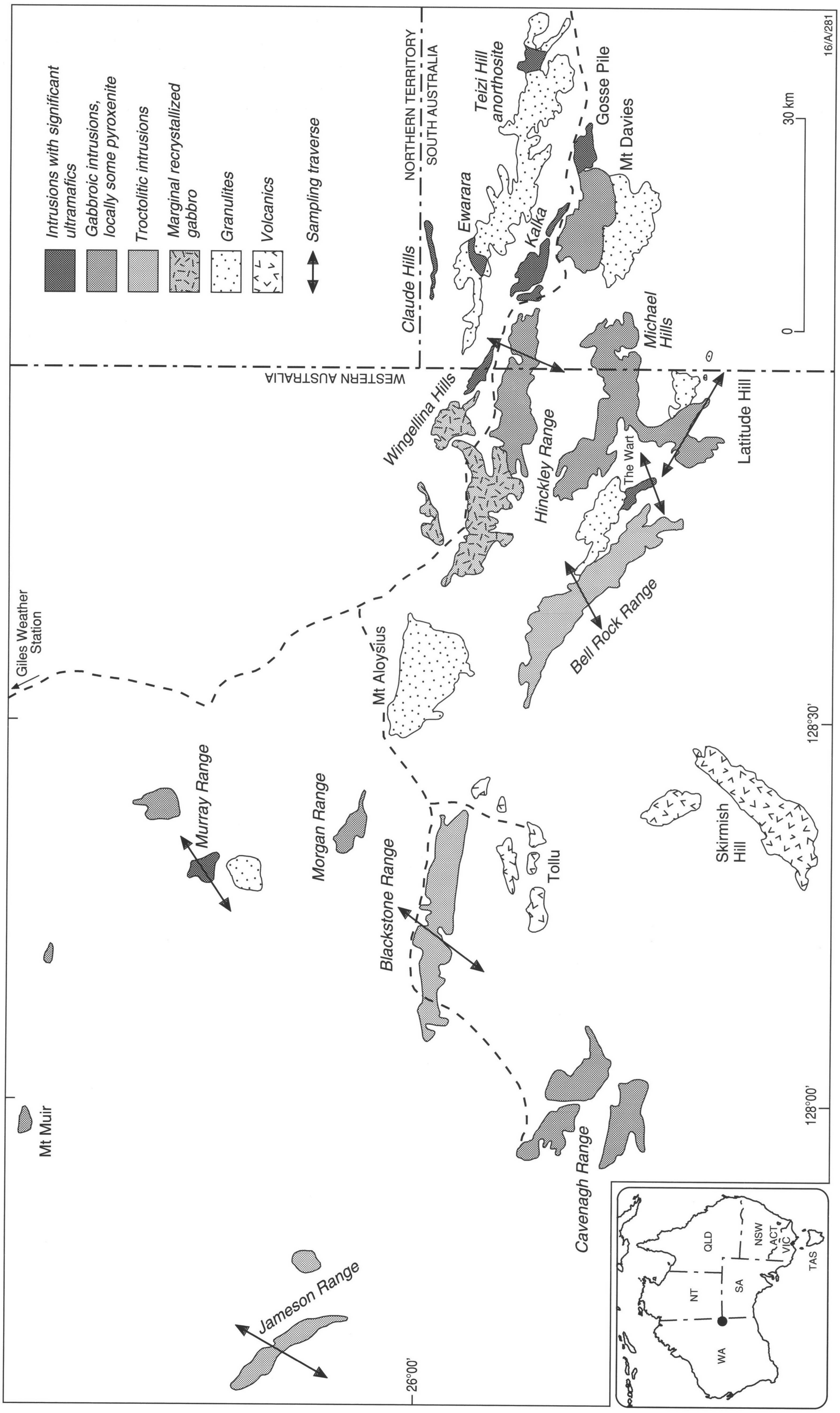

Figure 1. Major intrusions of the Giles Complex and granulite outcrops in the western Musgrave block, central Australia.

The range in mineral compositions is summarised in Figure 4 and plotted against Mg/(Mg+Fe) or Mg-number of orthopyroxene. Olivine ranges from Fo_{88} to Fo_{77}, with maximum forsterite in the well-layered ultramafic sequence around the 2000 m elevation. Orthopyroxene replaces olivine as the liquidus phase at about Fo_{77}. Clinopyroxene is, at a given olivine composition, significantly more magnesian than coexisting orthopyroxene. This applies especially to small neoblasts that have equilibrated to low temperature. Cr/(Cr+Al) in clinopyroxene is the ratio most sensitive to chemical fractionation. Up to 0.25 in the most magnesian olivine-rich cumulates, it drops to about 0.05 in the most fractionated gabbronorites. In cumulus spinel and coexisting clinopyroxene Cr/(Cr+Al) varies coherently. Ca/(Ca+Na) in plagioclase ranges from about 0.8 to 0.2 and shows little sympathetic variation with olivine composition. Plagioclase is, for a given Mg-number of coexisting olivine or orthopyroxene, comparatively sodic (cf. Ballhaus & Glikson 1989).

The Murray Range sequence is a clear example of a multiply replenished magma chamber (cf. Irvine 1980). The cryptic layering pattern in Figure reveals two gradual chemical reversals toward more primitive (i.e. more Mg and Ca-rich)

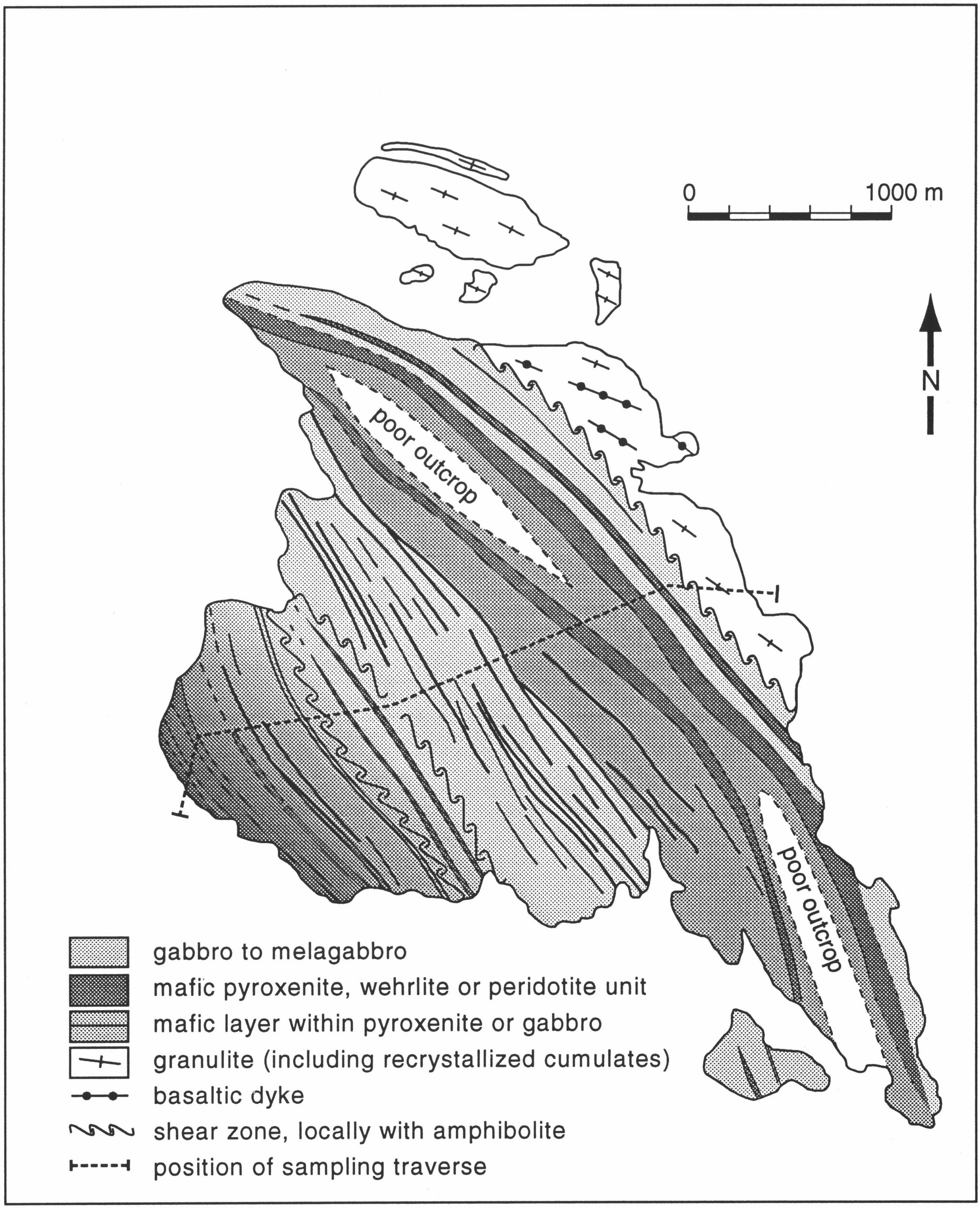

Figure 2. Schematic geology of the Murray Range ultramafic intrusion.

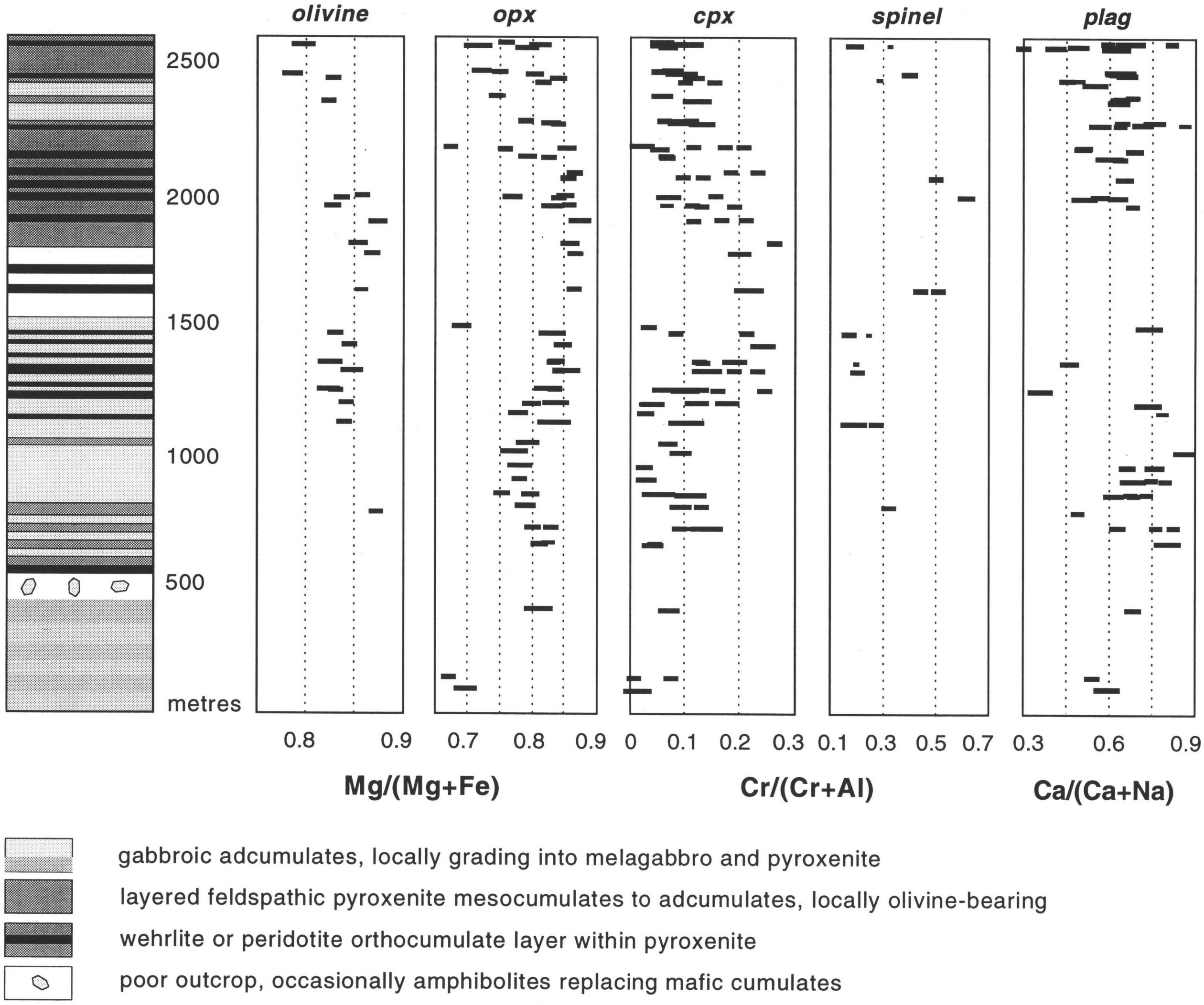

Figure 3. Magmatic stratigraphy and cryptic layering of the Murray Range ultramafic intrusion (for position of the sampling traverse see Fig. 2).

mineral compositions, each followed by extended periods of normal fractionation. The lack of overall chemical differentiation makes it difficult to decide which way the sequence may be younging. We believe that the southern contact marks the bottom of the intrusion, for three reasons: (1) the chemical reversals are broadly situated where the sequence changes from predominantly gabbroic to predominantly ultramafic lithologies; (2) the bases of ultramafic cycles are typically orthocumulates, suggesting that they formed in a high thermal gradient (Campbell 1987; Ballhaus & Glikson 1989); and (3) several ultramafic intercalations are preceded by hybrid zones in which patches and schlieren of ultramafic cumulate material occur intermingled with more fractionated gabbroic material (cf. Ballhaus & Glikson 1989). Such hybrid zones may form when the first batches of a major pulse collect on the magma chamber floor and freeze before they can homogenise with the cooler resident melt. As such, they must define the footwall contact of an ultramafic unit. Accordingly, the stratigraphic sequence of the Murray Range intrusion youngs toward the northeast.

We infer from crystallisation sequences and mineral compositions in the most mafic units that the parental melt to the Murray Range intrusion was saturated with olivine and an aluminous spinel, and was near-primitive with respect to MgO content. The crystallisation sequence was (1) olivine±aluminous spinel, (2) olivine(orthopyroxene)–clinopyroxene, and (3) (olivine)–orthopyroxene–clinopyroxene–plagioclase. The megascale layering is a direct consequence of the undersaturated nature of the replenished melt. Any pulse of olivine-only saturated liquid into multiply saturated resident melt must have resulted in the loss of at least one liquidus phase, commonly two, and a corresponding change in cumulate mineralogy.

