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PALAEOARCHAEAN TO MESOPROTEROZOIC (*c*. 3500 - 1000 Ma) ULTRAMAFIC AND MAFIC INTRUSIONS OF THE KAAPVAAL CRATON AND NEIGHBOURING METAMORPHIC BELTS: A REVIEW

C. R. ANHAEUSSER

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by

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ABSTRACT

The Kaapvaal Craton and surrounding higher-grade metamorphic belts (Limpopo, Natal-Namaqualand) have experienced considerable ultramafic, mafic and felsic magmatism beginning in the Palaeoarchaean granite-greenstone terranes (*c.* 3600-3200 Ma) and culminating more recently with Mesozoic Karoo magmatism (*c.* 200-150 Ma). Other igneous events on the craton include the intrusion, between 2 100 and 1 200 Ma, of a series of alkaline and carbonatite complexes (e.g., Phalaborwa, Schiel, Pilanesburg) and the emplacement, between 1900 Ma and 70 Ma, of numerous kimberlite intrusions that occur as volcanic pipes, dykes and sills.

The largest igneous intrusion in the world (viz., the Bushveld Complex), was emplaced into the central part of the Kaapvaal Craton in early Palaeoproterozoic times, approximately 2050 Ma ago. This mafic-ultramafic complex, which hosts vast reserves of chromite, titanium- and vanadium-bearing magnetite and the platinum-group elements, has received considerable attention in the scientific literature and hence will not discussed further in this contribution. Likewise, the alkaline and carbonatite complexes as well as the Karoo magmatism is also not discussed here. Instead, this paper reviews most of the remaining ultramafic and mafic igneous intrusions on the Kaapvaal Craton and in the neighbouring high-grade metamorphic belts immediately flanking the craton.

Most of the intrusions on the Kaapvaal Craton are associated with Archaean granite-greenstone terranes (e.g., Barberton, Murchison, Johannesburg Dome), but also include igneous bodies (e.g., Rooiwater, Usushwana, Stella) that intruded into an evolved, *c.* 3000 Ma granite-gneiss crust that, in turn, post-dated the greenstone terranes. Other intrusions into the craton include likely satellite bodies associated with the Bushveld magmatic event (e.g, Molopo Farms, Losberg, Uitkomst) and the late Mesoproterozoic (*c.* 1100 Ma) Umkondo magmatic event (e.g., Timbavati, Anna's Rust/Vredefort).

The high-grade metamorphic terranes flanking the Kaapvaal Craton host a number of intrusive complexes that were emplaced into orogenic zones that probably developed as a result of processes involving early collisional plate tectonics. In the north, the *c.* 3150 Ma Messina Layered Intrusion was emplaced into the Central Zone of the Limpopo Belt and was subsequently deformed, metamorphosed and dismembered during several subsequent stages of orogeny. In the south, the Natal-Namaqualand Belt was thrust north- and north-eastwards onto the Kaapvaal Craton and experienced stages of collisional tectonism and accompanying magmatism that endured over a time span ranging between 1250-900 Ma. Into this orogenic environment were emplaced several intrusive igneous complexes in the KwaZulu-Natal sector of the belt (e.g., Tugela Rand, Mambula, Sithilo), and the Oranjekom Complex and other related bodies in the East Namaqualand sector.

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INTRODUCTION

The Kaapvaal Craton has had a protracted and complex history of igneous intrusion commencing in the Eoarchaean (>3600 Ma) and extending to the late Cretaceous period (*c*. 65 Ma). The intrusions have been of a wide-ranging type, including rocks of mafic and ultramafic affinity, granitoid rock types of variable composition and age, and carbonatite and alkali intrusions. Most of the granitoid rocks on the Kaapvaal Craton, were emplaced between *c*. 3600 Ma and 2500 Ma and are discussed by Poujol *et al.* (2003) and Robb *et al*. (2005). The Bushveld Complex, the largest igneous intrusion on the craton, was emplaced at *c*. 2057 Ma, and has been described, among many others, by Eales and Cawthorn (1996) and Cawthorn *et al*. (2005). The intrusive alkaline and carbonatite complexes have been shown to belong to two time groups. The older group, which includes the Phalaborwa and Schiel complexes, falls into the time-span *c.* 2200-2100 Ma, and is described by Verwoerd and Du Toit (2005). The younger alkaline complexes, including among others the Pilanesberg, Spitskop and Goudini complexes, fall into the time-span *c*. 1450-1200 Ma, and are described by Verwoerd (2005).

In this contribution attention will be given to Palaeoarchaean to Mesoarchaean layered ultramafic and mafic intrusions located within, and in close proximity to, many of the Archaean greenstone belts situated on the Kaapvaal Craton. In addition, younger Neoarchaean to Mesoproterozoic, generally mafic igneous bodies, unrelated to Archaean greenstone belts are described, as are igneous intrusions that occur in the high-grade metamorphic terranes surrounding the Kaapvaal Craton. This review purposefully excludes the Bushveld Complex, which has received much attention in past literature, but rather discusses a number of smaller intrusions on the craton that are variously regarded as satellite bodies related to the Bushveld event.

PALAEOARCHAEAN ULTRAMAFIC-MAFIC COMPLEXES IN THE BARBERTON AREA

Barberton Greenstone Belt and surrounding areas

The Barberton Greenstone Belt (Fig.1.1) is a northeast-trending, isoclinally folded, metamorphosed volcano-sedimentary succession entirely surrounded by intrusive granitiod rocks (Anhaeusser *et al*., 1983; Walraven and Hartzer, 1986; Brandl *et al*., 2005; Robb *et al*., 2005). Mafic and ultramafic komatiites and high-Mg basalts predominate in the lower part of the sequence (Tjakastad Subgroup), which is overlain by mafic to felsic volcano-sedimentary rocks with calc-alkaline affinities (Geluk Subgroup). Capping the entire volcanic succession (viz., the Onverwacht Group) is a variety of sedimentary rocks that constitute the Fig Tree and Moodies Groups.

The lower ultramafic-mafic part of the greenstone sequence hosts over 20 layered ultramafic to mafic complexes (Fig. 2) whereas the upper mafic to felsic part of the succession hosts only about five known intrusions (Anhaeusser, 1985; 1986). Most of the complexes show pronounced magmatic differentiation and the common development of cyclically repeated layering consisting dominantly of dunite, orthopyroxenite and harzburgite, and volumetrically subordinate websterite, gabbro and anothositic gabbro-norite units. Although numerous Archaean layered intrusions are known from around the world, most are considerably less magnesian than the Barberton ultramafic intrusions that have dunite, peridotite and harzburgite phases forming as much as 80 % by volume of some of the complexes, the balance frequently consisting of different varieties and abundances of pyroxenite. Plagioclase-bearing rocks, such as gabbro, gabbro-norite and rarely anorthositic-gabbro or anorthosite occur in some of the intrusions.

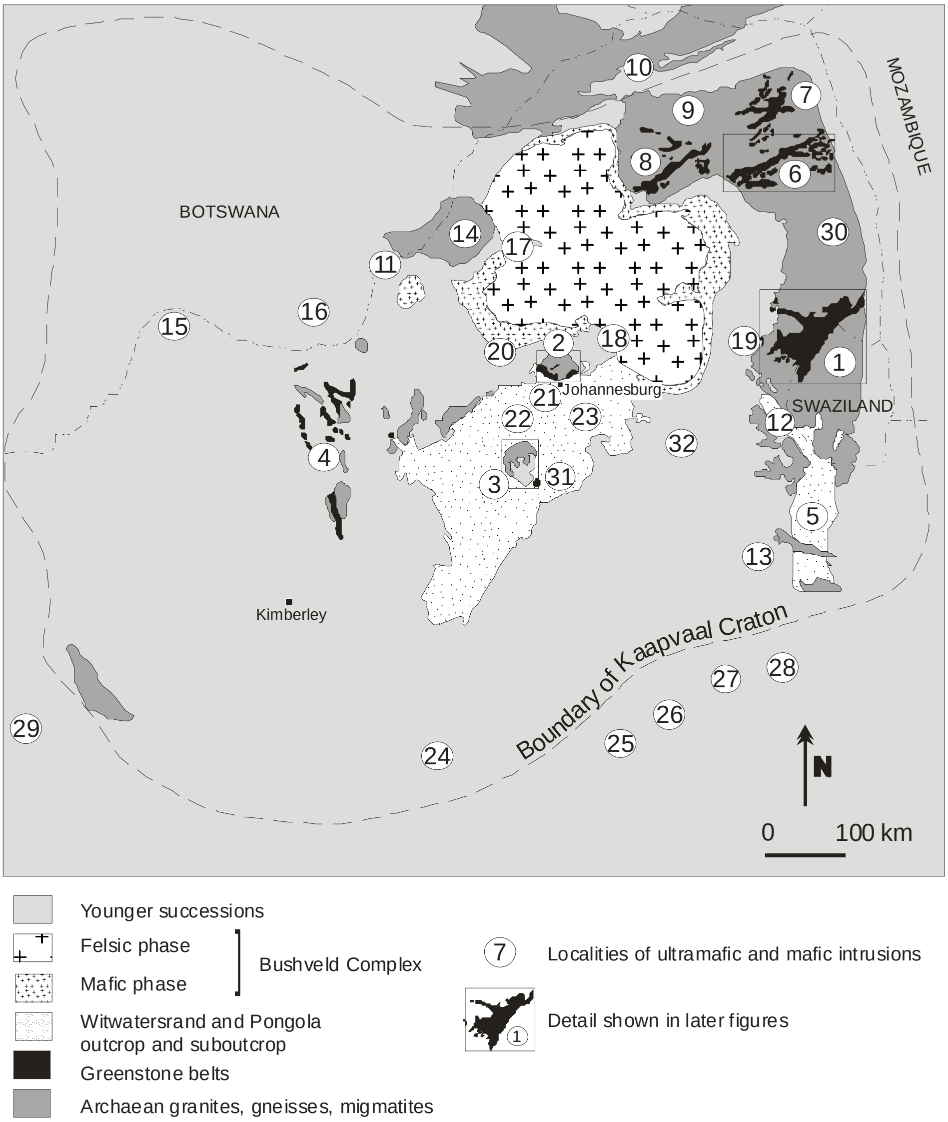

Figure 1. *Simplified geological map of the Kaapvaal Craton and immediate surrounds showing the localities of the ultramafic-mafic igneous intrusions discussed in the paper. More detailed maps are provided elsewhere for blocked areas (map modified after Eglington and Armstrong, 2004).*

Estimates of the bulk composition of a number of widely separated ultramafic complexes in the Barberton region indicate that the parental magma composition of these intrusions was initially komatiitic with contents of about 28 % MgO.

The age of the ultramafic intrusions has not been determined directly, but evidence suggests they were emplaced early in the evolution of the Barberton granite-greenstone terrane. Estimates ranging from *c.* 3540-3260 Ma have been considered likely for the mafic and ultramafic volcanic and igneous rocks in the greenstone belt (Hamilton *et al*., 1977; Kamo and Davis, 1994; Lahaye *et al.*, 1995; De Ronde and Kamo, 2000). The layered bodies have, without exception, undergone deformation involving folding and faulting and have been affected by low-grade regional metamorphism resulting from the intrusion of the Archaean granitic rocks surrounding the Barberton Greenstone Belt in South Africa and Swaziland. The oldest granitoids, consisting of trondhjemitic and tonalitic gneisses dated at *c.* 3680-3212 Ma (Kamo and Davis, 1994; Poujol *et al*., 2003; Eglington and Armstrong, 2004), are considered more likely to have been responsible for the structural and metamorphic disturbance of the ultramafic intrusive bodies than any of the later granitic intrusions.

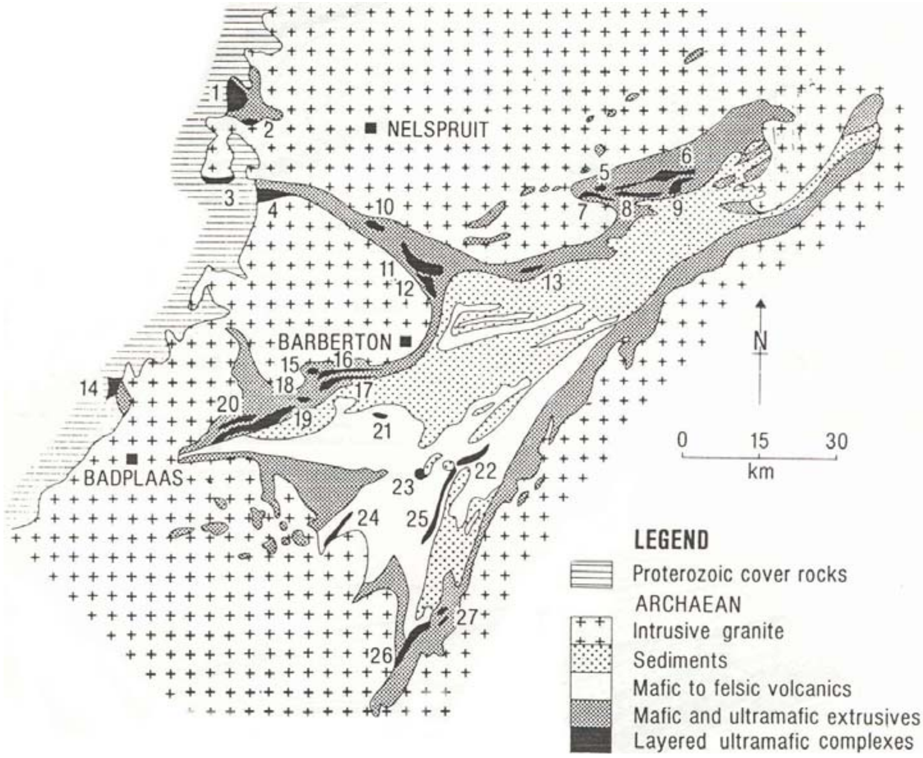

Figure 2. *Simplified locality map showing the general geology of the Barberton Greenstone Belt and the distribution of Archaean layered ultramafic-mafic intrusions (after Anhaeusser, 1985, 1986).*

Geotectonic reconstructions by Anhaeusser (2002) indicated that many of the Barberton ultramafic complexes are developed in a zone, believed to be a possible suture or oceanic crustal collisional zone, which is situated along the northern flank of the Barberton Greenstone Belt. Precise U-Pb zircon dating has demonstrated that the Barberton Greenstone Belt is a compound terrane formed through long-term magmatic activity and late-stage tectonic accretion that occurred over a period of between 330-490 Ma (De Ronde and De Wit, 1994; Lowe, 1999). These authors have argued that collision-like processes were responsible for the late-stage tectonism reflected in the amalgamation and suturing of earlier-formed protocontinental blocks. Anhaeusser (2002) envisaged that many of the ultramafic complexes, particularly those on the northern flank of the Barberton Greenstone Belt, represent a further manifestation of the convergence of two separate crustal blocks in a manner akin to obducted oceanic crust. Similar ultramafic bodies are commonly found in suture zones and sutured mélange terranes of Phanerozoic orogenic belts formed as a result of plate-tectonic processes.

Barberton Ultramafic Complexes

Early accounts of the intrusive ultramafic-mafic rocks, some of which host chrysotile asbestos and magnesite deposits, were provided by Hall (1918, 1921, 1930), Visser *et al*. (1956), and Van Biljon (1964).

Complexes that have received more recent attention include the following (see Fig. 2 for locations):

(1) Kaapmuiden-Malelane area in the northeast part of the greenstone belt (Koedoe, Ship Hill Magnesite-Canal, and Central - Viljoen and Viljoen, 1970; Ward, 1999);
(2) North-central area between Noordkaap and Kaapmuiden (Bon Accord - De Waal, 1986; Sugden Siding - Anhaeusser, 1963);

(3) Jamestown Schist Belt-Kaapsehoop area, north and northwest of Barberton (Handsup, Mundt's Concession - Anhaeusser, 1972, 1976, 1985, 1986; Ward, 1999; Kaapsehoop - Laubscher, 1986; Ward, 1999);
(4) Barclayvale Schist Belt (Richmond, Core Zone - Robb, 1977);
(5) Oorschot-Weltevreden Schist Belt area southwest of Barberton (Pioneer, Sawmill, Emmenes, Morgenzon - Wuth, 1980);
(6) Kalkkloof Schist Belt north of Badplaas (Kalkkloof - Menell *et al*., 1986);
(7) Nelshoogte Schist Belt northeast of Badplaas (Stolzburg - Anhaeusser, 1985, 1986, 2001; De Wit *et al*., 1987; Rodel, 1993; Ward, 1999; Sterkspruit - Conway, 1997);
(8) The southern part of the Barberton Greenstone Belt, between Badplaas and the Swaziland border (Rosentuin - Rodel, 1993); and
(9) The area southeast of Barberton, straddling the border between South Africa and Swaziland (Msauli - Voight *et al*., 1986; Ward, 1999; Havelock - Barton, 1982, 1986; Ward, 1999).

Kaapmuiden-Malelane area

Ship Hill-Budd-Koedoe-Magnesite-Canal-Central Complexes

Between Kaapmuiden and Malelane, situated approximately 55 km northeast of Barberton on the northern flank of the Barberton Greenstone Belt, are six layered ultramafic bodies (Fig. 2, 5-9), which have been described by Viljoen and Viljoen (1970). The intrusions occur as separate ultramafic bodies interlayered with Onverwacht Group mafic and ultramafic metavolcanic rocks and grunerite-quartz metasediments. The ultramafic bodies have all been subjected to various episodes of structural deformation and regional greenschist metamorphism, are generally subvertical in attitude, vary in length from about 5-9 km and range from about 800-1600 m in width. The various bodies occur mainly as linear resistant ridges, but the Koedoe intrusion (Fig. 3A) is exposed in an assymetrical, northeast-trending syncline with a wide northern limb and a poorly developed, tectonically aborted southern limb (Fig. 3B). The fold axis plunges 60˚ ENE parallel to a major left-lateral strik-slip fault (Stentor Fault), which acted as a detachment plane during the development of the fold structure.

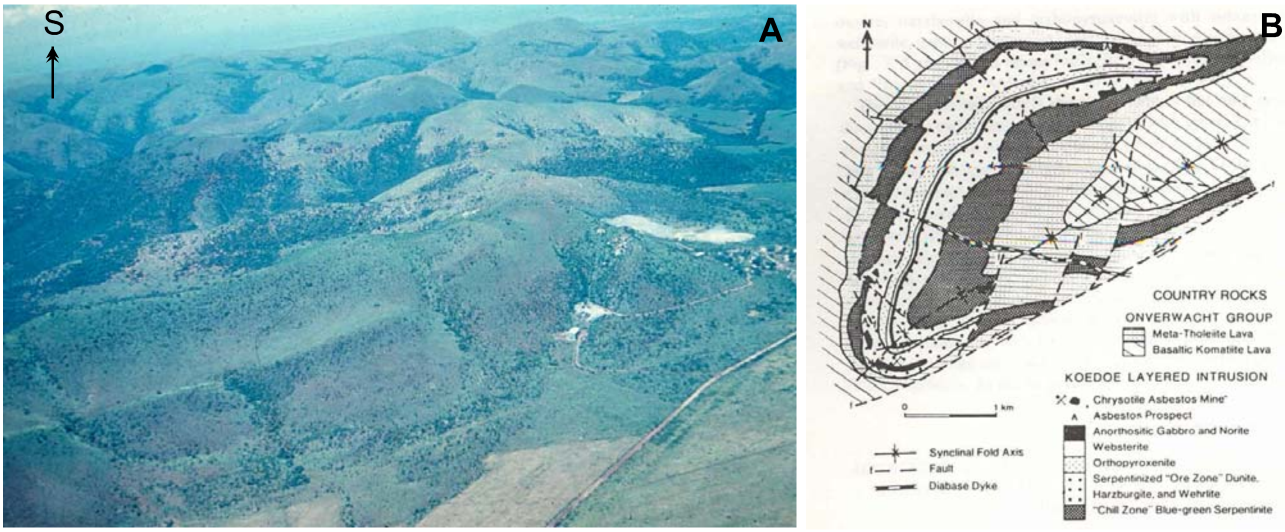

Figure 3. ***A***. *Aerial photograph, looking south, of the Koedoe layered complex near Malelane in the northeastern part of the Barberton Greenstone Belt. The hills in the background, consisting of Fig Tree Group shales, greywackes and banded iron formation, are separated from the layered body by the strike-slip Stentor Fault. Chrysotile asbestos workings can be seen in the hinge zone of the Koedoe syncline (photograph supplied by R.P. and M.J. Viljoen);* ***B***. *Geological map of the Koedoe Complex (after Viljoen and Viljoen, 1970).*

Each ultramafic body has a differentiation sequence of rock types which, although varying in their proportions, appear to have been derived from the same magma source. Calculations of the bulk chemistry of the Ship Hill and Koedoe bodies suggests that they have similar compositions and were formed from a komatiitic parent magma (Viljoen and Viljoen, 1970). Three of the bodies (Ship Hill, Budd, Koedoe) display differentiation sequences that commence with a peridotitic chill zone at the base, followed by a main dunite-peridotite zone, an orthopyroxenite zone, a clinopyroxenite (websterite) zone, and anorthositic gabbro-norite zone (Fig. 4). This differentiation cycle is then overlain by a second massive dunite-peridotite sequence. In the Koedoe and Ship Hill bodies intrusive pods of coarse-grained pegmatoid occur in the upper dunite-peridotite zones. These pegmatoids consist of large actinolite crystals (some up to 6 cm in length) altered from original clinopyroxene, the latter surrounded by large plagioclase laths (andesine) that have undergone deuteric alteration to clinozoisite and epidote.

Figure 4. *Stratigraphic columns for the Koedoe, Budd and Ship Hill layered complexes (after Viljoen and Viljoen, 1970).*

According to Viljoen and Viljoen (1970) the rock types encountered in the Kaapmuiden-Malelane layered intrusions vary from body to body. The Koedoe and Ship Hill bodies are, for example, better preserved than the remaining intrusives in the region. The orthopyroxenite, websterite and anorthosite-gabbro-norite zones in the Koedoe body are exceptionally well preserved, but these rock types are only fresh in scattered localities in the Ship Hill and Budd bodies. By contrast the cumulate dunite-peridotite zones in the Koedoe body are altered and serpentinised and no relic olivine or pyroxene was observed. These rocks in the Ship Hill and Budd bodies are, however, rather well preserved, but the intercumulus material is altered.

