ECONOMIC GEOLOGY RESEARCH UNIT

University of the Witwatersrand
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ARCHAEAN LAYERED ULTRAMAFIC COMPLEXES IN THE BARBERTON MOUNTAIN LAND SOUTH AFRICA

C.R. ANHAEUSSER

INFORMATION CIRCULAR NO. 161

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by

C.R. ANHAEUSSER
(Deputy Director, Economic Geology Research Unit)

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ABSTRACT

At least 27 Archaean sill-like bodies of ultramafic composition intrude the Barberton volcano-sedimentary sequence. These sills, some of which are over 16 km long and up to 1,5 km wide, are intimately associated with basaltic and peridotitic komatiite extrusives and subordinate, thin, chemical sedimentary units, and are mainly developed in the lower part of the Barberton volcanic pile. A lesser number of generally serpentinized layered complexes occur in the upper mafic-to-felsic part of the volcanic succession.

The sills nearly all show pronounced magmatic differentiation and the common development of cyclically repeated layering consisting predominantly of dunite, orthopyroxenite and harzburgite and volumetrically subordinate websterite and anorthositic gabbro-norite units. The layered bodies have undergone deformation involving folding and faulting and have been affected by low grade regional metamorphism and, less commonly, contact metamorphism resulting from the intrusion of Archaean granitic rocks. Despite being generally altered there are some complexes that are relatively well-preserved and which have retained original minerals and textures. Using several of these better preserved complexes as examples a general review of the principal features that characterize the layered bodies is provided.

The parent magma for the Barberton intrusions appears to have been rich in MgO (± 28%) and is considered to be like that of the peridotitic komatiite extrusives found in the region. Fractionation of olivine, orthopyroxene, and clinopyroxene from this komatiite liquid yielded a variety of cumulate rocks and residual liquids, the latter probably represented by the contemporaneous basaltic lava sequences which invariably host the ultramafic complexes.

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I. INTRODUCTION

Pre-metamorphic, subalkaline, mafic-to-ultramafic sill-like intrusions are now known to occur in many Archaean volcano-sedimentary greenstone belt sequences the world over. Best documented among these are some of the layered intrusions found in Canada (Naldrett and Mason, 1968; MacRae, 1969; Irvine and Ridler, 1972; Jolly, 1977; Raudsepp and Ayres, 1982) and Western Australia (McCall and Doepel, 1969; McCall, 1971; Williams, 1971, 1972; Hallberg and Williams, 1972; Williams and Hallberg, 1973, Jaques, 1976), where sequences ranging from dunites through peridotites, pyroxenites, norites and gabbros to granophyres and anorthosites are now recognized. In southern Africa numerous layered complexes of Archaean age have been recorded in the greenstone belts of Zimbabwe (Keep, 1929; Ferguson, 1934; Laubscher, 1964, 1968; Wilson, 1968a, b) and South Africa (Visser *et al.*, 1956; Anhaeusser, 1969, 1972, 1978; Viljoen and Viljoen, 1970; Robb, 1977; Wuth, 1980). The southern African layered ultramafic complexes, almost without exception, are host rocks to important deposits of chrysotile asbestos (Hall, 1930; Laubscher, 1964, 1968; van Biljon, 1964; Anhaeusser, 1976, 1978) and as a producer of chrysotile fibre southern Africa ranks third in the world after Canada and the U.S.S.R. Whereas most of the chrysotile asbestos produced in these latter two countries emanates from Palaeozoic to Late Precambrian "alpine-type" masses of peridotite and pyroxenite intruded and deformed in the Appalachian and Urals orogenic regions, the southern African production is almost exclusively derived from Archaean layered differentiated ultramafic-mafic complexes (Anhaeusser, 1976). The prominence of chrysotile asbestos in the southern African layered intrusions serves to distinguish them from their counterparts elsewhere in the world. This distinction is further enhanced by contrasting geochemical and petrological characteristics as well as differing lithologic abundances.

Some of the best preserved layered ultramafic complexes in southern Africa occur in the Barberton greenstone belt and neighbouring xenoliths. A total of 27 layered bodies have so far been identified in the region (Fig. 1) but there is reason to suspect that further occurrences may eventually be recognized in the tectonically disturbed successions along the eastern flank of the Barberton greenstone belt.

The exposure and preservation state of the intrusions vary considerably and most of the detailed work has so far been confined to the Ship Hill, Magnesite-Canal, Budd, Central and Koedoe bodies east of Nelspruit (Viljoen and Viljoen, 1970), the Handsup-Mundt's Concession bodies north of Barberton (Anhaeusser, 1969, 1972), and the Emmenes, Sawmill, Pioneer and Stolzburg bodies south-west of Barberton (Anhaeusser, 1976, 1979, 1982; Wuth, 1980). Less intensive work yeilding additional information has been carried out on the Core Zone and Richmond bodies west of Nelspruit (Robb, 1977), the Kalkkloof complex north of Badplaas (Menell *et al.*, 1981), and the Rosentuin body east of Badplaas (Viljoen and Viljoen, 1969a).

In this paper the field relations, petrography and chemistry of the Barberton layered intrusions are discussed with particular emphasis being placed on the findings resulting from studies of the Koedoe, Handsup-Mundt's Concession and Stolzburg complexes.

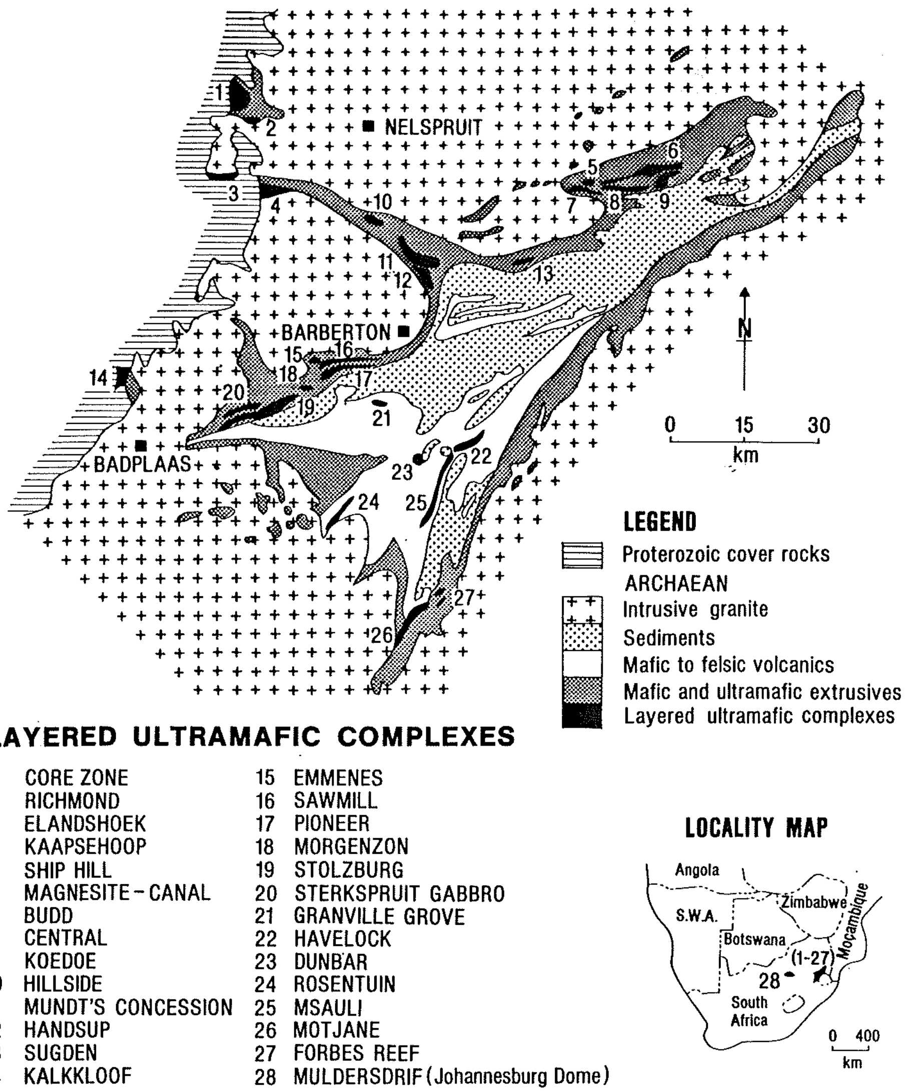


Figure 1 : *Locality map showing the general geology of the Barberton greenstone belt and the distribution of layered ultramafic complexes.*

II. REGIONAL GEOLOGIC SETTING

The Barberton greenstone belt (Fig. 1) consists of a north-east-trending, isoclinally folded, volcano-sedimentary succession entirely surrounded by intrusive granitic rocks ranging in composition from tonalite and trondhjemite gneisses and migmatites to granodiorites, adamellites, and granites (*sensu stricto* – Anhaeusser and Robb, 1981). Mafic and ultramafic komatiites and high-magnesian basalts predominate in the lower part of the greenstone succession and are overlain sequentially by a dominantly mafic-to-felsic sequence of volcanic and pyroclastic rocks cyclically interlayered with cherts (Viljoen and Viljoen, 1969a, b). A wide variety of sedimentary rocks including shales, greywackes, banded iron-formations, cherts, conglomerates, quartzites, and sandstones occupy the central core of the greenstone belt and stratigraphically overlie the lower volcanic formations.

The layered ultramafic sills occur predominantly in the lower stratigraphic portion of the volcanic sequence where they are intimately associated with the extrusive mafic and ultramafic flow units. A small number of intrusive sills also occur interlayered with the upper calc-alkaline volcanic sequences, the most important of these being the Havelock and Msauli complexes which are hosts to two of the largest chrysotile asbestos deposits in southern Africa (Anhaeusser, 1976). All the layered complexes appear to pre-date the sedimentary sequences but are sometimes in direct contact with these rocks due largely to faulting.

The Barberton volcanic sequences have yielded a precise Sm-Nd age of 3 540 ± 30 Ma (Hamilton *et al.*, 1979) and all available evidence suggests that these rocks were subsequently intruded by various granitic rocks ranging in age from approximately 3 450 - 2 500 Ma (Anhaeusser and Robb, 1981; Barton, 1981, 1983; Barton *et al.*, 1983). Locally, near granitic contacts, the volcanic successions are metamorphosed to amphibolite or upper greenschist facies. Elsewhere (and including most of the layered complexes), low grade metamorphic conditions generally prevail.

III. GENERAL FEATURES OF THE LAYERED COMPLEXES

As shown in Fig. 1 most of the layered complexes are associated with assemblages made up predominantly of komatiitic basalts and komatiites (peridotites) as well as high-Mg basalts or tholeiitic basalts. Some of the layered bodies are clearly sill-like intrusions injected into the volcanic sequences, sometimes along thin sediment layers consisting of banded iron-formation or banded grunerite-chert rocks (Viljoen and Viljoen, 1970; Robb, 1977). Elsewhere the bodies are massive and broadly concordant with the volcanic assemblages. Where relationships with the country rocks are transgressive tectonic influences are generally responsible. In some cases the sills bifurcate or occur as multiple sills (Viljoen and Viljoen, 1970; Robb, 1977; Wuth, 1980).

The complexes, some of which are up to 1 500 m thick, show marked differentiation and are often cyclically layered (Figs. 2-8). Several coarse-textured conformable ultramafic pods, now largely serpentinized and steatized, show no indications of either differentiation or layering whereas others, like the Koedoe, Budd and Ship Hill bodies (Figs. 2, 3) are characterized by having only one complete but nevertheless well-developed differentiation cycle.