The Wart intrusion

The Wart intrusion is an ultramafic intrusion situated east of the southwestern tip of the Bell Rock intrusion (Fig. 5). The magmatic sequence along the traverse (Fig. 6) dips steeply between about 80 and 90°. The intrusion is composed of an exceptionally well-layered suite of clinopyroxenite to melagabbro mesocumulates to adcumulates. Many (several tens) layers of lenticular wehrlite to peridotite orthocumulate are intercalated, as well as numerous microgabbro sills with textural transitions from rapidly chilled rocks to genuine cumulate layers (cf. Ballhaus 1993). The cumulates and sills, in turn, are cut by at least three compositionally different generations of basaltic dykes; one with subhedral clinopyroxene and elongate plagioclase laths as phenocrysts, a second with olivine and plagioclase, and a third with partially resorbed orthopyroxene phenocrysts. Total thickness of the cumulate pile exceeds 1800 m. Most contacts are covered by alluvium, although the northeastern margin features cumulates with intrusive relationships into felsic granulites. Original chilled margins have not been seen.

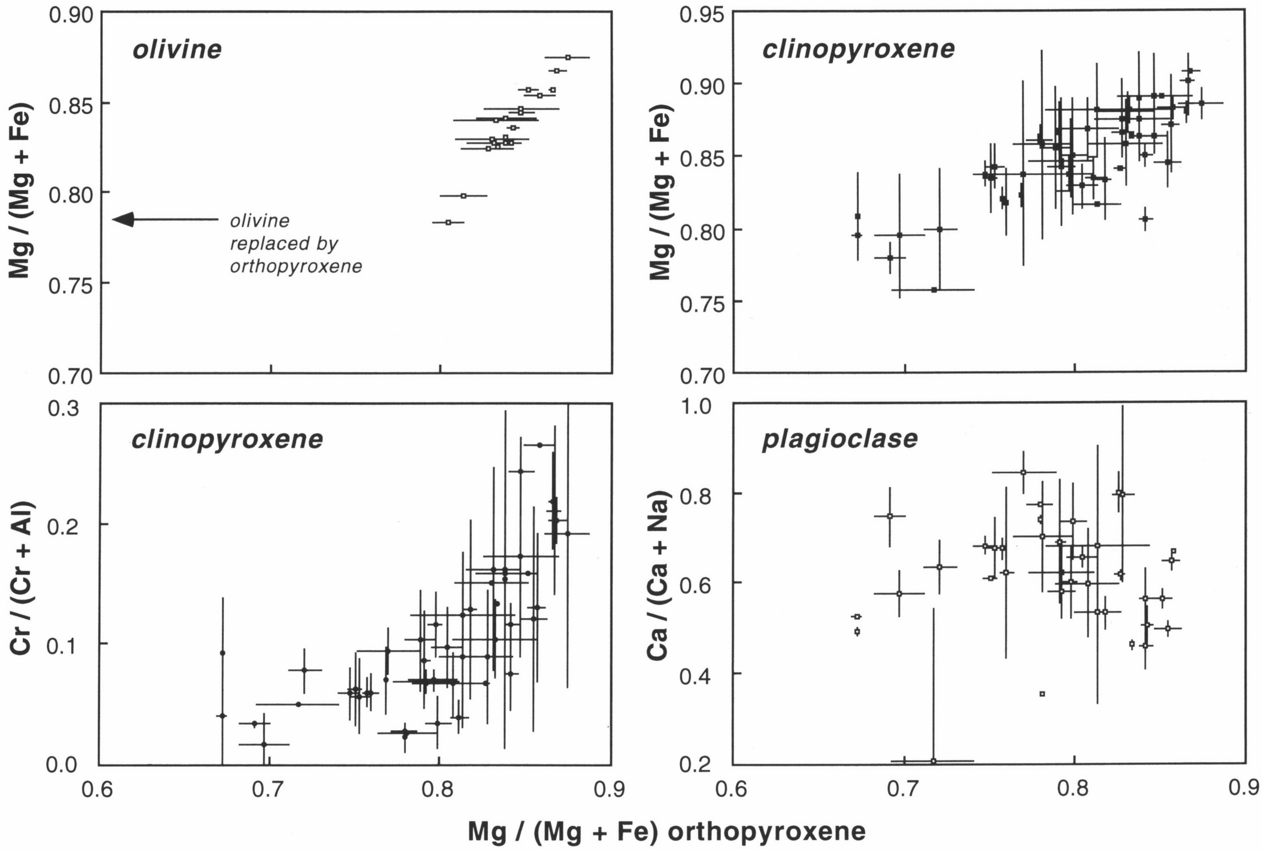

Figure 4. Average phase compositions in the Murray Range cumulates (error bars are two standard deviations).

In terms of phase composition (Fig. 7), The Wart sequence is nearly as primitive as the Murray Range or Wingellina Hills (Ballhaus & Glikson 1989) sequences. Olivine falls within a compositional range of Fo_{87-78}, below which it becomes replaced by orthopyroxene. In comparison with the Murray Range sequence, orthopyroxene is much rarer and clinopyroxene is more fractionated, with Cr/(Cr+Al) ratios not exceeding 0.16. A cumulus spinel phase is not observed, probably because the magma was depleted in Cr by extensive clinopyroxene crystallisation. Plagioclase is, for a given olivine composition, far more calcic than in the Murray Range intrusion.

The modal layering in The Wart sequence arises from the intrusion of numerous small to medium-sized batches of primitive parent magma, into a continuously differentiating body of somewhat more fractionated resident melt. From stratigraphic relationships, it is suggested that this layered sequence youngs to the southwest and could, therefore, form the base of the Bell Rock intrusion. Most ultramafic units commence with a sharp modal change to olivine-rich orthocumulates, followed by an upward gradation to wehrlite and then pyroxenite. This cyclic pattern is likely to result when olivine-rich liquid ponds on the magma chamber floor and gradually mixes with the overlying cooler resident melt. The lower northeastern half of the sequence, up to the 1050 m stratigraphic level, signifies a period of multiple magma addition, while the upper half indicates chemically more stagnant conditions with fewer magmatic replenishment events.

The parent melt characteristics are similar to those of the Murray Range intrusion. The melt was near-primitive with respect to its Mg-number. The common lack of orthopyroxene and spinel indicates that silica activity and Cr contents may have been slightly lower than in the Murray Range magma, possibly because the magma experienced some pyroxene fractionation prior to emplacement into the crustal magma chamber.

Latitude Hill intrusion

The Latitude Hill intrusion (Fig. 8), a folded segment of the Michael Hills gabbro, is one of the thickest cumulate sequences in the Giles Complex. Classified as mafic gabbroic in character, it consists of two steeply dipping (80–90°), uniform, olivine-bearing gabbro units with numerous layers and lenses of olivine-bearing pyroxenite and rare peridotite, altogether about 8000 m thick (Fig. 9). The two magmatic units are separated by a zone of altered, highly strained, recrystallised gabbro, infiltrated by pseudotachylite veins. The magmatic suites of the Latitude Hill intrusion feature several unusually fine-grained 'doleritic-textured' units, which Ballhaus (1993) interpreted as intraplutonic chill zones. The Latitude Hill gabbro is one of the few cumulate packages of the Giles Complex with demonstrably intrusive contacts with felsic granulites.

Mineral compositions are displayed in Figure 10. The Latitude Hill sequence is significantly more fractionated than the primitive Murray or The Wart sequences. Olivine is relatively rare and ranges in composition from Fo_{83} to Fo_{67}. Mg-numbers of orthopyroxene are slightly offset relative to olivine to more magnesian values and range from 0.85 in the most primitive ultramafic units to about 0.58 in the central deformed granulitic zone. Orthopyroxene replaces olivine at Fo_{68}. Cr/(Cr+Al) in clinopyroxene varies sympathetically with Mg-numbers of orthopyroxene and rarely exceeds 0.1. Ca/(Ca+Na) in plagioclase ranges from about 0.5 to 0.85 and varies coherently with Mg-numbers of olivine and orthopyroxene.

The stratigraphic orientation of the sequence, as inferred in Figure 9, is arbitrary, as there is no textural indication of where bottom and top contacts are situated, nor does the shape of the cryptic fractionation patterns (Fig. 9) provide a clue. The two magmatic piles on either side of the central deformed zone feature a major chemical reversal followed by a similarly extensive period of normal fractionation. Abrupt changes in modal mineralogy and megascale layering are rarer and less obvious than in the more primitive Murray Range and The Wart cumulate sequences.

The parent melt to the Latitude Hill sequences was close to multiple saturation with olivine, pyroxenes, and plagioclase. As a result, megascale layering is poorly developed because new magma pulses did not lead to major changes in the crystallisation sequence. Suggested crystallisation sequences are: (1) olivine+orthopyroxene, (2) orthopyroxene+clinopyroxene, and (3) orthopyroxene+clinopyroxene+plagioclase. Cr/(Cr+Al) in clinopyroxene and the Mg-numbers at which olivine became replaced by orthopyroxene are lower than in the ultramafic sequences. This indicates that the Latitude Hill liquids were more fractionated and lower in silica activity than the melts of the ultramafic intrusions, possibly owing to pyroxene fractionation before emplacement.

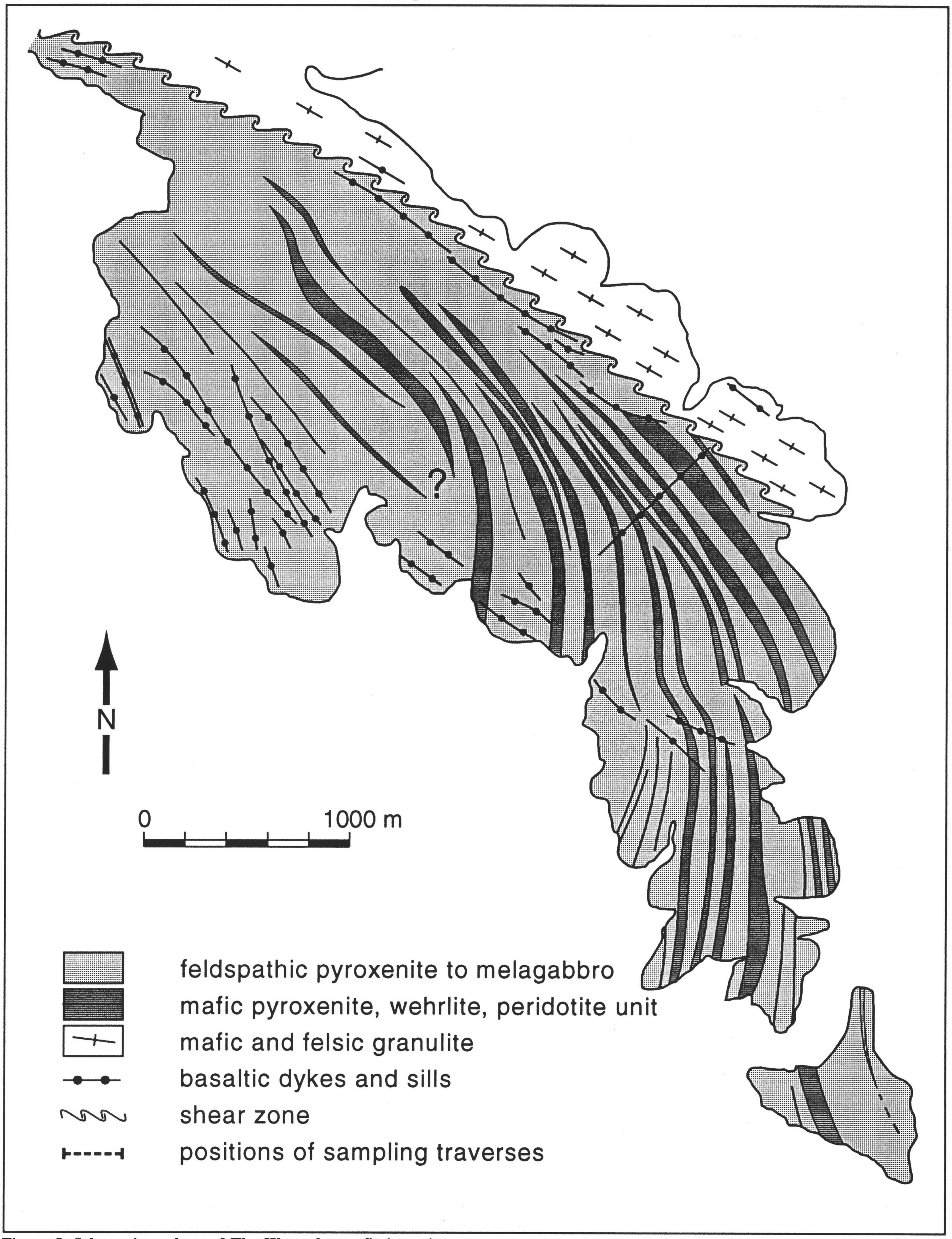

Figure 5. Schematic geology of The Wart ultramafic intrusion.