The Kaapmuiden-Malelane ultramafic complexes differ somewhat from most other intrusions in the Barberton region in that they: (1) do not show multiple cyclicity or repeated layering as seen for example in the Stolzburg and Handsup-Mundt's Concession bodies; (2) they are host rocks to both chrysotile asbestos (e.g., Koedoe - Hall, 1930; Anhaeusser, 1986; Ward, 1999) as well as magnesite deposits (Fig. 5) (e.g., Magnesite, Budd, Ship Hill - Van Zyl, 1942; Viljoen and Viljoen, 1969c; Ward, 1999); and (3) they have distinctive zones of anorthositic gabbro-norite terminating the lower layered sequences and are marked in the field by "inch-scale layering" of anorthositic (~60%

Figure 5. *Road cutting at Pettigrew's Nek, south of Kaapmuiden in the northeastern part of the Barberton Greenstone Belt, showing magnesite veins in altered dunite from the Budd Complex.*

cumulate plagioclase + clinopyroxene) and anorthositic-norite layers, the latter possessing greater concentrations of clinopyroxene. The plagioclase compositions are very calcic with compositions ranging from An_{92}-An_{94} (Viljoen andViljoen, 1970). "Inch-scale layering" of the type described has only been recorded elsewhere in the Stolzburg Complex (Anhaeusser, 1985, 2001; Rodel, 1993). Anorthositic gabbros were reported in the Sawmill, Pioneer and Emmenes bodies (Wuth, 1980).

Besides the three main bodies described earlier several other coarse-grained ultramafic bodies as well as a layered differentiated mafic body are present in the Kaapmuiden-Malelane area. As outlined by Viljoen and Viljoen (1970) the Magnesite and Central bodies occur as large, apparently conformable pods, which appear to be the serpentinised and steatised products of original olivine cumulates (dunites) - there being no indications of pyroxene- or plagioclase-bearing rocks within them. The Magnesite body can be traced over a strike length of 16 km. The Canal body to the north consists mainly of pyroxenites and gabbros with few olivine-bearing rocks and was regarded by (Viljoen and Viljoen, 1970) as the differentiation product of mafic (tholeiitic) magma.

Noordkaap - Kaapmuiden (north central area)

Bon Accord - Sugden Siding intrusions

Intrusive ultramafic rocks occur in two localities on the northern flank of the Barberton Greenstone Belt approximately 20 km northeast of Barberton. At the one locality on Bon Accord Stock Farm 282 JU massive serpentinites have been emplaced into and have distrupted Moodies sediments forming part of the Lily Sycline. Noteworthy in this area is the Scotia Talc Mine and the Bon Accord nickel sulphide deposit, both of which occur in the serpentinites north of Sheba Siding (Anhaeusser, 1964; Keenan, 1986). The Bon Accord West deposit, also in this area, was described by De Waal (1986), and is unique among nickel deposits of the world in that it has a high nickel content (~36% NiO), is almost devoid of sulphur, and contains a series of spinels that are intermediate products of a reaction in which chromian spinel is partly altered to nickeliferous magnetite (viz., trevorite $NiFe_2O_4$). De Waal (1986) presented evidence suggesting that the deposit represents either an oxidised and subsequently metamorphosed Ni-rich meteorite, or an oxidised and metamorphosed segregation of Ni-rich sulphide.

The second ultramafic body, known as the Sugden Siding serpentinite intrusion (Fig. 2.13), occurs about 6 km to the east of the Bon Accord serpentinite on the farm Annex Riverbank 279 JU, and contains showings of magnesite and talc, some of which was mined in earlier years. The serpentinite body, which is about 150 m wide and has an ENE strike of 3 km, is steeply inclined and is flanked in the south by tremolite-actinolite schists and in the north by hornblende amphibolite schists (Anhaeusser, 1963). The serpentinite, which was probably a dunite prior to alteration, contains relic olivine crystals, but is essentially composed of antigorite, talc, magnetite and chromite. A magnesite-rich zone in the centre of the intrusion also displays relic olivine crystals in places and variable amounts of antigorite, magnetite, talc, carbonate (mainly magnesite) and chlorite.

Jamestown Schist Belt -Kaapsehoop areas

A number of narrow, tapering, generally arcuate schist belt remnants occur wedged between granitiod plutons in the areas flanking the Barberton Greenstone Belt. The Jamestown Schist Belt, located north of Barberton, is the largest of these schist belt remnants and extends for approximately 35 km in a northwesterly direction, orthogonal to the northeast trend of the Barberton Greenstone Belt (Fig. 2). The schist belt, which is wedged between the *c.* 3227 Ma Kaap Valley pluton in the south and the *c.* 3105 Ma Nelspruit batholith in the north (U-Pb zircon ages after Kamo and Davis, 1994), is about 8 km wide in the east and thins westward to a width of about 3 km before disappearing beneath the younger cover rocks of the Transvaal Drakensberg escarpment near Kaapsehoop. Serpentinised ultramafic rocks occur throughout the entire schist belt as a number of massive, layered complexes (e.g., Handsup-Mundt’s Concession, Hillside, Kaapsehoop, Elandshoek) or as smaller pods or irregular bodies interlayered with mafic and ultramafic as well as felsic metavolcanic and metasedimentary schists (Anhaeusser, 1969, 1972). All the rocks in the schist belt, including the ultramafic bodies, have been deformed and are folded, faulted and sheared and generally have subvertical dips. The rocks have all been affected by low-grade greenschist facies metamorphism and only rarely are remnants of the original mineralogy preserved. The rocks have also been variably affected by carbonate introduction and where sheared give rise to talc-carbonate schists. Many of the ultramafic bodies have also acted as hosts to a number of chrysotile asbestos, talc, verdite, and in some cases gold deposits.

Handsup-Mundt’s Concession Complexes

Two of the largest ultramafic bodies occur in the eastern part of the Jamestown Schist Belt. The Handsup Complex (Fig. 2.12) occurs as a massive fold immediately adjacent to a major left-lateral strike slip fault (the northwest-trending Albion Fault) and represents a disharmonic anticlinal fold structure plunging steeply to the northeast. North of the Handsup body is a major east-west-striking anticlinal fold structure known as the Mundt’s Concession Complex (Fig. 2.11). Both complexes (Fig. 6A,B) were considered by Anhaeusser (1969, 1972) to be part of the same layered intrusion prior to deformation.

The Handsup layered complex consists of at least nine cyclically repetitive units. In the lower part of the intrusion the cyclic units consist of serpentinised dunites alternating with pyroxenites, whereas higher in the succession harzburgites are prominent. Interlayered pyroxenites are dominantly websterites, but in places altered orthopyroxenites may also be present. In the upper cyclic units the amount of metagabbroic rocks accompanying the clinopyroxenite layers increases and there is a corresponding decrease in the amount of harzburgite.

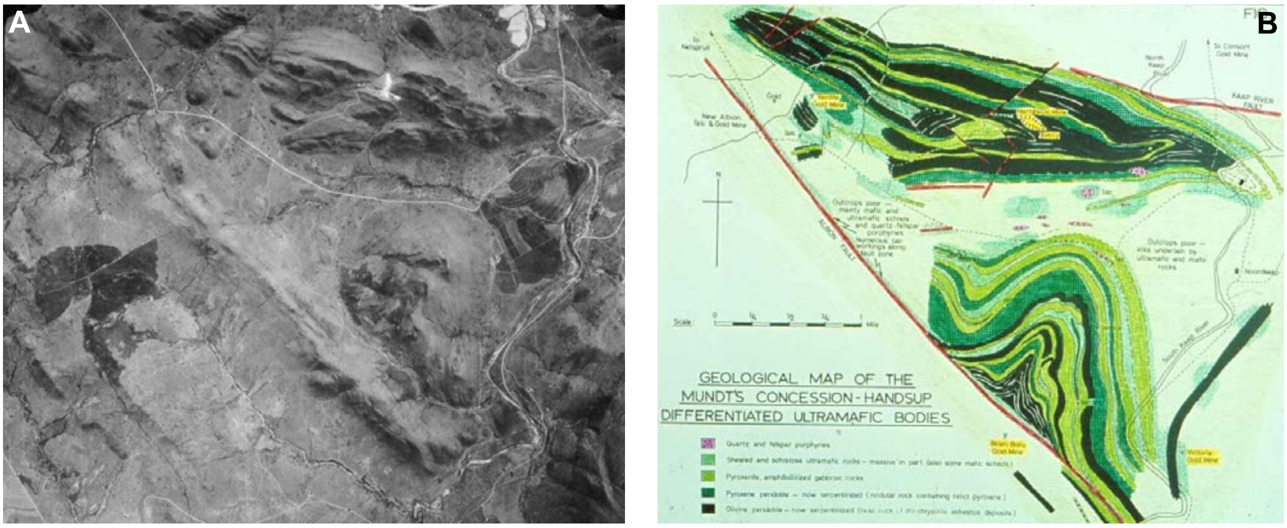

Figure 6. ***A.*** *Aerial view of the Handsup layered intrusion (disharmonic fold, lower right, produced by left-lateral detachment along the northwest-striking Albion Fault, Anhaeusser, 1972, 1984) and the Mundt's Concession layered intrusion (anticlinal fold, upper half of photograph). The two complexes are part of the same succession, but are separated by zones of shearing near the Albion Fault;* ***B.*** *Geological map of the Handsup-Mundt's Concession layered intrusions (after Anhaeusser, 1972, 1985). The layering consists of cyclically repetitive units of dunite, harzburgite, pyroxenite, and gabbro. Shearing has produced a variety of mafic and ultramafic schists in the area and small talc deposits occur adjacent to quartz-feldspar porphyry intrusives. Chrysotile asbestos, gold, and verdite have also been mined in the area shown.*

In the Mundt's Concession Complex layers of serpentinised dunite and harzburgite predominate (Fig. 7) and at least five cyclic units are terminated by clinopyroxenite or gabbro layers. In places the massive serpentinised ultramafic rocks experienced carbonate replacement (Fig. 8) and intraformational shearing resulted in the formation of mafic and ultramafic schists and "slatey serpentinites". A chrysotile asbestos deposit was mined in the core of the fold structure (Anhaeusser, 1976, 1986) and, in places, a number of semiprecious verdite deposits occur at contacts between dunite-harzburgite and pyroxenite-gabbro layers (Anhaeusser, 1972).

Figure 7. *Aerial view, looking northwest, of the Mundt's Concession layered ultramafic complex, which forms a major anticlinal fold in the eastern part of the Jamestown Schist Belt. The former Marbestos chrysotile asbestos deposit occurs in serpentinised dunite in the core of the fold structure. The North Kaap River can be seen in the top right of the picture (photograph supplied by R.P. and M.J. Viljoen).*

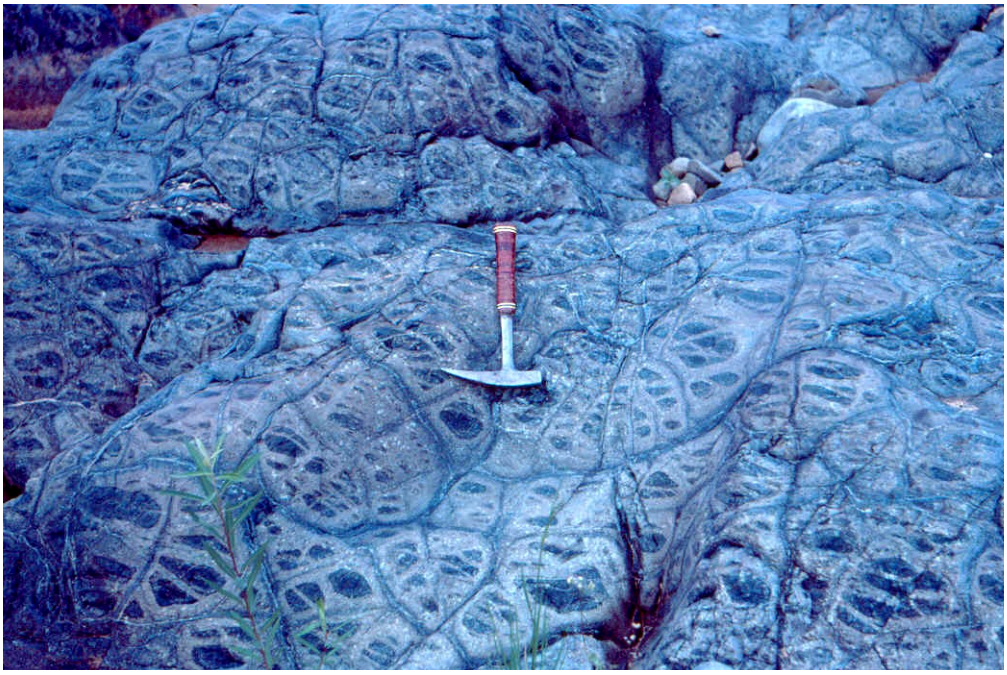

Figure 8. *Remnants of serpentinised dunite (dark colour) jointed and partly replaced by talc and carbonate (grey). Locality – northern limb of Mundt's Concession Complex in the North Kaap River, on Lots 68 and 69, near the site of the historic Jamestown mining camp.*

Hillside intrusion

The Hillside layered intrusion on the farm Hillside 459 JT, approximately in the central part of the Jamestown Schist Belt (Fig. 2.10), consists predominantly of alternating serpentinised dunite and harzburgite layers folded along a detachment fault on the northern side of the intrusion. Good exposures of the ultramafic rocks occur in the Noordkaap River, but the rocks are extensively serpentinised and replaced by carbonate. Ultramafic dykes intrude the massive serpentinites and a few verdite occurrences are present (Anhaeusser, 1972).

Kaapsehoop Complexes

The Kaapsehoop Complex is situated at the extreme western end of the Jamestown Schist Belt and disappears beneath Transvaal Supergroup cover rocks near Kaapsehoop. The succession reappears again further west in the Elands River valley, south of Elandshoek Siding, on the farm Goed Geluk 444 JT. The Kaapsehoop and Elandshoek ultramafic bodies (Fig. 2, 3-4) consist mainly of a cyclically repeated serpentinised dunite and orthopyroxenite layers that form conspicuous ridges. The rocks were previously referred to as "light green serpentinites" and "hard-blue serpentinites" (Visser *et al.,* 1956; Van Biljon, 1964; Laubscher, 1986).

The alternating serpentinised dunite-orthopyroxenite layers are best developed on the southern limb of a major fold structure that has, in turn, been disrupted by several faults which acted as local detachment or strike-slip faults (Anhaeusser, 1976). The structure, appears to be a large, dismembered syncline with an east-west fold axis, a plunge of approximately 45˚E and a southern limb dipping between 30-60˚N. The upper layers of the succession consist of metagabbroic rocks, which are also prominent on the structurally disturbed northern limb (Anhaeusser, 1976). Zones of talc-carbonate schist between the gabbroic masses, particularly prominent on the northern limb of the body, probably represent sheared and steatised ultramafic rocks of dunitic or peridotitic composition.

Differential movement between the competent orthopyroxenite layers and the serpentinised dunite resulted in the development of chrysotile asbestos fibre of exceptional quality and three asbestos mines exploited the deposits sporadically from about 1915 onwards to about 1980 (Hall, 1921,1930; Van Biljon, 1964; Laubscher, 1986). The layered complex is also noteworthy for the development of the unusual and rare lilac-coloroured mineral stichtite, which occurs exclusively in Cr-rich serpentinites (Ashwal and Cairncross, 1997).

Barclay Vale Schist Belt

Richmond Complex

The Richmond layered body, situated approximately 23 km west of Nelspruit in Mpumalanga Province at the southern edge of the Barclay Vale Schist Belt (Fig. 2.2), forms a prominent east-west trending ridge on the farm Richmond 287JT. According to Robb (1977) the body, which is about 6 km long and 150-200 m thick at its widest point, has the form of an intrusive sill, conformable with the surrounding amphibole-chlorite-talc schists. Despite being extensively altered the differentiated nature of the body is still recognisable in places. The base of the intrusion consists of serpentinised dunite (antigorite pseudomorphous after cumulate olivine crystals) overlain by a thick sequence of serpentinised dunite-harzburgite, which forms the main part of the Richmond body.

Overlying the serpentinite, and exhibiting a cross-cutting relationship with it, is a coarse-grained pyroxenite layer, the pyroxene being altered in part to amphibole. The pyroxenite layer, in turn, is overlain by an amphibolite layer regarded by Robb (1977) as altered gabbro, which caps the differentiated sequence.

Core Zone Complex

The Core Zone layered body (Fig. 2.1) occurs approximately 3 km northwest of the Richmond Complex and about 26 km west of Nelspruit on the farm Barclays Vale 288 JT. The complex occupies the core region of the Barclay Vale Schist Belt and occurs as a large synclinal structure concave to the west where it is overlain along the Transvaal Drakensberg escarpment by late Neoarchaean rocks of the Black Reef Quartzite Formation at the base of the Transvaal Supergroup. As shown by Robb (1977), the Core Zone complex consists of two bodies: (1) a lower unit of massive serpentinite approximately 300-400 m thick, underlain by banded iron formation and overlain by a sequence of chlorite and talc chlorite schists with pillow lavas preserved in places; and (2) an upper succession, approximately 1000-1750 m thick, consisting of four repetitive cycles of massive serpentinised dunite layers (antigorite pseudomorphous after cumulate olivine crystals, the latter rimmed by magnetite) alternating with uralitised metapyroxenite (mainly tremolite pseudomorphous after clinopyroxene).

The Core Zone complex differs from other layered intrusions in the Barberton region in that at least three, thin, banded iron formation units occur intraformationally within the layered bodies and separate individual serpentinite and metapyroxenite layers. This suggests that the layered body was formed as a result of successive magma injections and intruded in a sill-like manner, the main process of differentiation possibly taking place in the magma chamber prior to intrusion (Robb, 1977).

Oorschot-Weltevreden Schist Belt

Pioneer-Sawmill-Emmenes-Morgenson Complexes

The Oorschot-Weltevreden Schist Belt occurs immediately southwest of Barberton Townlands 369JU and extends for a distance of about 22 km to the southwest before linking with the northeastern sector of the Nelshoogte Schist Belt (Fig. 2). To the north the schist belt abuts against the southern margin of the KaapValley tonalite pluton which was emplaced *c.* 3227 Ma ago (U-Pb zircon age; Kamo and Davis, 1994). To the south, Fig Tree and Moodies Group sediments are in faulted contact (Moodies Fault) with the schists, the latter consisting of deformed and metamorphosed komatiites, komatiitic basalts, high-Mg and tholeiitic basalts, and minor sedimentary and mafic and felsic interlayers. Conformably emplaced into this sequence are four large, subvertically orientated ultramafic complexes (Fig. 2, 15-18), three of which (Pioneer, Sawmill, Emmenes) have been described by Wuth (1980). A number of smaller magmatic bodies, either representing separate intrusive pods or tectonically dismembered parts of larger complexes also occur throughout the area.

The Pioneer Complex, the largest of the ultramafic bodies, extends along almost the entire length of the schist belt. The inter-tongueing relationship of the greenstone schists and the intrusive bodies are either structurally controlled or a manifestation of primary igneous emplacement. Extensive carbonation of the ultramafic bodies has occurred in areas where shear zones are present and the resultant rocks are altered to quartz-carbonate-fuchsite schists.

Wuth (1980) noted that each of the bodies, although varying in proportions, contain essentially the same rock units, which he felt left little doubt that the complexes were developed in response to the differentiation of the same, or compositionally equivalent magmas under similar geological and physiochemical conditions. Wuth (1980) also demonstrated that each of the complexes consist of numerous cyclically repetitive sequences comprising, from base to top the following layers: (1) dunite and/or olivine peridotite; (2) harzburgite or pyroxene peridotite; and (3) pyroxenite and/or gabbro or anorthositic gabbro.

All the rocks in the area, including those of the layered bodies, have undergone greenschist facies metamorphism and most of the ultramafic rocks have been serpentinised resulting in the almost complete alteration of the primary mineral phases. Alteration of the mafic layers is generally not as extensive thereby enabling the primary mineralogy to be ascertained.

Serpentinised dunites constitute important components of all the layered complexes and smaller pod-like bodies. According to Wuth (1980), cumulate textures are clearly discernable with large (up to 20 mm) antigorite pseudomorphs after olivine present together with magnetite, picrolite, chrysotile, serpophite, iddingsite and chlorite ubiquitous in these rocks. Some pyroxene altered to talc, tremolite and chlorite may be present in places and secondary magnetite, carbonate, tremolite, brucite, chlorite and talc are common.

Harzburgites occur widespread throughout the complexes and again show cumulate textures with antigorite pseudomorphs after olivine, relic enstatite and orthopyroxene altered to talc, bastite, tremolite and chlorite, and magnetite and chrysotile. In parts of the Pioneer and Emmenes complexes Wuth (1980) recorded the presence of lherzolites comprising altered olivine together with ortho- and clinopyroxene, magnetite, and accessory carbonate. Orthopyroxenites occur as coarse- to medium-grained rocks in all the complexes with cumulus orthopyroxenes comprising over 80 per cent of the rock. Enstatite mantled by diopside is also present as is some minor antigorite and saussuritised plagioclase. The pyroxenes are generally altered to bastite, tremolite, chlorite and talc and secondary magnetite and carbonate are again present. Websterites (clinopyroxene-orthopyroxene rocks) were recorded by Wuth (1980) in the Sawmill Complex on the farm Hilversum 696 JT, where the 3-7 m wide unit can be traced without interruption for over 3 km. The rock, which is porphyritic, contains diopside and approximately 25 per cent enstatite phenocrysts up to 4 mm in size. The pyroxenes are generally altered to chlorite, tremolite, bastite and talc and some intercumulus plagioclase is present. Gabbro units were noted in all three complexes studied by Wuth (1980), but are most prominent in the Sawmill Complex on Sassenheim 695 JT. The gabbros are medium-and coarse-grained with amphibole, uralitised diopside, saussuritised albite-oligoclase plagioclase, and minor amounts of epidote, clinozoisite and leucoxene. Anothositic gabbro layers are developed as clearly conformable, but often discontinuous lenses in the Sawmill Complex and less commonly in the Pioneer and Emmenes bodies. The rocks consist of tremolite-actinolite altered from diopsidic pyroxene. Epidote, zoisite, clinozoisite and sericite represent the alteration products of plagioclase (now albitic). Wuth (1980) also reported the presence of rodingite dykes in both the Sawmill and Pioneer complexes. These rocks are similar in most respects to the rodingitic rocks reported by Anhaeusser (1978) in the Stolzburg Complex. In addition Wuth (1980) recognised conformable layers of unusual “slaty serpentinites” in all the complexes southwest of Barberton. These are similar to those recorded in the Jamestown Schist

Belt by Anhaeusser (1969, 1972) who considered them to possibly represent sheared and schistose pyroxenites and gabbros in the deformed layered bodies.