Although low grade metamorphism has led to the development of greenschist facies mineral assemblages in most of the complexes the degree of alteration is variable and there are localities where some of the primary minerals are still well-preserved. Elsewhere, despite the alteration, the original igneous textures are still evident and it is only in extremely altered and tectonized zones that it is not possible to establish the nature of the original mineralogy.

The massive ultramafic pods usually consist of serpentinized dunite or pyroxenite but the cyclically differentiated bodies display a wide variety of cumulate rocks such as those shown in the idealized sequence provided in Table I.

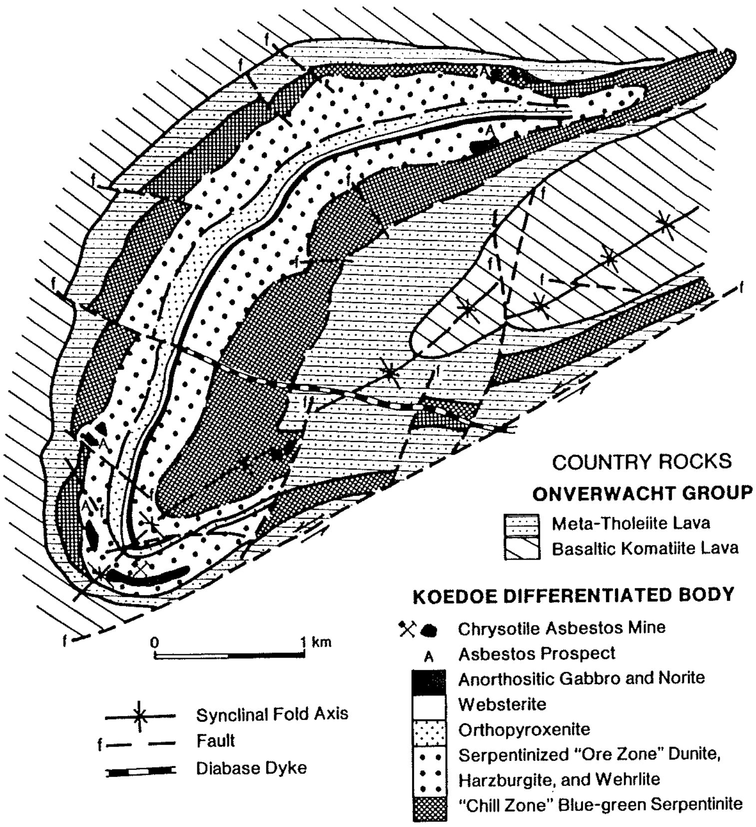


Figure 2 : *Geological map of the Koedoe layered intrusion (after Viljoen and Viljoen, 1970).*

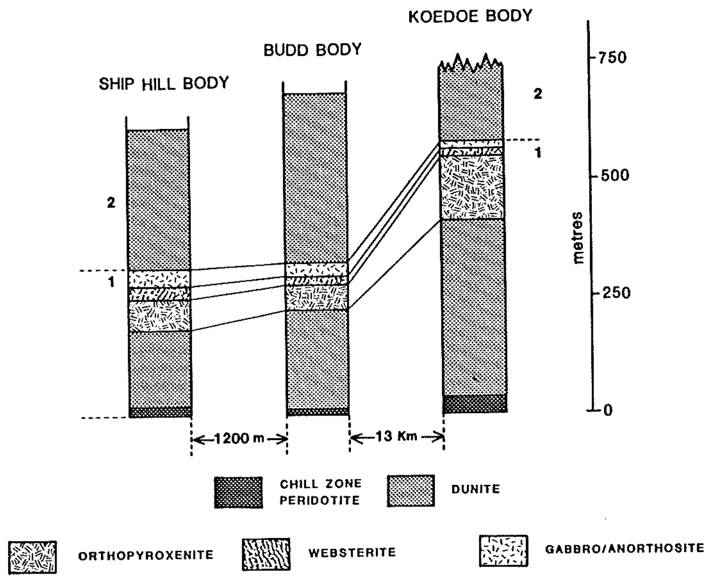


Figure 3 : *Stratigraphic columns for the Koedoe, Budd and Ship Hill layered bodies (after Viljoen and Viljoen, 1970).*

TABLE I

PRINCIPAL ROCK TYPES ENCOUNTERED IN THE BARBERTON LAYERED SILLS SHOWING THE MAJOR CUMULUS AND INTERCUMULUS MINERALS AS WELL AS COMMON ALTERATION PRODUCTS CAUSED BY SERPENTINIZATION AND METAMORPHISM

ROCK TYPES	CUMULUS MINERALS	INTERCUMULUS MINERALS	ALTERATION MINERALS
PEGMATOID	Plagioclase, Diopsidic Augite	Quartz	Tremolite-Actinolite, Epidote, Clinozoisite
ANORTHOSITIC GABBRO-NORITE	Plagioclase, Pyroxene	Clinopyroxene (diopsidic augite) Orthopyroxene (enstatite-bronzite)	Tremolite-Actinolite, Epidote, Zoisite-Clinozoisite, Sericite
GABBRO-NORITE	Plagioclase, Orthopyroxene Clinopyroxene	Clinopyroxene (diopside-augite) Orthopyroxene (enstatite-bronzite) Ilmenite, Magnetite, Sphene, Quartz	Uralitized Diopside, Saussuritized Plagioclase, Epidote, Clinozoisite, Leucoxene
RODINGITE	-	-	Garnet (hydrogrossular, grossular-andradite, hibschite) Vesuvianite, Diopside, Zoisite-Epidote, Amphibole (tremolite-actinolite-nephrite), Prehnite, Saussuritized and Sericitized Plagioclase
WEBSTERITE	Clinopyroxene (diopside, diopsidic augite) Orthopyroxene (enstatite-bronzite)	Plagioclase	Tremolite, Bastite, Chlorite, Talc, Saussuritized Plagioclase
LHERZOLITE	Olivine, Enstatite-Bronzite, Diopsidic Augite	-	Antigorite, Tremolite, Chlorite, Iddingsite, Talc, Carbonate
HARZBURGITE	Olivine, Enstatite-Bronzite (magnetite, chromite)	Clinopyroxene (diopside, diopsidic augite)	Serpentine (antigorite, chrysotile) Tremolite, Talc, Chlorite, Bastite, Iddingsite, Serpophite, Carbonate
ORTHOPYROXENITE	Enstatite-Bronzite (magnetite, chromite)	Clinopyroxene (diopside, diopsidic augite), Plagioclase	Serpentine (bastite), Uralitized Diopsidic Augite, Tremolite, Talc, Chlorite, Epidote
DUNITE	Olivine (magnetite, chromite)	Orthopyroxene (enstatite - bronzite)	Serpentine (antigorite, picrolite, chrysotile), Tremolite, Talc, Chlorite, Iddingsite, Serpophite, Stichtite-Barbertonite, Brucite, Opal, Magnesite, Carbonate
PERIDOTITE (Massive fine-grained or spinifex-textured chill phase)	-	-	Serpentine (antigorite), Tremolite, Talc, Chlorite, Carbonate

Also shown in this table are the principal cumulus and intercumulus minerals as well as the dominant alteration products found in the various lithological units that make up the layered bodies. The transition from one lithological unit to the next in the ultramafic complexes is generally sharp suggesting phase layering. In places gradational contacts exist between ortho- and clino-pyroxenites and between the gabbroic, noritic and anorthositic units in the upper parts of the layered sequences.

The Barberton layered complexes are characteristically dominated by ultramafic components (mainly dunite, harzburgite and orthopyroxenite). Subordinate are the clinopyroxenite, gabbro, norite and anorthositic gabbro/norite phases (Figs. 3, 5, 8). Minor occurrences of rodingite and pegmatoid have also been reported (Viljoen and Viljoen, 1970; Anhaeusser, 1979; Wuth, 1980). It is rare for any one cycle to display the full range of rock types listed in Table I. The most complete sequence is probably that found in the single cycle Ship Hill, Budd and Koedoe layered complexes (Fig. 3). More commonly the rock assemblages making up individual cycles vary progressively from base to top in multicyclical complexes (Fig. 5), while in other cases incomplete or repetitive cycles may be developed.

Deformation, involving folding and faulting, has influenced most of the Barberton layered complexes. Invariably the successions exposed are steeply dipping and in some cases the layered bodies occur as disharmonic folds developed adjacent to subvertical detachment (décollement) faults (Figs. 2, 6, 7). The folding and faulting has played a dominant role in the development of chrysotile fibre (Anhaeusser, 1976) and almost all the asbestos mines in the district are located in or near fold hinges, or are in close proximity to faults or zones where differential movement has taken place between layers varying in competency. Where deformation has been more intense the usually massive units have undergone severe flattening or shearing and mafic and ultramafic schists are developed. In other cases schistose zones are confined to select stratigraphic units or are developed at some phase contacts. Differential movement between layers in disharmonic folds (Figs. 7, 8) has also produced schists as well as unusual ultramafic "slates" (Anhaeusser, 1969, 1972; Wuth, 1980).

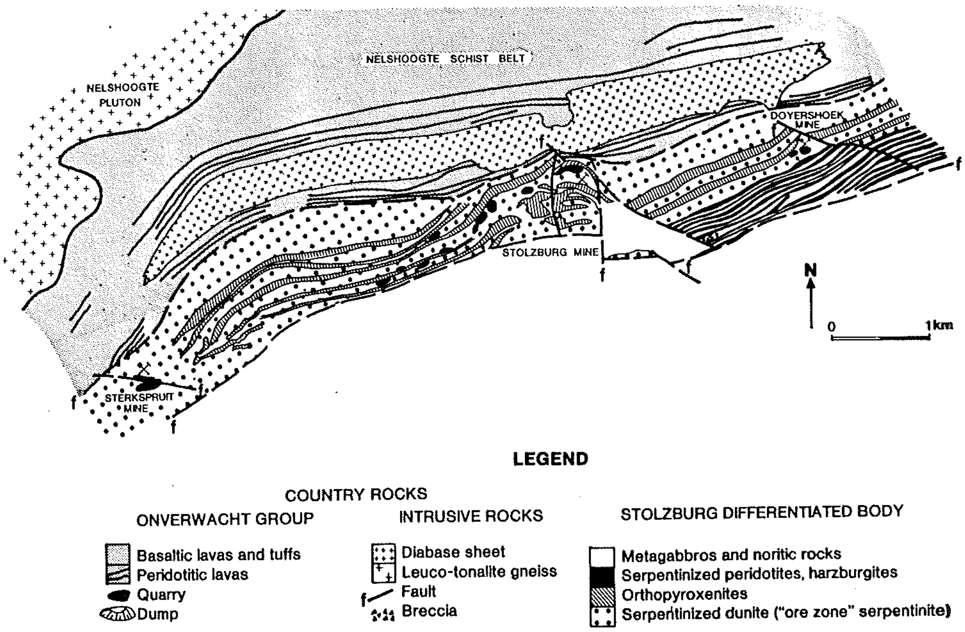


Figure 4 : *Geological map of the Stolzburg layered body showing the cyclically repetitive nature of the subvertically dipping differentiated sequence which youngs to the south-east (simplified after geological map of the Stolzburg-Nelshoogte area in Anhaeusser, 1982).*

Little is known about the layered ultramafic complexes developed in the mafic-to-felsic upper volcanic stratigraphy of the Barberton greenstone belt. The only published details relate to the Rosentuin body (Fig. 1) which, it has been suggested, represents a broad, crystal segregated, lava flow deposited in a zone comprising pillowed tholeiites overlain by altered felsic lavas and a discontinuous banded black and white chert constituting the immediate footwall of the Rosentuin body (Viljoen and Viljoen, 1969a). Serpentinized dunite, wehrlite or lherzolite occur in the lower zone of the ultramafic body which is approximately 76 m thick. Pyroxenites, mainly websterite, form the upper zone which is approximately the same thickness and the top of the pyroxenite zone comprises brecciated and carbonated agglomerate, felsic lava and a grey-green chert.