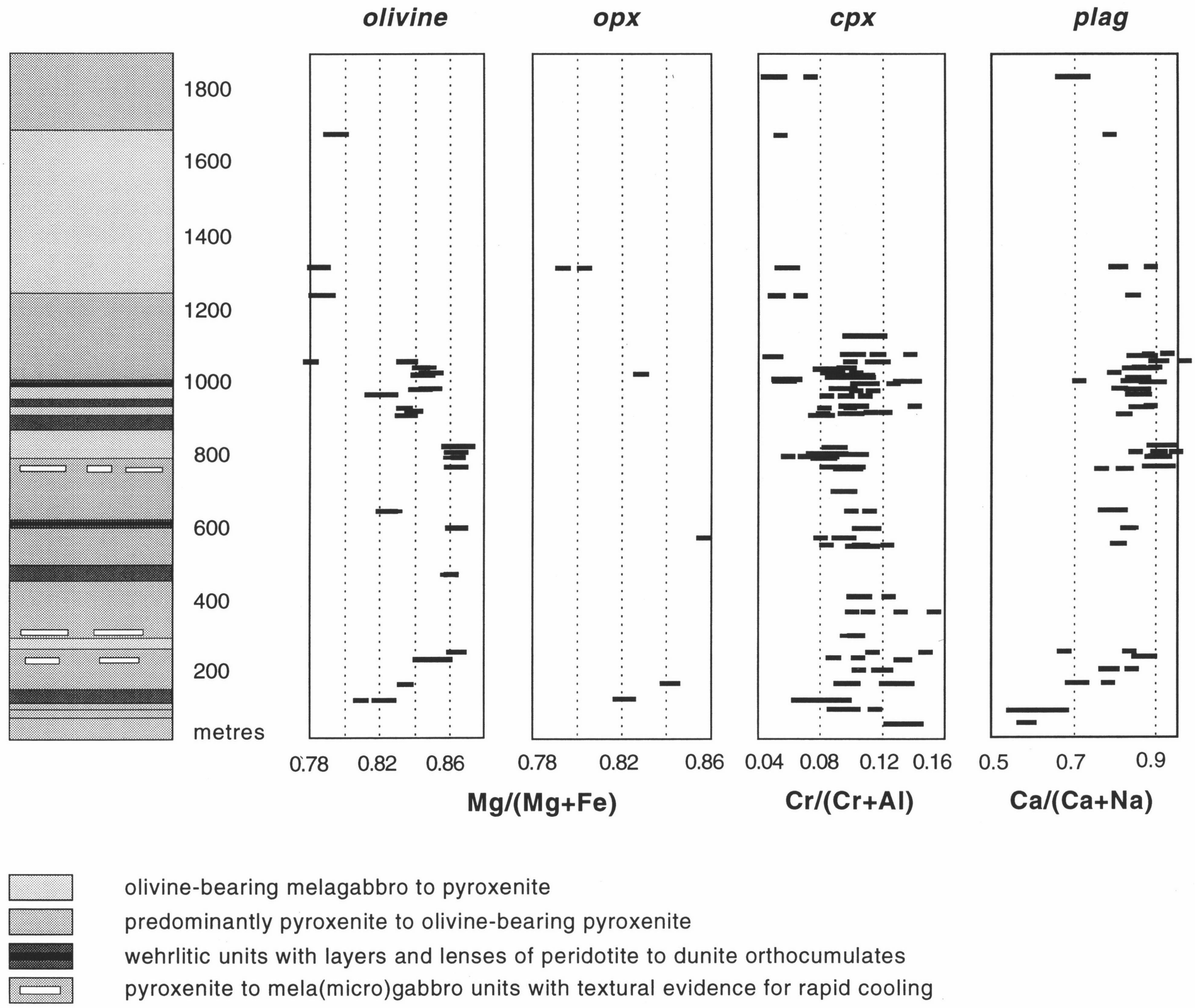

Figure 6. Magmatic stratigraphy and cryptic layering pattern of The Wart intrusion (for position of the sampling traverse see Fig. 5).

Hinckley Range intrusion

The Hinckley Range intrusion (Fig. 11) is one of the largest and most deformed intrusions of the Giles Complex. The magmatic sequence is approximately 5800 m thick and dips steeply north at 70 to 80°. Its western and northwestern units are affected by a metamorphic overprint, identified by Glikson & Stewart (1990) and Clarke (1992) as recrystallised gabbros intruded by felsic veins (cf. Fig. 1). Cumulate textures and magmatic layering are poorly preserved. The eastern (magmatic) extension of the intrusion is well layered and has largely escaped the metamorphic overprint evident in the west.

The Hinckley Range intrusion is mainly gabbroic, with the most common cumulates being gabbroic troctolite, troctolitic gabbro, gabbronorite, anorthosite, and locally minor pyroxenite (Fig. 12). The sequence is interlayered with multiple intraplutonic chill zones, i.e. multiple repetitions of fine-grained 'marginal' layered microgabbros and doleritic-textured (Ballhaus 1993) gabbroic sills. Phenocryst populations in these finer grained units resemble the phase assemblages in the surrounding layered cumulates. Parts of the sequence are cut by layer-parallel mylonite zones rich in pseudotachylite veins. The most prominent is the Hinckley thrust fault (Goode 1978), where pseudotachylite networks superimposed onto each other and gabbroic fragments are several metres thick (Glikson & Mernagh 1990).

Mineral compositional trends are summarised in Figure 13 and plotted against Mg-numbers of orthopyroxene. The Hinckley Range sequence is comparatively fractionated. Olivine ranges from Fo_{75} to Fo_{59}, below which it is replaced by orthopyroxene. Cr/(Cr+Al) in clinopyroxene is low, reflecting significant fractionation of the melt prior to emplacement. Plagioclase composition is highly variable in single samples and single grains, especially in more recrystallised cumulates. With protracted fractionation, there is a poorly defined trend toward more sodic average plagioclase compositions.

Cryptic layering patterns (Fig. 12) are consistent with normal fractionation from the south to the north, interrupted by a poorly defined reversal above the 2000 m level. With protracted fractionation upward in the sequence there is a steady increase in modal orthopyroxene and clinopyroxene at the expense of olivine. The morphology of the cryptic layering profiles and graded and cross-layering features suggest that the Hinckley Range gabbro youngs towards its northern contact, i.e. an opposite orientation to the Wingellina Hills intrusion (Ballhaus & Glikson 1989).

The parent magma of the Hinckley Range suite must have been fairly fractionated. At the time of emplacement, the magma was multiply saturated with olivine and plagioclase, and just undersaturated with clinopyroxene. The increase in orthopyroxene and clinopyroxene upwards indicates that the fractionating phase assemblages were, mostly, lower in bulk silica content than the parent melt.

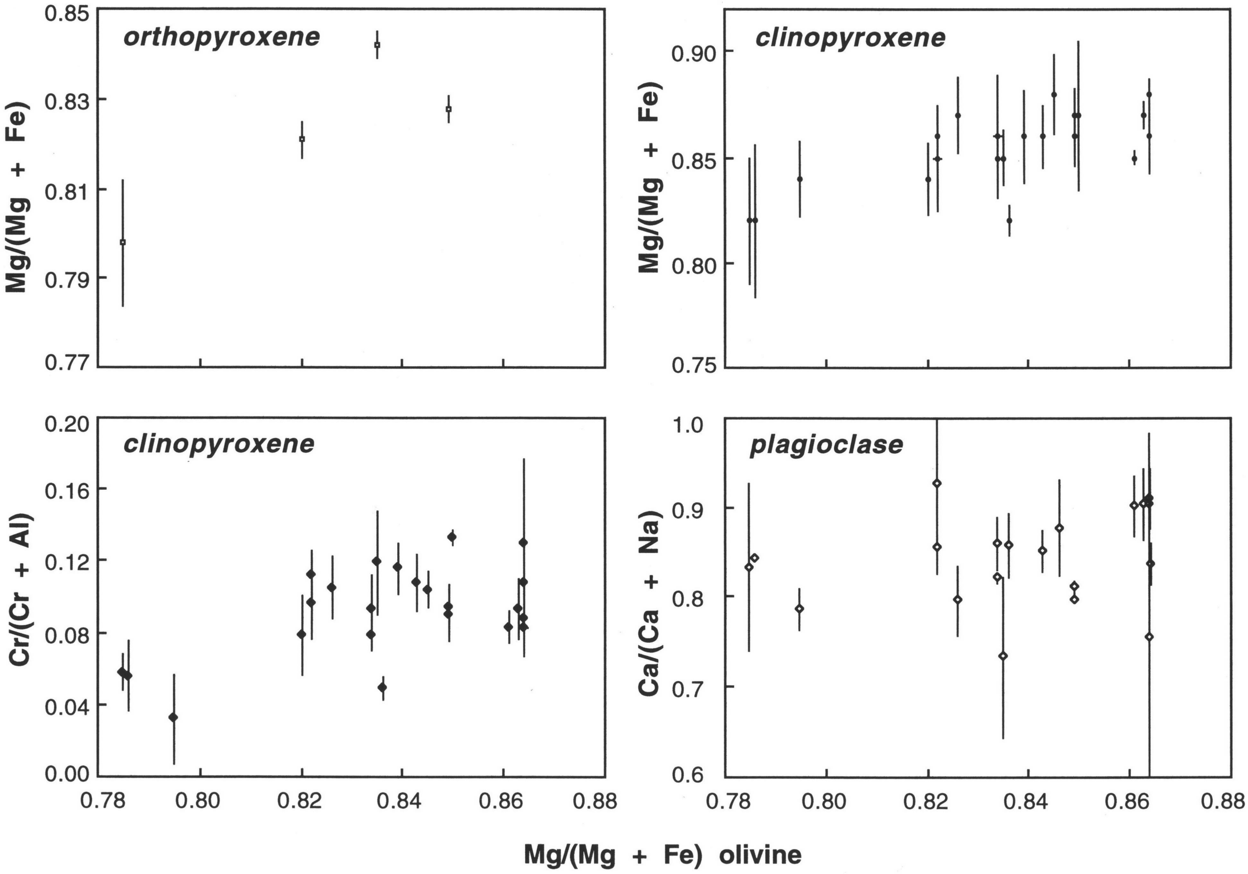

Figure 7. Average phase compositions in The Wart cumulates (error bars are two standard deviations).

Bell Rock Range intrusion

The Bell Rock Range intrusion (Fig. 14) hosts one of the most fractionated magmatic sequences of the Giles Complex and belongs to the troctolitic suite (Fig. 1). Total exposed thickness is around 3800 m. The sequence dips steeply at 70° southwest. Most contacts with country rocks are hidden by alluvium. The units are composed of massive, laterally continuous magnetite-bearing troctolites, gabbroic troctolites, and anorthosites, each being several hundreds of metres thick (Fig. 15). A few thin dunite layers and magnetite seams, several centimetres thick, are intercalated with the gabbroic sequence. Part of the sequence displays numerous stratiform repetitions of microgabbro sills, which may be chilled equivalents of the coarser grained cumulates. Modal layering only occurs on a centimetre to metre scale (cf. Boudreau 1987). The megascale cyclicity, so typical of the more mafic intrusions of the Giles Complex, is poorly developed.

Mineral compositional ranges are shown in Figure 16. Olivine ranges from Fo_{68} to about Fo_{56}. No textural evidence is observed to indicate that olivine becomes replaced by orthopyroxene (i.e. no peritectic reaction relationship with the melt); for example, modal orthopyroxene does not increase with falling Mg number upward in the sequence, in contrast to the gabbroic and ultramafic intrusions. Relative to olivine, orthopyroxene is displaced to higher Mg-numbers and varies from 0.72 to 0.62. Clinopyroxene compositions show no systematic chemical trend, probably because clinopyroxene is a late intercumulus phase. Mg-numbers of clinopyroxene are poor indicators of magmatic differentiation because clinopyroxene becomes more magnesian as it exsolves orthopyroxene during subsolidus equilibration. Ca/(Ca+Na) of plagioclase is highly variable between 0.85 and 0.55 and shows little systematic variation with coexisting olivine compositions.

The stratigraphic orientation of the Bell Rock Range sequence (Fig. 15) remains ambiguous; clearly, the morphology of the cryptic layering pattern could be interpreted either way. However, unless it is overturned, the general dip of the cumulate units suggests that the sequence youngs to the southwest. Grading and cross-layering structures also suggest southwestward younging, and there is also a tendency for modal magnetite to increase in the same direction. The parent magma must have been highly fractionated and saturated with olivine and plagioclase (and possibly also clinopyroxene and magnetite) at the time of emplacement. As a direct consequence, there is no departure from olivine–plagioclase co-precipitation even at stratigraphic levels where chemical reversals signify influxes of fresh melt. Silica activity does not seem to increase with protracted fractionation; i.e. there is no increase in modal orthopyroxene upward in the sequence, probably because the fractionating phase assemblages were at all times richer in silica than the equilibrium melt.

Blackstone Range intrusion

The Blackstone Range intrusion is a major troctolitic magmatic sequence (Fig. 17). Similar to the Bell Rock Range intrusion, it consists of fractionated troctolites, olivine gabbros, and anorthosites, with occasional monomineralic dunite and massive magnetite layers (Fig. 18). Megascale phase layering is poorly developed. The stratigraphic sequence is continuous for about 3900 m and magmatic layers dip south at 70 to 75°. Along the northern periphery, cumulates are recrystallised to fine-grained massive phlogopite-bearing mafic granulite, possibly incorporating former chilled margins. Along the southern contact the sequence is faulted against the Bentley Supergroup (cf. Daniels 1974). Contacts with felsic granulite country rocks are not exposed.

Mineral compositional variations are plotted against orthopyroxene composition in Figure 19. Olivine ranges from

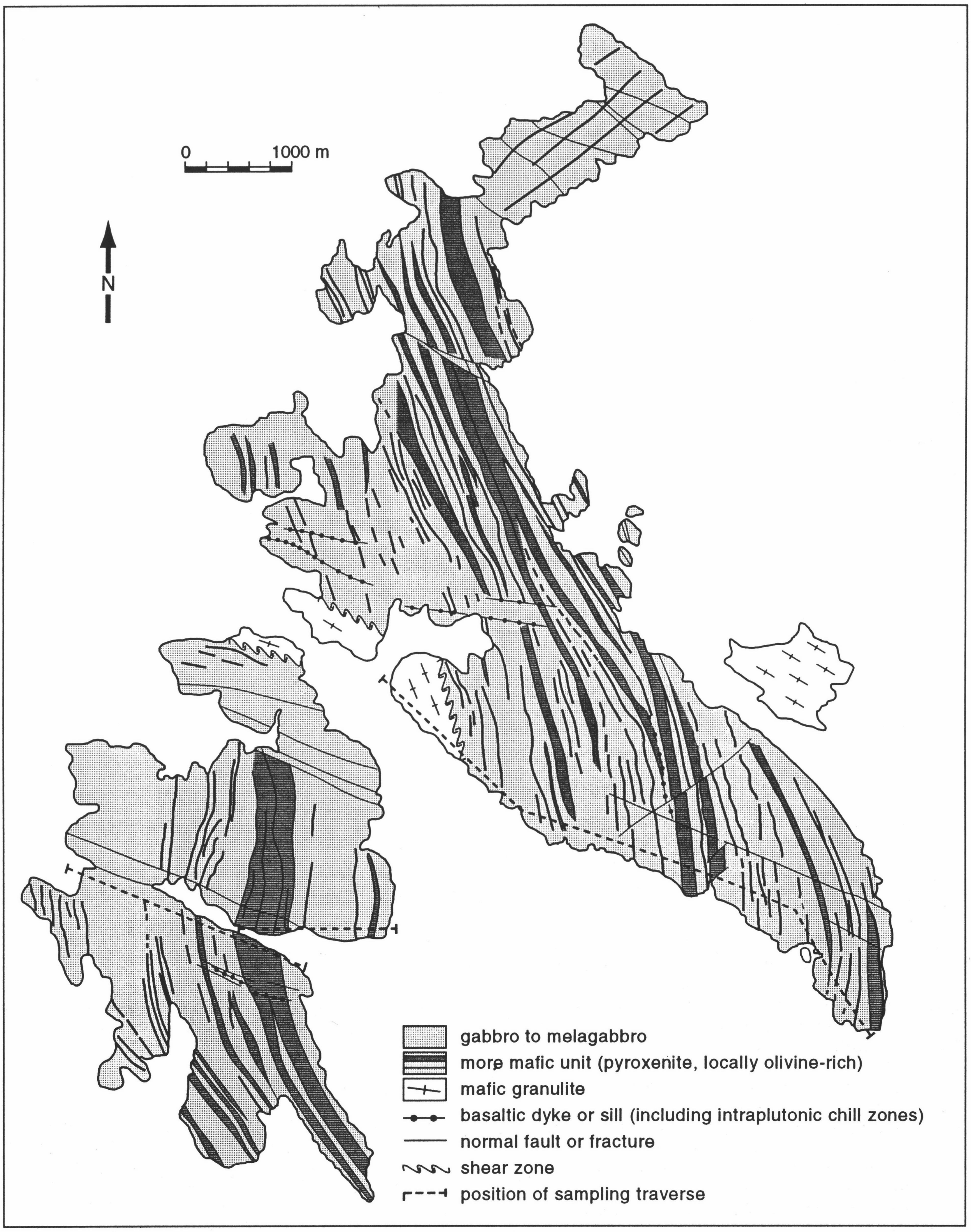

Figure 8. Schematic geology of the Latitude Hill gabbroic intrusion.