Kalkkloof Schist Belt

Kalkkloof Complex

The Kalkkloof Complex occurs in an Archaean greenstone enclave (Kalkkloof Schist Belt) situated approximately 10 km north of Badplaas (Fig. 2.14), and is separated from the Nelshoogte Schist Belt in the Barberton Greenstone Belt 15 km to the east by trondhjemitic gneisses of the Nelshoogte pluton (dated at *c.* 3236 Ma; U-Pb zircon age - De Ronde and Kamo, 2000). Late Neoarchaean sedimentary rocks of the Transvaal Supergroup cover parts of the Kalkloof ultramafic body, which is best exposed over a distance of about 5 km on the farm Kalkkloof 706 JT in valleys incised into the Transvaal Drakensberg escarpment in the upper drainage system of the Komati River. The complex as a whole is, however, exposed sporadically over a total north-south distance of about 10 km, is in faulted contact with siliceous schists and chert on its eastern flank, dips at between 50-60˚ to the west, and has a maximum width of exposure of about 1.5 km. Menell *et al.* (1986) noted that the Kalkkloof layered body consists of at least two major cycles of alternating serpentinised dunite and orthopyroxenite layers together with interlayers of pure and impure talc schist. The succession, they believed, youngs to the west and the entire complex is heavily tectonised and the original cumulate mineralogy (olivine, orthopyroxene, clinopyroxene) has undergone extensive alteration (serpentinisation), including CO_2, Mg and SiO_2 metasomatism.

The Kalkkloof layered ultramafic complex is host to at least six chrysotile asbestos ore bodies which were mined between 1928 and 1977. According to Menell *et al*. (1986) the layered body has many similarities with other layered bodies in the Barberton Greenstone Belt, particularly the Stolzburg Complex in the Nelshoogte Schist Belt described by Anhaeusser (1976, 1986, 1999) and the Kaapsehoop complex in the Jamestown Schist Belt described by Hall (1921, 1930) and Laubscher (1986). Additional support for this contention lies in the fact that only the Kalkkloof and Kaapsehoop bodies are known to host the rare lilac-coloured mineral stichtite, a factor supporting the view that the Jamestown Schist Belt was originally positioned immediately adjacent to and parallel with the Barberton Greenstone Belt and was later forced northwards following the intrusion of the Kaap Valley tonalite pluton (Anhaeusser, 1969, 2002).

Nelshoogte Schist Belt

Stolzburg Complex

The Stolzburg layered ultramafic complex (Fig. 9), located in the Nelshoogte Schist Belt, in the extreme southwestern portion of the Barberton Greenstone Belt (Fig. 2.19), represents one of the best-preserved Archaean ultramafic complexes in the world (Anhaeusser, 1976, 1985, 2001; De Wit *et al*., 1987; Rodel, 1993). The complex is fault bounded, is exposed over a strike length of about 14 km, is approximately 1.2 km thick, has a subvertical attitude, and youngs from northwest to southeast. Anhaeusser (1979, 2001) subdivided the complex into a Lower Division consisting upwards of six cyclic units, each cyclic unit consisting mainly of cumulate dunite and orthopyroxenite rock types (Figs. 10-12), and an Upper Division consisting of a further ten or more cyclic units The Upper Division cyclic units consist of various combinations of dunite, harzburgite, lherzolite, wehrlite, pyroxenite, gabbro and gabbroic anorthositic rock types (Fig. 11). A calcium-metasomatised zone made up of rodingites, clinopyroxenites, gabbros and anorthositic gabbros separates the Lower Divison from rocks of the Upper Division.

Figure 9. *View, looking north, of the Stolzburg layered ultramafic complex in the Nelshoogte Schist Belt. The complex, which youngs from northwest (left) to southeast (right), is bounded by major faults that occur in the two valleys shown. The resistant ridges shown consist of orthopyroxenite layers, which alternate with less resistant dunites layers.*

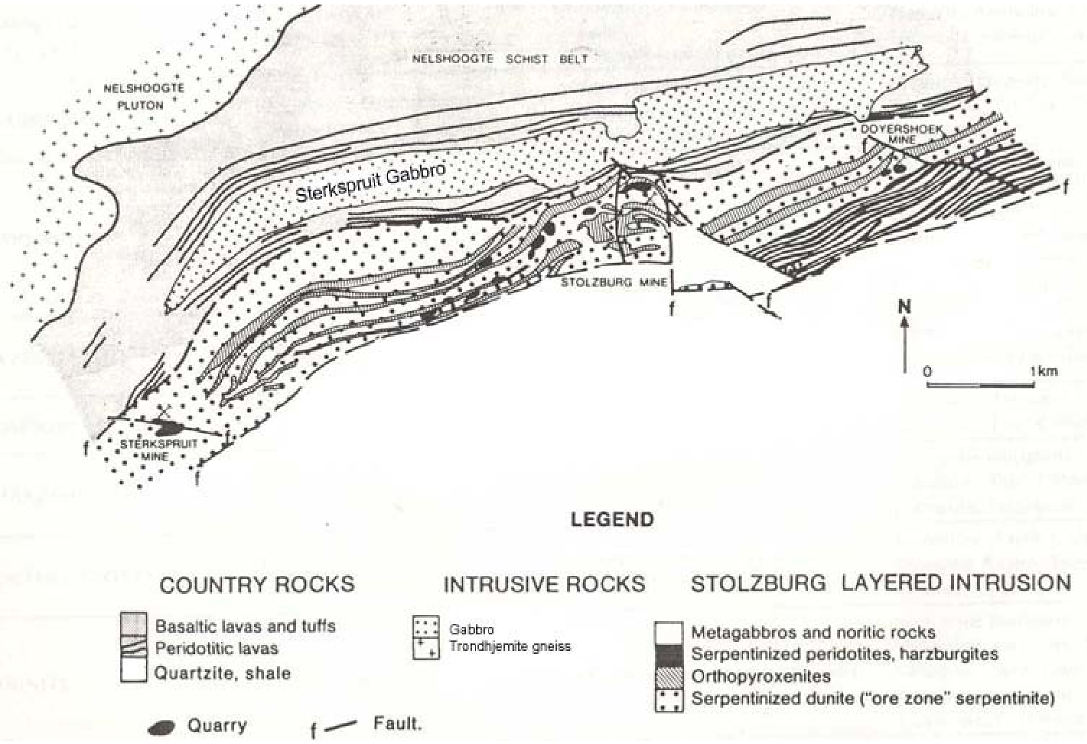

Figure 10. *Simplified geological map of the Stolzburg layered ultramafic complex showing the cyclically repetitive, subvertically dipping, differentiated sequence, which youngs to the southeast. Lower Division cyclic units consist of dunite and orthopyroxenite layers (see Figs. 11 and 12A), whereas the cyclic units in the Upper Division consist of dunite-harzburgite, websterite, gabbro and anorthositic gabbro-norite.*

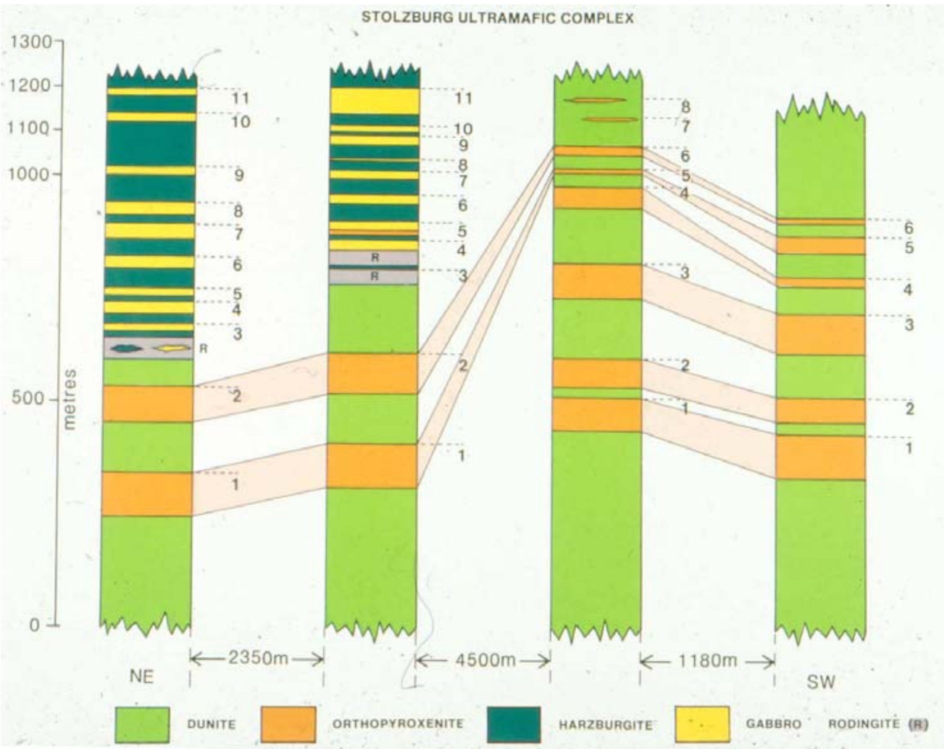

Figure 11. *Stratigraphic columns across various parts of the Stolzburg layered complex. The southwestern sections are dominated by alternating Lower Divison dunite-orthopyroxenite cycles like those shown in Figs. 9 and 12A. The sections to the northeast show Upper Division rocks characterised by cyclical units terminated by gabbro or gabbro-norite-anorthosite layers. A zone of Ca-metasomatised rocks (R = rodingites) separates the two divisions. Numbers refer to separate cyclic units.*

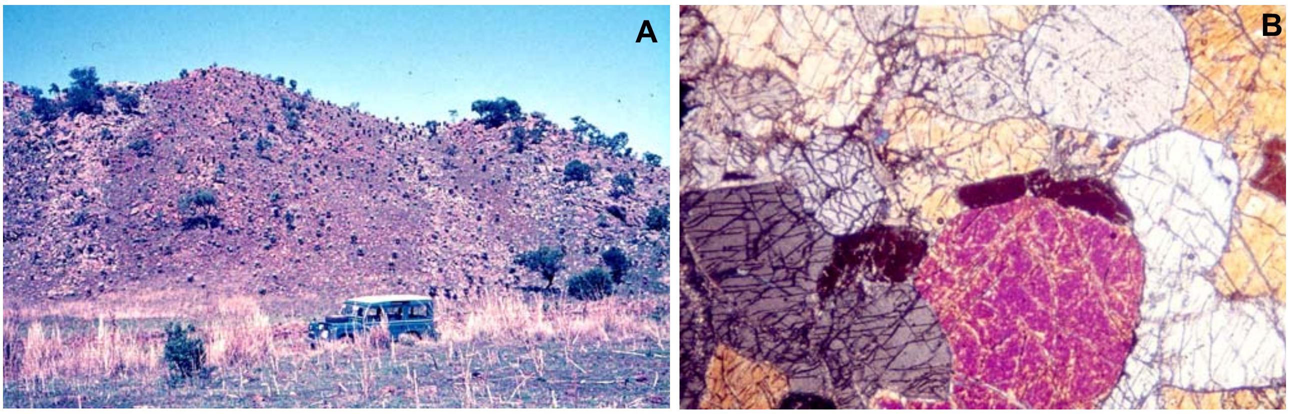

Figure 12. *A.* *View, looking south, showing Lower Division cyclical units consisting of dunite (grey) and orthopyroxenite (reddish brown) from the area located midway between the Sterkspruit and Stolzburg mines. The sequence shown youngs from northwest (right) to southeast (left);* ***B.*** *Photomicrograph of euhedral cumulus orthopyroxene (enstatite-bronzite) with minor intercumulus plagioclase. The orthopyroxenites are rarely as fresh as the example shown, but are usually partially altered (steatised) to talc and bastite. Locality – sample from area shown in Fig.12A. Some of the larger crystals shown exceed 2 mm in cross section. Crossed nicols.*

The dunite layers of the Lower Division vary in thickness up to about 480 m and act as host rocks to three chrysotile asbestos deposits in the complex, whereas the orthopyroxenite layers extend up to 120 m in thickness (Fig. 11). A thin chromitite seam (20-30 cm thick), traceable for about 10 m, was noted in the orthopyroxenites south of the Sterkspruit Mine (De Wit and Tredoux, 1988). The orthopyroxenites in places form prominent resistant ridges in contrast to the serpentinised dunites, which commonly have negative relief (Fig. 9). In the field the weathered serpentinised dunites tend to be grey or yellowish-green (“ore-zone serpentinites”), whereas the orthopyroxenites have a conspicuous reddish-brown colour (Fig. 12 A).

The dunites and orthopyroxenites have cumulate textures and consist of coarse-grained (1-10 mm), essentially monomineralic phases of olivine and enstatite-bronzite, respectively, the former possessing minor amounts of intercumulus orthopyroxene and chromite and the latter displaying some chromite and intercumulus plagioclase and clinopyroxene (Anhaeusser, 1985, 2001; Rodel, 1993). Pervasive serpentinisation of the dunites has produced serpentine minerals (chrysotile, antigorite, iddingsite) and caused the release of iron from olivine, which concentrates as magnetite rimming antigorite pseudomorphs after olivine, or in veins and shear zones in the altered dunite. In places the orthopyroxenites are exceptionally fresh (Fig. 12B) and have a waxy lustre. In most cases, however, the rocks have been steatised and are variably altered to talc, tremolite or bastite. Microprobe data obtained by Rodel (1993) showed the composition of the orthopyroxene to be enstatite-bronzite (En_{89-87}) and the intercumulus clinopyroxene is diopsidic and is altered to actinolite in places.

The rocks of the cyclic units in the Upper Division consist mainly of harzburgite with lesser amounts of dunite, lherzolite, wehrlite, olivine peridotite, olivine websterite, websterite, feldspathic websterite, gabbro, anorthositic gabbro-norite and anorthosite (Anhaeusser, 1985, 2001; Rodel, 1993). These rocks show varying degrees of alteration and are similar to examples already described from other Barberton layered complexes. The harzburgites, which consist of olivine, orthopyroxene and accessory chromite, and which have a nodular texture in places (Fig. 13A), commonly display a well-developed poikilitic texture with rounded olivine crystals encased in orthopyroxene oikocrysts (Fig. 13B). Differing combinations of olivine, orthopyroxene and clinpyroxene account for the compositional variations of most of the ultramafic rock types in the lower parts of cyclic units, while relative abundances of plagioclase and clinopyroxene account for the variations in the upper parts of cyclic units. Heterogeneous gabbroic rock types predominate in the upper parts of cyclic units and consist of varying proportions of 1-4 mm long diopside crystals that have invariably been uralitised to tremolite-actinolite. Plagioclase occurs mostly as an intercumulus phase, but small (0.5-1 mm) cumulus phases were also noted (Rodel, 1993). The originally calcic plagioclase has been albitised and saussuritisation of the feldspar to zoisite and epidote is common. Fine-scale or “inch-scale layering” of the gabbros (Fig. 14A) was noted in the vicinity of the Doyershoek asbestos mine. The layers of gabbro or gabbro-norite alternate with anorthositic layers rich in albitic plagioclase and lesser amounts of diopsidic pyroxene (Fig. 14B).

A zone of Ca-metasomatised gabbroic rocks intervenes between the Lower and Upper Division successions in the northeast segment of the Stolzburg Complex and consists of garnetised gabbros and websterites and rodingite dykes in the dunite (Anhaeusser, 1979; Rodel, 1993). The rodingites consist of a complex and diverse variety of calcium-aluminium silicates, including hydrogrossular, vesuvianite, nephrite, hibschite, diopside, prehnite, zoisite and many others. Anhaeusser (1979) was of the opinion that Ca-rich fluids, released from Ca-rich plagioclases and pyroxenes during serpentinisation and other forms of mineral alteration already described, caused widespread, but patchy replacement of mainly gabbroic rock types in the Complex.

Petrological studies have shown that the crystallisation order common to most of the Barberton layered complexes was olivine, followed by orthopyroxene (enstatite-bronzite), clinopyroxene (diopside), and calcic plagioclase (labradorite-bytownite-anorthite). Bulk compositional calculations carried out on the Stolzburg Complex as a whole (Anhaeusser, 1985, 2001) as well as on rocks believed to be from a chill contact west of the Stolzburg Mine (Rodel, 1993), confirmed the high MgO (± 28%) content of the bulk magma which was doubtless of komatiitic as opposed to tholeiitic parentage.

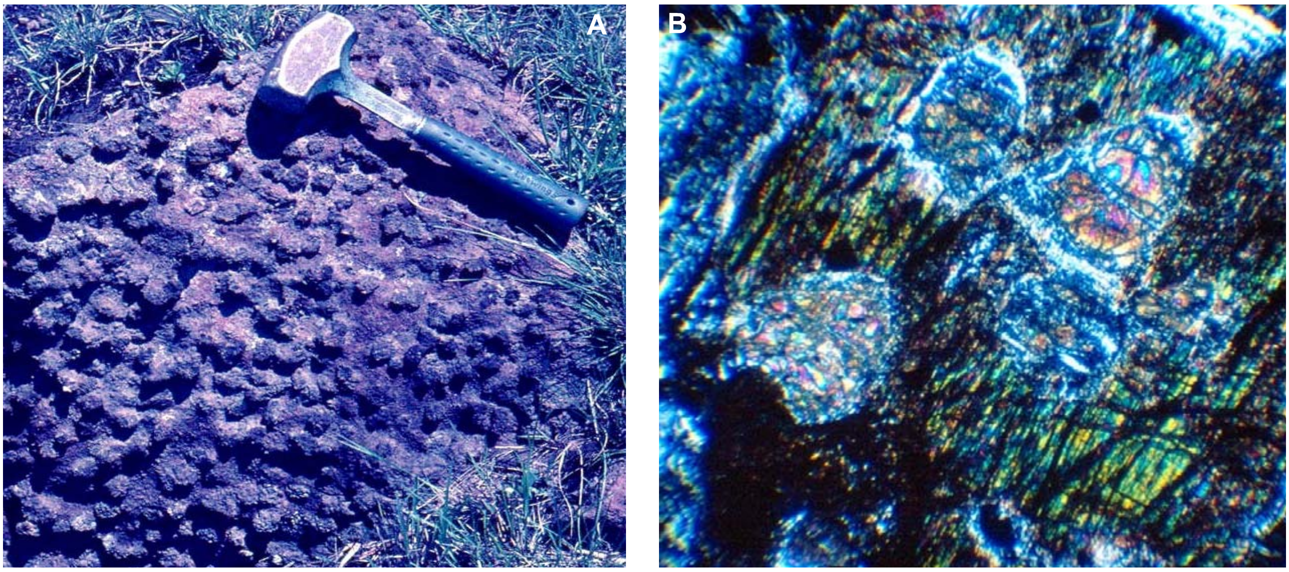

Figure 13. ***A.*** *Upper Division nodular harzburgite from the area between the Stolzburg and Doyershoek asbestos mines. The positively weathering nodules consist of partially altered cumulate olivine and orthopyroxene crystals with some intercumulus clinopyroxene. The negatively weathered areas consist mainly of serpentine (antigorite, chrysotile), talc and bastite;* ***B.*** *Photomicrograph from a harzburgite nodule showing rounded, partly serpentinised olivine crystals poikilitically enclosed by orthopyroxene that is, in turn, partly altered to bastite. Secondary magnetite, chlorite and carbonate occurs in minor amounts. The olivine crystals average 0.5 mm in diameter. Crossed nicols.*

Figure 14. ***A.*** *Alternating anorthositic and gabbro-norite layers ("inch-scale layering") from the Upper Division of the Stolzburg Complex southeast of the Doyershoek asbestos mine;* ***B.*** *Photomicrograph of partially sericitised crystals of cumulus plagioclase (labradorite-bytownite) and clinopyroxene (diopside) from a plagioclase-rich "inch scale" anorthositic layer similar to that shown in Fig. 14A. The plagioclase crystals shown average approximately 0.5 mm in length. Crossed nicols.*

Sterkspruit Gabbro intrusion

The Sterkspruit intrusion, situated in the Nelshoogte Schist Belt in the southwestern portion of the Barberton Greenstone Belt (Fig. 2.20), is a sill-like body containing rocks of gabbroic to dioritic composition (Conway, 1997). The intrusion, which has a subvertical orientation, differs from others in the Barberton region, including the Stolzburg Complex located less than 300 m to the southeast (Anhaeusser, 2001), in that it lacks ultramafic components and has no affinities with the surrounding mafic and ultramafic lavas of the Onverwacht Group. The Sterkspruit body is elongated in a ENE-WSW direction, parallel to the adjacent Stolzburg body, is generally conformable with the surrounding ultramafic-mafic metavolcanic rocks, and measures approximately 8 km in length and averages about 500 m in width. The sill-like nature of the intrusion, indicated by geochemical trends and the steep subvertical layering seen in places (Fig. 15), suggest the body has been tilted along with the surrounding metavolcanic rocks.

Figure 15. *Subvertical layering seen in a river section crossing the Sterkspruit gabbro body north of the Stolzburg asbestos mine. Mineralogically, the gabbro/diorite suite, which is extensively altered, contains actinolite, chlorite, epidote, zoisite, albite, leucoxene and minor quartz. The darker layers contain mainly uralitised pyroxene, actinolite, chlorite, ilmenite-leucoxene and minor plagioclase.*

Conway (1997) noted that the Sterkspruit gabbroic suite contains an unusual abundance of quartz and the chill margin shows an evolved quartz-normative, tholeiitic parental magma. He subdivided the intrusion into four gabbroic zones and a zone of quartz diorite, regarded as the end product of a differentiating magma. The basal portion of the body, on the northwestern side of the intrusion, has a 2 m-thick chill zone and the quartz diorite zone, which is less than 50 m thick, occurs roughly in the centre of the body.

The gabbro/diorite suite is extensively altered, with the ortho- and clinopyroxenes partly or completely uralitised and the plagioclase having undergone varying degrees of saussuritisation, albitisation, epidotisation and sericitisation. The main minerals in the gabbros include actinolite, chlorite, epidote, zoisite, albite and leucoxene. Some pyroxenes are preserved in the marginal and lower zones and the quartz diorite has less altered plagioclase and quartz in roughly equal amounts, uralitised clinopyroxene, chlorite, carbonate and epidote, and minor biotite, ilmenite and leucoxene.

Geochemically, Conway (1997) demonstrated that calculations of the bulk composition of the main gabbro body correlated well with the chill margin composition, thereby supporting the tholeiitic magma parentage of the intrusion and contrasting it with the ultramafic (komatiitic) parental magma composition determined by Anhaeusser (1985) for the neighbouring Stolzburg Complex.

The age of the Sterkspruit intrusion has not been determined directly. It is cut by numerous, undeformed and unmetamorphosed, essentially northwest-trending mafic dykes, believed to be predominantly of Mesoarchaean to Palaeoproterozoic age, emplaced between *c.* 3000 and 1876 Ma (Hunter and Halls, 1992; Layer *et al*., 1998). However, the fact that the Sterkspruit body is sill-like and steeply tilted with the surrounding lavas, the latter, in turn, having been deformed by the *c.* 3236 Ma Nelshoogte pluton (De Ronde and Kamo, 2000) and the *c.* 3227 Ma Kaap Valley pluton (Kamo and Davis, 1994), suggests that the gabbroic body may have formed earlier. Conway (1997) proposed that the Sterkspruit gabbro might conceivably represent a magma having formed in a subvolcanic magma chamber which could possibly have acted as a feeder to tholeiitic lavas higher up in the Onverwacht volcanic sequence, such as the *c.* 3334 Ma Kromberg Formation (Byerly *et al.*, 1996).