According to Viljoen and Viljoen (1969a) most of the ultramafic rocks in the upper volcanic sequence of the Barberton greenstone belt take the form of concordant sill-like bodies closely associated with chert layers and showing signs of magmatic segregation. The largest ultramafic occurrence of this type is the Msauli-Havelock body (Fig. 1). Recent investigations suggest that this important asbestos-bearing complex, which now consists almost entirely of serpentinite and steatite, appears to have formed from an alternating sequence of dunite and orthopyroxenite (Büttner, 1983).

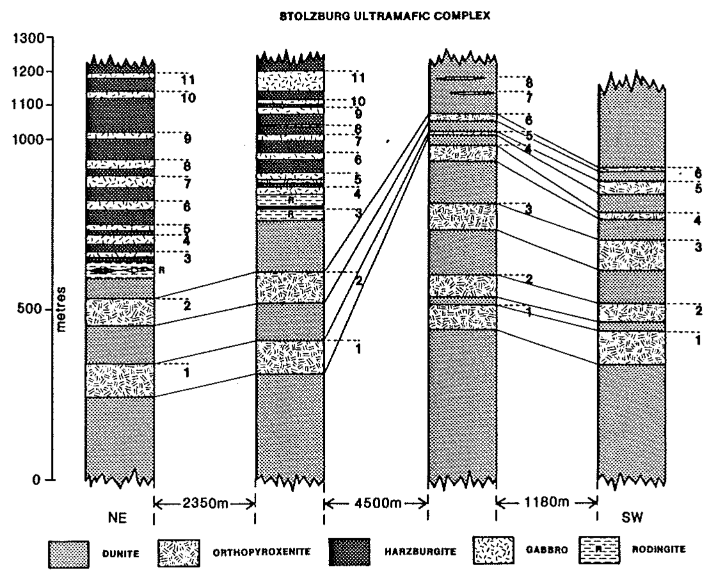


Figure 5 : *Stratigraphic columns across various parts of the Stolzburg layered complex. The south-western sections are dominated by alternating dunite-orthopyroxenite cycles whereas those further north-east have uppermost cycles consisting mainly of alternating harzburgite, pyroxenite and gabbro.*

One other intrusive body requiring mention is the Sterkspruit gabbro located midway between Barberton and Badplaas (Figs. 1, 4). This body is intruded into komatiitic pillow basalts and peridotites in much the same manner as all the other occurrences in the region but differs compositionally in that it consists entirely of gabbroic rocks. Most of the body appears to be massive but vertical layering occurs in places. The age of the sill-like

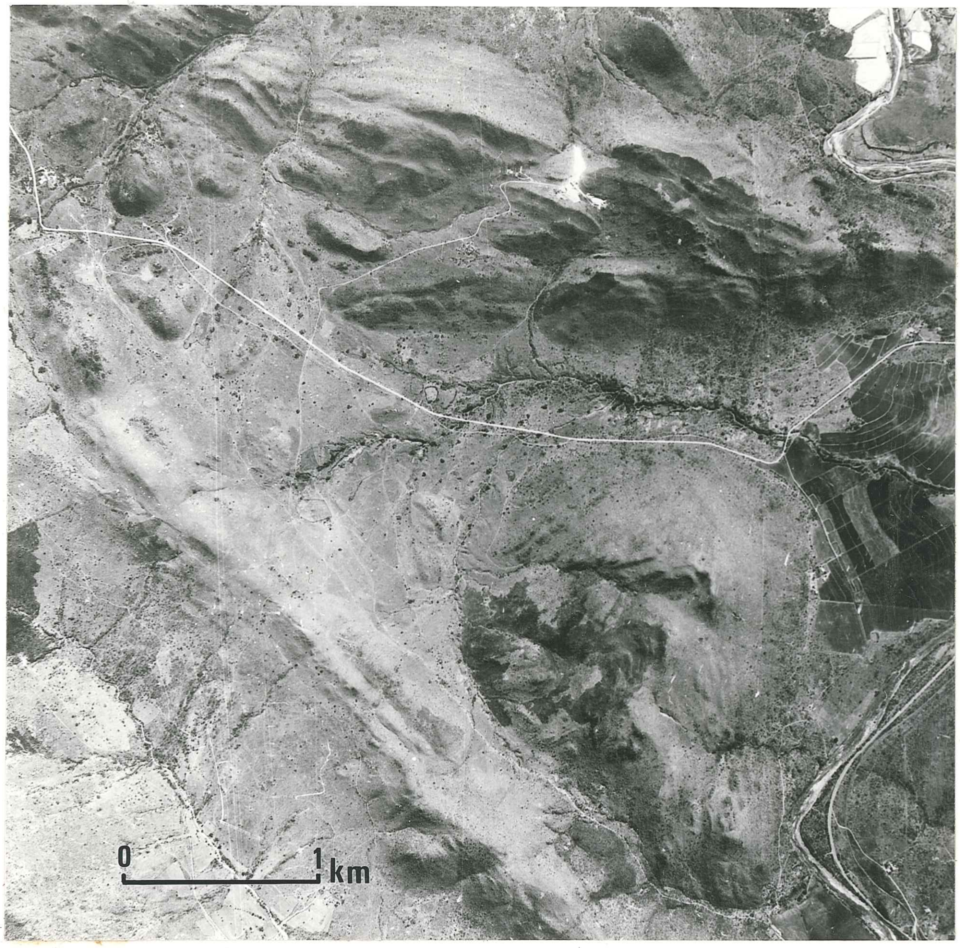


Figure 6 *Aerial photograph showing the layering in the Mundt's Concession anticline (top) and in the Handsup disharmonic fold (lower right). The geological interpretation of this area is provided in Fig. 7.*

intrusion is unknown but it possibly represents magma injected late in the evolution of the Barberton greenstone pile. Unlike all the ultramafic complexes in the region it apparently has no genetic relationship to the neighbouring komatiitic and basaltic komatiitic country rocks.

IV. FIELD RELATIONS AND PETROGRAPHY

The general nature of the Barberton intrusive complexes is largely exemplified by the field relations and petrography of the four best exposed and least altered layered bodies shown in Figs. 2, 4 and 7. Although widely separated from north-east to south-west along the western flank of the Barberton greenstone belt (Fig. 1) these bodies show a considerable degree of similarity. So as to avoid repetition the principal characteristics of these bodies will be discussed collectively in this section.

A. Structure

All four layered bodies outcrop prominently with most of the resistant units consisting of pyroxenite. In some cases dunites and harzburgites form resistant ridges (as for example in the Mundt's Concession complex, Fig. 6).

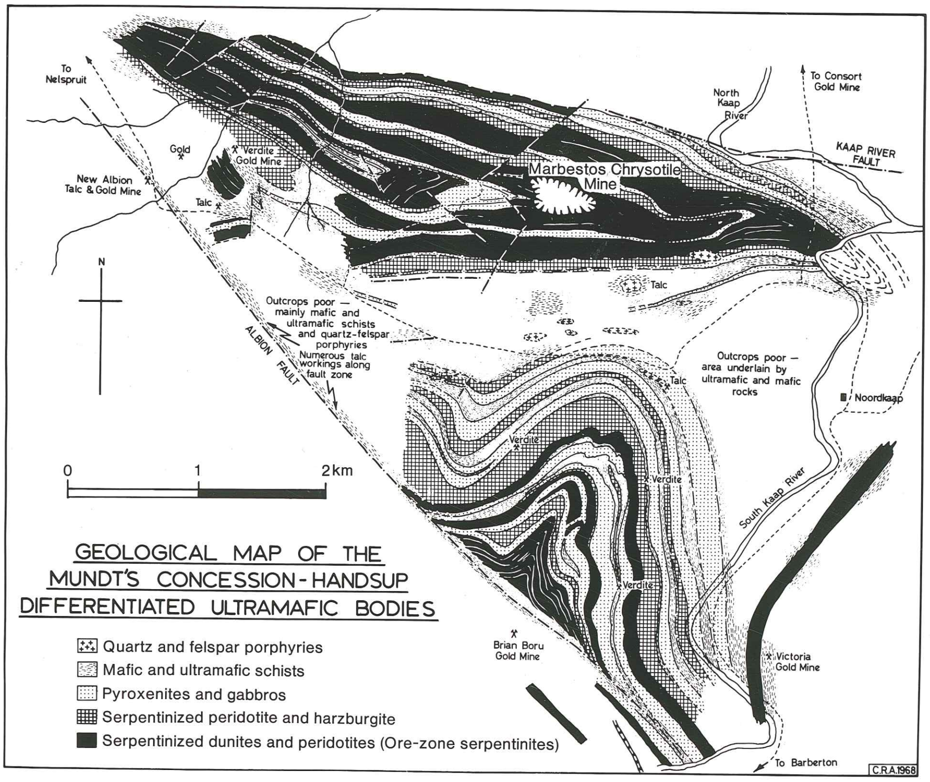


Figure 7 : *Geology of the Mundt's Concession-Handsup layered complexes. The Albion fault acted as a detachment plane (dècollement) along which the Handsup disharmonic fold developed.*

The layered sequences are generally steeply dipping and many are folded. The Koedoe body (Fig. 2) takes the form of an asymmetrical syncline with a wide, open, north limb and a poorly developed, tectonically aborted, south limb. The fold axis plunges 60° west-south-west, parallel to a major left-lateral strike slip fault which has acted as a detachment plane held partly responsible for the fold structure (Viljoen and Viljoen, 1970). The Handsup complex (Fig. 7) is also folded adjacent to a left-lateral strike slip fault and represents a disharmonic anticlinal fold structure plunging steeply to the north-east (Anhaeusser, 1972). North of the Handsup body is another major anticlinal fold comprising the Mundt's Concession layered complex. The attitude of this structure is not known precisely but is believed to be subvertical. The Handsup-Mundt's Concession bodies are considered to be part of the same layered intrusion with the geology of the area connecting the two bodies being poorly exposed and strongly tectonized north of the Albion fault (Figs. 6, 7). The Stolzburg complex (Fig. 4) is, by contrast, faulted bounded and the regularly layered sequence either dips vertically or steeply to the north-west. The layered succession, which youngs to the south-east is therefore overturned in places. Younger sediments abut against the south-eastern fault contact (Fig. 1) with an angular discordance but the north-western contact is conformable with komatiitic pillow basalts and ultramafic flow units (Fig. 4). The regular layering is locally disturbed by cross faults which offset the stratigraphy and cause localized folding as in the Stolzburg Mine area. The cross faulting in this area and the folding in the other layered complexes discussed above illustrates the control deformation had on the localization of chrysotile asbestos fibre development. The other important factor controlling fibre formation is the presence of serpentinized dunite (Anhaeusser, 1976).