Fo_{67} to Fo_{40}, the latter being the most fractionated olivine reported from the Giles Complex. Mg numbers of coexisting orthopyroxenes vary from about 0.7 to 0.55 and are slightly compressed relative to those of olivine. Cr contents in clinopyroxene are close to detection limit and show no sensible stratigraphic trend. Ca/(Ca+Na) of plagioclase is highly variable and ranges from above 0.8 to about 0.5.

The cryptic layering pattern strikingly resembles that of the Bell Rock Range intrusion (Fig. 18). It is suggested that the minimum Mg number at the 2400 m level coincides with a similar minimum at the 3600 m level in the Bell Rock Range sequence. Likewise, the dunite layers at the 400–450 m level of the Blackstone Range sequence may correlate with a similar sequence at the 1500 m level at Bell Rock. There is again no clear indication which way chemical fractionation was directed and where the bottom and top contacts may have

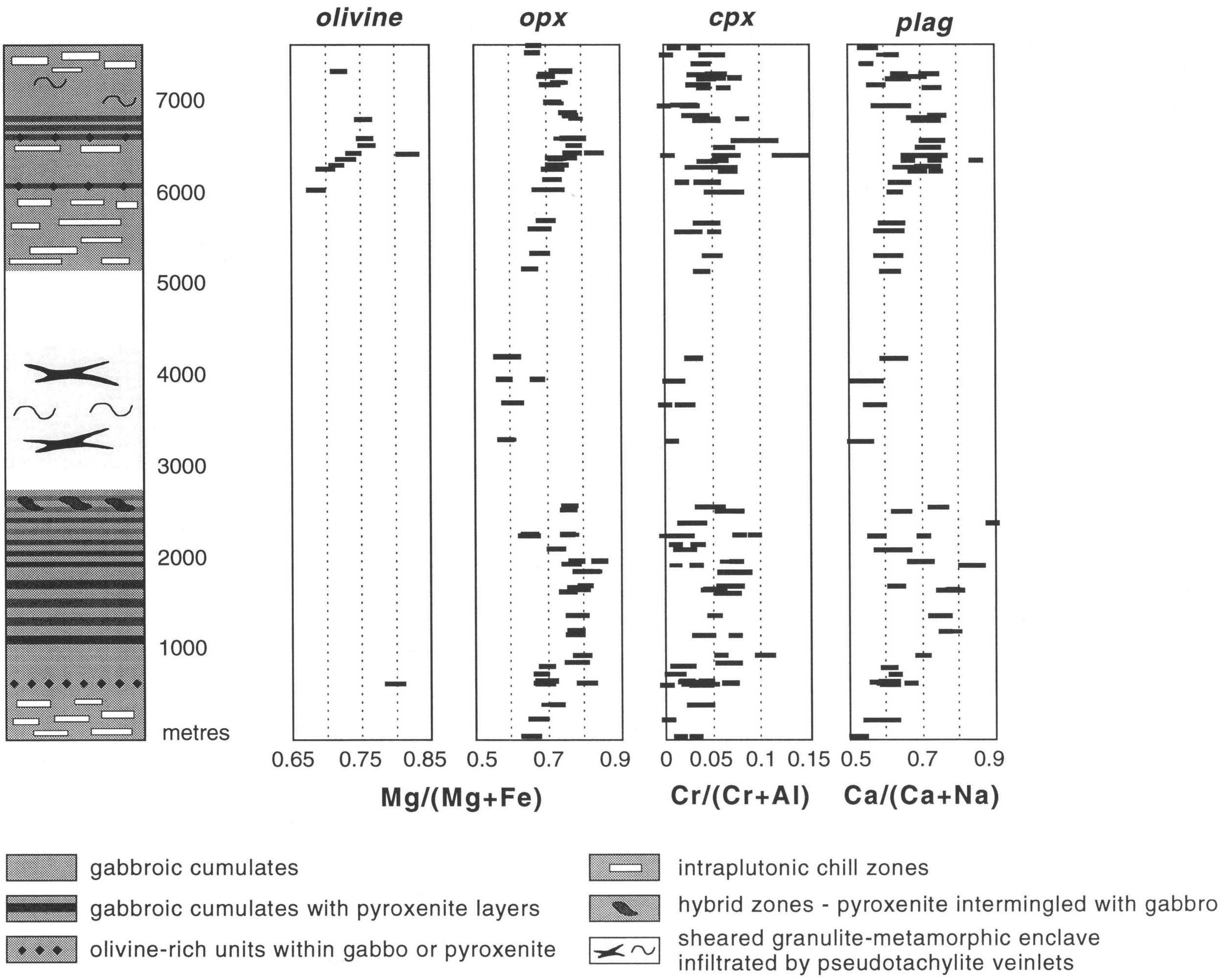

Figure 9. Magmatic stratigraphy and cryptic layering pattern of the Latitude Hill intrusion (for position of the sampling traverse see Fig. 8).

been situated. However, unless the sequence is overturned, it youngs toward the south. We concur with Daniels (1974) that the Bell Rock Range and Blackstone Range sequences originally formed one coherent intrusion.

Jameson Range intrusion

The Jameson Range intrusion is composed of approximately 2500 m of layered Fe-rich troctolite, gabbroic troctolite, and anorthosite adcumulates with various proportions of disseminated magnetite (Fig. 20). About two-thirds of the magmatic sequence is covered by alluvium. Closely interlayered centimetre-scale units are common. The Jameson sequence hosts several massive vanadiferous titano-magnetite seams (Daniels 1974). Bottom and top contacts of the intrusion are not exposed and the nature of the contacts remains unknown. The intrusion hosts some of the most fractionated cumulates in the Giles Complex (Fig. 21). Olivine ranges from about Fo_{65} to Fo_{51}, and Mg numbers of coexisting orthopyroxenes from 0.72 to 0.62. There is again no indication of a peritectic relationship between olivine and orthopyroxene, nor does modal orthopyroxene increase with increasing degree of fractionation. Clinopyroxene is significantly more magnesian than orthopyroxene and Cr is at detection limit. Ca/(Ca+Na) in plagioclase varies randomly from 0.75 to 0.49, sometimes with a 20 per cent variation within single grains. This can be attributed to incomplete plagioclase equilibriation during subsolidus recrystallisation.

Sampling density across strike is insufficient to identify any clear cryptic variation pattern (Fig. 20), nor can abrupt changes in cumulus mineralogy or any megascale layering be identified except where the massive magnetite seams occur, i.e. between the 1200 and 1700 m levels. Mineralogic phase layering occurs through gradual variation in (olivine+pyroxene)/plagioclase modal ratios and variation in disseminated magnetite. There is no obvious stratigraphic variation in modal olivine/orthopyroxene ratio or any correlation of that ratio with chemical fractionation, implying that the magma was too Fe-rich for olivine to react with its equilibrium melt, nor is there clear geochemical evidence to indicate younging direction. The shallow southerly dip of the magmatic layers makes it likely that the sequence youngs to the southwest.

Discussion

The Giles Complex consists of three major types of cumulates—ultramafic, gabbroic, and troctolitic. In the following sections we identify, in broad terms, the parent melt compositions that gave rise to these types of cumulates and discuss how they may be related.

Parental magmas to the Giles intrusions

Although chilled margins occur locally (Kalka, Mount Davies), their contaminated state requires reconstruction of parent melt compositions from crystallisation sequences and phase compositions of the most primitive cumulates in each intrusion. Implicit in this is that the crystallisation sequences in the cumulates resemble the liquidus relations of the parent melts. On this basis we identify three major types of parental magmas;

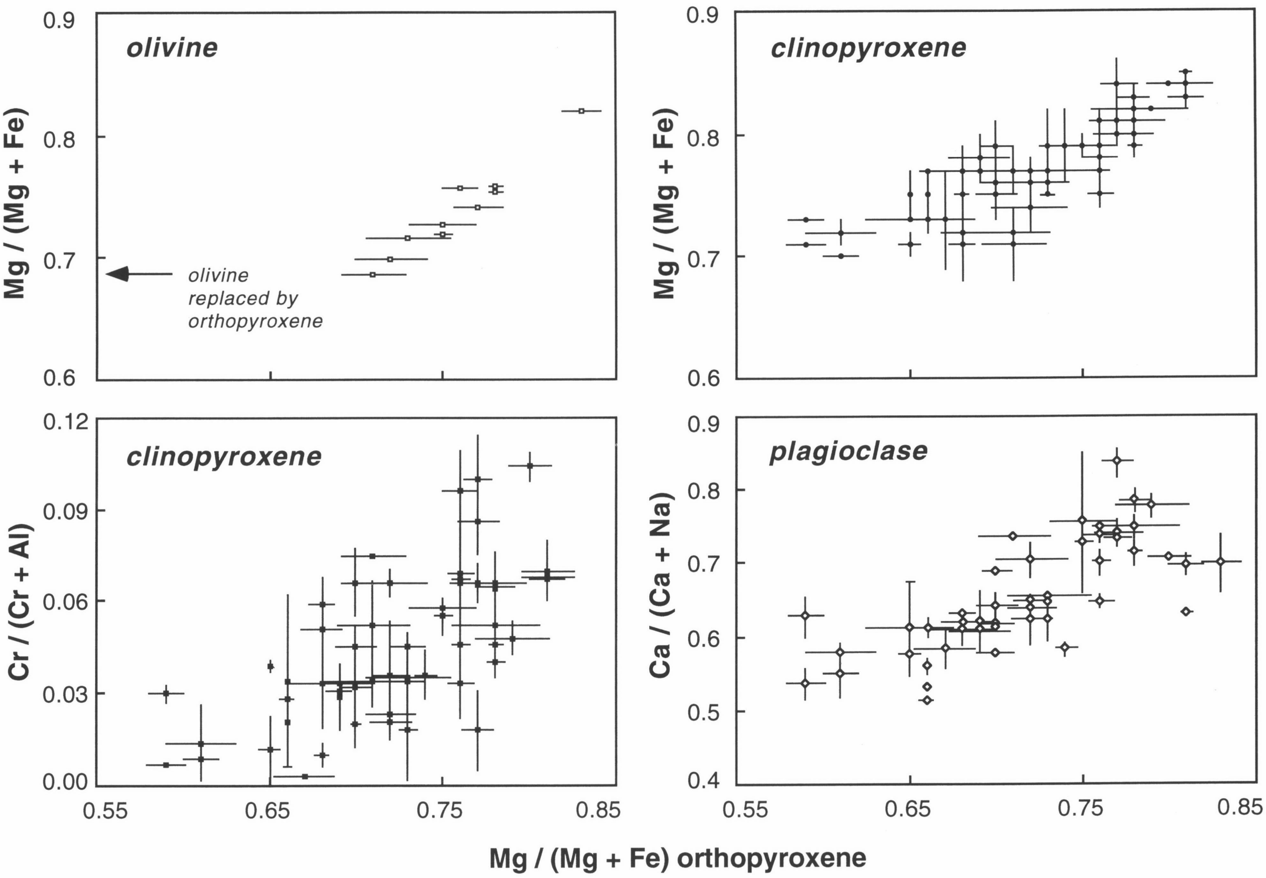

Figure 10. Average phase compositions in the Latitude Hill cumulates (error bars are two standard deviations).

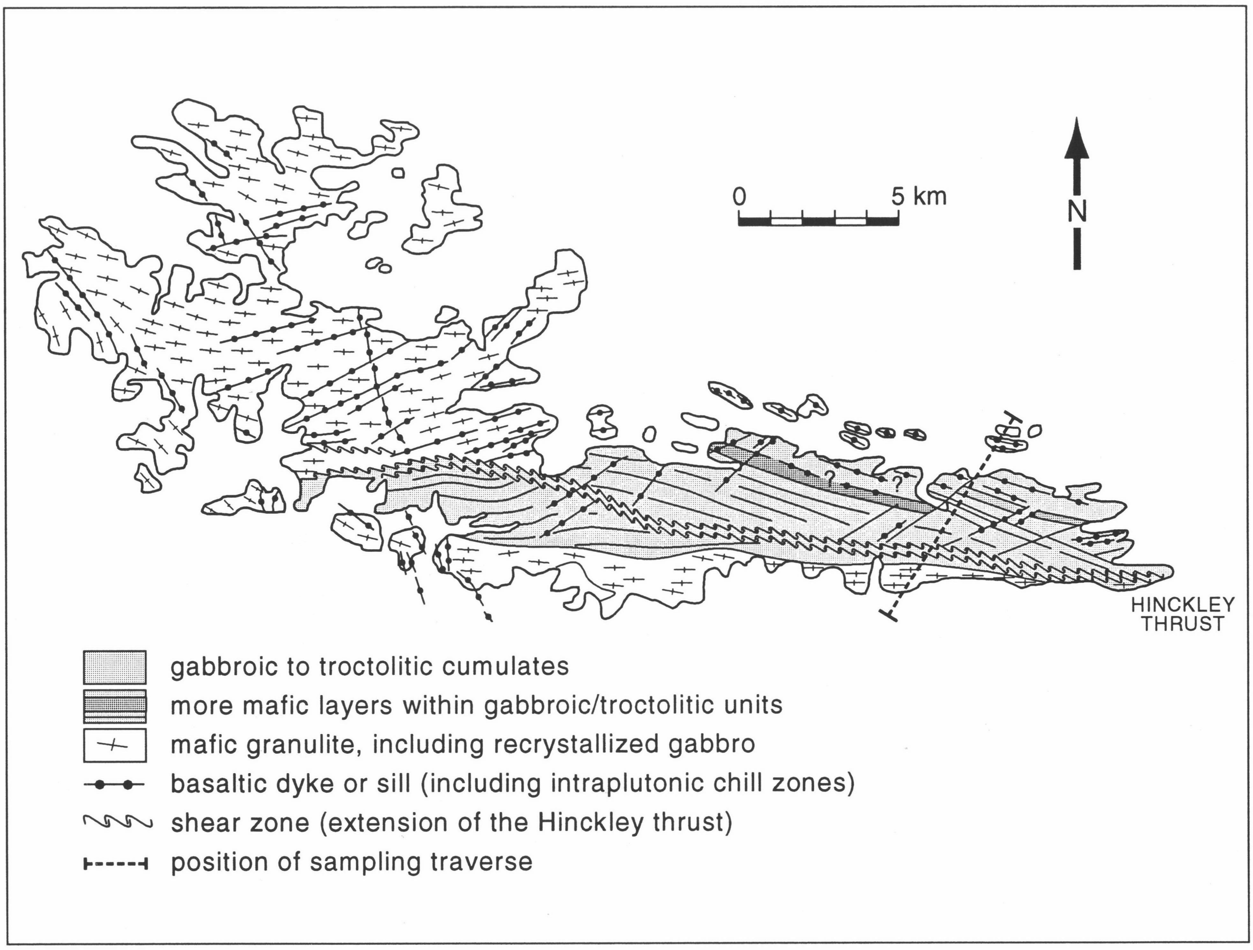

Figure 11. Schematic geology of the Hinckley Range mafic gabbroic intrusion.