Areas south and southeast of Barberton

Rosentuin Complex

The Rosentuin Complex is situated in Mpumalanga Province, about 35 km southeast of Badplaas (Fig. 2.24), and falls mainly within the confines of the Songimvelo Nature Reserve, where it occurs south of the Komati River. The intrusion was first described by Viljoen and Viljoen (1969), who found the complex to be a concordant, magmatically segregated, sill-like body, interlayered with volcanic rocks of the Hooggenoeg Formation of the Upper Onverwacht Group (Geluk Subgroup). They divided the Rosentuin Complex into a lower peridotitic zone, consisting of serpentinised dunite, wehrlite or lherzolite, overlying a footwall succession consisting of silicified and pillowed metatholeiites capped by thin, discontinuous, banded black and white chert. The upper pyroxenitic zone consists of porphyritic websterite, which is overlain by a 20 m-thick carbonated agglomeratic breccia, followed by thin silicified mafic volcanic rocks and grey-green chert. The layered succession has been traced over a strike length of 11 km and is approximately 176 m thick, with the rocks dipping steeply to the southeast - this being also the direction of younging of the complex.

Petrological and geochemical studies carried out on two boreholes drilled into the complex by Gold Fields of South Africa Limited, led to a more detailed subdivision of the intrusion into a lower peridotitic zone, an upper pyroxenitic zone and an upper peridotitic zone (Rodel, 1993).

The ***lower peridotitic zone*** is approximately 90 m thick and consist of serpentinised lherzolite, dunite and wehrlite. A thin unit (3.7 m) of massive lherzolite forms the base of the lower peridotitic zone and is in sharp contact with the footwall rocks. Overlying the lherzolite is a 40 m-thick serpentinised dunite unit, the latter cut by a 3 m-thick, deformed rodingite dyke. The dunite unit grades upwards into an approximately 50 m-thick wehrlite unit, which forms the upper portion of the lower peridotitic zone. The wehrlite has a mottled appearance caused by serpentinised olivine surrounded by clinopyroxene oikocrysts, the poikilitic texture being better developed towards the top of the wehrlite unit due to an increase upwards in the proportion of pyroxene relative to olivine.

The ***upper pyroxenitic zone*** is in sharp contact with the lower zone, is over 40 m thick, and consists of at least three cyclically repetitive units of (1) porphyritic to massive olivine websterite, in places with phenocrysts of orthopyroxene; (2) porphyritic websterite with orthopyroxene phenocrysts; and (3) feldspathic websterites, which are also porphyritic and contain orthopyroxene phenocrysts set in a finer-grained matrix.

The *upper peridotitic zone* is 30 m thick and caps the pyroxenitic zone forming the uppermost unit in the Rosentuin Complex. The peridotite, overlain by brecciated and carbonated talc schist in the hanging wall, is a very fine-grained, massive rock with numerous serpentine-bearing veins.

Rodel (1993) noted that serpentinisation has been the main alteration process affecting the ultramafic rocks of the intrusion, but also includes steatisation and carbonation. The mafic components have been affected by calcium metasomatism (rodingitisation), uralitisation, saussuritisation, epidotisation and albitisation.

Mineralogical studies showed that the lherzolites encountered near the base of the Rosentuin Complex consist of olivine (~85%) with subordinate ortho- and clinopyroxene, magnetite, and veins of chrysotile (Rodel, 1993). The overlying serpentinised dunites have been altered such that no relic olivine has been preserved and the rocks now consist of antigorite pseudomorphs after olivine, chrysotile, magnetite and iddingsite. Intercumulus oikocrystic clinopyroxene enclosing some of the olivine gives the dunite a poikilitic texture in places and has almost entirely been replaced by serpophite, chlorite and tremolite. The wehrlites are medium-grained orthocumulates that originally consisted of cumulus olivine poikilitically enclosed in clinopyroxene. The rocks are now almost totally altered to antigorite, tremolite, magnetite, iddingsite and chlorite. The olivine websterites contain approximately 10-30% olivine, 10-30% orthopyroxene and 40-70%

clinopyroxene. According to Rodel (1993) the primary mineralogy has been overprinted due to the effects of serpentinisation, uralitisation and steatisation producing alteration minerals antigorite, iddingsite, hornblende, chlorite, bastite, talc, magnetite and chromite. The websterites typically consist of varying amounts of cumulus clinopyroxene (~60-80%) and orthopyroxene (~15-40%) with subordinate intercumulus plagioclase (<5%). In some rocks clinopyroxene is the only phase present and Rodel (1993) referred to these rocks as diopsidites or clinopyroxenites. The clinopyroxene is generally altered to tremolite-actinolite, the orthopyroxene to bastite, chlotite and talc, and the plagioclase to epidote. The feldspathic websterites, which have a porphyritic texture, occur only in the upper pyroxenitic zone and consist of clinopyroxene (~60%), altered to tremolite; orthopyroxene (~15-20%), altered to chlotite, tremolite and talc; and plagioclase (~5-25% albite), altered to zoisite, clinozoisite and epidote.

Fine-grained olivine peridotites occur in the upper peridotitic zone and consist of antigorite pseudomorphs of cumulus olivine, secondary magnetite, intercumulus clinopyroxene largely replaced by tremolite, and calcite veining.

Rodel (1993) also recorded the presence of an anorthosite vein as well as a rodingite vein in the Rosentuin dunites. The anorthosite consists of about 70% cumulus plagioclase with the remaining 30% being intercumulus. The cumulus phase has been little altered relative to the intercumulus phase which is extensively saussuritised to epidote and clinozoisite. Unlike the rodingite dykes in the Stolzburg Complex (Anhaeusser, 1979), the calcium-bearing minerals of the Rosentuin rodingite are dispersed throughout the serpentinite and include hydrogrossular garnet, vesuvianite and diopside (Rodel, 1993).

Calculation of the bulk geochemical composition of the Rosentuin body led Rodel (1993) to conclude that it is comparable with that of other layered ultramafic complexes in the Barberton region and that the parent magma was considerably more ultramafic (viz., komatiitic parent magma - see Viljoen and Viljoen, 1970; Anhaeusser, 1985) than that recorded for most other igneous intrusions worldwide, including the Bushveld Complex, which have basaltic- to tholeiitic-basalt parental magma compositions.

Attempts made by Rodel (1993) to date the Rosentuin body using the Sm/Nd isotopic technique proved to be inconclusive, although the results obtained were consistent with crystallisation at *c.* 3454 Ma. This accords well with the U-Pb zircon ages of *c.* 3470 - 3454 Ma obtained by Armstrong *et al*. (1990) and Kamo and Davis (1994) for the Komati Formation, which directly underlies the Hooggenoeg Formation hosting the Rosentuin Complex.

Msauli-Havelock Complexes (Barberton-Swaziland area)

A sill-like serpentinised ultramafic body, over 4 km in length and about 200 m thick, is associated with talc-carbonate schists and chert of the upper Onverwacht Group, on the farm Diepgezet 388 JU, approximately 24 km south of Barberton. Despite intense folding and faulting the same serpentinite body can be traced intermittently for an additional 7 km northeastwards into Swaziland. Two of the largest chrysotile asbestos deposits in southern Africa (viz., the Msauli Mine in South Africa - Büttner, 1984; Voight *et al*., 1986, and the Havelock Mine in Swaziland - Barton, 1982, 1986) appear to be associated with the same serpentinite body.

The Msauli ultramafic body (Fig. 2.25) occurs as an approximately conformable layer dipping steeply (~ 70˚) to the ESE (Büttner, 1984) and consists of cumulus dunite (ore zone serpentinite) with the olivine grains now completely pseudomorphed by lizardite, chrysotile and minor antigorite. Magnetite, chromite, heazlewoodite, chlorite, magnesite and secondary brucite were also noted.

The serpentinised dunites are underlain by a footwall alteration zone consisting of chlorite-talc-carbonate rocks and talc-carbonate schists and are overlain by metapyroxenites, metagabbros and rodingites. Büttner (1984) was of the opinion that the Msauli body was emplaced either as a shallow sill-like intrusion or as a differentiated submarine ultramafic lava flow that, in turn, was subsequently intruded by felsic porphyry bodies.

The Havelock ultramafic body (Fig. 2.22) consists of serpentinised dunite-harzburgite with olivine, orthopyroxene, chromite and minor clinopyroxene being the original magmatic cumulate protolith phases (Barton, 1986). The primary serpentinite assemblage consists of lizardite-chrysotile-brucite-magnesite with minor antigorite. Rodingites occur as discontinuous lenses along the faulted southern contact of the serpentinite and the calcium-rich mineralogy is consistent with Ca-metasomatism during serpentinisation. Internal mineralogical variations within the Havelock body are conspicuously lacking, there are no compositional layers or gabbroic lithologies, and the transition from dunite to harzburgite is a progressive change in composition, consistent with fractional crystallisation in a layered intrusion.

The ultramafic body, which has been intensely deformed, is in tectonic contact with footwall banded iron formations and hanging wall amphibolite and chert with a volcaniclastic texture. Structural relations and the absence of mafic differentiates led Barton (1986) to suggest that the Havelock body was not emplaced into its present position by magmatic processes, but was rather intruded as a result of tectonic activity. The suggestion by Viljoen and Viljoen (1969b, c) and Büttner (1984) that the Havelock body represents a fragment of a sill may be correct, but Barton (1986) disputed the contention that the serpentinite body occupies a stratigraphic position, suggesting rather that it was emplaced along fractures as a solid body.

Dunbar serpentinite and pyroxenite pods

Poorly exposed ultramafic intrusive rocks occur approximately 21 km due south of Barberton (Fig. 2.23) on the farms Dunbar 383 JU and Josefsdal 382 JU (Visser *et al*., 1955, 1956), where they occupy the floor of the Dunbar and Manzima valleys. According to Visser *et al.* (1956), one large and several smaller, irregular-shaped bodies of serpentinite intrude Fig Tree shale. Paris (1984) found these rocks to be highly sheared and slickensided and developed in small pods. Also noted were pyroxenites consisting almost entirely of clinopyroxene.

Granville Grove serpentinites

Approximately 19 km SSW of Barberton (Fig. 2.21), on the farm Granville Grove 720 JT, Visser *et al*. (1955, 1956) recorded a serpentinite mass intruded into upper Onverwacht felsic lavas. No details are available for this body, which is referred to as the Granville Grove intrusion.

ULTRAMAFIC-MAFIC COMPLEXES ON THE JOHANNESBURG DOME

Studies on the Johannesburg Dome (Fig. 1.2) have led to the recognition of a variety of Archaean granitoid rocks (Anhaeusser, 1973, 1999) and a suite of ultramafic and mafic rocks analogous to the komatiitic lavas and layered ultramafic complexes found in the Barberton Greenstone Belt (Anhaeusser, 1977, 1978, 1985, 1992). U-Pb zircon dating has yielded ages of *c*. 3340 Ma for trondhjemitic gneisses on the northern half of the dome, an age of *c*. 3201 Ma for tonalitic gneisses on the southern rim, and ages ranging between *c.* 3121 and 2947 Ma for K-enriched granodiorites and pegmatites in the south-central parts of the dome (Poujol and Anhaeusser, 2001).

The ultramafic-mafic rocks are exposed intermittently within a WNW-ESE - trending zone across the southern portion of the Johannesburg Dome (Fig. 16), extending from beyond Muldersdrif in the west (Anhaeusser, 1977, 1978) to the Edenvale-Kempton Park area in the east (Anhaeusser, 1973; Chaumba, 1992) - a distance of approximately 50 km. Brief accounts are provided below of each of the complexes as they occur across the dome. From west to east they include the Muldersdrif, Roodekrans, Zandspruit, Cresta-Robindale and Edenvale-Modderfontein complexes.

The principal rock types in these ultramafic complexes include serpentinised dunite, harzburgite, lherzolite, ortho- and clinopyroxene and gabbro. In a manner similar to that envisaged for the Barberton region, and described earlier, it has been suggested that these complexes may represent slivers of upper mantle or oceanic lithosphere (ophiolites), preserved in a collisional or suture zone, separating ancient continental masses in a manner similar to that depicted in Phanerozoic collisional tectonic models (Anhaeusser, 2004). In the region being considered here, one such continental mass may be represented by the *c.* 3340 Ma gneissic and migmatitic terrane on northern half of the Johannesburg Dome, with the southern mass largely hidden from view beneath the Witwatersrand Basin. Arguably, the basement gneisses and migmatites of the Vredefort Dome may constitute remnants of this southern continental terrane. The collisional event, in turn, may correspond with the emplacement, at *c.* 3201 Ma, of hornblende-tonalite gneisses intruded into and fragmenting the ultramafic-mafic complexes along the collisional suture zone.

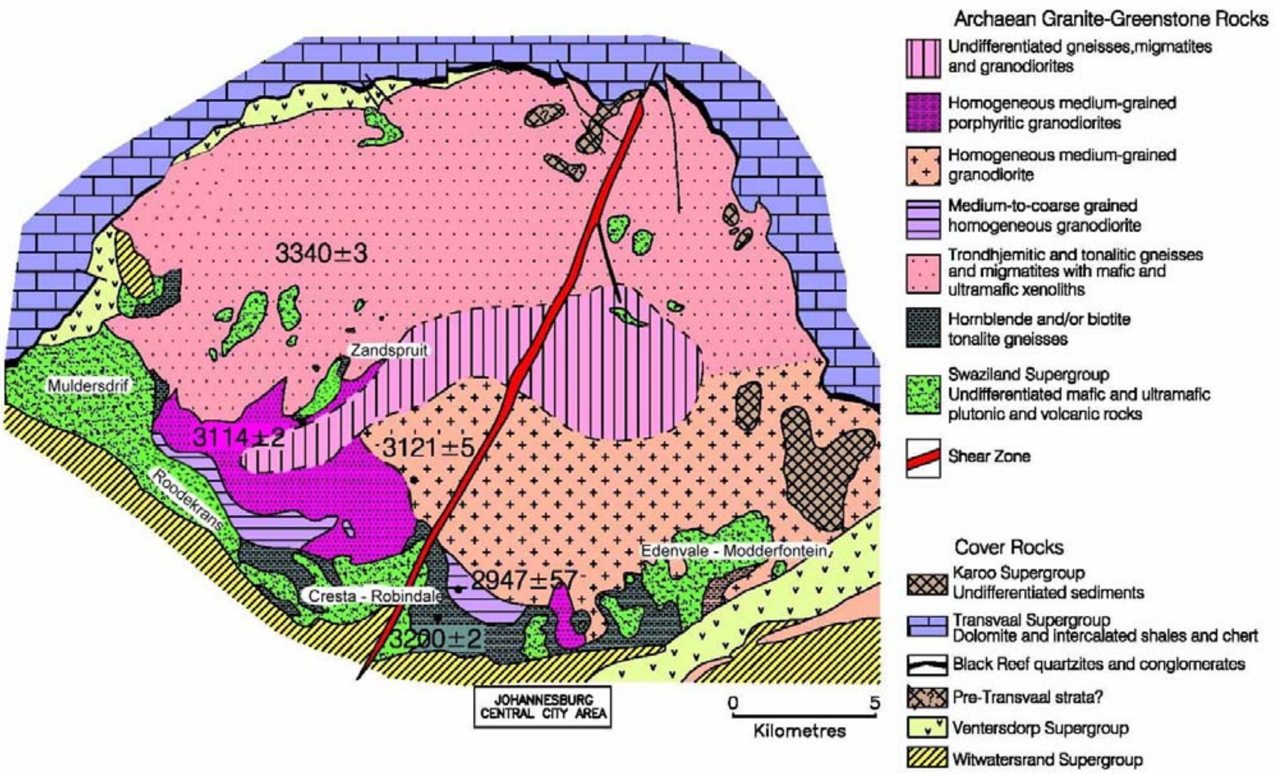

Figure 16. *Simplified geological map of the Johannesburg Dome showing the location of the Muldersdrif, Roodekrans, Zandspruit, Cresta-Robindale and Edenvale-Modderfontein layered ultramafic complexes developed in a zone extending from west to east across the southern margin of the Dome. The various intrusive Archaean granitoid rocks and their ages are also shown in millions of years (map modified after Anhaeusser, 1973).*

Muldersdrif Complex

The Muldersdrif Ultramafic Complex (Anhaeusser, 1978) is located in an Archaean greenstone remnant situated on the western edge of the Johannesburg Dome, approximately 30 km northwest of the Johannesburg City Centre (Fig. 16). The complex is hosted within poorly exposed mafic and ultramafic lavas, the former displaying spherulitic pillow structures in places and being compositionally similar to the komatiitic basalts found in the Barberton Greenstone Belt.

The Muldersdrif ultramafic body occupies an area of about 10 km^2 and is topographically relatively flat-lying in the south, except for a few low hills and ridges of serpentinite. The central and northern parts of the complex consist of a series of prominent ridges and intervening valleys which trend approximately west-northwest across the area (Fig. 17). Archaean porphyritic granodiorites intrude the complex in the south, east and north and Ventersdorp and Transvaal Supergroup rocks overly the complex in the northwest and west, respectively.

Ultramafic rocks, all of which have been extensively altered to serpentinites and various amphibole, chlorite and talc schists, make up the bulk of the layered body. Subordinate, but important marker horizons comprise thin, fine- to medium-grained, metagabbroic layers, many of which are less than one metre thick.

Figure 17. *Aerial photograph, looking west, of part of the Muldersdrif layered ultramafic complex northwest of Johannesburg. The layered body consists predominantly of serpentinised dunite and harzburgite together with pyroxenites and minor gabbro layers, which occur at the tops of cyclic units. Small chrysotile asbestos deposits occur in the serpentinised dunite.*

An unknown number of cyclic units, each commencing with a variety of serpentinised ultramafic rocks and terminating with metagabbro occur widely throughout the complex. Despite being serpentinised original cumulate textures are commonly preserved in rocks that were originally dunites, harzburgites and pyroxenites.

The dunites, which are olive-green to greenish-grey in colour, and in places strongly deformed (Anhaeusser, 1978, fig.7), consist of antigorite, talc, tremolite, chlorite, chrysotile, picrolite, brucite and magnetite as well as the olivine alteration products serpophite and iddingsite. Generally, the olivine has not survived the effects of alteration and is totally pseudomorphed by antigorite. Locally, some opal and chalcedony occur in the deformed and differentially weathered dunites. The harzburgitic rocks (probably also including lherzolites and wehrlites) consist of antigorite pseudomorphous after olivine, together with bastite and talc, both of which are pseudomorphous after large cumulate pyroxene crystals. The pyroxenes are almost totally altered, but relic orthopyroxene (enstatite, bronzite) and clinopyroxene (diopside) were found in places, the orthopyroxenes being the most abundant. Trace element quantities of Ni (~ 2760-2860 ppm) and Cr (~ 2190-2230 ppm) were recorded in the dunite/harzburgite (Anhaeusser, 1978).

Serpentinised pyroxenites form most of the resistant, west-northwestly striking ridges that cross the central and northern parts of the complex. The pyroxenites (both ortho- and clinopyroxenites) vary in colour from grey-green to blue-black and can be distinguished in places from the other serpentinized ultramafic rocks by the presence of large cumulate pyroxenes that are almost invariably pseudomorphed by bastite, hornblende or talc. Antigorite occurs interstitial to the altered pyroxenes and accessory magnetite (± chromite) may also be present. Relatively high trace element abundances of Cr (~ 4200 ppm) and lower values of Ni (~820 ppm) were recorded in the pyroxenites (Anhaeusser, 1978).

Metagabbroic rocks terminate the cyclical units and, when traced in the field, outline a complex series of interference folds (some doubly plunging to the east and to the west; Anhaeusser, 1986, fig.10) indicating that the layered body has been subjected to superimposed, differential compression. The gabbroic rocks are generally fine-grained, black, or dark greyish-green in colour on fresh surfaces, but have a distinctive dark reddish-brown colour on weathered surfaces. Exposures of these rocks are rather poor, but prospect trenches for chrysotile asbestos facilitated the detailed mapping undertaken by Anhaeusser (1978; figs. 2, 8). Most of these excavations have recently been filled and many of the gabbro exposures are now largely lost from view.

Mineralogically the metagabbroic rocks consist of decussate-textured amphibole (mainly actinolite), together with varying amounts of epidote (saussuritised plagioclase), sphene, and opaque oxides (magnetite, ilmenite, leucoxene).

Chrysotile asbestos attracted the attention of early prospectors and three pre-World War II asbestos mines were established in the area (Gelden, Scott, West Rand). However, the operations were small and short-lived as quality asbestos fibre was limited. Almost invariably the asbestos fibre of significance was located in the basal portions of the serpentinized dunite or harzburgite layers where these rocks are immediately overlain by the massive, fine-grained, metagabbroic layers representing terminal phases of a preceding differentiated cycle. Suitable host rocks, combined with competency contrasts and differential structural movement at these contacts, were clearly responsible for chrysotile fibre development (Anhaeusser, 1976; 1978, fig. 10; 1986). The serpentinite has also been quarried in the past for use as a flux in the ferro-alloy industry and for use in the manufacture of calcium-magnesium phosphate fertilizers.

The age of the Muldersdrif Ultramafic Complex, like all other ultramafic-mafic complexes on the Johannesburg Dome, has not been determined directly because of the lack of suitable material for dating. The complex is, however, intruded by porphyritc granodiorites dated at *c.* 3114 Ma. As explained elsewhere, the greenstones on the Johannesburg Dome predate these granitoids and may even be older than the *c.* 3200-3340 Ma intrusive tonalitic and trondhjemitic gneisses recorded elsewhere on the dome (Poujol and Anhaeusser, 2001).

Roodekrans Complex

A few kilometres southeast of the Muldersdrif Ultramafic Complex (Fig. 16) is an adjoining Archaean greenstone remnant, approximately 16 km^2 in area, which occurs on the original farm Roodekrans 183 IQ, the northern part of which has recently been subdivided into Ruimsig 265 IQ. The greenstone terrane, in the southwestern sector of the Johannesburg Dome, and mapped in detail by Anhaeusser (1977), has largely been developed as the Ruimsig and Poortview housing estates (townships linked to the Roodepoort Municipality) and few exposures remain to be seen in the area. To add to the confusion, the Roodekrans Ultramafic Complex, named and described by Anhaeusser (1977), now falls within the area of the Ruimsig subdivision. Although now largely obliterated by housing developments, a small tract of land has been preserved in the Ruimsig Entomological Reserve, which coincides with the area of best preservation of the layered ultramafic-mafic Roodekrans succession.