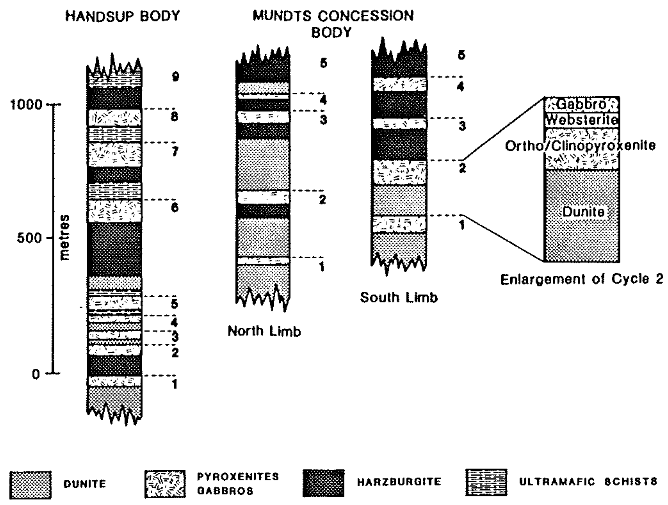


Figure 8 : *Stratigraphic sections across the Handsup and Mundt's Concession ultramafic complexes illustrating the multi-cyclical nature of the layering.*

B. Layering

With the exception of the Koedoe body all the examples discussed are cyclically layered. In the Stolzburg body at least 12 cyclic units are present in the Doyershoek Mine area, while in the Stolzburg and Sterkspruit mine areas to the south-west the number decreases and only cycles of the lower division of the complex are present (Anhaeusser, 1976, 1979, 1982), the upper cycles being truncated by the fault cutting obliquely across the layered intrusion (Fig. 4). The change from the lower to the upper division cycles is also illustrated in the stratigraphic section diagram (Fig. 5). The lower cycles consist of alternating serpentinized dunites (olivine cumulates) and generally altered but in places remarkably fresh orthopyroxenite layers (enstatite, bronzite cumulates). The upper cycles in the Doyershoek Mine area consist mainly of serpentinized harzburgites and peridotites (including lherzolites and wehrlites), pyroxenites (ortho- and clinopyroxenite-websterite), and altered gabbros, norites and anorthositic gabbros. A zone of calcium metasomatic rocks separates the monomineralic cumulate phases (dunites, enstatites, bronzitites) from the upper units which contain two or more mineral phases (harzburgites, lherzolites, wehrlites, websterites, diopsidites, gabbros). In this zone of prominent calcium enrichment rodingites are developed and occur either in the form of dykes or as irregular pods or replacement bodies closely associated with, and gradational into, the predominantly gabbroic rocks found in the region transitional between the lower and upper divisions of the layered complex (Anhaeusser, 1979).

The Handsup layered body consists of at least 9 cyclic units (Figs. 7, 8). Towards the base the cyclic units contain dunites whereas higher in the succession harzburgites become progressively more prominent. The pyroxenites in the sequence are predominantly websterites but some serpentinized orthopyroxenites are present in places. The upper cycles show an increase in the amount of gabbro associated with the clinopyroxenites and a decrease in the harzburgitic component. In the Mundt's Concession body dunites and harzburgites predominate (Figs. 7, 8) and at least 5 cyclic units are terminated by thin layers of clinopyroxenite or gabbro. The sequence seen in the Mundt's Concession body is most similar to that found occupying the core zone of the Handsup body.

Intraformational shearing within the cyclic units has produced mafic and ultramafic schists and "slates", particularly in the Handsup fold structure. Also developed in this complex are a number of verdite occurrences (semiprecious dark-green variety of serpentine) which are generally located at the contacts between harzburgite and pyroxenite/gabbro layers (Anhaeusser, 1972). Small quartz-feldspar porphyry bodies intrude the ultramafic successions in the crestal zone of the Handsup fold and are locally responsible for the development of talc deposits (Fig. 7).

The Koedoe complex consists of a single complete differentiation sequence commencing with a basal peridotitic chill zone overlain, in turn, by zones of dunite, orthopyroxenite, websterite and anorthositic gabbro/norite (Figs. 2, 3). This is followed by an upper dunite zone in which occur a number of intrusive pods of coarse-grained pegmatoid. Studies by Viljoen and Viljoen (1970) indicated that the large-scale layering in the Koedoe and neighbouring Ship Hill and Budd bodies is due to changes in the relative proportions and compositions of the mineral phases upwards in the sequence as well as abrupt changes resultings from the appearance and/or disappearance of particular phases during crystallization. There is evidence for both cryptic and phase layering in these and other intrusions in the Barberton region but rhythmic layering has not been recorded. As has been found in many of the Western Australian Archaean layered intrusions described by Williams and Hallberg (1973), the cryptic layering is not always directly determinable because the original minerals were destroyed during metamorphism.

In the anorthositic gabbro/norite zones of some layered complexes (e.g. Koedoe and Stolzburg) there is a type of layering characterized by thin layers less than an inch thick (< 25 mm) which may be repeated many times. Referred to as *inch-scale layering* by Hess (1960) these regularly repeated layers consist of alternations of pyroxene and plagioclase (see Fig. 11.4).

Phase layering is considered responsible for the cyclic units like those so well-displayed in the Stolzburg complex. A characteristic of phase layers is their persistence over considerable distances; often they extend through entire magma bodies. According to Jackson (1970) cyclic units are thought to represent a series of events involving simple fractionation and crystal settling of small batches of magma separated by breaks in supply of material available for crystallization. Jackson felt it was difficult to avoid the conclusion that sequences of cyclic units represent successive batches of magma introduced in sudden pulses into the zone of crystallization and settling.

Without firm evidence to the contrary this explanation remains viable for the Barberton ultramafic complexes. An alternative mechanism to account for cyclical repetitions is that proposed by Cameron (1978, 1980) who suggested that changes in total pressure, causing shifts in phase boundaries on the liquidus, may have been the prime factor controlling the changes in mineral assemblages seen in layered sequences. To bring about an abrupt change in total pressure all that would be required is some tectonism to affect the shape of the chamber thereby temporarily reducing the lithostatic pressure of the roof rocks on the magma body and shifting the boundaries on the liquidus until pressure was restored. A magma chamber might also lose pressure if it was successively expelling magma through some rupture feeding a developing volcanic pile.

C. Mineralogy and Petrography

A general account of the principal rock types and mineral assemblages present in the Barberton layered complexes was given earlier (see Table I). Based on findings from the four complexes described in this paper the primary mineralogy appears relatively simple with most rocks consisting of olivine, orthopyroxene, clinopyroxene and plagioclase in different combinations and varying proportions and displaying diverse textural relationships. In the ultramafic rocks magnetite and chromite occur in accessory amounts whereas in the mafic-to-felsic phases magnetite, ilmenite, sphene, quartz and rare sulphides may be encountered.

Alteration resulting from serpentinization and regional as well as contact metamorphism is accountable for the development of a long list of secondary minerals (also listed in Table I). Original textures are frequently preserved and are even distinguishable in some of the highly altered zones that have not been influenced tectonically. Pseudomorphs of different primary minerals are commonly encountered, particularly in the ultramafic units where olivines and orthopyroxenes are affected. Despite the alteration fine textural detail and crystal forms are preserved supporting the view that both serpentinization and metamorphic alteration has involved little or no volume change. A similar interpretation was made by Williams and Hallberg (1973) who observed almost identical conditions in the altered Archaean layered intrusions they described in Western Australia.

Cumulate rocks make up the bulk of the Barberton layered intrusions and it is generally only in the gabbroic phases that this distinction is sometimes not possible. Some of the thin mafic units have, in places, a fine-grained texture and may represent liquid residue possibly filter-pressed from spaces between solidifying cumulus crystals.

1. Basal Chill-zone Peridotite. Exposure in all but the Koedoe, Ship Hill and Budd bodies does not allow the basal contacts of the Barberton complexes to be examined in detail. In the case of the Ship Hill and Budd bodies fine-grained chilled peridotites lie directly on banded chert-amphibole sediments (Viljoen and Viljoen, 1970). The peridotite zones in these examples vary in thickness between 12 and 36 m and have been extensively altered. Antigorite pseudomorphically replaces olivine crystals averaging 0,5 mm in size, and tremolite, derived from diopsidic pyroxene, makes up approximately 50 per cent of the rock, the remainder having once been olivine. No remnant olivine kernels have been recorded in these altered peridotites which are generally unsuitable for the determination of the bulk chemical composition of the parental magma of the differentiated ultramafic bodies.

2. Dunite. In the field the dunite zones are invariably associated with orthopyroxenite zones, the two rock types generally making up a typical cycle near the base of the layered bodies (e.g. Stolzburg, Fig. 5). Relative to the orthopyroxenites the dunites are less resistant to weathering and often have a distinctive yellow-green to grey colour in outcrops. These rocks, which are extensively serpentinized, are the hosts to important deposits of chrysotile asbestos, magnesite and talc (Anhaeusser, 1969, 1972, 1976; Viljoen and Viljoen, 1970).

The dunites contain upwards of 70 per cent olivine or its alteration products (mainly antigorite, lizardite, talc and tremolite, Table I). The size of individual grains is variable (less than 1 mm up to 10 mm) and where fresh have yielded values of Fo_{92} to Fo_{100} (Anhaeusser, 1969; Viljoen and Viljoen, 1970). The large cumulus grains (Fig. 9.1) are accompanied by altered intercumulus material now consisting mainly of antigorite, talc and chlorite but believed to have originally been orthopyroxene with lesser amounts of clinopyroxene. Magnetite and, to a lesser extent, chromite occur as primary phases. Secondary magnetite commonly occurs around the margins of pseudomorphs after olivine and in veins and fractures in the dunites. Serpentinization of the olivine cumulates has generally been extensive and chrysotile veins and stringers occur within individual altered olivine crystals (Fig. 9.2) or as fibre veins large enough and sufficiently densely developed to warrant exploitation as chrysotile asbestos deposits.

3. *Orthopyroxenite.* Orthopyroxenite units are invariably associated with dunite- or harzburgite-bearing cyclic units and form topographically distinct ridges in most of the layered bodies. In the field they form massive, coarse textured, generally structureless zones (except for some jointing, Fig. 10.4), and outcrops have a distinctive brownish-red surface weathering. Fresh surfaces have a dark waxy greenish colour but are mostly dark blue-green where serpentinized. Orthopyroxene (enstatite, bronzite), makes up well over 90 per cent of the cumulate rocks with clinopyroxene and plagioclase as intercumulus phases (Fig. 10.1). Olivine is generally absent and accessory amounts of magnetite and chromite are sometimes encountered. Some orthopyroxene cumulates appear to have little or no intercumulus material and are monomineralic.

As with the dunite cumulates the orthopyroxenite units are extensively altered but some exceptionally well-preserved remnants remain in places. Alteration (serpentinization) to bastite and talc is variable. In some cases the orthopyroxenite is completely unaltered but may be partly or totally altered only metres away. Alteration begins with veins and stringers of talc and bastite penetrating fractures and cleavage planes in orthopyroxene crystals. More advanced alteration results in talc or bastite pseudomorphous after enstatite-bronzite (Figs. 10.1 and 10.2). The composition of the intercumulus plagioclase determined in the Ship Hill and Koedoe bodies gave values ranging between An_{84} - An_{86} whereas the orthopyroxenes varied between En_{90-95} at the base to En_{75-80} at the top of the orthopyroxenite zones (Viljoen and Viljoen, 1970). This variation within these orthopyroxenite units does not appear to be present in the cyclically layered Stolzburg body where major element chemical variation between base and top is barely evident (C.R. Anhaeusser - unpubl. data).