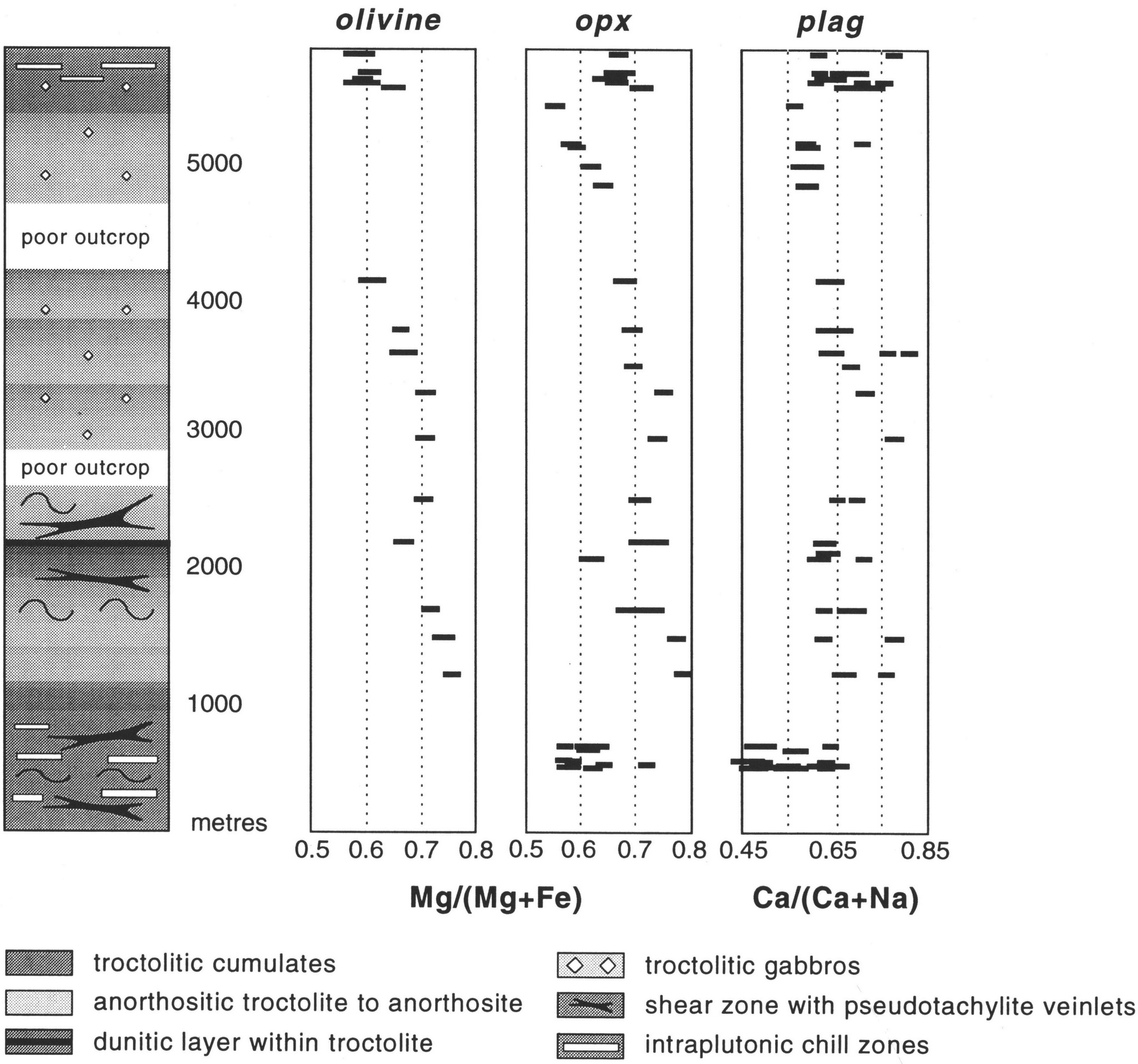

Figure 12. Schematic magmatic stratigraphy and cryptic layering pattern of the Hinckley Range intrusion (for position of the sampling traverse see Fig. 11).

(1) a primitive olivine-normative olivine–spinel saturated liquid, (2) a moderately fractionated quartz-normative pyroxene–plagioclase saturated gabbroic melt, and (3) a highly evolved nepheline-normative olivine–plagioclasemagnetite saturated troctolitic melt.

Primitive parental melt. Examples of cumulate sequences derived from a primitive melt are the Murray Range, The Wart, and Wingellina Hills intrusions (Ballhaus & Glikson 1989), and possibly the Kalka and Ewarara intrusions (Goode & Moore 1975, Goode & Krieg 1967), for which systematic phase compositions are not available. The following criteria allow characterisation of the parent melt:

- Olivine became replaced from the liquidus at Fo_{77} (Figs 4, 7); this, in combination with the observation that dunite cumulates are volumetrically minor rock types in all ultramafic intrusions of the Giles Complex, suggests that the normative olivine content of the melt could not have been very high.
- The most primitive cumulates (Murray Range and Wingellina Hills intrusions) are dunitic orthocumulates where the most magnesian olivine is Fo_{88-89}. Assuming that total Fe as FeO in the melt was around 10 wt per cent (reasonable for continental tholeiitic melts), this gives an MgO content in the melt of around 12 wt per cent (Roeder & Emslie 1970).
- Typical Ni content in the most primitive olivines is around 2500 ppm; available partition coefficients constrain Ni in the equilibrium melt to around 200 ppm (Henderson 1982; Hirschmann & Ghiorso 1994).
- Maximum Cr content of the texturally earliest cumulus clinopyroxene ranges from 1800 to 2200 ppm, suggesting a Cr content of the equilibrium melt of around 150–200 ppm (e.g. Philpotts 1990).
- Every reversal in the cryptic layering patterns of the ultramafic intrusions is matched in the cumulate sequence by loss of at least one cumulus phase, commonly two (clinopyroxene and plagioclase). This suggests that, at the pressure of emplacement, the primitive magma was only saturated with olivine (+ spinel).

The above points summarise the chemical characteristics of a low-pressure basaltic melt in near-equilibrium with mantle parageneses (cf. Green & Ringwood 1967a; Jaques & Green 1980). We conclude that the parent melt to the ultramafic intrusions of the Giles Complex was broadly tholeiitic and just olivine normative. It experienced negligible phase fractionation or contamination prior to emplacement in the crustal magma reservoirs.

Gabbroic parental melt. The cumulate series of the gabbroic intrusions (Hinckley and Latitude Hill) formed from multi-

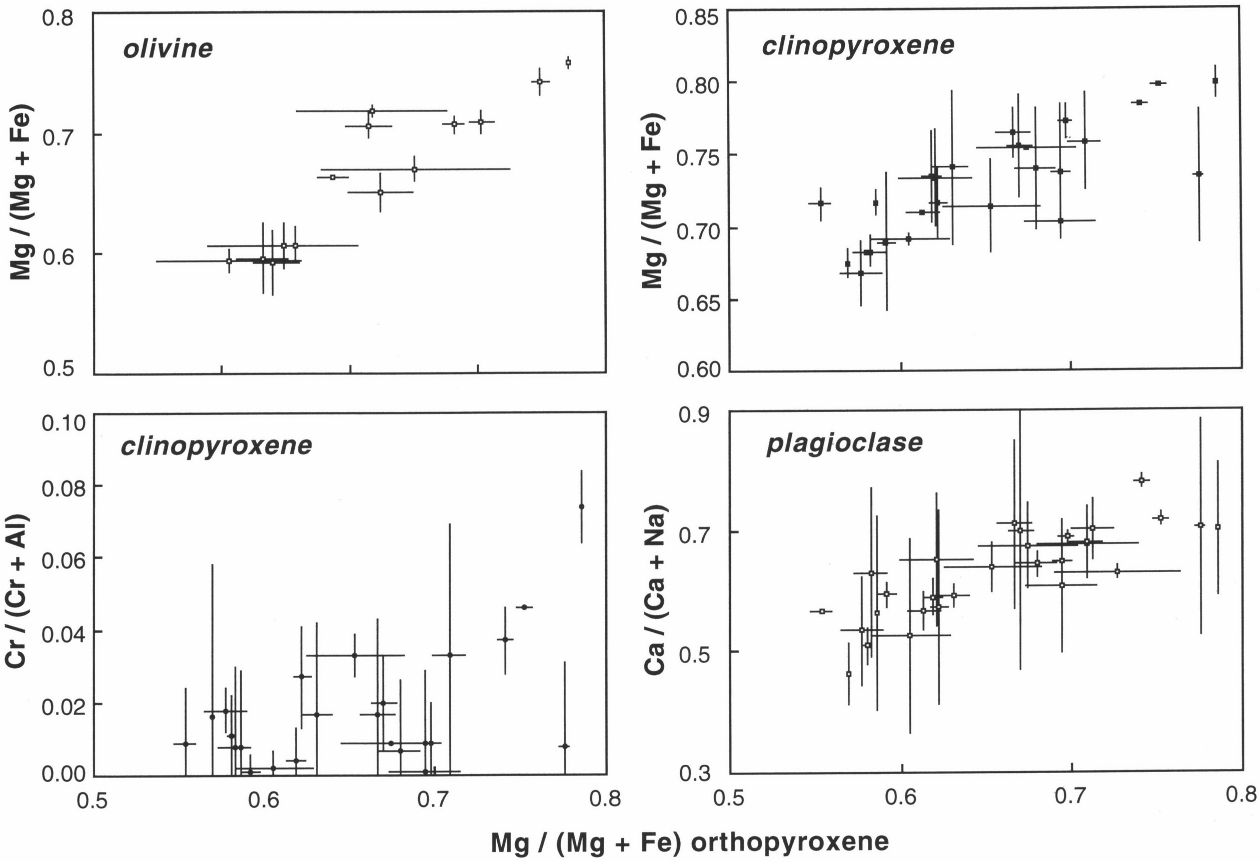

Figure 13. Average phase compositions in the Hinckely Range cumulates (error bars are two standard deviations).

ply-saturated parental melts significantly more evolved than the parent liquids to the ultramafic intrusions. The melts must have been saturated with olivine–(orthopyroxene), clinopyroxene, and plagioclase at the time of emplacement. As a direct result there is little change in cumulus mineralogy, even where reversals in mineral composition signify a major influx of new magma into the magma chamber. A new melt pulse can only change cumulate mineralogy (and initiate megascale layering) if it is compositionally far removed from a cotectic. In cases where a melt is close to multiple phase saturation, a modal change will only result if the mass ratio of added (more primitive) to resident (more fractionated) melt is high.

Overall, the gabbroic parent magma must have experienced appreciable pyroxene±olivine fractionation prior to emplacement. The most primitive olivine compositions encountered are Fo_{83} at Latitude Hill and Fo_{75} in the Hinckley Range sequence, and these became replaced by orthopyroxene when olivine had evolved to Fo_{67} and Fo_{56}, respectively. Cr in the gabbroic parental melt was also severely depleted. Cr/(Cr+Al) in clinopyroxenes of the Latitude Hill sequence is below 0.15, while in the Hinckley Range sequence it is near detection limit.

Troctolitic parental melt. The parent melt to the troctolitic intrusions (Bell Rock, Jameson, and Blackstone Ranges) was saturated with Fe-rich olivine and sodic plagioclase, and close to magnetite saturation. Silica activity in the melt was low and the bulk silica content of the fractionating phases (olivine, plagioclase, magnetite) must have been higher than that of the equilibrium melt. Consequently, there was no silica enrichment in the melt and no increase in modal orthopyroxene with protracted fractionation upward in the sequence, as confirmed by the scarcity of orthopyroxene in the most Fe-rich cumulates as well as the most primitive samples. The melt that gave rise to the troctolitic suites must have been enriched in ferrous iron, resulting in a stable cotectic relation between Fe-rich olivine and orthopyroxene and between these phases and the melt (cf. Bowen & Schairer 1935). In addition, the magma was low in normative clinopyroxene in comparison with the gabbroic and the mafic parental melts, and despite clinopyroxene increasing in modal abundance with falling Mg number (increasing degree of fractionation) in the gabbroic intrusions (Hinckley Range or Latitude Hill).

The low silica activity, high Fe contents, and low normative clinopyroxene are chemical fingerprints of a melt that experienced severe fractionation prior to emplacement. The enrichment of the melt in terms of FeO resulted in the equilibrium olivine being no longer in peritectic reaction relationship with its melt (cf. Bowen & Schairer 1935). To derive strongly undersaturated troctolite melts, the fractionating assemblages must have had a bulk silica content at least as high as that of their equilibrium melt. As suggested below, this can ensue from pre-emplacement high-pressure pyroxene fractionation.

Chemical relationships among the parent melts

At first sight, it seems straightforward to derive all parent melt compositions and cumulates from one primitive mantle liquid, by simply fractionating the phase assemblages that occur as cumulate layers in intrusions of the Giles Complex. Implicit in this model is that the ultramafic cumulate suites form the basal sequence, the gabbroic intrusions the main section, and the troctolitic intrusions the highly evolved roof section of a single magma chamber (Sprigg & Wilson 1959), and that the complex later became dismembered by post-granulite metamorphic thrusting (cf. Harley 1990).