The Roodekrans greenstone remnant is flanked in the north by intrusive porphyritic granodiorites and is overlain in the south by West Rand Group shales and quartzites of the Witwatersrand Supergroup (Anhaeusser, 1977, fig. 4). The greenstone succession consists of a largely metabasaltic northern sector adjacent to the granitic contact, and a predominantly ultramafic sector in the south, which is covered by sedimentary rocks and scree from the topographically elevated Witwatersrand ridge. The metabasalts consist of massive and pillowed lavas, the latter displaying spherulitic structures, amygdales and vesicles (Anhaeusser, 1977, figs. 5, 6). The rocks have been metamorphosed to amphibolite grade and are locally schistose near the granite contact. Narrow interlayers of ultramafic lavas occur in places and, compositionally, the mafic-ultramafic volcanic rocks are similar to the high-Mg basalts and komatiites recorded in the Barberton Greenstone Belt.

South of the metabasaltic zone is a sequence of vertical to steeply inclined, layered ultramafic rocks consisting of cyclically repetitive, alternating serpentinites and amphibolites striking ESE-WNW. Superimposed on these rocks is a NE-trending cleavage that dips steeply to the northwest (~ 75˚).

Low ridges comprising serpentinized dunite-harzburgite layers alternate cyclically with high-Mg amphibolite schists consisting of tremolite ± chlorite ± talc ± carbonate. The serpentinites, in turn, consist of antigorite, tremolite, chlorite, talc, magnetite and carbonate. Anhaeusser (1977) originally argued that the succession did not constitute part of a differentiated layered ultramafic sequence, preferring to rather view the layers as an eruptive succession of ultramafic flows units. However, the cyclicity, and the massive nature of the serpentinte layers, which could represent sill-like intrusions, makes it equally possible for the succession to be one of a mixed extrusive-intrusive nature. The rocks are poorly exposed and extensively altered making it difficult to resolve this issue.

The age of the Roodekrans Complex, like others on the Johannesburg Dome, is not known directly. In the south the *c.* 2914 Ma or older (Robb and Robb, 1998) West Rand Group sediments of the Witwatersrand Supergroup overlie the ultramafic rocks. However, as with the Muldersdrif Complex to the west, the Roodekrans Complex is intruded in the north by porphyritic granodiorites dated at *c.* 3114 Ma (Poujol and Anhaeusser, 2001). Earlier, it was argued that the greenstone remnants on the Johannesburg Dome could be older than the *c.* 3200 - 3340 Ma tonalitic and trondhjemitic gneisses that elsewhere contain greenstone xenoliths.

Zandspruit Complex

An Archaean greenstone remnant in the North Riding area of the Johannesburg Dome (Fig. 16) is exposed on the farm Zandspruit 191-IQ where it crops out discontinuously over a distance of approximately 4 km and forms a low, northeast-trending ridge. The greenstones constitute a layered ultramafic complex consisting of alternating, cyclically repetitive layers of serpentinised dunite, harzburgite and metapyroxenite (Anhaeusser, 1992). At least four cyclical units can be identified at one locality near the southern end of the body, but not all of the units can be followed continuously along strike because of poor exposure and the disruption caused by intrusive granitic rocks as well as dykes and sill-like sheets of diabase or porphyritic diabase.

The harzburgites, in particular, display pseudostratification or cumulte layering, which dips at 10-30º southeast. The ultramafic rocks have been metamorphosed mainly to serpentinite and amphibolite and numerous inclusions of partially assimilated greenstone occur in the enveloping porphyritic granodiorites. Locally, assimilation, alteration and granitisation of the greenstones has been intense and the granitic rocks have been contaminated with ferromagnesian components (amphibole, chlorite, talc) resulting in development of hybridised dioritic rocks. Anhaeusser (1992) also described an unique occurrence of potash-metasomatised greenstone (originally either harzburgite, lherzolite or olivine websterite), containing large euhedral microcline porphyroblasts in a matrix dominated by biotite.

The original mineralogy of the massive serpentinites has largely been obliterated and the rocks now consist mainly of antigorite with some talc, carbonate and magnetite. By contrast the harzburgites, which are dark blueish-black in colour, show positively weathering, altered cumulate pyroxene crystals up to 8 mm in size, studded throughout the rock. The pyroxenes are generally totally altered (serpentinised, steatised and uralitised to large plates of serpentine, often with admixed talc, brucite and anthophyllite) and were probably originally orthopyroxene crystals. Some fresh olivine was seen poikilitically enclosed in the altered pyroxene, but is mostly altered to serpentine, talc and magnetite. Tremolite and chlorite are also present in some rocks that may originally have been lherzolitic.

The massive grey-green metapyroxenite layers consist of felted needles or blades of tremolite, anthophyllite and chlorite with minor magnetite. These rocks have affinities with the Ca-Mg-enriched diopside-bearing websterites found in the cyclically layered ultramafic complexes in the Barberton region (Viljoen and Viljoen, 1970; Anhaeusser, 1985).

The age of the Zandspruit ultramafic complex has not been determined directly as there are no rocks suitable for this purpose. However, it can be shown that the greenstones are unequivocally older than the intrusive porphyritic K-rich granitoids dated at 3114.2 ± 2.4 Ma (U-Pb zircon age; Poujol and Anhaeusser, 2001) and may well be older than the *c.* 3200 Ma tonalite gneisses intruded into similar greenstones found on the Johannesburg Dome in the Roosevelt Park-Cresta-Robindale vicinity (Anhaeusser and Burger, 1982; Poujol and Anhaeusser, 2001). They may even be older than the trondhjemitic gneisses on the northern half of the Johannesburg Dome (U-Pb zircon ages of 3340 ± 3 Ma; Poujol and Anhaeusser, 2001), which also contain ancient greenstone xenolithic remnants (Anhaeusser, 1973, 1999).

Cresta-Robindale Complexes

A number of ultramafic-mafic bodies occur in the northwestern suburbs of Johannesburg, extending for about 10 km from west to east through the Weltevreden Park, Fairland, Cresta, Robindale areas (Fig. 16), where they are exposed in places in a number of low hills and ridges. No published account of these rocks is available, but the author has undertaken limited mapping and petrological/geochemical studies of the area, which is largely obscured by housing developments and shopping complexes. There are, however, a few parks in the area that expose mainly serpentinites and amphibolites.

Because of the built-up nature of the region and the limited exposure, no complete understanding of the geology could be determined. Little evidence exists as to the nature of the greenstone rocks hosting the ultramafic bodies, as only scattered exposures of massive or schistose hornblende amphibolite (originally komatiitic basalts) could be found. The ultramafic bodies are developed across the entire area and occur as massive as well as layered igneous intrusions. It could not be established if they represent only a few intrusions that have been structurally dismembered, or if they occur as multiple sill-like intrusions.

Most of the accessible localities display massive, structureless, serpentinite bodies, but a few hills consist of massive, black, hornblende amphibolite. A layered differentiated ultramafic body, preserved in a park in the Robindale area, consists of a massive serpentinised dunite ridge,grading progressively upwards (westwards) into serpentinised harzburgite and ortho- and clinopyroxenites. A medium-grained amphibolite (metagabbro), showing intrusive veins of tonalite from the adjacent granitic contact, caps the subvertical succession which is about 20-30 m thick. A prominent hill in the suburbs of Windsor East and Jacanlee consists of massive, coarse-grained amphibolite formed from massive, cumulate-textured, uralitised orthopyroxene crystals 5-15 mm in size.

The serpentinised dunites in the region can readily be distinguished geochemically from the other serpentinised ultramafic rocks. The serpentinised dunites have high-MgO values (32-39%), high Cr (3068-5335 ppm) and high Ni (1663-2240 ppm), whereas the serpentinised pyroxenites have lower MgO (19.11-24.45%), lower Ni (447-1179 ppm) and lower Cr (3239-3868 ppm) - (Anhaeusser, unpubl. data). Petrologically, the dunites have antigorite pseudomorphous after olivine, plus magnetite, tremolite, chlorite, talc and carbonate. The altered pyroxenites have variable quantities of antigorite, hornblende (± bastite), actinolite, and magnetite. The metagabbros contain mainly hornblende-actinolite, quartz and minor plagioclase.

The Cresta-Robindale ultramafic complexes, like others on the Johannesburg Dome, have not been dated directly, but in this area are intruded by hornblende-biotite tonalitic gneisses that have yielded U-Pb zircon ages of *c*. 3200 Ma (Anhaeusser and Burger, 1982; Poujol and Anhaeusser, 2001). As pointed out earlier the ultramafic bodies and their greenstone host rocks might even be older than the *c.* 3340 Ma trondhjemitic gneisses found on the northern half of the dome.

Edenvale-Modderfontein Complex

On the southeastern edge of the Johannesburg Dome, approximately 10 km northeast of Johannesburg City Centre (Fig. 16), is an Archaean greenstone remnant referred to by Chaumba (1992) as the Edenvale Ultramafic Complex. The greenstone succession occurs immediately north of Edenvale township, and south of the former Modderfontein Dynamite Factory, and occupies a poorly exposed area approximately 10 km^2 in extent. Trondhjemitic gneisses are exposed in places on the western side of the ultramafic complex and are intruded into the greenstone successions along the north-south striking granite-greenstone contact. Elsewhere exposures are poor and housing developments have encroached on the terrane, which consists mostly of ultramafic rocks.

The dominant lithologies in this terrane include massive and schistose serpentinite, talc-chlorite and talc-carbonate schist and tremolite-bearing amphibolite. Pyroxenites occurring in the eastern sector of the area have been uralitised and steatised to talcose schists and amphibolite. The rocks throughout the region are generally steeply dipping to subvertical, with changes in strike suggesting that they are deformed into large-scale fold structures. Exposures are, however, inadequate to allow for any detailed assessment of the structure of the region.

Two zones in the western part of the area mapped by Chaumba (1992) display layering comprised of alternating cyclical units of serpentinite and tremolite amphibolite. Low ridges of serpentinite (up to about 1 m in height) are interspaced with low-lying, poorly exposed amphibolites. At least 14 cyclical units were identified by Chaumba (1992) in the southern zone, which is best exposed near the granite contact in the southwest. The northern zone is not as extensive and well developed, but the cyclical layering remains evident.

Mineralogically the serpentinites, which mostly consist of altered harzburgite, contain antigorite, chlorite, tremolite and magnetite, the latter resulting from the alteration of olivine. Relic olivine crystals poikilitically enclosed in orthopyroxene were seen (Chaumba, 1992) and chrome abundances of 2000-3700 ppm suggest this mineral may also be present in the serpentinites.

As with other ultramafic-mafic occurrences exposed on the Johannesburg Dome the age of the Edenvale-Modderfontein Complex has not been determined due to the absence of material suitable for dating. By inference, the rocks exceed the age of the intrusive trondhjemitic and tonalitic granitoids occurring on the dome, which have ages ranging from *c*. 3200-3340 Ma (Anhaeusser and Burger, 1982; Poujol and Anhaeusser, 2001).

INTRUSIONS IN THE VREDEFORT DOME AREA

A number of Neoarchaean to Mesoproterozoic mafic and ultramafic intrusions consisting of sills and dykes, as well as differentiated bodies, intruded the core and collar rocks of the Vredefort Dome, which is situated approximately 100 km south of Johannesburg (Fig. 1.3). Descriptions of the geology of the Vredefort region are numerous (e.g., Nel, 1927a, b; Bisschoff, 1972a, b, 1999; Stepto, 1990; Reimold *et al*., 2000; Gibson and Reimold, 2001). In particular, the mafic-ultramafic rocks have been grouped into various age categories and may be distinguished as either pre- or post-impact intrusions on the basis of their relationship to the 2020 Ma impact-related deformation features (Stepto, 1990; Bisschoff, 1999; Gibson and Reimold, 2001). They include: (1) ‘primitive’ mafic-ultramafic intrusions; (2) an older and younger set of epidiorite sills and dykes of possible Ventersdorp or lower Witwatersrand age; (3) a group of sills, dykes and layered intrusions of tholeiitic composition and possible Bushveld age; (4) a group of post-Transvaal dioritic and alkali granite complexes; (5) a mafic granophyre representing impact melt rock resulting from the Vredefort impact event; and (6) post-Waterberg igneous intrusions.

‘Primitive’ mafic-ultramafic intrusions

Stepto (1990) recognised a set of ‘primitive’ mafic-ultramafic intrusions emplaced into the core of the Vredefort basement. These comprise an amphibole-orthopyroxene suite restricted to the amphibolite-paragneiss sequence of the Steynskraal Formation (renamed the Steynskraal Metamorphic Suite by Bisschoff, 1999), which occurs along the outer rim of the ‘so-called’ Inlandsee Leucogranofels. In addition, metamorphosed harzburgite and pyroxenite pods and dykes occur in places within the Inlandsee Leucogranofels core and adjacent Steynskraal Metamorphic Suite, the age of which has not yet been determined accurately, but is believed to be of the order of *c.* 3400 Ma (Hart *et al.*, 1990b; Menuge, 1982; Lana, 2004).

Epidiorite intrusions

Bisschoff (1999) identified an older group of altered and metamorphosed (also shock affected) sills and dykes of basaltic to andesitic composition (amphibole-plagioclase rocks, referred to as epidiorites) occurring in the lower Witwatersrand Supergroup rocks in the collar of the dome (Hospital Hill Subgroup) and in the Archaean granitoid rocks on the dome. A younger group of sills and dykes, consisting mostly of norites, gabbro-norites and dolerites, were also recorded in the upper Government and Jeppestown Subgroups. In addition, epidiorite dykes, common in the Turffontein Subgroup, can be followed up to the Ventersdorp Supergroup and possibly served as conduits for the *c.* 2714 Ma Ventersdorp lavas. Some of the sills below the Jeppestown Subgroup may be genetically related to the *c.* 2914 Ma Crown lava (Bisschoff, 1999).

Mafic (tholeiitic) intrusions

Numerous sills and dykes of dolerite, gabbro-norite, norite, pyroxenite and diabase occur in the Transvaal Supergroup in the vicinity of the Vredefort Dome. Included in this group is the Losberg Complex (described later), which is intruded into shales and quartzites of the Transvaal Supergroup about 40 km north of Parys (Abbot and Ferguson, 1965). Many of these rocks have been linked to the Bushveld intrusive event at *c.* 2060 Ma (Bisschoff, 1972a, 1999), but studies by Pybus (1995) suggested that most of the intrusions exposed in the basement granitoids and collar rocks appear to be metamorphosed and shock-affected hypabyssal epidiorites of Ventersdorp age. However, there are numerous sills in the Transvaal Supergroup so these must be of post-Ventersdorp and pre-Vredefort impact age.

Dioritic intrusions

A number of post-Transvaal and pre-Bushveld dioritic intrusions occur in this group, including the Roodekraal, Rietfontein, and Koedoesfontein complexes, which were emplaced in the vicinity of major fault zones and which are cut by abundant pseudotachylite veins indicating a pre-impact age (Bisschoff, 1999). The Roodekraal Complex situated about 10 km southeast of Potchefstroom represents an ancient andesitic volcano into which a core of dioritic rocks has intruded (Bisschoff, 1972b). By contrast, the Rietfontein Complex, which occurs about 20 km NNW of Parys (Fig. 18), is a differentiated mafic-ultramafic intrusion consisting of wehrlite, olivine gabbro, troctolite and pyroxene-bearing troctolite and has been intruded by alkali granite (Bisschoff, 1973, 1999). The Koedoesfontein Complex, located about 12 km northwest of Parys, is a small, poorly exposed body consisting of dykes of wehrlite, spessartite and alkali granite (Bisschoff, 1972b).

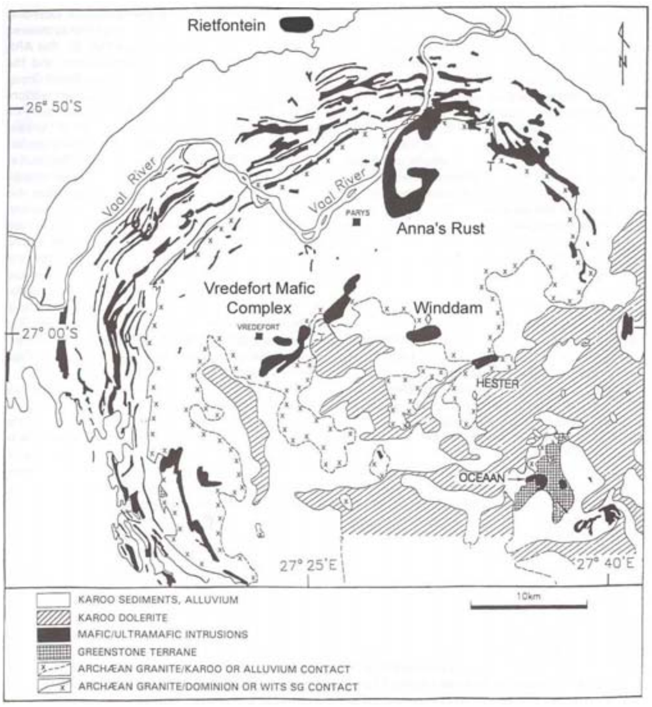

Figure 18. *Simplified geological map showing the distribution of the Neoarchaean to Mesoproterozoic mafic-ultramafic intrusions in the region of the Vredefort Dome, central Kaapvaal Craton (map modified after Nel, 1927b and Reimold et al., 2000).*

Also included in this category by Bisshoff (1999) is the Winddam wehrlite body (Fig. 18), regarded by Stepto (1990) as being similar to and coeval with the wehrlites of the Rietfontein and Koedoesfontein complexes, but which does not display pseudotachylite veins or shatter cones. The absence of post-impact features in the Winddam wehrlite may be due to poor exposure of this body (Stepto, 1990; Bisschoff, 1999). It has also been suggested that the wehrlite may be related to the Bushveld Complex (Merkle and Wallmach, 1997).

A positive gravity anomaly near the centre of the Vredefort structure led Hart *et al*. (1990) to suggest that the core of the dome is underlain by a body of dense mafic-ultramafic rock, interpreted as Archaean upper mantle material. Tredoux *et al*. (1999), on the basis of Re-Os isotopic data, supported this model and concluded that the ultramafic rocks are not related to the Bushveld event, but instead represent rocks of the lower parts of a crust-on-edge profile that possibly contains a palaeo-Moho very near the Earth's surface. Hart *et al*. (1990a) showed that the dominant rock type, a medium- to coarse-grained hornblende-harzburgite, displays a gneissosity defined by the hornblende, which replaces, but is in textural equilibrium with olivine and pyroxene, indicating that the assemblage is metamorphic rather than igneous. The coarse hornblende and pyroxene display internal strain features, which may reflect shock deformation; however, the post-impact temperatures in these rocks have caused a strong recrystallisation of these features (Hart *et al*., 1990a). More recently Hart *et al*. (2004) suggested that these rocks, whilst representing mantle material, were thrust into mid-crustal levels. Gibson *et al*. (2004) argued that the thrusting most likely occurred prior to formation of the TTG crust and was probably related to initial intra-oceanic thickening. In the absence of direct age dating the origin of these rocks remains in doubt.

Mafic granophyre intrusions

This unique rock, referred to in the past as enstatite-bronzite or basic granophyre, and more recently as Vredefort Granophyre by Koeberl *et al*. (1996), is now widely regarded as an impact melt rock as first suggested by Dietz (1961). The rock, which occurs mainly as dykes in the core and inner collar of the dome, contains hypersthene, augite, pigeonite, plagioclase, orthoclase, quartz, biotite, magnetite and ilmenite. Numerous inclusions of granite-gneiss, quartzite, minor shale and rare mafic rocks are present in the granophyre and it is believed that many of the clasts were derived from overlying supracrustal successions suggesting downward intrusion from an overlying melt sheet following the impact event. The rocks give an U-Pb zircon age of 2023± 4 Ma (Kamo *et al*., 1996) - the currently accepted age of the Vredefort impact event.

Post-Waterberg intrusions

Intrusions emplaced after the formation of the Vredefort Dome include a number of smaller dioritic dykes as well as the N-S trending Wonderfontein nepheline-syenite dyke of Pilanesberg age, which cuts the Rietfontein Complex northwest of Parys. The most prominent mafic intrusions in this category comprise a suite of mineralogically and chemically related gabbroic intrusions of late Mesoproterozoic age, which occur in the core and collar of the Vredefort Dome (Nel, 1927a,b; Bischoff, 1972a,b; 1999). Among these are the Anna's Rust and Vredefort Mafic Complexes (Fig. 18), as well as dykes and sills in the Greenlands area of the dome, which are discussed in a later section dealing with magmatism linked to the Umkondo Igneous Province.

WESTERN AND NORTHWESTERN KAAPVAAL CRATON

Kraaipan Greenstone Belt

Stella Layered Intrusion

The Stella Layered Intrusion, is located in the western or Stella Belt of the Kraaipan Greenstone Belt, approximately 30 km north of Stella and 55 km south of the Botswana border on the western side of the Kaapvaal Craton (Fig. 1.4). The intrusion, which is obscured beneath several metres of Kalahari sand, was discovered in the early 1990s by Anglo-American Prospecting Services (AAPS) who detected PGE mineralization in the area. Follow-up investigations by Harmony Gold Exploration (Pty) Ltd (Harmony) discovered extensions to the mineralization and reported that the intrusion extends over a strike length of some 12 km, with a maximum subcrop width of around 1.5 km (Andrews, 2003). A change in strike direction divides the intrusion into two sectors – a southern area, Kromdraai, where AAPS discovered the mineralization and a northern area, Morester, where Harmony identified its lateral extension.

The intrusion comprises layered gabbros/anorthosites, magnetite gabbros/anorthosites and magnetitites, cut by various mafic and felsic intrusives, and lying with broad conformity within steeply dipping greenstones (chert, magnetite quartzite, banded iron formation) as well as granitic host lithologies (Andrews, 2003; Maier *et al*., 2003a). Preliminary investigations suggest the area is structurally complex with the intrusion having a subvertical dip with overturning to the west. The body is thought to represent the upper part of an originally larger, but tectonically dismembered, layered intrusion. According to Maier *et al*. (2003a) the basal 60 m of the intrusion consists largely of magnetite-poor gabbro overlain by ~25 m of gabbro containing 1-10% disseminated magnetite, increasing upwards to greater than 10% magnetite and containing numerous magnetite layers 0.1 - 4 m thick. The contacts between different rock layers vary from gradational to sharp and the succession has undergone greenschist facies metamorphism and is variably altered.

The thickness of the intrusion is unknown at this point in time as only the western/southwestern contact has been intersected where the highly altered rocks of the Stella body are bordered by greenstone lithologies consisting mainly of cherts and magnetite quartzites (Andrews, 2003). The magnetic signature on the eastern/northeastern side of the intrusion suggests that granitic or Ventersdorp volcanic rocks predominate. Maier *et al.* (2003a) showed a borehole succession approximately 230 m thick with ~13 magnetitite layers and a 100 m-thick, PGE-enriched interval that includes a number of laterally continuous PGE reefs. The richest of the reefs is hosted by magnetitite and contains 10-15 ppm Pt+Pd over 1 m, but there is no correlation between magnetite and PGE concentrations. Instead the PGEs are interpreted by Maier *et al*. (2003a) to have been concentrated by sulphide melt, after S saturation had been reached in the advanced stages of magmatic differentiation, in response to magnetite crystallization. The magnetite is both titaniferous and vanadiferous and deuteric fluids have modified the PGMs to an arsenide- and antimonide-dominated assemblage, and remobilized some of the sulphides (Andrews, 2003).