4. *Harzburgite.* The cyclic units in the Stolzburg, Handsup and Mundt's Concession bodies contain harzburgite layers that occur in the field as massive, dark, bluish-black to grey or green outcrops generally forming rough boulder-strewn ridges. In other layered intrusions in the Barberton region harzburgites are the most widespread rock type and are dark brown on weathered surfaces. Orthopyroxene phenocrysts (some up to 3 cm in length, Wuth, 1980) may form either positive or negative weathering features in these rocks.

Cumulate phases generally include olivine, orthopyroxene, magnetite and chromite. In places the rocks also contain clinopyroxene (diopside, augite) and can ge regarded as lherzolite. In rare instances olivine and clinopyroxene may occur together to form wehrlite. Although these rocks are generally altered to serpentinite there are zones where relic olivine kernels may be preserved or where partly altered olivine crystals occur poikilitically encased in orthopyroxene phenocrysts (Figs. 9.3 and 9.4).

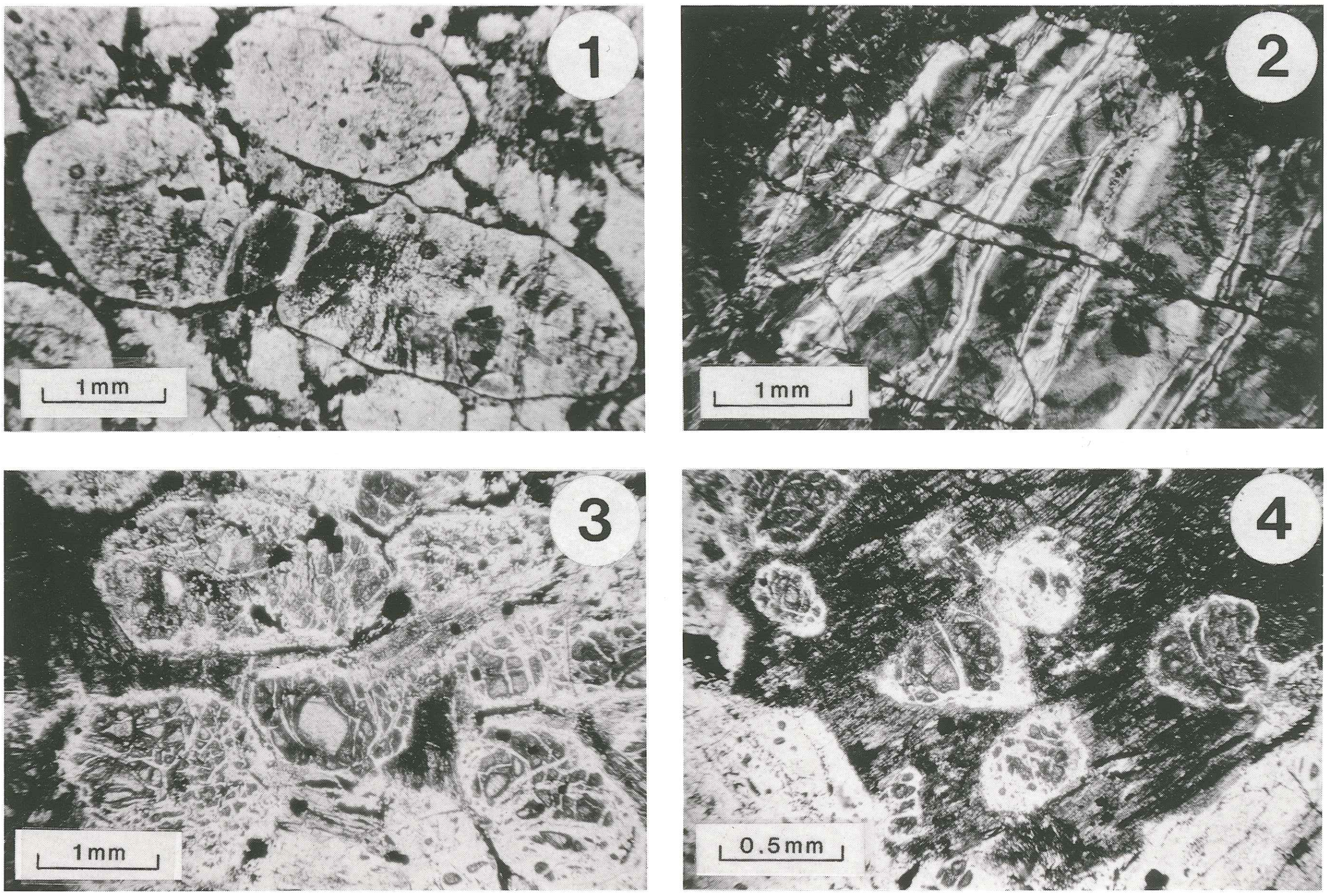


Figure 9

1. *Large cumulus olivine crystals from serpentinized dunites in the Stolzburg layered body. The olivine is surrounded by intercumulus phases now consisting of antigorite, talc, tremolite and magnetite. Plane polarized light.*

2. *Serpentinized olivine in altered dunite from the Stolzburg body. The matrix material containing veins of chrysotile is the variety of serpentine called lizardite. Crossed nicols.*

3. *Partly altered cumulus olivine crystals from harzburgite in the Stolzburg body. Relic cores of olivine are rimmed and veined by serpentine (white). The dark areas between the olivines contain iron oxide, antigorite and chlorite. Other phases present include euhedral magnetite (upper centre) and orthopyroxene, the latter partly altered to bastite (centre). Plane polarized light.*

4. *Rounded, partly serpentinized olivine crystals poikilitically enclosed by orthopyroxene (enstatite partly altered to bastite) in harzburgite from the Stolzburg body. Iron oxides, antigorite and chlorite are also present. Plane polarized light.*

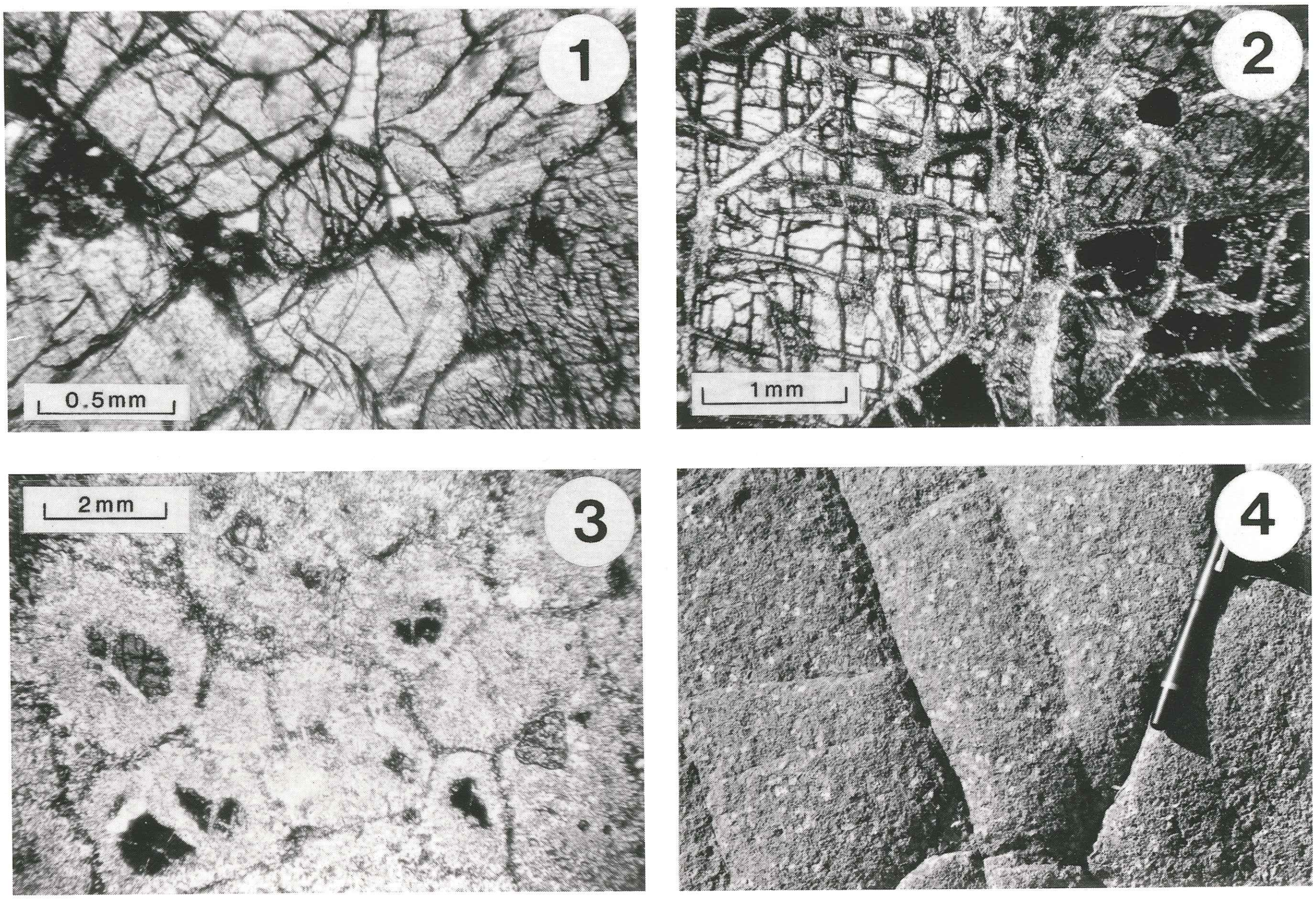


Figure 10

1. *Euhedral cumulus enstatite-bronzite crystals with minor intercumulus plagioclase (white) from an orthopyroxenite unit in the Stolzburg complex. Apart from accessory magnetite the orthopyroxenites are virtually monomineralic rocks. Plane polarized light.*

2. *Euhedral cumulus enstatite-bronzite crystals from orthopyroxenite of the Stolzburg complex showing incipient alteration to talc along veins and fractures in the pyroxene crystals. Some bastite and magnetite is also evident in the photomicrograph. Plane polarized light.*

3. *More advanced alteration of cumulus enstatite-bronzite crystals from Stolzburg complex orthopyroxenites. Relic pyroxene cores are preserved in some crystals now largely altered to talc. Plane polarized light.*

4. *Massive, jointed, cumulus-textured orthopyroxenite typical of surface exposures in the Stolzburg complex. The orthopyroxene crystals may be unaltered or only partially altered as shown in Figs. 10.1 and 10.2 or totally pseudo-morphed by talc as shown in Fig. 10.3. The degree of alteration is not always readily apparent in the field.*

Intercumulus phases are obscure but probably consist mainly of clinopyroxene judging from the nature of the matrix material between the ovoid crystals of antigorite which is pseudomorphous after olivine (Table I). Secondary magnetite, released from the olivine during serpentinization is ubiquitous and minor amounts of talc, chlorite and chrysotile are not uncommon. The showings of chrysotile in these rocks has led to them being examined for potential asbestos deposits but so far without success.