The above model, however, is consistent with the behaviour of olivine. Olivine persists as a fractionating phase through a range of cumulates, from Fo_{89} in the Murray Range intrusion down to Fo_{40} in the Blackstone Range intrusion (cf. Fig. 22). The expected trend in a single basaltic magma chamber would be that olivine temporarily disappears from the liquidus when

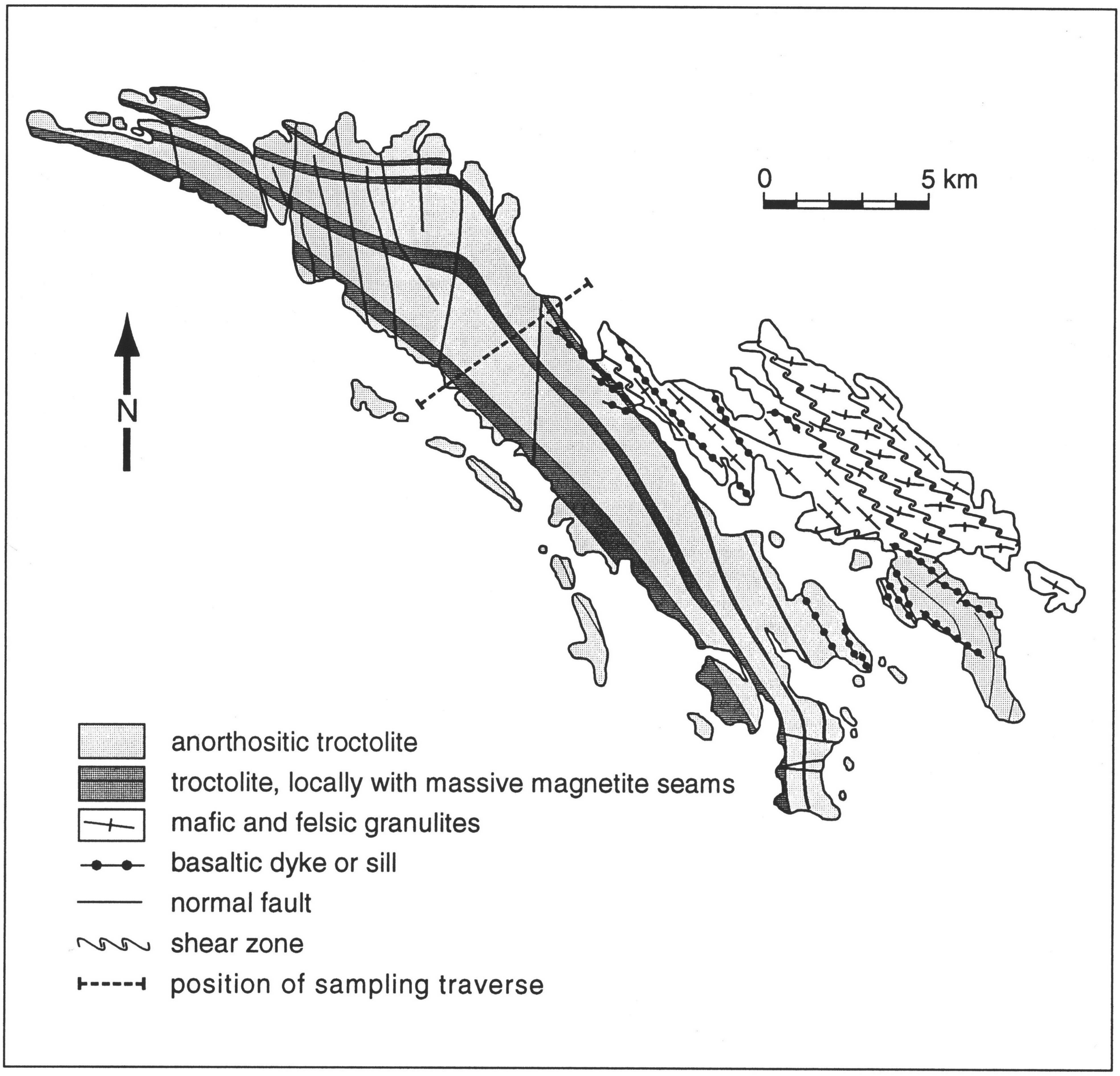

Figure 14. Schematic geology of the Bell Rock Range troctolitic intrusion.

the silica activity of the melt exceeds that of the olivine–orthopyroxene peritectic of the melt, to reappear as a fayalite-rich olivine when FeO is high enough that olivine and orthopyroxene are in cotectic relationships. A classic example where this happens is the Bushveld sequence (Willemse 1969). Most Giles Complex intrusions indeed show replacement of olivine by orthopyroxene: at Fo_{78} in the Murray Range and Wingellina Hills sequences; at Fo_{68} in the Latitude Hill intrusion; and at Fo_{59} in the Hinckley Range gabbro. However, it is unlikely that olivine could reappear on the liquidus in successive cumulate piles while Mg numbers continued to fall (cf. Fig. 22).

High-pressure pyroxene fractionation?

The trend in Figure 22 suggests derivation from a single magma composition, if the fractionating assemblages had bulk MgO, CaO, and silica contents higher than their equilibrium melts. An elegant way to achieve this is by high-pressure fractionation (Ballhaus & Glikson 1992). At low confining pressure, up to about 0.8 GPa, a tholeiitic melt initially in equilibrium with mantle assemblages will fractionate olivine followed by clinopyroxene and plagioclase (cf. Green & Ringwood 1967a). A typical intrusive cycle within a replenished magma chamber will thus commence with the deposition of primitive dunite and peridotite orthocumulates followed by more fractionated olivine-bearing pyroxenites, pyroxenites, and then gabbros (cf. Ballhaus & Glikson 1989). Chemical evolution will be along an olivine control line, whereby Mg numbers of the cumulus phases fall and the activity of silica in the equilibrium melt rises. The fractionating mineral assemblages have at all times lower bulk silica content than the magma from which they separated. When silica exceeds that of the olivine–orthopyroxene peritectic, olivine will be replaced by orthopyroxene and further fractionation will not include olivine until high FeO terminates the peritectic relationship between olivine and melt.

This scenario changes if crystallisation takes place at higher confining pressure. The olivine–orthopyroxene peritectic shifts toward the olivine stability field until it becomes a cotectic phase boundary. The clinopyroxene and spinel stability fields expand at the expense of the olivine and plagioclase fields until troctolitic assemblages (olivine plus plagioclase) become unstable (Green & Ringwood 1967a,b; Presnall et al. 1978). A direct consequence is that the silica content of melts along the olivine–orthopyroxene cotectic will be lower than the silica content of the equilibrium orthopyroxene (e.g. Kushiro 1969;

Presnall et al. 1978, 1979). Crystal fractionation under such conditions will consist of pyroxene+olivine and will deplete the melt in MgO and CaO relative to FeO and Na_2O without enrichment in silica, because the fractionating phases have bulk silica contents as high, or higher than, their equilibrium melts.

It is suggested that the fractionation trends observed in the Giles Complex can be explained by high-pressure fractionation followed by low-pressure fractionation. The range in parent melt compositions could have been produced by high-pressure pyroxene±olivine fractionation when olivine and orthopyroxene were in cotectic relationships, preventing a buildup in silica in the melt (Fig. 22). The individual fractionation trends inside the intrusions must have originated at lower pressure, when olivine was in a reaction relationship with the melt. It is envisaged that fractions of the evolving high-pressure melt were periodically squeezed off into shallower pressure magma reservoirs in the crust at various degrees of chemical fractionation. As a result, melts that were fractionating pyroxeneolivine at high pressure experienced a relative compositional shift into the olivine-only stability field when decompression occurred. Further fractionation at low pressure was then dominated by olivine, allowing silica activity to increase as fractionation continued. Depending on the stage in the high-pressure fractionation history at which a derivative melt fraction became squeezed off its high-pressure reservoir, the liquid crystallised to gabbroic or troctolitic cumulates.

Evidence in support of high-pressure crystallisation. Ample evidence exists to support high-pressure fractionation for parts of the Giles Complex (cf. Goode & Moore 1975):

- In all troctolitic intrusions, clinopyroxene remains a minor phase and appears late (if at all) in the crystallisation sequence. This is only understandable if the parental melts were severely depleted in normative clinopyroxene through a prolonged history of high-pressure fractionation, prior to emplacement in their crustal reservoirs.
- The Murray Range sequence includes cumulates where olivine and orthopyroxene coexist as cumulus phases at an olivine composition as primitive as Fo_{88} (Ballhaus 1993). This may suggest that both minerals crystallised along a cotectic phase boundary very early in the fractionation history. The minimum pressure to achieve this must have been at least 0.7 to 0.8 GPa judging from the work of Green & Ringwood (1967a), assuming that the parental liquid was a tholeiitic low-pressure mantle melt and just olivine-normative.

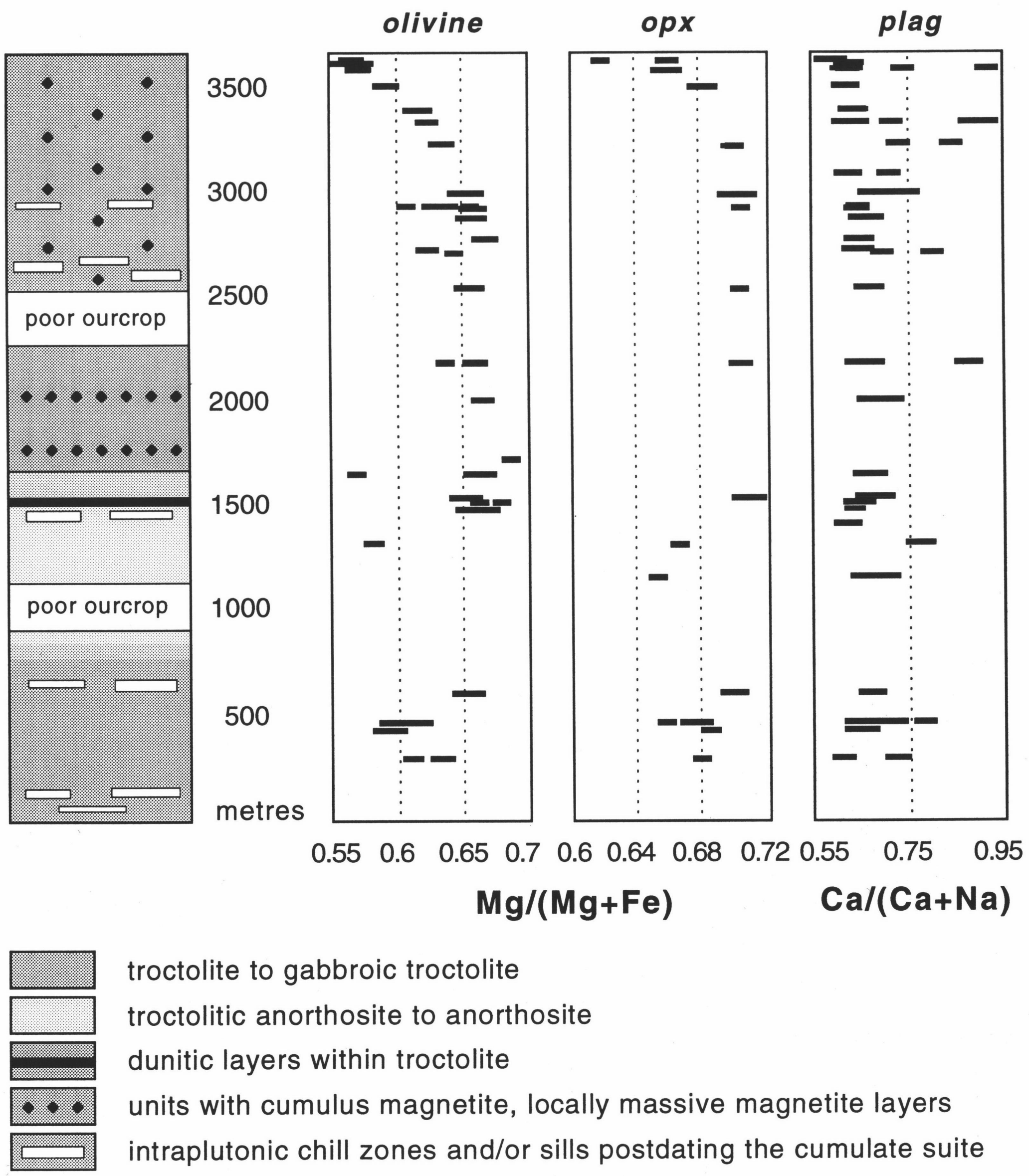

Figure 15. Schematic magmatic stratigraphy and cryptic layering pattern of the Bell Rock Range intrusion (for position of the sampling traverse see Fig. 14).