The Stella intrusion is structurally complex, the main deformation resulting in folding and the development of layer-parallel ductile shear zones along contacts between competent and less competent lithologies. Texturally, the rocks are generally coarse and even grained, although alteration has locally obliterated much of the primary cumulate texture. The body is cut by meta-diabase dykes and sills and various, locally abundant, pre- or post-tectonic granitic veins.

The intrusion has clearly been involved in the metamorphism and tectonism that affected the surrounding greenstones as well as by the syn- or post-tectonic granitic intrusion. The Stella body thus appears to predate most of the potassic granitic rocks in the northern Kraaipan region that range in age from *c.* 2917 to 2718 Ma (Anhaeusser and Walraven, 1999; Poujol *et al*., 2002). An unpublished U-Pb zircon age of 3033.5±0.3 Ma (M. Schmitz, 2002 – pers. commun. to V. Gartz) for anorthositic gabbros of the Stella intrusion is quoted in Andrews (2003) and Maier *et al.* (2003a). This *c.* 3033 Ma age is consistent with pre-tectonic intrusion into the greenstone succession, but does not preclude the possibility of intrusion into older trondhjemitic gneiss basement of *c.* 3162-3070 Ma recorded in the area by Anhaeusser and Walraven (1999).

Madibogo serpentinite pods

Ultramafic rocks, mainly in the form of serpentinite, talc-, talc-carbonate- or talc-chlorite schists have been reported from various localities in the Kraaipan granite-greenstone terrane (Fig. 1.4) on the western side of the Kaapvaal Craton, but are rarely exposed (Van Eeden *et al*., 1963; SACS, 1980; Kiefer, 2004). Two small pod-like bodies of serpentinite crop out approximately 6 km ESE of Madibogo (midway between Vryburg and Mafikeng), where they are enveloped by magnetite-hematite quartzites of the Gold Ridge Formation (Zimmermann, 1994). The serpentinites are pale yellowish-green in colour and produce rough, differentially weathered outcrops. Carbonate alteration occurs in places resulting in the development of massive and schistose talc-carbonate rocks. The serpentinites consist mainly of antigorite, pseudomorphous after olivine, with variable amounts of chrysotile, tremolite, magnetite, brucite, calcite, magnesite and quartz. The magnetite, formed from the serpentinisation of olivine, occurs scattered throughout the rock, but in place veins of magnetite up to 10 cm thick and several meters in length were noted.

The age of the serpentinite pods is not known directly, but they appear to have been deformed and metamorphosed together with the surrounding rocks of the Kraaipan greenstone belt. The greenstone succession predates the granitoid rocks in the region, which range in age from *c.* 3178-2846 Ma (Anhaeusser and Walraven, 1999; Poujol *et al*., 2002).

Modipe Gabbro Complex

The Modipe Gabbro Complex is mainly situated in southeast Botswana (Fig. 1.11), approximately 25 km east of Gaborone (Jones, 1963), but offshoots and stocks are found in the area about 20 km WSW of Derdepoort in the Marico District of the North West Province of South Africa (Jansen *et al*., 1974). At Modipe a large mass of gabbroic rock forms a series of prominent hills, some over 300m above the surrounding plain. The rocks of the complex have not been studied in detail, but in South Africa reportedly consist mainly of gabbro with associated norite, gabbro-norite, pyroxenite, wehrlite, dunite, serpentinite, anorthosite and bands of magnetite (Jansen *et al*., 1974). Palaeomagnetic studies have been undertaken by Evans and McElhinny (1966) and yielded a palaeomagnitic pole at 33˚S and 31˚E.

Rb-Sr total rock measurements yielded an age of 2630 ± 470 Ma with an initial ratio R_o = 0.7010 ± 0.001 (McElhinny, 1966). K-Ar ages from plagioclase separates gave ages at 1800 Ma, suggesting the gabbro suffered mild reheating at this time, and pyroxene ages in the range 2670-3000 Ma. This latter age range is more in keeping with the age of the body, which must exceed the 2785-2830 Ma age range recorded by Sibiya (1988) and Moore *et al*. (1993) for the Gaborone Granite Complex which intrudes the Modipe gabbro (Jones, 1963; McElhinny, 1966).

NORTHERN KAAPVAAL CRATON

Giyani Greenstone Belt

The Giyani (formerly Sutherland) Greenstone Belt (Fig. 19) is situated approximately 45 km north of the Murchison Greenstone Belt, in the northeastern sector of the Limpopo Province (Fig. 1.7) (Brandl *et al*., 1985a, 1987). The greenstone belt is generally poorly exposed, but in some parts of the region outcrops may be found on low hills and ridges. Ultramafic rocks occur as metavolcanic rocks in the greenstone belt, mainly as schistose komatiites, komatiitic basalts, high-Mg tholeiites and tholeiitic basalts. In addition, massive and sill-like intrusive bodies occur within the greenstone belt as well as in xenolithic remnants in the surrounding Klein Letaba gneisses (Van Zyl *et al*., 1942; Prinsloo, 1977; Vorster, 1979; Anhaeusser, 1981).

The southwestern part of the Giyani Greenstone Belt has been intruded by the diapiric Meriri trondhjemite gneiss, causing it to split into an east-west striking northern, or Khavagari belt, and a southwesterly striking Lwaji belt. The Khavagari belt consists predominantly of ultramafic rocks associated with the Leonde intrusion, which has been interpretted by Prinsloo (1977) to represent a deformed sheet-like body forming disconnected hills of serpentinite covered to a large extent by birbirite. The serpentinites also contain magnesite, which has been mined historically for traditional and ceremonial purposes, and in a number of more recent quarries (Van Zyl *et al*., 1942). Prinsloo (1977) believed the serpentinites were derived from altered harzburgites. Other rocks in the area include tremolite-actinolite, talc-tremolite, tremolite-chlorite, and chlorite schists, but some of these may represent, in part, the altered host rocks to the serpentinite bodies.

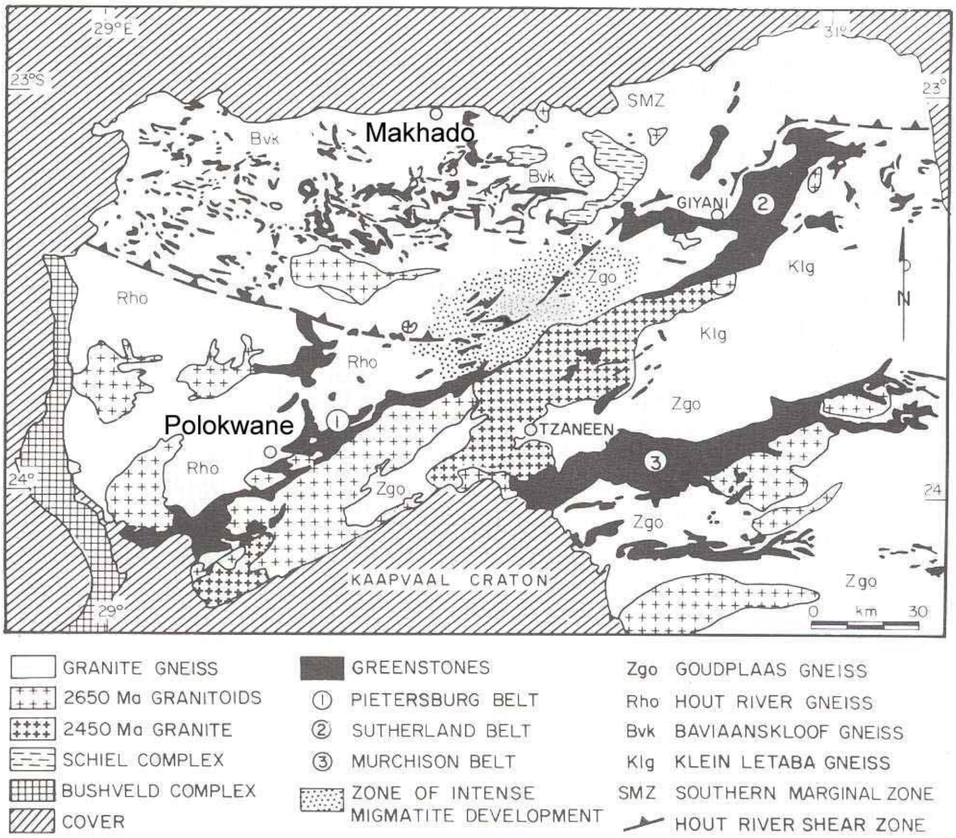

Figure 19. *Simplified geological map showing the distribution of granites and greenstones in the Southern Marginal Zone of the Limpopo Belt and adjoining Kaapvaal Craton (modified after Brandl, 1985a,b).*

Approximately 20 km due east of Giyani township a number of greenstone xenoliths occur in the Klein Letaba gneiss east of the Giyani Greenstone Belt contact. These include a number of small serpentinite bodies as well as the larger serpentinite body forming the Busizi Hills (Vorster, 1979). The serpentinites are massive, fine-grained rocks containing relic olivine, antigorite/lizardite, talc, chlorite, magnetite and magnesite. On the western side of the Busizi Hills Vorster (1979) also noted some ortho- and clinopyroxenites containing minor intercumulus plagioclase. These rocks are largely altered to amphibolites containing tremolite-actinolite and some magnetite.

No age dating has been carried out on the ultramafic rocks in the Giyani granite-greenstone terrane. However, felsic metavolcanics in the greenstone belt and tonalitic-trondhjemitic gneisses south of the belt, including the Groot Letaba gneiss between the Murchison and Giyani Greenstone Belts, provided Pb-Pb zircon evaporation ages ranging between *c.* 3203 - 3171 Ma (Kröner *et al*., 2000; Brandl and Kröner, 1993). The ultramafic bodies in the Giyani region are likely to be older than the upper age limits obtained.

Pietersburg Greenstone Belt

The Pietersburg Greenstone Belt is an elongate, northeast-trending feature with an exposed strike length of 125 km and a maximum width of 25 km (Figs. 1.8, 19). It comprises a basal sequence of extrusive-intrusive volcanic and plutonic rocks overlain by a succession of sediments (Grobler, 1972; Brandl, 1985b, 1986; Brandl and De Wit, 1997; Kröner *et al*., 2000; Brandl *et al*., 2005). Within the basal sequence, mafic and ultramafic rocks are the dominant lithologies (Van Schalkwyk, 1991), with serpentinites, talc-carbonate schists and quartz-carbonates occurring southwest of Polokwane (formerly Pietersburg). Some of the ultramafic rocks have been interpretted as representing intrusions into predominantly extrusive sequences of komatiitic metavolcanics. A small layered intrusive body about 1 km^2 in extent, referred to as the Rooikop Complex (Kröner *et al*., 2000), occurs about 12 km south of Polokwane on the farm Palmietfontein 24 KS. The intrusion, which is approximately 150 m-thick, forms a conspicuous ridge consisting of repetitive, alternating layers of serpentinised dunite and metapyroxenite that dip about 50˚ to the northwest (N. Baglow, person. commun.).

Conventional U-Pb dating and Pb-Pb evaporation ages of single zircons suggest the Pietersburg Greenstone Belt ranges from *c*. 2950 - 2853 Ma, coeval with the felsic volcanism of the Murchison Greenstone Belt farther east (Kröner *et al*., 2000; Poujol *et al*., 2003). For the Pietersburg basal sequence, consisting of mafic and ultramafic rocks, an imprecise whole-rock Pb/Pb age of 3460 Ma has been reported by Byron and Barton (1990).

Southern Marginal Zone of the Limpopo Belt

A number of pod-like ultramafic bodies ranging up to 2 km in diameter, and large, fragmented mafic xenoliths occur in the Southern Marginal Zone (SMZ) of the Limpopo Belt (Figs. 1.9, 19) between Polokwane (Pietersburg) and Makhado (Louis Trichardt). These rocks constitute members of the Bandelierkop Formation and are considered to represent the high-grade metamorphosed equivalents of Archaean greenstone belt lithologies (Du Toit, 1979; Du Toit *et al*., 1983). Their age has not been determined directly, but these rocks have been intruded and metamorphosed by granitoids of the granulite facies Matok pluton dated at between 2667 and 2664 Ma (U-Pb zircon ages, Barton *et al*., 1992), which gives a minimum age for the rocks of the Bandelierkop Formation.

The ultramafic pods are composed predominantly of peridotite, followed volumetrically by pyroxenite, dunite and hornblendite. The peridotite and the dunite are intensely serpentinised and consist of large relic crystals of olivine and enstatite in a matrix of antigorite and magnetite. Diopside is the main pyroxene and accessory amounts of anthophyllite and cummingtonite occur together with ubiquitous calcite and spinel. All the ultramafic rocks are relatively MgO-rich with values ranging from 28-35% suggesting a lherzolitic precursor (Van Schalkwyk, 1991; Van Schalkwyk and Van Reenen, 1992; Brandl and De Wit, 1997).

Deposits of corundum associated with the ultramafic rocks are widespread throughout the SMZ (Oosterhuis, 1998) and include plumasite occurrences described by Hall (1920) as having formed by the desilication of pegmatites reacting with mafic-ultramafic rocks into which they intruded. On the farm Lemoenfontein 443LS, approximately 45 km southwest of Makhado, a low, circular-shaped hill, comprising carbonated serpentinites, contains a small body of high-grade chromite (Willemse, 1948; Smit, 1984). The ultramafic rocks of the Lemoenfontein body and the Bandelierkop Formation are essentially lherzolites and dunites and contain mineral assemblages consisting of orthopyroxene + olivine ± spinel ± various amphiboles and rare clinopyroxene. According to Smit (1984), the podiform chromite occurrence has similarities with ultramafic igneous rocks of the alpine type described by Thayer (1967).

Cental Zone of the Limpopo Belt

Messina Layered Intrusion (Messina Suite)

A metamorphosed sequence of rocks, including anorthosites and leucogabbros, with subordinate gabbros and ultramafic rocks occurs conformably interlayered with a variety of metasediments and metavolcanics (quartzites, magnetite quartzites, metapelites, calc-silicate rocks and marble, amphibolites, leucogneisses and other granitoid gneisses) of the Beit Bridge Complex in the Central Zone of the Limpopo Belt (Fig. 1.10). These rocks, first described by Söhnge (1945), were considered to have been emplaced as sill-like bodies, which locally display primary igneous features such as cumulate textures. They also contain layers of chromitite and titaniferous magnetitite suggesting that they were originally layered magmatic bodies (or a single body) that had been subsequently metamorphosed and intensely tectonically deformed (Fig. 20). Thus, these rocks post-date the deposition of the metasediments and the gneisses, but pre-date the major metamorphism and tectonism that affected the Limpopo Belt.

Figure 20. *Boudins of metagabbro in meta-anorthosite-gabbro gneisses of the Messina Layered Intrusion, deformed and infolded within the Sand River Gneisses in the Central Zone of the Limpopo Belt, approximately 10 km southeast of Musina.*

Exposures of the intrusive rocks, which crop out intermittently over a distance of more than 300 km ENE and WSW of Musina (formerly Messina) (Fig. 21) were regarded by Barton *et al*. (1977, 1979) as constituting a single body they named the Messina Layered Intrusion. This was subsequently renamed the Messina Suite (SACS, 1980). According to Barton (1996) the layered intrusion was metamorphosed and deformed prior to 3000 Ma, but subsequently endured granulite facies metamorphism at *c.* 2000 Ma. The intrusion has yielded a Rb-Sr whole rock isochron date of 3153±47 Ma (initial $^{87}Sr/^{86}Sr$ ratio R_o = 0.70331±0.00006) from 20 anorthositic and gabbroic samples (Barton *et al*., 1979) and a Pb-Pb whole rock age of 3270+105/-112Ma obtained from four samples of the same material (Barton, 1983). However, these age relationships may need to be revisited following recent Pb/Pb sphene and U-Pb zircon dating of some of the host metasediments grouped with the Beit Bridge Complex (Buick *et al*., 2003). These authors also reported anomalously high carbon isotope values ($\delta^{13}C$ = +4.6 - +7‰) in granulite-grade marbles from the Gumbu Group similar to those found in carbonate rocks of the Transvaal Supergroup. Together, these findings may suggest that at least some of the Central Zone rocks could be Palaeoproterozoic in age (i.e., the protolith sediments may have been deposited after 2680 Ma and not 3300 Ma as previously believed) and that the layered intrusive rocks of the Messina Suite may also be younger than the Archaean ages presently ascribed to them.

According to Söhnge (1945), the suite comprised gneisses, granulites and schists of igneous origin ranging from leucocratic to hypemelanic (ultramafic) types. Most common are amphibolites, hornblende gneisses and hornblende schists forming persistent lenticular sheets concordant to the regional gneissic structure. Their spatial association with extensive sills of banded anorthosite suggested they are mainly differentiation products of an Archaean sill complex. This was confirmed by Hor *et al*. (1975) who described a differentiation sequence from leucogabbro to anorthosite near Musina. Söhnge (1945) also described widely scattered bodies of ultramafic rocks (including dunite, harzburgite, lherzolite, wehrlite, and ortho- and clino-pyroxenites) invariably metamorphosed and locally altered to amphibolite and serpentinite. These he classified into three genetic groups, but stressed that the various intrusive assemblages could all probably be related in origin.

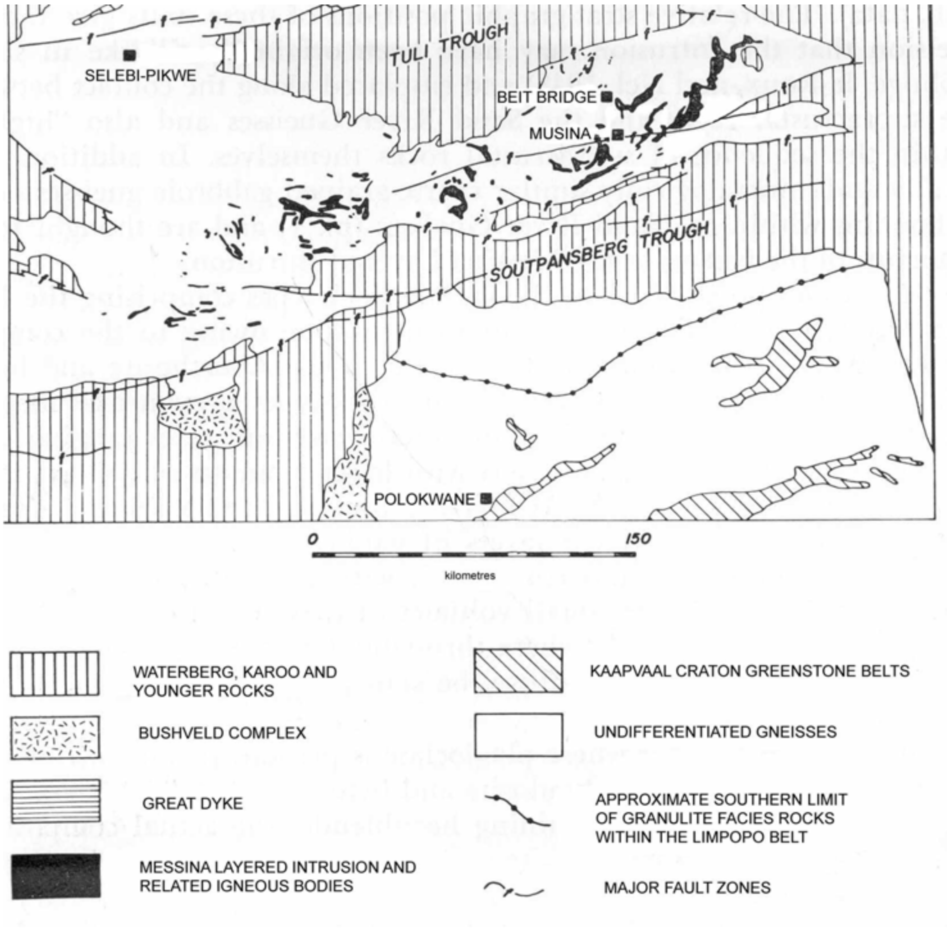

Figure 21. *Generalised geological map showing the distribution of rocks belonging to the Messina Layered Intrusion and other related mafic igneous bodies in the Central Zone of the Limpopo Belt (map after Barton et al., 1979).*

The groups included: (1) ultramafic rocks associated with the differentiated basic sill-like intrusions of amphibolite-anorthosite; (2) ultramafic rocks forming isolated bodies in the gneissic country rocks; and (3) partly or wholly serpentinised bodies of ultramafic rocks not spatially related to the differentiated sill-like intrusions. Barton *et al*. (1979) maintained that anorthosite and leucogabbro constituted over 90% of the Messina Suite and they showed that the plagioclase present in all these rock types ranges in composition between labradorite and bytownite (An_{70}-An_{85}). These authors also chose to include in the layered intrusion only those layers of gabbro, melagabbro and ultramafic rocks adjacent to and concordant with the layers of leucogabbro and anorthosite, but conceded, however, that the smaller occurrences of the more mafic and ultramafic rock types may, in time, also be shown to form part of the larger layered intrusion.

Estimates of the parental composition of the intrusion by Hor *et al*. (1975) suggested that the magma had calc-alkaline to tholeiitic affinities, but Barton *et al*. (1979) concluded that the magma was quartz-tholeiitic, derived from a heterogeneous sub-continental mantle and crystallising alternately plagioclase, olivine and orthopyroxene. These authors estimated, further, that the intrusion was emplaced at a high crustal level (<12 km depth) at the contact between the older basement gneisses and the overlying supracrustal rocks of the Beit Bridge Complex as well as within the supracrustal succession itself.

NORTHEASTERN KAAPVAAL CRATON

Murchison Greenstone Belt and surrounding areas

Rooiwater Complex

The Rooiwater Complex is located in the northeastern part of the Kaapvaal Craton (Fig. 1.6), along the northern margin of the Murchison Greenstone Belt (Hall, 1912; Van Eeden *et al.*, 1939; Vearncombe, 1991; Vearncombe *et al.*, 1992; Mienie, 1995; Brandl *et al.*, 1996; Poujol *et al.*, 1996). Field relations indicate that the Complex is intrusive into the > 2970 Ma greenstones to the south. As its northern contact with the granitoid gneisses is essentially linear, this contact may be tectonic and could be related to the Letaba Shear Zone. The Complex has a subvertical attitude, youngs to the south, is approximately 65 km in length and has a maximum thickness of 7.5 km, similar to the Bushveld Complex. Deformation is heterogeneous, resulting often in large lenses of undeformed rocks enveloped by zones of well-cleaved rocks or discrete shear zones. The Complex thins progressively towards the east (Fig. 22) into a zone of vertically orientated shearing and appears to terminate about 24 km east of Gravelotte (Brandl *et al.,* 1985a); however, reconnaissance investigations by the author suggest that some poorly exposed metagabbros seen in the Kruger National Park north of the Letaba River may be easterly extensions of the Rooiwater Complex.