5. *Websterite.* Clinopyroxene-rich units occur in the upper parts of some of the Barberton layered intrusions. These units do not generally outcrop very prominently, are usually not very wide and are often obscured by talus from the neighbouring dunite, orthopyroxenite or harzburgite ridges. Exceptions occur and conspicuous ridges of websterite (clinopyroxene-orthopyroxene rock) outcrop in the Koedoe and Sawmill complexes and to a lesser extent in the Handsup and Mundt's Concession bodies (Anhaeusser, 1969, 1972; Viljoen and Viljoen, 1970; Wuth, 1980).

In the field the websterite is pale greenish-grey and typically consists of small, stubby, randomly orientated crystals of clinopyroxene (diopside-diopsidic augite) and somewhat larger orthopyroxene (enstatite) phenocrysts, the latter constituting as much as 25 to 40 per cent of the rock in places (Viljoen and Viljoen, 1970; Wuth, 1980). In the Handsup-Mundt's Concession bodies orthopyroxene is less prominent and the cumulus phases are dominated by tabular or stubby diopside crystals usually associated with minor intercumulus plagioclase and subordinate orthopyroxene (Fig. 11.1). Depending upon the relative amounts of clinopyroxene, orthopyroxene and plagioclase the rocks may be referred to as diopsidite, websterite or norite/gabbro. These rock types are more or less transitional into one another, particularly in the Koedoe body.

Alteration is once again prevalent with the clinopyroxene uralitized to tremolite-actinolite, the orthopyroxene altered either to chlorite, bastite, or less commonly talc, and the plagioclase converted entirely to albite, or saussuritized to epidote or clinozoisite (Fig. 11.2).

6. *Anorthositic Gabbro-norite Zones.* Collectively grouped together under this sub-heading are the rocks in which plagioclase is a prominent but variable constituent. Rocks of gabbroic affinity frequently terminate cyclic units and in the field generally outcrop somewhat poorly forming the troughs or hollows between more resistant ultramafic components. They are usually overlain by harzburgites of the immediately following cyclic unit and tend to be partly or wholly buried beneath scree falling back into the hollows. Some of the best exposures of gabbroic rocks occur in the Handsup, Mundt's Concession and Stolzburg bodies where they demonstrate the variability brought about by changing proportions of plagioclase and ferromagnesian components (usually amphiboles). Locally the gabbroic rocks may be coarse textured and almost pegmatoid-like in character. Usually, however, they have medium-to- fine-grained textures and, as mentioned earlier, may not all be cumulates but rather residual liquids or magma left over following crystallization of earlier-formed phases.

Alteration and metamorphism has again changed the original mineralogy and the plagioclases are generally albite or oligoclase, and the pyroxenes are mainly altered to amphibole (tremolite-actinolite) or chlorite. The original composition of the plagioclase is considered to have been calcic. Evidence in support of this contention comes from the Koedoe body where a 12 m-wide anorthositic gabbro-norite zone contains cumulus plagioclase that comprises up

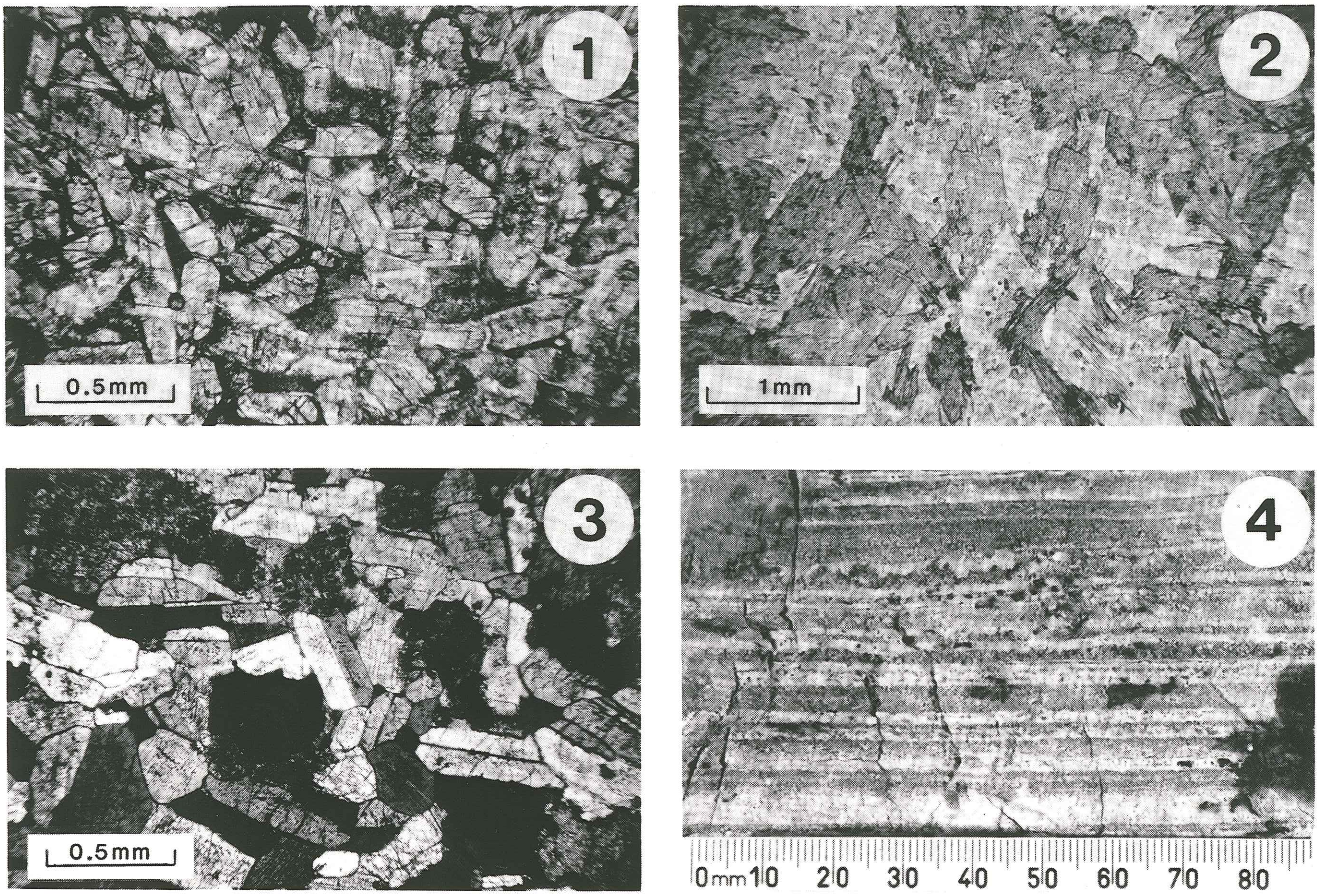


Figure 11

1. *Dense, interlocking, euhedral cumulate crystals of clinopyroxene (diopside or diopsidic augite) from a websterite unit in the Mundt's Concession layered body. Other phases present include bastite (altered orthopyroxene) and intercumulus plagioclase (partly saussuritized). Plane polarixed light.*

2. *Altered gabbro from the Mundt's Concession layered body showing fibrous to bladed and prismatic crystals of actinolite or ferroactinolite (green pleochroic amphibole, grey) associated with partially sericitized and saussuritized plagioclase (albite, white). Fresh pyroxenes and calcic plagioclase are only rarely encountered in the gabbros of the Barberton layered complexes. Plane polarized light.*

3. *Slightlysericitized tabular cumulus plagioclase(An_{92}-An_{94}) associated with partly altered clinopyroxene (diopside, dark grey) from the anorthositic gabbro-norite zone of the Koedoe complex. Crossed nicols.*

4. *Surface outcrop showing finely-developed inch-scale layering in anorthositic gabbro-norite cumulates from the Stolzburg complex. The light material consists of partly altered plagioclase and the darker bands contain clinopyroxene (diopsidic augite partly altered to tremolite-actinolite).*

to 60 per cent of the rock in places (Fig. 11.3). Anorthositic norites in the sequence contain intercumulus clinopyroxene and in places some large orthopyroxene phenocrysts are developed. The plagioclase has been little altered in some areas and gave compositions varying from An_{92}-An_{94} (Viljoen and Viljoen, 1970).

In addition to the albitization of plagioclase there have been variable degrees of saussuritization and sericitization to produce epidote, zoisite and sericite and pyroxenes are uralitized to amphibole. Quartz makes an appearance in some areas and accessory minerals include magnetite, ilmenite, sphene and leucoxene.

Other variations encountered in the anorthositic gabbro-norite zones include the development of rodingites or garnetized gabbros, inch-scale layering of clinopyroxene- and plagioclase-rich bands (Fig. 11.4), and zones where the gabbros have a blotchy, multi-textured outcrop appearance and are intruded by irregular plagioclase and quartz-rich veins and dykes.

7. Pegmatoid. Pods and irregular bodies of coarse-grained pegmatoid have been recorded in some complexes. In the Koedoe and Ship Hill bodies Viljoen and Viljoen (1970) noted that pegmatoid occurs mainly in the upper dunite zone overlying the basal differentiated sequence (Fig. 3). In the Stolzburg body pegmatoid-like patches occur in some of the gabbroic phases.

The pegmatoids generally contain large (up to 10 cm long) elongated blades of amphibole (mainly tremolite-actinolite) seen altering from original pyroxene (diopsidic-augite). These are surrounded by large plagioclase laths that have been partly saussuritized to epidote or clinozoisite.

8. Rodingite. In the Stolzburg, Sawmill and Pioneer complexes rodingites occur either in the form of dykes or as irregular pods or replacement bodies closely associated with, and gradational into, gabbroic rocks. They also occur as dykes or pods in serpentinized dunites (Anhaeusser, 1979; Wuth, 1980, Büttner, 1983). In the field the dykes are distinctive in that they generally outcrop positively in relation to the surrounding serpentinites and gabbros and are readily identified owing to their characteristic buff, or pale fleshy-pink coloured, weathered surfaces. Some dykes are pale greenish grey or white and vary in width, in the Stolzburg body, from a few centimetres to over 5 m.

The rodingites are mineralogically complex rocks and contain a wide range of calcium-rich minerals including hydrogrossular, hibschite, vesuvianite, diopside, nephrite, prehnite, zoisite and many others (Anhaeusser, 1979). Their origin is believed to be multi-faceted but broadly involves the release of calcium from Ca-rich mineral phases (e.g. diopside-diallage, and the anorthite molecule in plagioclase) and the metasomatic replacement of suitable host rocks. In the Stolzburg body the necessary ingredients included the serpentinization, uralitization and saussuritization of the ultramafic-mafic sequences. These alteration processes provided the mechanism for the release of lime and alumina from the pyroxenes and plagioclases in the area and the subsequent garnetization or metasomatic replacement of available dykes and lenses (including also the zone of gabbros midway up in the layered sequence - Fig. 4).

V. GEOCHEMISTRY

In the preceding sections dealing with mineralogy it was emphasized that few successions had escaped the effects of alteration brought about by serpentinization and regional as well as contact metamorphism. From this it follows that opportunities are limited for obtaining complete and meaningful geochemical data from the approximately 3 500 Ma old layered ultramafic complexes in the Barberton greenstone belt.