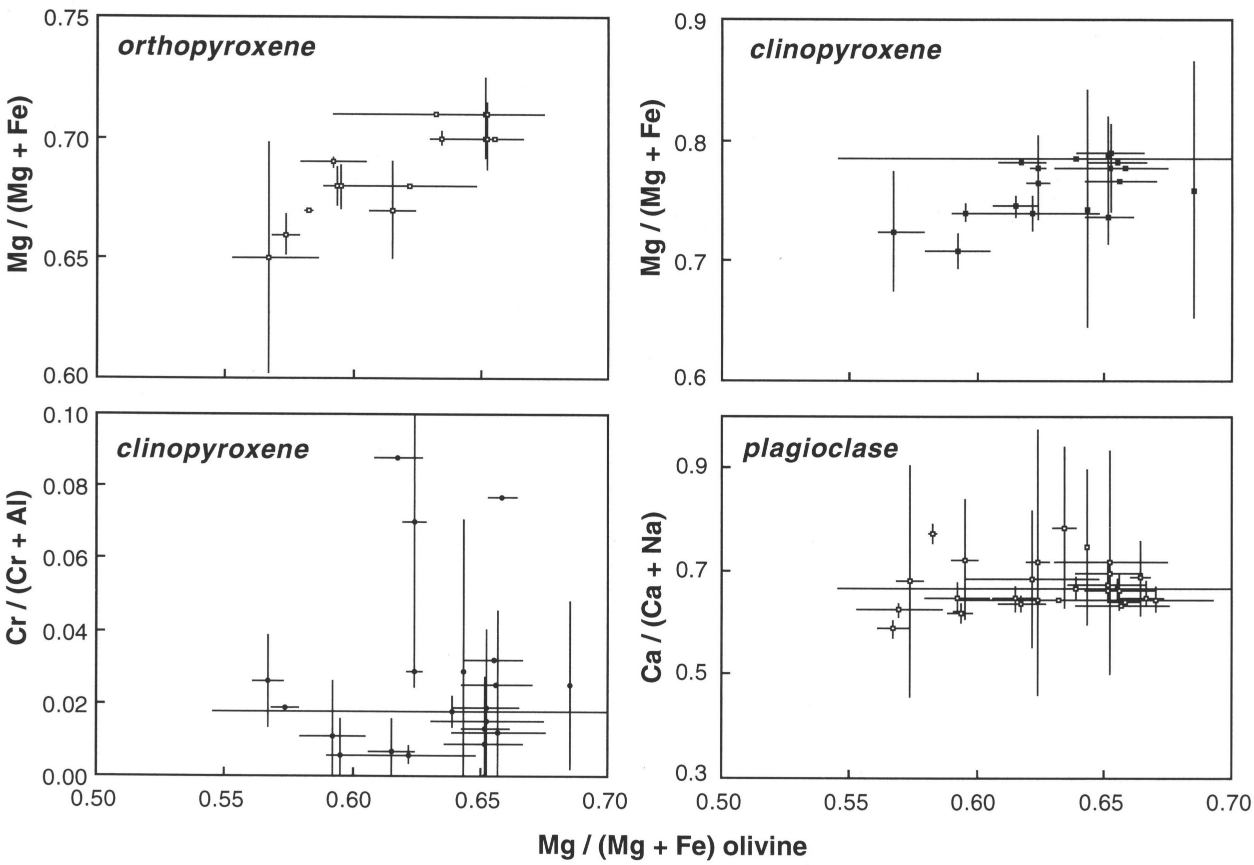

Figure 16. Average phase compositions in the Bell Rock Range cumulates (error bars are two standard deviations).

- Plagioclase in the Murray Range sequence is more sodic at any given olivine composition than in other, similarly mafic sequences of the Giles Complex. This may in part be attributed to the fact that, in the Murray Range intrusion, plagioclase appears later in the crystallisation sequence than olivine and clinopyroxene, i.e. crystallised from a magma that was depleted in CaO and enriched in silica by olivine–clinopyroxene fractionation. Both factors will tend to stabilise more sodic plagioclases. On the other hand, elevated pressure will also stabilise diopside and aluminous spinel relative to anorthite (Green & Ringwood 1967b; Green & Hibberson 1970; Presnall et al. 1979), and thus delay nucleation of plagioclase.
- Pyroxenes are high in alumina and other non-quadrilateral components, notably in the ultramafic cumulates of the Murray Range sequence (cf. Ballhaus & Glikson 1989). The primary reason for this must be a high crystallisation temperature; indirectly, however, high temperature may indicate high confining pressure, since pressure displaces the liquidus of a dry basaltic melt to higher temperature.
- One set of dykes includes partially resorbed orthopyroxene as the only phenocryst generation, in a matrix containing olivine microphenocrysts (Ballhaus 1993). These dykes may represent quenched fractions of a high-pressure basaltic melt, tapped from greater depths, that managed to preserve samples of the high-pressure fractionating phase as intratelluric phenocrysts.

Towards an emplacement model for the Giles Complex

Magmatism of the Giles Complex and associated metamorphism may have resulted from a thermal anomaly situated in the upper mantle below the Musgrave Block (see also Sun & Sheraton 1992). Emplacement of melts into the crustal reservoirs must have coincided with an extensional period during the granulite–metamorphic event, possibly as a result of lithospheric thinning above a thermal anomaly in the upper mantle. Some fractions of the primitive mantle-derived magma were emplaced directly into crustal reservoirs where pressures were low enough to allow extensive olivine fractionation, followed by clinopyroxene and plagioclase fractionation. The cumulate sequences from these batches of primitive magma are denoted as 'primitive' in Figure 1, i.e. the Murray Range, Wingellina Hills, Kalka, Ewarara, Gosse Pile, and Claude Hill intrusions.

Other fractions of the primitive mantle magma must have ponded at greater depths, possibly in reservoirs within the lower crust or even in the shallow lithosphere. Owing to higher confining pressure, the stable liquidus phases included orthopyroxene and clinopyroxene in addition to olivine. These melts experienced silica depletion with progressive fractionation.

Development of particular tectonic conditions may have resulted in the squeezing of fractions of the evolving high-pressure melt into shallower crustal (secondary) reservoirs. Decompression caused an expansion of the olivine and plagioclase stability fields relative to those of pyroxene and spinel, and a relative shift in melt composition away from multiple saturation into the olivine stability field. Following emplacement at shallow pressure, these melts now fractionated predominantly olivine and plagioclase. Depending on the stage at which these melts became squeezed off their high pressure reservoirs, they gave rise to either gabbroic or troctolitic cumulate sequences.

Conclusions

The mafic–ultramafic intrusions of the Giles Complex formed from separate batches of variably fractionated parent melts (cf. Nesbitt et al. 1970; Daniels 1974). The parent melt compositions can be related chemically to a primitive man-

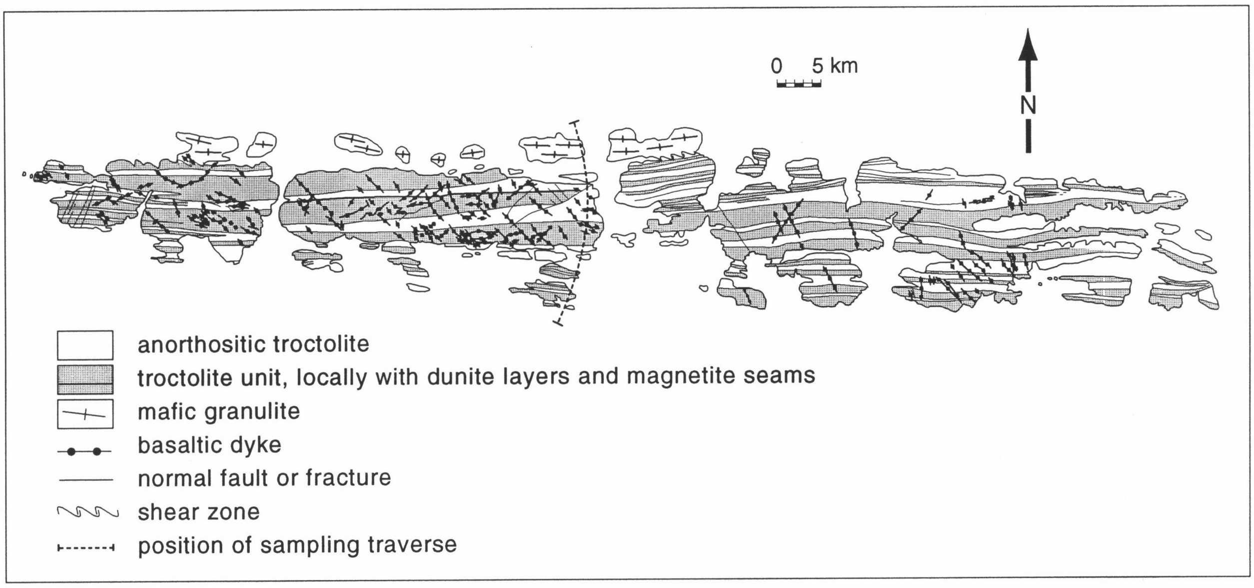

Figure 17. Schematic geology of the Blackstone Range troctolitic intrusion.

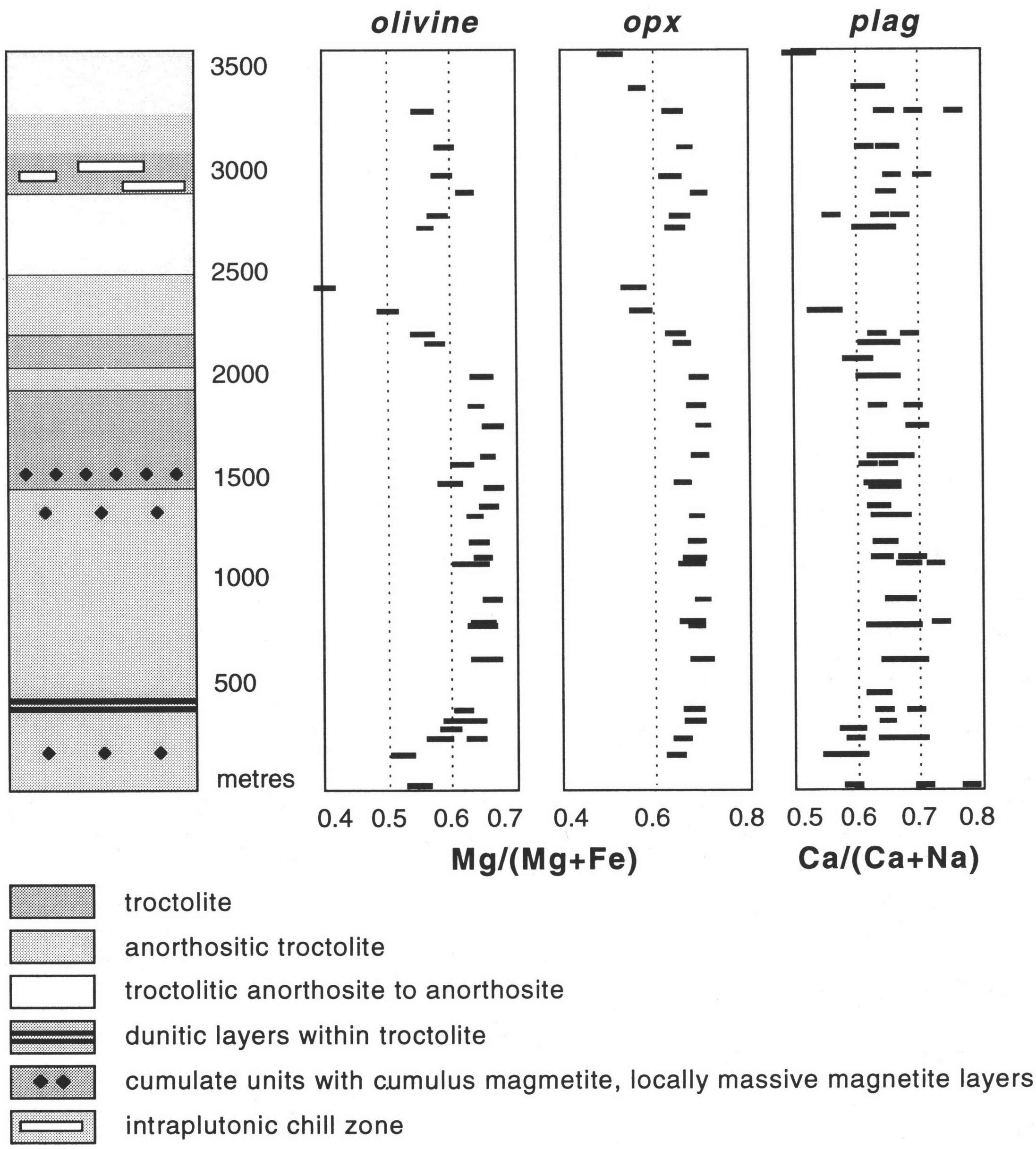

Figure 18. Schematic magmatic stratigraphy and cryptic layering pattern of the Blackstone Range intrusion (for position of the sampling traverse see Fig. 17).

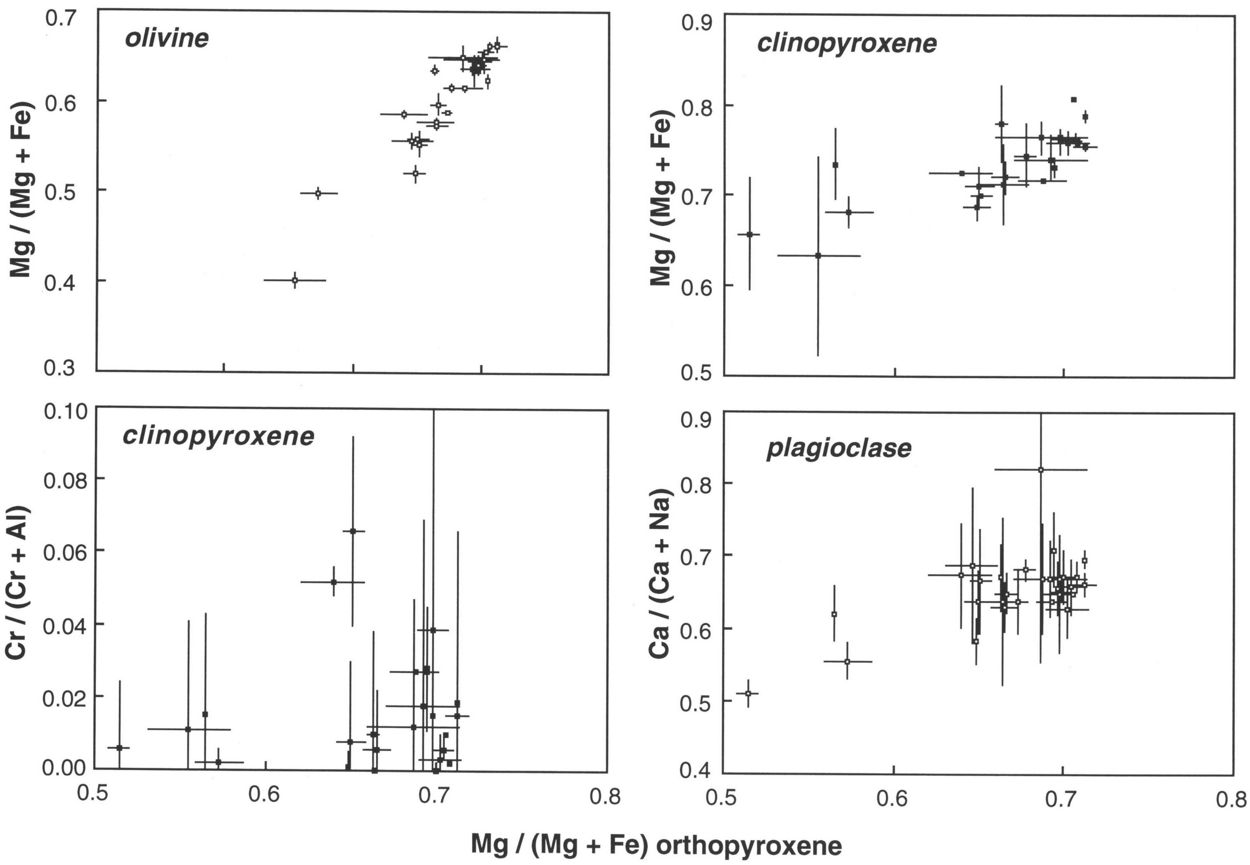

Figure 19. Average phase compositions in the Blackstone Range cumulates (error bars are two standard deviations).

tle-derived parental liquid by polybaric pyroxene±olivine fractionation.