The Complex is subdivided into a lower Novengilla Suite, a central Quagga Quartz Amphibolite and an upper Free State Suite (Vearncombe *et al*., 1992). The lower unit comprises metamorphosed gabbro with subordinate anorthosite and pyroxenite. Although the primary igneous textures of these rocks are still recognizable, they have been pervasively altered, with almost no primary mineral compositions preserved. Plagioclase is commonly saussuritised, and pyroxene is replaced by hornblende, which, in turn, can be altered to chlorite and epidote. Locally, actinolite and secondary biotite are developed, with the latter often being altered. Of economic importance is the presence of titaniferous magnetitite layers, which occur as three discontinuous, up to 7 m-thick layers over most of the approximately 14 km strike length of the upper Novengilla Suite. They contain 14.5 - 24.5 % TiO_2 and 0.8-1.4 % V_2O_5 and represent potential ores for the production of high-titania slag, vanadium pentoxide and iron and steel (Reynolds, 1986b; Mienie, 1995).

The Quagga Quartz Amphibolite, which shows metamorphosed mineral layering, consists of hornblende, plagioclase, quartz, magnetite and garnet. Its spatial association and layering suggest that it is part of the intrusion and that it is transitional between gabbro-anorthosite and the overlying hornblende granite (Vearncombe *et al*., 1992).

The Free State Suite is characterised by a leucocratic hornblende-granite with a maximum thickness of 2 000 m. This rock, which has also been subjected to moderate alteration, is made up mainly of albite and large, often bluish, quartz with minor hornblende, the latter partially altered to chlorite in places. Magnetite, apatite and sphene are accessories. As the granite commonly has gradational contacts with the underlying gabbros it is generally considered a differentiation product of the mafic rocks (Van Eeden *et al*., 1939).

A $^{207}Pb/^{206}Pb$ zircon age of 2740±4 Ma has been obtained for the hornblende-granite (Poujol *et al*., 1996) and is considered the most likely emplacement age of the Rooiwater Complex. In the past the Rooiwater Complex was interpreted to represent a subvolcanic magma chamber genetically related to the Rubbervale Formation of the adjacent Murchison Greenstone Belt. As the Rubbervale volcanics now have a well-constrained age of *c.* 2970 Ma (Brandl *et al*., 1996; Poujol *et al*., 1996; it is clear that the Rooiwater Complex is more than 200 Ma younger than the greenstone belt volcanics and the earlier view is no longer tenable.

Ofcolaco-Mica-Phalaborwa ultramafic-mafic bodies

A number of mafic-ultramafic bodies occur south of the Murchison Greenstone Belt (Figs. 19, 22) and were first recorded by Hall (1912). They include massive bodies of serpentinite, amphibolite and gabbro as well as schistose rocks, including hornblende, talc and chlorite schists. Exposures are generally poor, but these rocks can be seen to extend sporadically from beneath the Neoarchaean Wolkberg Group formations of the Transvaal Drakensberg Escarpment in the west towards Phalaborwa and the Kruger National Park in the east - a distance of approximately 120 km (see 1: 250 000 map sheets 2430 Pilgrim's Rest-Walraven, 1986, and 2330 Tzaneen; Brandl, 1985a). The largest bodies occur in the west near Ofcolaco and north of the Makhutswi River east of Alsace. A few of the larger bodies also occur in the east in the Kruger National Park, north of the Olifants River. In between these localities, from just west of Mica to the region south of Ba-Phalaborwa (formerly Phalaborwa), the bodies have been dismembered by intrusive granitoid rocks, including numerous pegmatites of the Selati Line - Olifants River mica field (Robb and Robb, 1986).

Reconnaissance investigations by the author suggest that the ultramafic bodies south of the Murchison Greenstone Belt are similar to the layered ultramafic complexes described in the Barberton area (Viljoen and Viljoen, 1970; Anhaeusser, 1985; Wuth, 1980) and in the Johannesburg Dome (Anhaeusser, 1977, 1978). Their age has not been determined precisely, but they are intruded by granitoid rocks ranging in age from 2700-3330 Ma (Poujol *et al*., 2003), including U-Pb zircon results pointing to a minimum age of 2850 Ma for the pegmatites (Poujol and Robb, 1999).

Together with the Barberton ultramafic-mafic complexes and those described on the Johannesburg Dome the occurrences of serpentinised ultramafic rocks in the Ofcolaco-Mica-Phalaborwa region constitute the largest development of this rock association on the Kaapvaal Craton. It is also possible that these rocks may represent ophiolitic-type remnants dispersed along a suture, or oceanic crustal collisional zone, like those proposed for the Barberton and Johannesburg Dome ultramafic-mafic bodies (Anhaeusser, 2002, 2004).

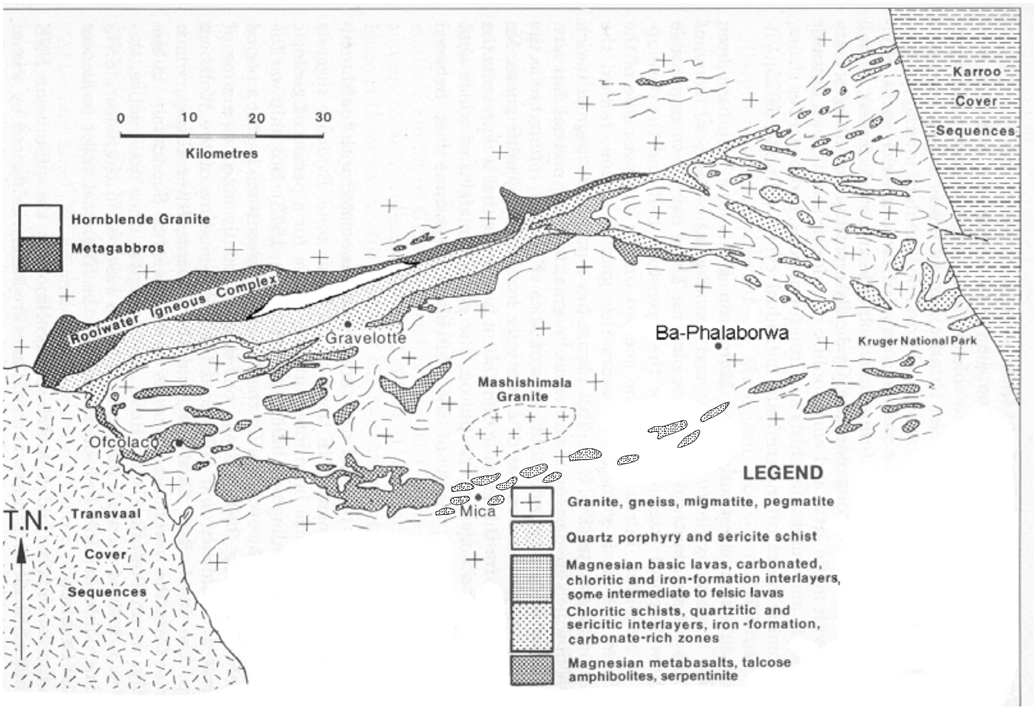

Figure 22: *Simplified geological map of the Murchison Greenstone Belt and surrounding Archaean granitoid gneiss terrane in the northeastern part of the Kaapvaal Craton. Shown along the northern contact with the greenstone belt is the Rooiwater Complex. The distribution of numerous serpentinised ultramafic-mafic bodies south of the greenstone belt is shown in a zone extending from Ofcolaco in the west, through Mica to the Kruger National Park in the east. The ultramafic bodies have been metamorphosed and fragmented by various intrusive Archaean granitic rocks and associated pegmatites (map modified after Hall, 1912; Van Eeden et al., 1939; Brandl et al., 1985a; Anhaeusser, 1981).*

SOUTHEASTERN KAAPVAAL CRATON

Southeastern Mpumalanga and northern and central KwaZulu-Natal Provinces

A number of relatively small Archaean greenstone remnants occur in the granite-gneiss-migmatite terrane extending from the Barberton Greenstone Belt in Mpumalanga Province in the north to the southern margin of the Kaapvaal Craton in central KwaZulu-Natal (Fig. 1.5). From north to south these include (1) greenstone occurrences south of the Komati River, notably the Weergevonden and Schapenburg greenstone remnants (Anhaeusser, 1980; 1983); (2) the Dwalile, Assegaai, Commondale and De Kraalen greenstone remnants in the vicinity of Piet Retief (Smith, 1987; Hunter, 1991; Hunter *et al*., 1992; Wilson, 2003); and (3) the Nondweni and Ilangwe greenstone remnants between Vryheid and the craton margin in the south (Versfeld, 1988; Matthews *et al*., 1989; Wilson and Carlson, 1989; Mathe, 1997).

The Archaean greenstone remnants consist mainly of mafic and ultramafic metavolcanic rocks with accompanying minor metasediments. However, also present, almost without exception, are variable amounts of intrusive rocks, including massive and layered intrusions, which occur as sills consisting of variably serpentinised ultramafic rocks - mainly dunite, harzburgite, pyroxenite, gabbro, quartz gabbro and diorite (e.g., Schapenburg - Anhaeusser, 1983; Commondale - Smith, 1987; Wilson, 2003; Ilangwe - Mathe, 1997).

Dating of these igneous intrusives has not been carried out directly, but the rocks are deformed, and metamorphosed together with the metavolcanic host rocks with which they also share geochemical and petrological similarities, suggesting close genetic ties. Ages obtained from granitoid rocks intruded into the greenstone remnants indicate that they are mainly Palaeoarchaean in age and range from *c*. 3644 - 3250 Ma (Hunter, 1991; Poujol *et al*., 2003; Eglington and Armstrong, 2004).

Usushwana Complex

In the southeastern part of the Kaapvaal Craton the largest intrusion is the Usushwana Complex (Fig. 1.12) that crops out in three discrete areas of eastern Mpumalanga, northern KwaZulu-Natal and Swaziland where it was first recognised in the Usushwana valley (Hunter, 1970). The Complex comprises a suite of ultramafic, mafic and felsic rocks, intruded as two northwesterly trending dyke-like bodies. The southwestern dyke is exposed over a distance of about 100 km and has a maximum outcrop width of 20 km near Amsterdam where a raft of Pongola Supergroup rocks occupies the central position of the dyke (Fig. 23). The northeastern dyke is exposed over a length of 30 km and is approximately 6 km wide. These bodies are linked in Swaziland by a layered gabbro-granophyre sheet or sill up to 6.5 km wide, extending for 25 km in a southwesterly direction, and which was intruded at the contact between the Archaean granitoid basement and the overlying Pongola volcano-sedimentary sequence (Hunter, 1981; Hunter and Reid, 1987). The sill has, in turn, been intruded by the Ngwempisi and Sicunusa plutons in Swaziland, but continues as a northwest-trending dyke (the southwestern dyke) in the vicinity of Piet Retief (Humphrey and Krige, 1931; Hammerbeck, 1982).

Gravity surveys undertaken across the northeastern dyke confirmed that its margins are steep-sided. However, relic, inward-dipping layering is preserved locally, individual layers consisting of coarse-grained norite, medium-grained and pegmatitic gabbros, and anorthositic rocks (Hunter and Reid, 1987). According to Hunter (1981) the best-preserved layering, which dips at 10˚SW towards the centre of the dyke, occurs on the northeastern flank of the northeastern dyke. From the base upwards the succession includes: (1) medium-grained gabbro (15 m); (2) medium-to coarse-grained quartz gabbro (105 m); (3) medium-grained to pegmatitic gabbro with disseminated chalcopyrite and pyrrhotite (10 m); (4) medium- to coarse-grained quartz gabbro (450 m); (5) fine-to medium-grained gabbro underlain by dsicontiuous lenses of serpentinite (75 m); (6) coarse-grained hypersthene gabbro with disseminated pyrrhotite and chalcopyrite (12 m); (7) spotted plagioclase rock (anorthositic) (3 m); and (8) coarse-grained hypersthene gabbro with layers of medium-grained gabbro of unknown thickness. Discontinuous magnetitite layers are present in the uppermost gabbro where a granophyre cap is also preserved. A quartz gabbro, intruded late in the magmatic history, largely destroyed the early formed layering. The gabbroic rocks are essentially similar, but display subtle variations and proportions of augite, hypersthene, plagioclase, quartz, magnetite and ilmenite.

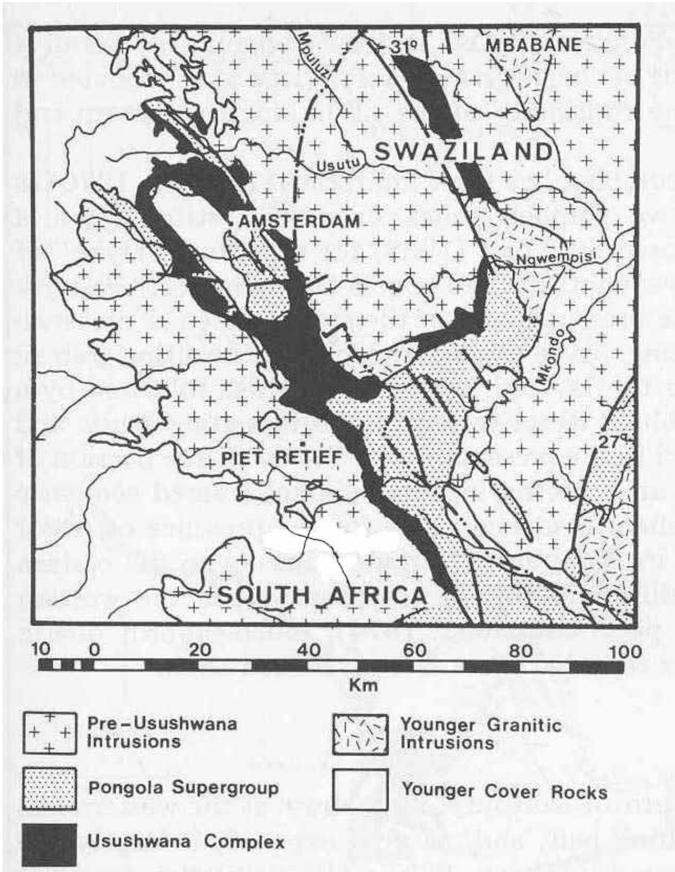

Figure 23. *Simplified geological map showing the distribution of the Usushwana Complex straddling the border between Swaziland and South Africa on the eastern side of the Kaapvaal Craton (map after Hunter, 1981).*

In northwest Swaziland, Hunter (1970) recorded occurrences of pyroxenite in the northerneastern dyke a few kilometres south of the Usushwana River and in the southwestern dyke straddling the border with South Africa, approximately 25 km north of Piet Retief. The pyroxenite is generally coarse-grained and is composed of olivine, hypersthene, augite, and interstiatial plagioclase. Some antigorite, tremolite and rare chromite and biotite are present. Boreholes drilled into the pyroxenites also revealed apparently interlayered bands of gabbro up to 7.5 m thick present in places.

Traces of Cu-Ni mineralisation have been reported in several localities associated with the gabbros, but to date none have proved to be of economic significance. Nine titaniferous magnetite layers vaying between several hundred metres and 2 km in length, and 1-15 m in thickness, occur in places in the gabbros and are characterised by very low V_2O_5 (0,31%) and moderate TiO_2 (~14%) values (Reynolds, 1978). Magnetitite layers have also been noted in gabbroic xenoliths in the quartz gabbro (Hunter, 1970).

Uncertainty surrounds the precise age of emplacement of the Usushwana Complex. Davies *et al*. (1970) obtained a Rb-Sr isochron age of 2874±30 Ma for granophyres (average initial ratio R_o = 0.7029) and a corresponding R_o value averaging 0.7031 for mafic rocks. A Sm-Nd whole rock/mineral age of 2873± 31 Ma was reported by Hegner *et al*. (1984) for the pyroxenite, but these authors noted that the isotope systematics were affected by mixing. Walraven and Pape (1994) determined an age of 2671± 18 Ma (Pb-Pb isochron) for a magnetitite layer in gabbro. However, this age is younger than that of the Ngwempisi and Sicunusa plutons of *c*. 2720 Ma (Poujol *et al*., 2003), both of which unequivocally intrude the Usushwana Complex. The Complex intrudes homogeneous Archaean granites of the Mpuluzi batholith (*c.* 3105 Ma, Kamo and Davis, 1994) and overlying Pongola Supergroup rocks (*c.* 2940 Ma, Hegner *et al*., 1984), which provide a maximum age. A 'best-estimate age' of *c*. 2860 Ma has been proposed by Hunter and Reid (1987) for the Complex.

In addition to the main Usushwana intrusions a number of sparsely exposed ultramafic bodies known as the *Thole ultramafics* occur as small lenses on the southwestern flank of the northern Usushwana intrusion in Swaziland and as intrusions into the Mozaan Group in the Piet Retief area (Hammerbeck, 1982). Medium- to coarse-grained quartz gabbro is the major constituent of a mafic phase that was named the *Piet Retief Gabbro Suite* by Hammerbeck (1982) and in which layering is absent or poorly developed. Discontinuous lenses of magnetitite occur in the gabbro as the overlying granophyres and micrograntes are approached. Layering is defined by variations in grain-size and by compositional changes (i.e., norite and gabbro) and the layers range in thickness from 3 to 70 m. Disseminated chalcopyrite and pyrrhotite are locally present in some layers, but not in economic concentrations. Reynolds (1981) reported that the layers and lenses of titaniferous magnetite found in the Piet Retief area are characterised by low TiO_2 (12-14%) and very low V_2O_3 (0.25%) making them unsuitable as a potential source for either of these commodities. The Piet Retief Gabbro Suite is overlain by microgranite that is commonly granophyric in texture. The term Hlelo Granite Suite has been applied to this microgranite, which probably owes its origin to a combination of crustal contamination and differentiation (Hammerbeck, 1982).

Hlagothi Complex

Numerous sills consisting of peridotitic, pyroxenitic, and gabbroic layers, and referred to as the Hlagothi Igneous Complex by Du Toit (1931), intrude the Pongola Supergroup in the upper Nsuze valley of northeastern KwaZulu-Natal (Fig. 1.13). The sills are found within an approximately 18 km-long, east-west trending zone extending from the upper Nsuze River to the Mhlatuze River northwest and north of Nkandla. Individual sills are less than 200 m thick, except for the body exposed at Hlagothi mountain, which may be somewhat thicker (Groenewald, 1988). Along the Nsuze River, where the most extensive outcrops are located, five sills are separated by 5 to 60 m-thick remnants of the Nsuze Group, which here includes sedimentary units.

The lower part of each sill comprises peridotite and/or pyroxenite, which are typically altered to assemblages of chlorite, talc, and tremolite or antigorite. Fine chromite grains are common, and secondary magnetite defines the outlines of original cumulus olivine crystals. The ultramafic lithologies are overlain by medium-grained rocks ranging in composition from gabbronorite to quartz gabbro. In the lower sills peridotite constitutes more than 50 per cent of the total thickness, but at the base of upper sills, pyroxenite is the dominant lithology overlain by gabbro. Locally skeletal pyroxene blades are present in a fine-grained, commonly variolitic groundmass identical to the spinifex texture seen in Archaean komatiitic basalts. Layering in the sills is the consequence of fractionation involving initial extraction of olivine followed by variable orthopyroxene and clinopyroxene crystallization. A weighted mean composition of the Hlagothi Complex is identical to that of a Barberton-type komatiite (Groenewald, 1988; Hunter and Wilson, 1988).

The Hlagothi Complex has yielded a poorly constrained Pb-Pb age of between 2980 and 3050 Ma suggesting that the complex was possibly contemporaneous with the Nsuze Group. If this age is confirmed, it supports a suggestion that the Nsuze Group represents a "failed greenstone belt" (Hegner *et al*., 1981).

BUSHVELD-RELATED COMPLEXES / INTRUSIONS

Several relatively small mafic-ultramafic igneous bodies occur scattered throughout the Kaapvaal Craton, many of which have not been studied in detail. Undoubtedly, the major magmatic event on the craton was the emplacement, at *c*. 2060 Ma, of the Bushveld Complex (Eales and Cawthorn, 1996), as well as many of the smaller satellite intrusions that have been linked to this event and which occur as sills, dykes or plugs. Brief descriptions of some of these bodies are given by Cawthorn *et al.* (2005) as well as in the following section, and include the Koringkoppies, Molopo Farms, Moshaneng, Rhenosterhoekspruit, Dwarsfontein, Uitkomst, Golden Valley, Vogelstruisfontein, Losberg, Kaffirskraal, and Trompsburg intrusions (Fig. 1). In addition, there are numerous pre- and post-Transvaal and Waterberg dykes and sills that have been discussed elsewhere by numerous writers (e.g., Hunter and Reid, 1987; Hunter and Halls, 1992; Uken and Watkeys, 1997), that will not be discussed further in this contribution. Short accounts of the Roodekraal, Rietfontein and Koedoesfontein intrusions are provided in the section dealing with the Vredefort Dome and surrounding terrane.

Koringkoppies intrusion

A prominent hill in the otherwise flat and featureless granitic basement terrane of the Makoppa Dome (Fig. 1.14), known as Koringkoppies, is situated approximately 40 km WNW of Thabazimbi in the Limpopo Province (Jansen *et al*., 1974). The hill, which strikes east-west, is about 1 km long and about 250 m wide, and consists entirely of massive, homogeneous, cumulate-textured, dark-green, chromiferous pyroxenite. Fresh surfaces display a waxy sheen and the rock is virtually monomineralic. The pyroxenite consists predominantly of orthopyroxene, with minor intercumulus plagioclase and specks of chromite. The pyroxenite has been interpreted to be part of an intrusive plug-like body, but it displays pseudostratification and appears to be a sheet or layer dipping approximately 30˚S. Although there is no age dating available for the pyroxenite body Jansen *et al*. (1974) and Anhaeusser and Poujol (2004), consider it to be an outlier similar to pyroxenites from the Lower Zone of the Bushveld Complex.

Molopo Farms Complex

The Molopo Farms Complex (Fig. 1.15) is a large layered intrusion, approximately 13 000 km^2 in area, mostly situated in southern Botswana, but also extending southwards into the immediately adjacent parts of South Africa near Bray on the Molopo River, approximately 230 km north of Kuruman. The Complex has an elliptical, lopolithic form, and is elongated in a NE-SW direction. It is completely covered by up to 220 m of Tertiary to Recent Kalahari Beds and was initially delineated by a regional geophysical survey (Gould *et al*., 1987). Follow-up drilling indicated that the Molopo Farms Complex is approximately 3000 m thick and is intruded into sedimentary and minor volcanic rocks of the Transvaal Supergroup (*c.* 2650-2200 Ma) and is unconformably overlain by rocks of the Waterberg Supergroup (*c.* 1880 Ma).