A. Major Element Variation

In Table II are assembled some of the best available major element analyses of the principal rock-types encountered in the least altered sequences studied to date. The degree of alteration, particularly the amount of hydration suffered by the dunite, peridotite and harzburgite units, precludes a direct appraisal of the chemical variation with height of the cyclically alternating units found in most of the complexes. The problem appears, however, to be universal within the Archaean. Raudsepp and Ayres (1982) listed several additional factors illustrating the difficulties involved with interpreting chemical variation with height as a function of fractional crystallization. As most of the rocks analysed from the layered complexes are cumulates they do not represent fractionated liquid compositions. Furthermore, volumes of the units present in the layered complexes cannot accurately be assessed making it impossible to calculate precisely the liquid compositions from weighted rock compositions. If the cyclically layered bodies are regarded as being the products of multiple intrusion this points to open-system behaviour which, in turn, complicates primary fractionation resulting from crystal accumulation. Lastly, it was pointed out that the secondary mineral assemblages, which predominate in all but a few exceptional cases, obscure the cryptic variations in the primary minerals.

Using data available from the Ship Hill and Koedoe bodies (two of the least altered complexes in the Barberton area) Viljoen and Viljoen (1970) were able to illustrate variations in the chemistry of the layered series plotted against height. In both examples clear differentiation trends emerged which could be closely correlated with the proportion and composition of the mineral phases in each zone. The similarity of the differentiation trends in the two bodies furthermore pointed to the conclusion that they were derived from the same parent magma.

Similar attempts were made to monitor chemical variations of the constituents of the Core Zone body (Robb, 1977), the Pioneer, Emmenes and Sawmill complexes (Wuth, 1980) and the Stolzburg body (Anhaeusser, unpubl. data). Despite incomplete data, differentiation trends can be confirmed in all cases. Some of these trends are illustrated in the AFM diagrams shown in Fig. 12. Complexes from the same geographical area are plotted, collectively, as the Noordkaap, Kaapmuiden and Weltevreden trends (Fig. 12a) and are compared with trends for the Skaergaard Complex (Wager and Brown, 1968) and two Canadian Archaean complexes known as the Dundonald Sill (Naldrett and Mason, 1968) and the Munro Lake Sill (MacRae, 1969). The Stolzburg trend, shown in Fig. 12b, is compared with the Mt Monger Sill from the Archaean of Western Australia (Williams, 1972; Williams and Hallberg, 1973) and the Munro Lake Sill. The most obvious distinction that can be made from the plots is that the Barberton complexes are clearly more ultramafic than their counterparts elsewhere in the world. All plot close to the MgO-FeO tie line and cluster near to the MgO apex of the AFM diagram. Whereas Fe-enrichment is apparent in the Barberton complexes this is not as marked as that found in the other Archaean and younger examples used for comparison. The subalkaline character of the Barberton bodies is another noteworthy characteristic.

TABLE II

CHEMICAL ANALYSES OF ROCKS FROM SOME ARCHAEAN LAYERED ULTRAMAFIC COMPLEXES IN THE BARBERTON MOUNTAIN LAND

	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	42.03	54.14	52.84	44.57	41.21	54.11	52.83	49.48	32.28	53.01	38.50	40.28	40.43
TiO_2	0.14	0.08	0.08	0.01	0.10	0.04	0.16	0.12	0.22	0.07	0.19	0.08	0.13
Al_2O_3	3.32	2.60	2.39	20.09	2.08	2.62	2.30	15.33	2.36	1.65	2.36	1.75	3.23
Fe_2O_3*	8.65	10.10	6.94	2.85	8.03	9.83	6.44	4.18	17.03	6.01	9.03	8.49	9.12
MnO	0.10	0.21	0.22	0.07	0.11	0.22	0.18	0.13	0.22	0.14	0.14	0.12	0.14
MgO	32.66	27.66	20.81	12.40	38.96	30.16	19.49	13.66	32.86	19.83	39.13	35.63	33.93
CaO	1.11	3.19	14.39	15.39	1.69	1.60	16.36	15.49	1.78	16.27	1.29	0.70	2.18
Na_2O	0.14	0.24	0.22	0.55	0.10	0.23	0.18	0.50	1.10	0.09	0.09	0.03	0.08
K_2O	0.03	0.07	0.08	0.03	0.10	0.02	0.04	0.05	0.04	0.02	0.04	0.01	0.02
P_2O_5	0.01	0.01	0.05	0.01	-	0.01	-	0.03	-	0.06	-	0.03	0.04
CO_2	nd	nd	nd	nd	0.84	0.05	0.07	0.07	0.27	nd	1.48	1.60	0.30
L.O.I.	9.98	0.30	0.23	3.12	6.03	1.19	1.89	1.28	4.27	2.03	5.96	10.94	10.33
Totals	98.17	(3)	(2)	99.09	99.21	(2)	99.94	(2)	99.88	99.18	98.21	(5)	(8)

	14	15	16	17	18	19	20	21	22	23	24	25	26
SiO_2	52.94	52.66	42.37	40.23	42.44	54.97	52.60	41.70	38.70	41.68	49.40	54.30	55.13
TiO_2	0.08	0.42	0.81	-	-	0.24	0.37	0.11	0.90	0.14	0.13	0.34	0.52
Al_2O_3	1.50	9.32	11.24	2.20	2.34	3.65	8.48	2.30	1.40	3.23	3.80	5.30	12.03
Fe_2O_3*	7.81	9.60	8.29	7.00	8.44	7.95	10.30	7.11	6.79	9.37	8.40	9.81	9.91
MnO	0.18	0.14	0.15	0.10	0.13	0.18	0.19	0.11	0.08	0.13	0.12	0.19	0.13
MgO	30.65	13.13	6.27	36.73	31.89	16.37	11.47	37.00	38.17	32.60	24.65	14.30	7.60
CaO	1.95	9.94	29.21	0.60	2.83	14.24	11.00	2.17	0.53	3.04	8.14	12.90	9.34
Na_2O	0.05	2.30	0.08	0.08	0.08	1.25	2.69	0.10	0.10	0.08	0.10	2.10	4.13
K_2O	0.09	0.21	0.03	0.02	0.02	0.03	0.10	0.04	0.02	0.05	0.04	0.04	0.28
P_2O_5	0.03	0.08	0.16	0.01	0.02	0.01	0.01	0.03	0.03	0.04	0.05	0.09	0.09
CO_2	0.13	0.20	0.06	0.87	0.66	0.16	nd	nd	nd	nd	nd	nd	nd
L.O.I.	4.61	2.55	1.77	11.92	10.48	1.63	3.08	9.37	13.97	9.04	4.68	0.71	0.80
Totals	(20)	(10)	(4)	99.76	99.33	100.68	(3)	100.04	(3)	(4)	(2)	100.08	(4)

* Total Fe as Fe_2O_3 nd = not determined - = below detection limits (3) average of 3 analyses

Explanation of Column Headings

KOEDOE COMPLEX

1. Serpentinized peridotite (chill zone)
2. Orthopyroxenite
3. Websterite
4. Anorthositic gabbro-norite

SHIP HILL COMPLEX

5. Dunite-peridotite (lower zone)
6. Orthopyroxenite
7. Websterite
8. Anorthositic gabbro-norite
9. Dunite-peridotite (upper zone)

BUDD COMPLEX

10. Websterite
11. Dunite-peridotite (upper zone)

STOLZBURG COMPLEX

12. Serpentinized dunite
13. Serpentinized harzburgite
14. Orthopyroxenite
15. Gabbro-norite
16. Rodingite

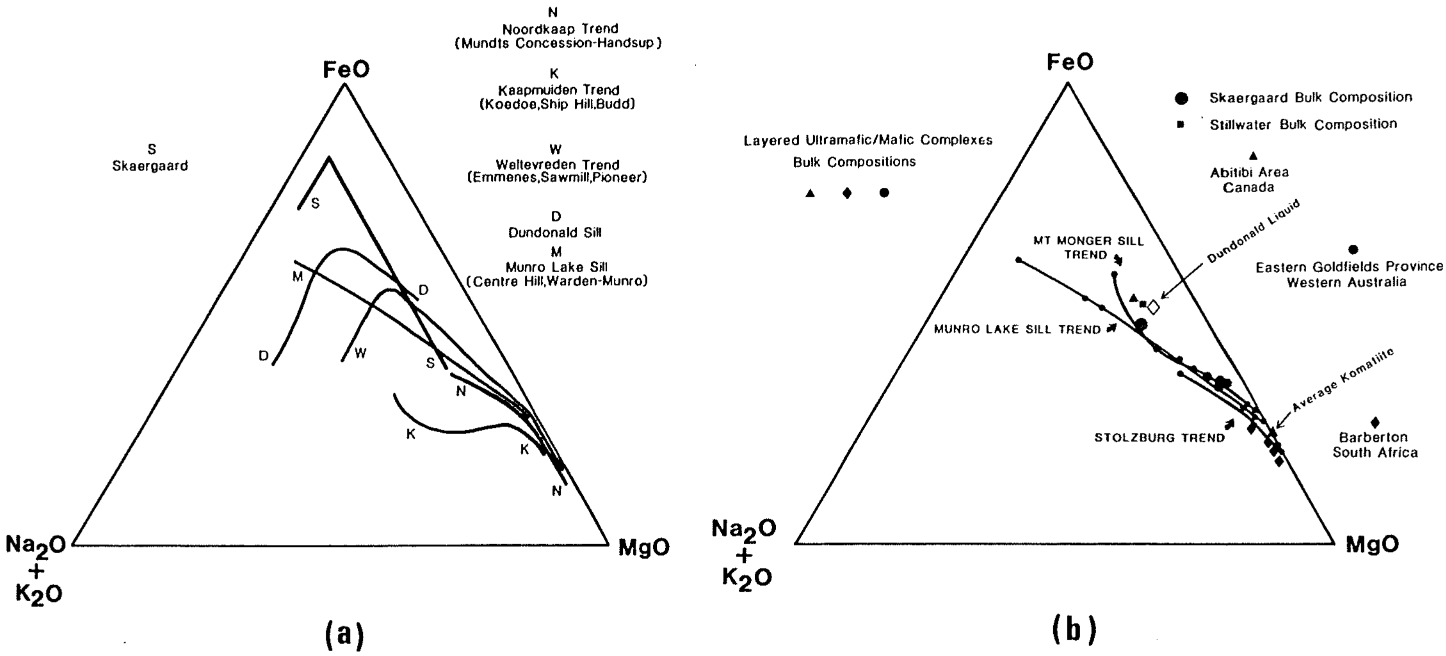
HANDSUP-MUNDT'S CONCESSION COMPLEXES

17. Serpentinized dunite
18. Serpentinized harzburgite
19. Websterite
20. Gabbro-norite

PIONEER-SAWMILL-EMMENES COMPLEXES

21. Spinifex textured chill zone serpeninite
22. Serpentinite dunite
23. Serpentinized harzburgite-peridotite
24. Orthopyroxenite
25. Websterite
26. Anorthositic gabbro

Analyses : 1-11 (Viljoen and Viljoen, 1969a); 16 (Anhaeusser, 1979); 12-15 (Anhaeusser, 1969,1967); 17-20 (Anhaeusser, 1969,1976 and unpublished data); 21-26 (Wuth, 1980)



<u>Figure 12</u> : *FeO-MgO-(Na_2O + K_2O) variation diagrams illustrating the trends of (a) the Noordkaap, Kaapmuiden, and Weltevreden complexes (Barberton) compared to the Dundonald and Munro Lake sills (Ontario), as well as the Skaergaard liquid trend and (b) the Stolzburg complex compared to the Munro Lake Sill and the Mt Monger Sill (Western Australia). Also shown are the bulk compositions of the Barberton layered complexes for comparison with those of the Abitibi area, Canada, the Eastern Goldfields Province, Western Australia and the Stillwater and Skaergaard complexes.*

B. Bulk Composition

Estimation of the composition of the parent magma for the Barberton layered intrusions cannot be determined directly from their chilled border zones as these are either poorly exposed or too altered. The alternative has been to employ the method of weighting analyses in accordance with the proportions of rock types developed in the layered intrusions. Despite the disadvantages of the approach adopted there has emerged a high degree of consistency in the results obtained independently from five separate complexes or sets of complexes in the Barberton region (Table III).