The present-day dimensions of the intrusions approximately reflect the sizes of individual middle to upper crustal magma chambers. Their geographic distribution may reflect vertical stacking of individual magma chambers within the Proterozoic crustal section exposed in the Tomkinson Ranges.

Identification of extensive high-pressure fractionation precursors of the Giles Complex implies that the lower crust of the Musgrave Block may host other pyroxene-dominated high-pressure intrusions, unexposed at present-day erosion levels. These high-pressure cumulates, if they exist, would be characterised by high modal pyroxene/olivine ratios and high-temperature/high-pressure crystallisation features, such as high Cr and Al contents in pyroxenes and very aluminous spinels. Plagioclase (if present) will be a minor phase and comparatively sodic. The only intrusions exposed at present-day erosion levels that fit these characteristics are the Murray Range intrusion and, possibly, the Ewarara and Gosse Pile intrusions, described by Goode (1967), Moore (1971a,b), and Goode & Moore (1975).

The geographic distribution of the Giles intrusions may have been controlled by magma densities, i.e. buoyancy differences between the magmas and the surrounding crust. Judging from high modal plagioclase in the cumulates, the parental liquids to the gabbroic and troctolitic sequences must have been less dense and more buoyant than the primitive parental liquid. As such, they intruded shallower crustal levels than the denser mantle-derived basaltic liquids, which ponded in deeper levels of the crust. Intrusions with similar parentage tend to occur in discrete belts, parallel to the regional compositional layering in the felsic granulites of the Musgrave Block (Fig. 1), as follows: (1) ultramafic intrusions along the northeastern margin of the Tomkinson Ranges; (2) the most fractionated troctolitic intrusions along the southern and western margins; and (3) gabbroic intrusions in positions intermediate between (1) and (2). It is suggested that this pattern was controlled by magma density, where each magma type intruded the crust at its level of neutral buoyancy. Implicit in this model is that the crustal section exposed in the Tomkinson Ranges progressively shallows from the Woodroffe Thrust in the northeast toward the southwest.

Prospects for the Giles Complex having potential for magmatic chromite–sulphide–PGE mineralisation are considered to be limited, as these intrusions have important differences from economically important complexes such as the Bushveld, Great Dyke or Stillwater intrusions (cf. Naldrett et al. 1986). Cumulate textures illustrated by Ballhaus (1993) suggest that the Giles Complex intrusions cooled faster than the above layered intrusions, leaving less chance for efficient accumulation of incompatible elements, such as the PGE (see Morse 1986 for cumulate growth mechanisms). Chromitite layers, often spatially associated with stratiform sulphide–PGE mineralisation, are also lacking, probably because the melt became depleted in Cr at an early stage, owing to high-pressure clinopyroxene fractionation (cf. Goode & Moore 1975). Should sulphide–PGE mineralisation be identified in the future, it may be restricted to single cumulate sequences, in view of the discrete nature of individual intrusive bodies and the difficulty in correlating cumulate sequences between intrusions.

Acknowledgments

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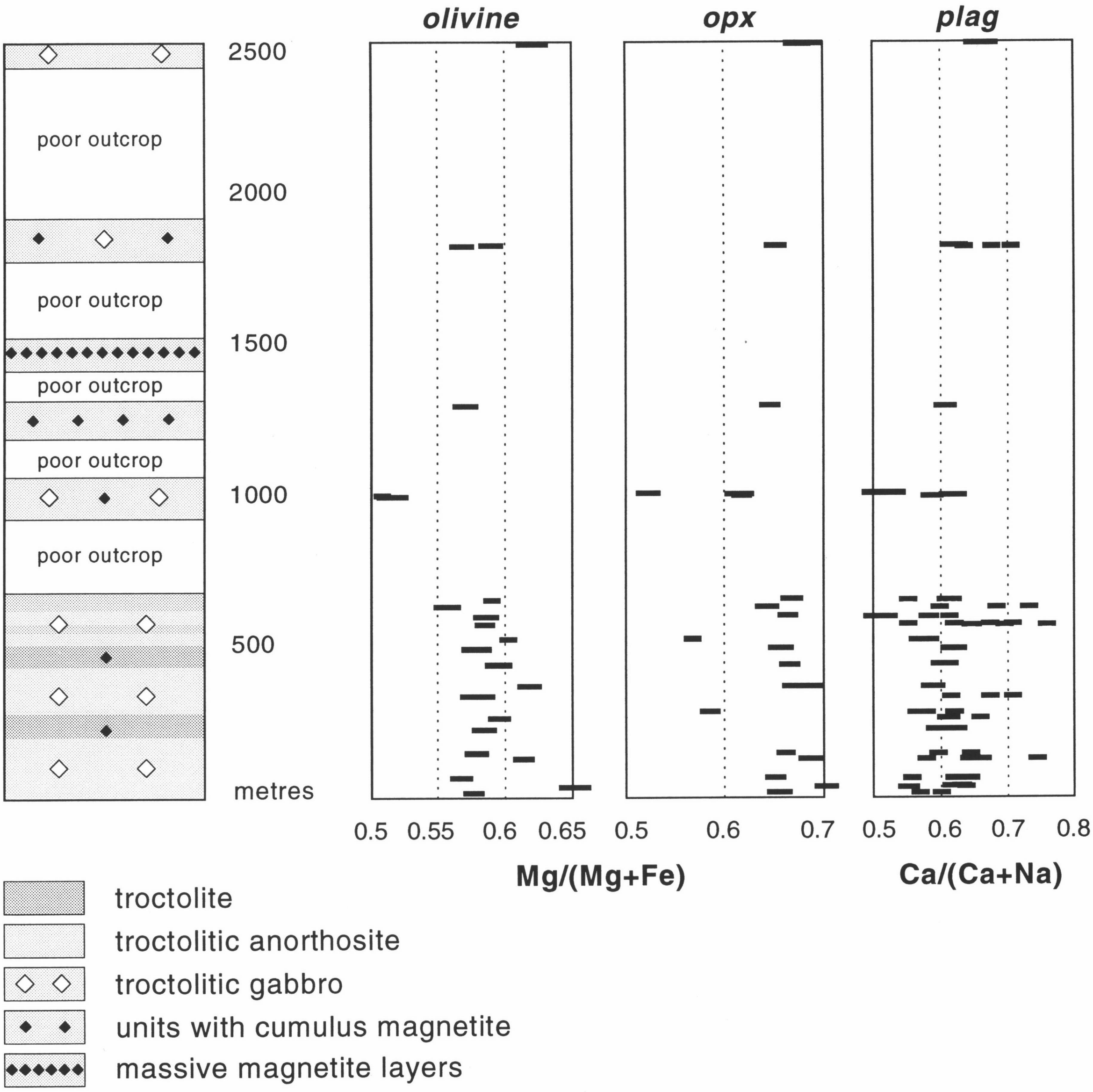

Figure 20. Schematic magmatic stratigraphy and cryptic layering pattern of the Jameson Range intrusion.

commenting extensively on the manuscript. Wieslav Jablonsky (Central Science Lab, University of Tasmania) maintained the microprobe in running order.

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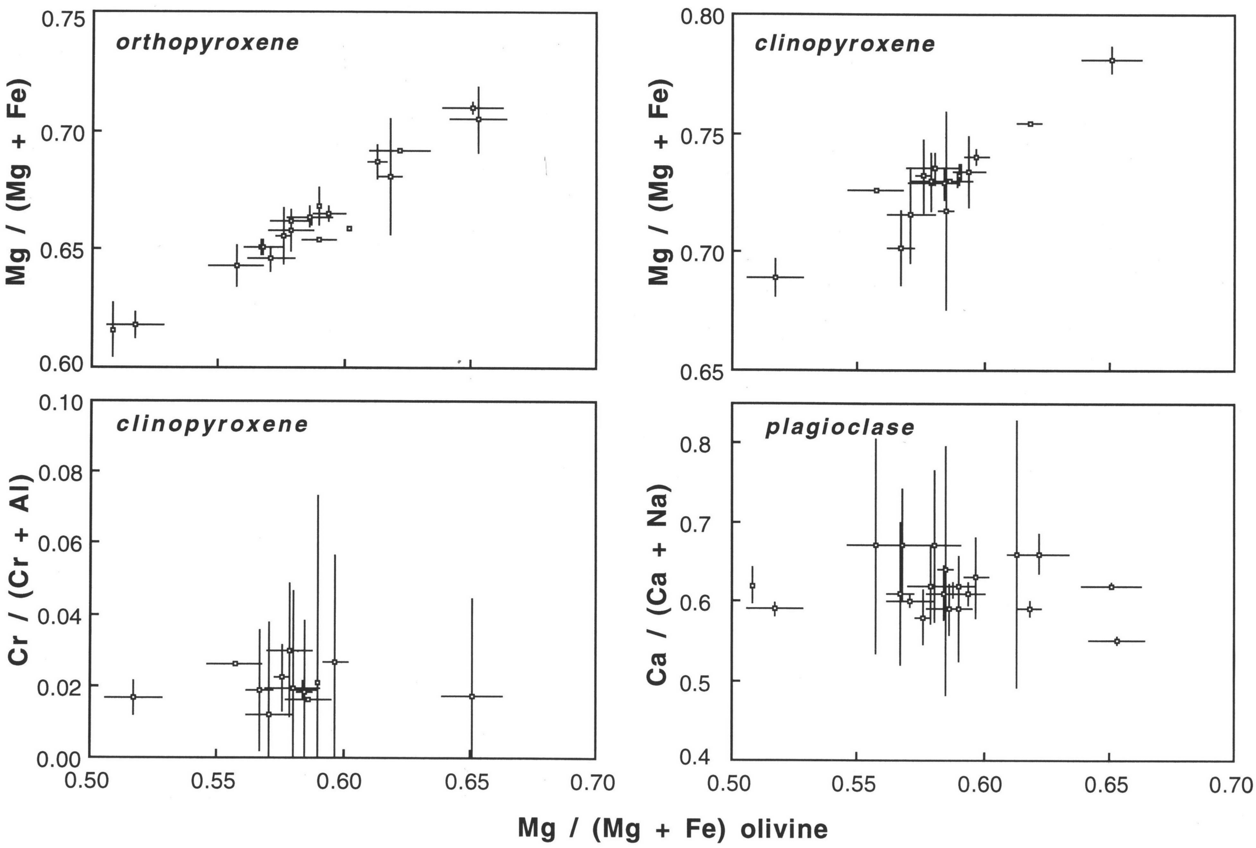

Figure 21. Average phase compositions in the Jameson Range cumulates (error bars are two standard deviations).

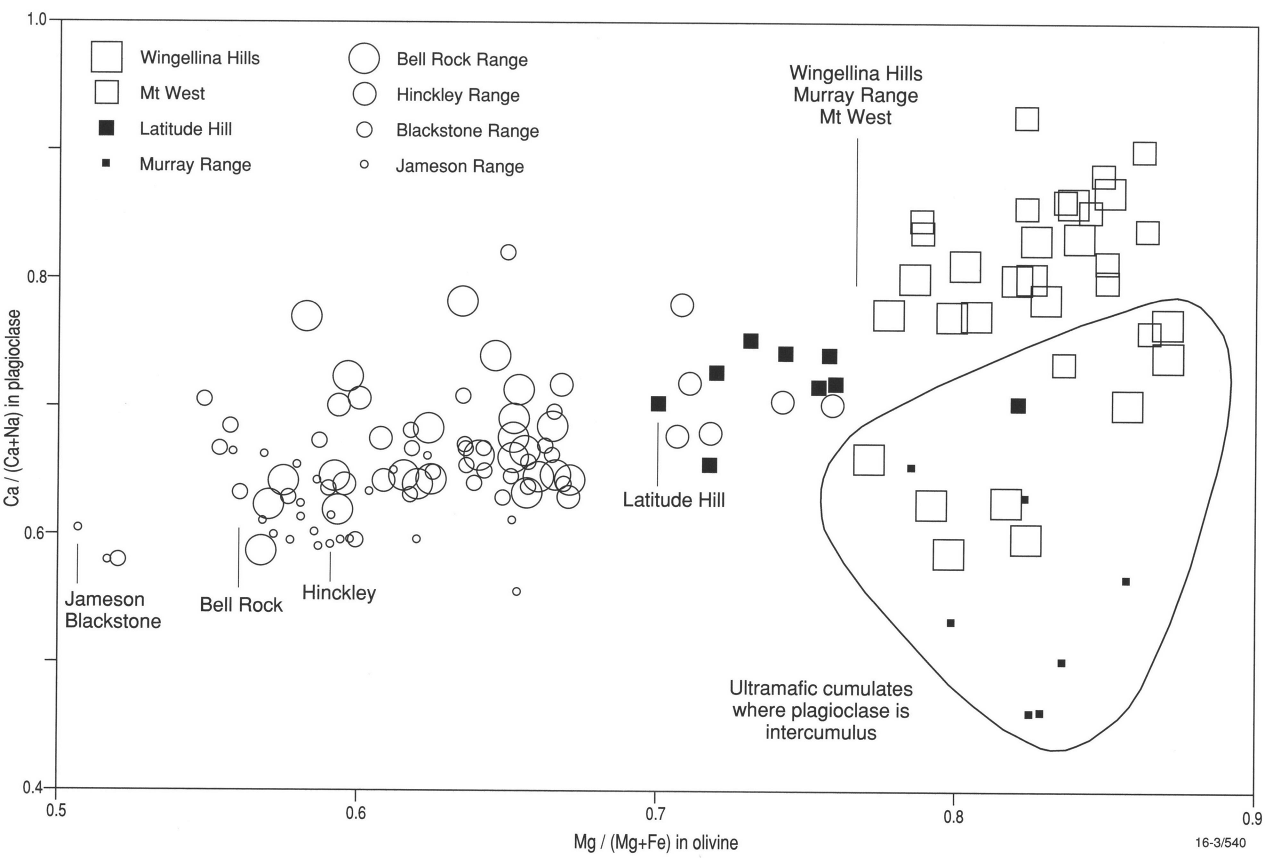

Figure 22. Olivine and plagioclase (average compositions) in cumulates of the Giles Complex. Arrows mark the most Fe-rich olivine composition of each cumulate suite. In the ultramafic and mafic gabbroic sequences, the most Fe-rich olivine marks the point in fractionation history where olivine became replaced by orthopyroxene. For implications see text.

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