The bulk compositions of all the intrusives show significantly high MgO values (30,70 - 35,71%) which probably reflect the cumulate nature of the rocks being considered. Also listed in Table III are chemical analyses of spinifex-textured komatiitic lava flows that occur in the lower volcanic succession of the Barberton greenstone belt. In addition to high-Mg komatiite basalts the komatiite lavas (see Arndt and Nisbet, 1982 for definition of komatiite) are typical of the country rocks hosting the layered sill-like intrusions. The conclusion is therefore drawn that the layered ultramafic

TABLE III

COMPARISON OF THE CALCULATED BULK COMPOSITIONS OF VARIOUS LAYERED ULTRAMAFIC COMPLEXES AND AVERAGE EXTRUSIVE KOMATIITES IN THE BARBERTON MOUNTAIN LAND

	1	2	3	4	5	6	7	8
SiO_2	47,47	47,48	50,46	49,89	47,38	48,14	47,00	45,68
TiO_2	0,09	0,14	0,14	0,09	0,19	0,40	0,36	0,32
Al_2O_3	2,59	4,08	4,28	3,23	4,01	4,22	3,92	3,35
Fe_2O_3*	10,82	9,94	9,50	8,43	9,33	12,56	12,92	11,99
MnO	0,19	0,17	0,15	0,14	0,12	0,20	0,19	0,17
MgO	35,71	33,09	30,70	32,28	34,07	26,20	28,88	33,67
CaO	2,53	4,85	4,02	5,23	4,17	7,39	6,73	4,83
Na_2O	0,52	0,20	0,67	0,67	0,58	0,82	-	-
K_2O	0,06	0,04	0,04	0,03	0,10	-	-	-
P_2O_5	0,02	0,01	0,04	0,01	0,05	0,07	-	-

* Total Fe as Fe_2O_3

Note: Analyses are volatile-free and recalculated to 100 per cent

Explanation of Column Headings

1. Bulk composition, Koedoe Complex (Viljoen and Viljoen, 1970)
2. Bulk composition, Ship Hill Complex (Viljoen and Viljoen, 1970)
3. Bulk composition, Stolzburg Complex (Anhaeusser, 1976)
4. Bulk composition, Handsup-Mundt's Concession complexes (Anhaeusser, 1976)
5. Bulk composition, Pioneer-Sawmill-Emmenes complexes (Wuth, 1980)
6. Fresh, spinifex-textured komatiite. Average of two analyses from the Schapenburg greenstone remnant (Anhaeusser, 1983)
7. Spinifex-textured, aphyric ultramafic komatiite lavas. Average of 13 samples from the Onverwacht type locality (Smith, 1980)
8. Average of 10 samples of porphyritic ultramafic komatiite from the Onverwacht type locality (Smith, 1980)

complexes most likely formed from parental magma having komatiitic affinities. Support for an almost complete evolutionary trend of magma development was noted by Anhaeusser (1977) who suggested that the fractionation of olivine, orthopyroxene and clinopyroxene from a melt containing approximately 26 per cent MgO was responsible for the generation of a wide range of cumulus-enriched liquids and melt composites ranging from dunite, orthopyroxenite, websterite and gabbro to peridotitic and basaltic komatiites, high Mg-basalts and oceanic tholeiites.

It appears from comparisons of the bulk compositions of Archaean sills elsewhere in the world that there is a strong genetic link between the sills themselves and their enveloping country rocks. The compositional equivalence coupled with the close spatial association of the intrusions and their volcanic hosts provides convincing support for the two being co-magmatic (Anhaeusser, 1969, 1977, 1978; MacRae 1969; Viljoen and Viljoen, 1970; Williams, 1972; Williams and Hallberg, 1973; Raudsepp and Ayres, 1982). This concept is further illustrated in Fig. 12b which shows plotted the bulk compositions of the Barberton, Western Australian and Canadian layered bodies as well as the Skaergaard and Stillwater complexes. The position of average peridotitic komatiite from Barberton falls close to the field defined by the high-Mg ultramafic intrusive complexes in the area. The Dundonald liquid (quoted in MacRae, 1969 after Naldrett and Mason, 1968) plots closer to the tholeiitic bulk composition of the Munro Lake Sill in the Abitibi area. Between these extremes is the Eastern Goldfields region of Western Australia where the Mt Monger and associated sills have parent magma compositions ranging from 15,7 - 18,7 per cent MgO (see also Table IV) and which are similar to the enclosing high-Mg basalts (Williams and Hallberg, 1973).

The Barberton ultramafic complexes, with the possible exception of some layered sills in the Timmins-Kirkland Lake area of Ontario (e.g. Dundonald Sill), and others in the south-central part of Zimbabwe (e.g. Filabusi), thus appear to be chemically unique. In Table IV this relationship is demonstrated by comparing the SiO_2 and MgO values obtained from estimates of parental magmas of a variety of layered complexes.

C. Mode of Emplacement and Crystallization Sequence

The Barberton layered complexes are believed to have formed as sill-like bodies injected penecontemporaneously into a developing pile of mafic and ultramafic lavas and associated, but subordinate, sedimentary units. Their broadly concordant relationships with country rocks dominated by pillowed and massive basaltic komatiites is noteworthy. Komatiite flows in close proximity to the ultramafic intrusions are rare. This is particularly evident in the vicinity of the Ship Hill, Budd and Koedoe bodies as well as the Stolzburg body. The Muldersdrif ultramafic complex north-west of Johannesburg (Fig. 1) provides a further example where basalts predominate in the area immediately surrounding a layered body (Anhaeusser, 1978). By contrast, layered ultramafic complexes are entirely lacking in areas where komatiite extrusives are common, as is the case in the Komati Formation type locality in the southern part of the Barberton greenstone belt (the area 35 km east of Badplaas, Fig. 1, described by Viljoen and Viljoen, 1969b). This suggests that komatiitic melts may have been prone to collecting in magma chambers if their passage to surface was in any way impeded. That their emplacement was controlled by the nature of the host rock appears evident as they are commonly associated with thin sedimentary units (usually banded chert, banded iron-formation).

TABLE IV

PARENT MAGMA COMPOSITIONS

ARCHAEAN AND YOUNGER LAYERED COMPLEXES

	SiO_2	MgO
Bushveld Igneous Complex (Davies *et al.*, 1980)	55,00	12,00
Skaergaard Complex (Wager and Brown, 1968)	48,10	8,60
Stillwater Complex (Hess, 1960)	50,99	7,72
Western Australia :		
Mt Monger Sill		
Yilmia Hill Sill	50,90 - 51,80	15,70 - 18,70
Mt Hunt Sill		
Seabrook Sill		
(Williams and Hallberg, 1973)		
Superior Province, Canada :		
Munro Lake Sill (MacRae, 1969)	50,41	10,84
Dundonald Liquid (MacRae, 1969)	51,40	11,05
Dundonald Sill (Naldrett and Mason, 1968)		
(gabbro : pyroxenite : peridotite)		
(1 : 1 : 2)	47,31	25,38
(1 : 1 : 6)	44,69	32,89
Barberton Greenstone Belt :		
Handsup-Mundt's Concession Complexes (Anhaeusser, 1969)		
(gabbro : pyroxenite : dunite)		
(1 : 1,14 : 1,35)	50,13	32,43
Ship Hill Sill (Viljoen and Viljoen, 1970)	46,64	32,50
Koedoe Complex (Viljoen and Viljoen, 1970)	45,70	34,37
Stolzburg Complex (C.R. Anhaeusser - unpubl. data)	46,58	28,34
Pioneer, Sawmill and Emmenes Complexes (Wuth, 1980)	49,27	27,29
Komatiite Lava Flows (Average): Smith (1980)	47,00	28,88

Once trapped in a chamber cooling periods for the magma were sufficiently long for cumulus minerals to form and settle according to a crystallization order dictated by the physico-chemical conditions of the environment. In the case of the Barberton complexes olivine formed first in great abundance to give rise to the extensive dunite zones. Intercumulus orthopyroxene in some of the dunite units suggests that the olivines settled through a pyroxenitic liquid trapping some of the material before the pyroxene itself became a cumulus phase. The crystallization order changed rapidly from one phase to the next in the cyclic units until ultimately clinopyroxene and plagioclase followed as cumulus phases (having been intercumulus phases earlier in the sequence). The alternating dunite-orthopyroxenite zones suggest that the liquid phase of the magma, at an early stage in the crystallization scheme, may have been on or close to the olivine-orthopyroxene boundary on the liquidus during accumulation of as much as half or more of the cumulate rocks of some complexes (e.g. Stolzburg and Koedoe bodies). Thereafter olivine and orthopyroxene crystallized simultaneously to form the harzburgite units. The observed order of crystallization then proceeded to clinopyroxene-orthopyroxene to form the websterite units, and clinopyroxene-orthopyroxene-plagioclase to form the gabbroic to anorthositic units. The plagioclase cumulates like those seen in the Koedoe complex might reflect some floatation of plagioclase.

VI. CONCLUSIONS

Despite their great age of approximately 3 500 Ma old the Barberton ultramafic intrusive complexes have withstood the ravages of deformation and alteration sufficiently well to enable an assessment to be made of their most salient features. The sill-like bodies which resulted from simple fractionation and gravity accumulation of cumulus crystals from a parent magma rich in magnesium are intimately associated with, and probably comagmatic with, extrusive volcanic rocks of closely equivalent composition. The intrusive bodies are considered to have formed from komatiitic parental magma as indicated by independently derived bulk composition estimates of a number of widely separated occurrences in the Barberton greenstone belt. Although numerous Archaean layered intrusions are known from around the world there are few examples with which to compare the unique characteristics of the ultramafic complexes described in this paper. The most important differences centre around the distinctive geochemistry and mineralogy of the lithological units and their relative abundances. Ultrabasic rocks that include dunite, peridotite and harzburgite account for as much as 80 per cent by volume of some of the complexes, the balance frequently being made up of different varieties of pyroxenite. Only in some of the larger complexes are there plagioclase-bearing lithologies present such as gabbro, norite and, more rarely, anorthosite. In addition the unique geochemical character of the Barberton layered bodies has played a role in the development of important chrysotile asbestos and magnesite deposits in these rocks.

With few exceptions the Barberton complexes are cyclically layered. This takes the form of phase layering with cryptic layering being less obvious and mainly evident in the Koedoe, Ship Hill and Budd complexes which have only one completed differentiation sequence. Inch-scale layering is locally confined to anorthositic gabbro-norite units found in only some complexes.

The complexes developed in magma chambers that may have acted as staging points for the distribution of lower melting fraction basaltic komatiites.

In the Barberton area these lavas range in composition from approximately 10-20 per cent MgO (Viljoen and Viljoen, 1969b; Smith, 1980), and are envisaged as having been squeezed out of some relatively shallow seated ultramafic repositories. The filter-pressed magma would then leave behind a residue consisting of cumulus enriched minerals, particularly the more refractory phases of olivine and orthopyroxene, found as the dominant constituents of the Barberton layered complexes.

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