The Molopo Farms Complex consists of an Ultramafic Sequence and an overlying Mafic Sequence with the former unit having a much wider areal distribution (Gould *et al*., 1987; Reichardt, 1994). Post-emplacement tilting and faulting has been recorded throughout the Complex resulting in considerable subvertical displacement and segmentation of the body and host country rocks. Strongly fractionated, ultramafic-mafic sill- or dyke-like offshoots also appear to be a common feature of the Complex, and can be distinguished petrologically from younger doleritic sills and dykes encountered in the area (Reichardt, 1994).

The Ultramafic Sequence is approximately 1300 m thick and consists of olivine and orthopyroxene cumulates comprising cyclically layered harzburgite, pyroxenite and minor dunite. The cycles may vary from more than 100 m to 2m in thickness and are most common in the lower portion of the succession where over 100 individual cycles have been recognised. (Reichardt, 1994) subdivided the Ultramafic Sequence into a lower 900 m-thick Harzburgite Succession, where variably serpentinised olivine-rich cumulates dominate, and an upper 400 m-thick Bronzitite Succession, dominated by reasonably well-preserved orthopyroxene-rich rocks. Intercumulus plagioclase shows a general, but unsystematic increase upwards and two thin norite layers occur 130 and 180 m below the upper contact of the Ultramafic Sequence. Chromite is invariably present in the dunite, harzburgite and pyroxenite, but is rare in the norite. Although no chromite layers were encountered two stratigraphic intervals near the base of the succession are chromite-enriched and display occasional chromite stringers 2-10 mm thick.

The Mafic Sequence, described in detail by Reichardt (1994), varies from 1000 m to about 1500 m in thickness and consists of generally mildly altered plagioclase-dominant cumulates with minor interlayered feldspathic pyroxenites. An overall upward fractionation from norite and gabbronorite to quartz-norite, and quartz-gabbronorite to quartz-hornblende-gabbro, was established. Within the lower part of the Mafic Sequence two pyroxenite units occur separated by a 140-180 m-thick plagioclase-rich succession of norite and gabbronorite and thin pegmatoidal layers hosting minor sulphides in places. The succession above the pyroxenite units consists of quartz-norite, quartz-gabbronorite and quartz-hornblende-gabbronorite with minor feldspathic pyroxenite layers and thin pegmatoidal partings in places.

The Molopo Farms Complex contains scattered Ni-Cu-PGE+Au mineralization at various intervals throughout the intrusion, but the apparently discontinuous and presumably lens-shaped nature of the higher-grade sulphide-enriched accumulations makes exploitation of the occurrences uneconomic at this point in time.

Rb/Sr isotopic measurements have suggested the age of the Molopo Farms Complex is almost identical to the age of the Bushveld Complex (i.e., *c*. 2060 Ma; Walraven *et al*., 1990). Isotopic studies (J. M. Barton - quoted in Gould *et al*., 1987; and F. J. Kruger, quoted in Reichardt, 1994) have yielded an age of *c*. 2050 Ma, and initial $^{87}Sr/^{86}Sr$ ratios that show considerable variation of between 0.703 and 0.705 for rocks in the Ultramafic Sequence to values between 0.707 to 0.709 in the Mafic Sequence. Reichardt (1994) argued that the considerable variation in the initial ratios suggested the involvement of at least two isotopically distinct parental liquids - one an ultramafic liquid which produced the massive, olivine-enriched cumulates of the Ultramafic Sequence and a gabbroic liquid which gave rise to the feldspathic pyroxenites of the Ultramafic Sequence and the gabbronoritic rocks of the Mafic Sequence. He added further that the isotopic and mineral-chemical evidence suggested that repeated mixing processes between the two liquids had led to the development of an approximately 1000 m-thick package of alternating lithologies, which form the upper part of the Ultramafic Sequence and the lower part of the Mafic Sequence. This is borne out by the pronounced variations in initial ratios encountered in the mixed succession and repetitive, pseudo-cyclic layering, numerous reversals in orthopyroxene compositions, and the pervasive occurrence of disseminated sulphides over almost the entire width of the mixed succession.

Moshaneng Complex

The Moshaneng Complex is situated in Botswana in the northwestern sector of the Kaapvaal Craton, about 80 km WSW of Gaborone and approximately midway between the Bushveld Complex in the east and the Molopo Farms Complex in the west (Fig. 1.16). The intrusion is exposed over an oval-shaped area of about 35 km^2, but its actual size has not been determined because of a blanket of Palaeoproterozoic Waterberg sedimentary rocks lying unconformably on the both the Complex and on the host Transvaal Supergroup dolomites.

Past uncertainties as to the nature and origin of the Moshaneng Complex appear to have been dispelled following investigations by Aldiss *et al*. (1989) and Mapeo *et al*. (2004) who described the intrusion as a normally zoned body composed of a dioritic-gabbroic core and a wider syenitic granitic rim. The main rock types of the *c*. 3 x 1 km core zone are coarse- to medium-grained gabbros and diorites, the latter formed by the mingling and mixing of mafic and felsic magmas. The surrounding rim rocks consist of porphyritic to fine-grained granites and pink syenites that are considered to have formed by the melting of crust in the vicinity of the mafic magmas of the intrusion.

U-Pb isotopic analyses of single zircon and sphene grains from the Moshaneng granites yielded a crystallization age of 2054±2 Ma suggesting that the Complex is coeval with the *c*. 2060-2050 Ma Bushveld Complex (Mapeo *et al*., 2004). The Moshaneng Complex is itself intruded by a mafic igneous body termed the Moshaneng Dolerite, which also regionally intrudes the Waterberg Group sedimentary sequence (Aldiss *et al*., 1989). The Dolerite, in turn, has a U-Pb zircon age of 1079 ±

2 Ma (Pancake, 2001), suggesting that it is part of the Mesoproterozoic Umkondo igneous province of southern Africa.

Rhenosterhoekspruit intrusion

The Rhenosterhoekspruit mafic body is situated approximately midway between Bela-Bela (Warmbaths) and Thabazimbi in southwestern Limpopo Province (Fig. 1.17) and intrudes Pretoria Group sediments of the Transvaal Supergroup. The body, which occurs on the farm Rhenosterhoekspruit 466KQ, has a length of approximately 5 km and a width of about 1.5 km and consists mainly of gabbroic rocks similar to those of the Upper Zone of the Bushveld Complex. A number of magnetitite layers are also present (Mathenjwa, 1995; Cawthorn *et al*., 2005)

Dwarsfontein intrusion

The Dwarsfontein ultramafic-mafic body (Fig. 1.18) is situated approximately 50 km southeast of Pretoria and about 27 km northeast of Delmas, and is regarded as a satellite intrusion of the Bushveld Complex (Cluff Mining Plc., 2004). It may, however, be directly linked to the main complex, falling in the zone intermediate between the Bushveld exposures northeast of Pretoria and the southeastern or Bethal limb of the Complex, which is hidden below younger cover sediments. The layered rocks encountered during exploration drilling on the farm Groenfontein 206 IR (Fonte Verde Prospect) constitute a condensed Bushveld Complex stratigraphy with analogues of the Lower, Main and Upper Zones, the Critical Zone being absent. Sulphide mineralisation was reported in clinopyroxene-olivine cumulates of the Lower Zone, the mineralised package ranging from 2-13 m in thickness and occurring on or near the basal contact of the intrusion. The Fonte Verde mineralisation reportedly has a style and mode of occurrence similar to the Platreef of the Bushveld Complex.

Uitkomst Complex

The Uitkomst Complex, located 20 km north of Badplaas in Mpumalanga Province (Fig. 1.19), and exposed over a distance of 9 km, is an approximately 800-850 m-thick, mineralised layered ultramafic-mafic intrusion with an anvil-shaped cross-section, which was emplaced into the lower sedimentary rocks of the Transvaal Supergroup. The intrusion was first described by Wagner (1929) as an ultramafic sill consisting of platiniferous amphibolitized pyroxenitic rocks with high Ni values. Subsequently, Kenyon *et al*. (1986) investigated the economic potential of the body and concluded that the complex showed inverted chemical layering. Later, Von Scheibler *et al*. (1995) intimated that several magma injections were responsible for the variability in abundance of sulphides found within the pyroxenites and peridotites.

Gauert *et al*. (1995) subdivided the Complex into six lithological units. From bottom upwards these include: (1) Basal Gabbro; (2) Lower Harzburgite; (3) Chromitiferous Harzburgite; (4) Main Harzburgite; (5) Pyroxenite; and (6) Gabbronorite.

The *Basal Gabbro Unit*, which varies from 0-15 m in thickness (average 5.6 m) represents a contaminated early pulse of magma and has a chilled margin up to 1.5 m thick resting on a sheared footwall of Black Reef Quartzite Formation. The predominantly gabbroic unit shows intense saussuritisation and uralitisation and carbonate veining is prominent.

The *Lower Harzburgite Unit* averages 50 m in thickness (max. 90 m), is highly altered and contains numerous xenoliths of country rock, including fragments of quartzite and carbonaceous material orientated parallel to the igneous layering. Poikilitic harzburgite is the dominant phase with feldspar-bearing lherzolite, sulphide-rich feldspathic olivine-wehrlite, amphibolite and pegmatoidal pyroxenite also present. Although the primary minerals are serpentinised, saussuritised and uralitised the original igneous textures are still well preserved.

The *Chromitiferous Harzburgite Unit* averages 60 m in thickness and is gradational from the underlying harzburgitic assemblage. Chromite gradually increases from tracee amounts in the underlying unit to become a major component in the harzburgites in this unit. It continues to become increasingly more massive and shows well-preserved igneous layering, with the top of the unit consisting of a 3-4 m-thick massive chromitite (Gauert *et al*., 1995). The original magmatic minerals associated with the chromite are almost completely replaced by talc, carbonate, phlogopite, chlorite and serpentine.

The *Main Harzburgite Unit* comprises more than a third of the thickness of the Complex having an average thickness of 330 m and consisting mainly of macro-layered, serpentinised harzburgite grading locally into dunite. Mineralisation is generally absent in this unit except in the lower 10 m.

The *Pyroxenitic Unit* has a sharp to transitional contact with the underlying harzburgites and dunites and is approximately 60 m thick. A lower sub-unit consists olivine-orthopyroxene. This is followed by a pure orthopyroxene sub-unit with minor chromite and sulphide in the middle, and an upper sub-unit consisting of norite to gabbronorite. The sequence, which is largely unaltered, marks the transition between the ultramafic lower units of the intrusion and the upper mafic unit in that olivine disappears and plagioclase enters the mineral assemblage (Gauert *et al*., 1995).

The *Gabbronorite Unit* follows with a gradational contact and forms the uppermost sequence consisting of approximately 250 m of gabbronorite, the upper part of which contains xenoliths of quartzite and shale and shows a chilled contact with the Lower Timeball Hill Shale hangingwall.

The Uitkomst Complex is an important source of Ni-Cu-Co-PGE+Au mineralization and also contains abundant chromite. Most of the sulphides are concentrated in the Basal Gabbro and Lower Harzburgite units and consist mainly of pyrrhotite, pentlandite, chalcopyrite, digenite and pyrite. Minor amounts of violarite, mackinawite, galena, sphalerite, Pt-group minerals, awaruite, native copper, arsenpyrite, cobalt and millerite have been recorded. In addition, titaniferous magnetite, ilmenite and chromite are also present (Wagner, 1929; Kenyon *et al*., 1986; Gauert *et al*., 1995).

The intrusion has generally been linked to the *c*. 2060-2050 Ma age of the Bushveld magmatic event. De Waal *et al*. (2001) published a ^{207}Pb/^{206}Pb SHRIMP age on zircons that yielded an age of 2044±8 Ma placing it close to the *c*. 2054 Ma Rb-Sr age obtained by Hamilton (1977), but less than the *c*. 2060 Ma age recorded by Walraven *et al*. (1990).

Golden Valley intrusion

Golden Valley (Fig. 1.20) is a small igneous body approximately 2 km by 1 km, located on the farm Golden Valley 621 IQ approximately 8 km south of Magaliesberg near the boundary between the Gauteng and North West Provinces. The intrusion, which consists mainly of pyroxenite, norite and gabbro, has been emplaced into Pretoria Group sediments of the Transvaal Supergroup. Drilling by Anglo American Prospecting Services encountered nickel-sulphide and platinoid mineralisation in the body, which is regarded as a satellite intrusion of the Bushveld Complex (A. Jamison, person. commun.).

Vogelstruisfontein intrusion

The Vogelstruisfontein body (Fig. 1.21), situated midway between Johannesburg and Randfontein on the farm Vogelstruisfontein 233 IQ, was first identified following a detailed gravimetric and magnetometric survey over a dolomite basin south of the Durban Roodepoort Deep Gold Mine (see 1: 250 000 Geological Series 2626 West Rand Sheet; Keyser, 1986). According to Borchers (1953), a circular, positive gravity anomaly was located in an area devoid of outcrops, and a magnetic anomaly was detected near the northern edge of the feature. Drilling revealed an igneous body approximately 3 km in diameter consisting of feldspathic pyroxenite, the latter intruded into dolomites of the Transvaal Supergroup. Borchers (1953) was of the opinion that the rocks were associated with the Bushveld Complex, and had contributed to the structural complexity seen in the Witwatersrand and Transvaal successions in the West Rand Gold Field.

Losberg Complex

The Losberg Complex, located approximately 70 km southwest of Johannesburg in the North West Province (Fig. 1.22), is a subhorizontal, sheet-like layered mafic body intruded into shales and quartzites of the Transvaal Supergroup (Jansen, 1954). According to Abbott and Ferguson (1965) the intrusion can be divided into three units. From the base upwards the sequence, which is approximately 130 m thick, consists of: (1) a zone of harzburgite, comprising an orthopyroxene-olivine cumulate; (2) a quartz-norite zone, consisting of a plagioclase-orthopyroxene-clinopyroxene cumulate assemblage; and (3) a quartz-gabbro zone, consisting of a plagioclase-clinopyroxenite cumulate. Rocks formed immediately below the roof are not cumulates and include chill-phase gabbro and some late residual liquids gave rise to non-cumulate late-phase augite granophyre.

The harzburgite cumulate zone at the base is approximately 18 m thick and shows rhythmic layering. The quartz-noritic zone is only about 10 m thick, but exposures of this rock type 3-5 km south of the main intrusion suggest that the norite sheet had a wider distribution than is now evident. The overlying quartz-gabbroic zone is approximately 102 m thick. Following the intrusion of the harzburgite crystal fractionation was modified by two subsequent less mafic major additions of magma indicating that differentiation took place in depth prior to emplacement (Abbott and Ferguson, 1965).

The intrusion is approximately horizontal in the east, but dips southwards at the western end and bears a discordant relationship to the Transvaal Supergroup sediments. Abbott and Ferguson (1965) maintained that the form of the intrusion suggested it was not influenced by the Vredefort structure to the south and that the Losberg magma was emplaced after the doming event, which is thought to have occurred at 2023±4 Ma (Kamo *et al*., 1996). However, Coetzee and Kruger (1989) obtained a Rb-Sr age of 2041± 41 Ma on mica from the Losberg Complex and maintained that the geology, age, strontium isotopic signature and chemistry of the Losberg intrusion are within error of the ‘preferred’ age of the Bushveld Complex (2061±27 Ma; Walraven *et al*., 1990) and they, together with Cousins (1959) held the view that these (and several other mafic igneous bodies, such as Kaffirskraal, Vogelstruisfontein and Brandfort) could be regarded as coeval and part of the same magmatic event.

Kaffirskraal Complex

The Kaffirskraal Complex (Fig. 1.23), located 16 km southwest of Heidelberg (Gauteng Province), is a relatively small, poorly exposed, pear-shaped layered body measuring approximately 1.6 km in length and 1km in width. It is intruded into lavas of the Ventersdorp Supergroup and has been described by Frick (1975, 1979) as a zoned ultramafic complex originating from the multiple intrusion of magmas differentiated in depth. The first magma yielded gabbros and norite, which are not prominently exposed. The second, more mafic magma, appears to have erupted through the earlier gabbro and norite resulting in the development of a Layered Zone consisting magnetite clinopyroxenite and magnetitite. Xenoliths of gabbro and norite from the early intrusion as well as inclusions of quartzite and sillimanite hornfels, believed to be from the underlying Witwatersrand Supergroup, occur in the magnetite clinopyroxenite. Frick (1975) also recognised a 1 m-thick Marginal Zone consisting of porphyritic norite, with large phenocrysts of orthopyroxene set in a fine-grained matrix of plagioclase, clinopyroxene and magnetite, lying unconformably below the magnetite clinopyroxenite. A chemical analysis of a sample from the marginal phase yielded approximately 20% MgO and the rock was defined by Frick (1975) as being hornblende-peridotitic.

The magnetite clinopyroxeneite, which is a coarse-grained rock, consists of augite, titaniferous magnetite and ilmenite with secondary biotite and uralite and displays igneous layering due to the orientation of the clinopyroxene crystals. The magnetitite constitutes the top of the exposed succession and occurs as a 8m-thick layer conformably overlying the magnetite clinopyroxenite. The magnetitite is an essentially monomineralic rock consisting of titaniferous magnetite and minor, but variable amounts of granular ilmenite and augite. Oxidised alteration products of the ores include titaniferous maghemite, martite, goethite and leucoxene. The titaniferous magnetite is also vanadium-bearing with V^2O^3 contents ranging between 0.7 and 0.59 per cent and Reynolds (1980) regarded the Kaffirskraal ores as being both chemically and texturally similar to the titaniferous iron ores of Subzone C of the Bushveld Complex.

The Kaffirskraal Complex appears to have a funnel shape, with steeply dipping outer contacts. The outer marginal phase has a steep dip of about 70º towards the centre of the intrusion, but the overlying layered portion of the complex, including also the magnetitite, shows a centroclinal dip of only about 4 degrees.

According to Frick (1975), the Kaffirskraal Complex can be considered a layered intrusion, but it also exhibits features which indicate the body differs significantly from those usually found in layered complexes, such as an inverted succession of rock types, an ultramafic marginal phase, a disproportionately large metamorphic aureole and mineral characteristics similar to those reported in zoned ultramafic complexes in Alaska and the Urals (Taylor and Noble, 1969).

The Kaffirskraal Complex has not yet been dated, but it is post-Ventersdorp Supergroup in age and is most likely related to the *c.* 2060 Ma Bushveld Complex.

Trompsburg Complex

A roughly circular gravity anomaly of unique magnitude, located near the Free State Province town of Trompsburg (Fig. 1.24), was first outlined by B.D. Maree of the Geological Survey of South Africa in 1942. Subsequent gravimetric and magnetometric surveys confirmed the presence of a *c.* 50 km diameter gravity high with a maximum amplitude of 99.5 mGal coinciding with a modest magnetic high (Buchmann, 1960). Drilling revealed the presence, at depths approaching 1200m below surface, of an igneous mass, intrusive into dolomite/marble (believed to be part of the Transvaal Supergroup) and overlain unconformably by Karoo sediments (Ortlepp, 1959; Buchmann, 1960). Two magnetic anomalies (amplitudes of 300-400γ) were also found in the NW sector of the area surveyed, an outer anomaly along the margin of the intrusion and an inner anomaly closer to the centre of the intrusion, which was reportedly due to the presence of titaniferous magnetite.

The drilling also indicated a lopolithic mafic layered intrusion estimated to be 2000-3000 m thick by Ortlepp (1959). Buchmann (1960) and later Maré and Cole (2004), created three dimensional models suggesting that the thickness could be as much as 10 000 m. The age of the Trompsburg Complex was first reported by Davies *et al.* (1970) to be 1372±142 Ma (Rb-Sr isotopic age: R_o= 0.7066±0.0196), but a more recent SIMS U-Pb age on zircons from gabbroic samples places the intrusion at 1915.2±5.6 Ma (Maier *et al*., 2003b). This positions the Trompsburg Complex closer to the *c.*2054 Ma Bushveld Complex age determined by Hamilton (1977). Although Buchmann (1960) and Reynolds (1978) supported the view that the rocks of both these complexes are strikingly similar Maier *et al.* (2003b) maintained that the lower Sr initial ratio of the Trompsburg Complex (R_o = *c.* 0.704) rendered a genetic link with the Bushveld unlikely. This, however, may not entirely rule out a closer link as McCarthy and Cawthorn (1980) demonstrated that fractionation of Rb/Sr ratios, coupled with protracted crystallisation can produce changes in $^{87}Sr/^{86}Sr$ ratio greater than analytical error.

Studies of borehole core (Ortlepp, 1959; Buchmann, 1960; Reynolds, 1978) revealed the presence of mainly coarse-grained gabbros and anorthosites, characterized by an abundance of titaniferous magnetite. Nineteen titaniferous magnetite layers ranging from 150mm to 4.5m occur in the upper 300 m of one of the boreholes. These are generally well developed and seven are more that 2.4 m thick. Reynolds (1978) described these as ores composed of large multi-phase titaniferous magnetite grains containing minor lamellar ilmenite and abundant ulvospinel and pleonaste micr-intergrowths. Variable amounts of granular ilmenite are present and high vanadium contents (*c.*1.82% V_2O_5) were recorded in the magnetites (Ortlepp, 1959).

The gabbro consists mainly of plagioclase (labradorite and anorthite), diallage, olivine, biotite, enstatite, hornblende, hypersthene and apatite. Primary sulphide minerals include pyrrhotite (some containing exsolution pentlandite), chalcopyrite and pyrite with secondary marcasite. The anorthosite is mottled or speckled with plagioclase (anorthite and labradorite), pyroxene (diallage), magnetite and sulphides. Olivine gabbro (troctolite) is concentrated towards the outer rim and contains more olivine and pyroxene than the main gabbro. Coarse-grained red granite, similar in appearance to Bushveld Granite (Buchmann, 1960), was encountered in one borehole near the centre of the gravity anomaly and narrow dykes of aplogranite were recorded in all the other boreholes (Ortlepp, 1959).

Despite the age constraints outlined above the lithological similarities of the Trompsburg Complex with the Bushveld suggests that the body may represent a satellite body of the Bushveld Complex located near the southern edge of the Kaapvaal Craton. The large intrusive body could represent a significant exploration target for platinum group metals, but the great depth of the intrusion will probably preclude any mineral occurrences being exploited in the foreseeable future.

NAMAQUA-NATAL METAMORPHIC BELT

Natal Tectonic Belt (Tugela Terrane)

Mesoproterozoic rocks, variously ascribed to the Tugela Terrane (Thomas, 1989), the Natal Metamorphic Province (Thomas *et al*., 1990) or the Natal Tectonic Belt (Pather *et al*., 2000), occur in a series of poorly exposed basement inliers in the Tugela Valley of KwaZulu-Natal. These rocks, which have an east-west structural grain, fall within the age range of *c.* 1250-900 Ma (Eglington *et al*., 1989; Thomas and Eglington, 1990), and are in tectonic contact with the Archaean rocks of the Kaapvaal Craton situated to the north (Matthews, 1959). Matthews (1972) and Matthews and Charlesworth (1981) suggested that the northern part of the tectonic belt represents a deformed and metamorphosed obduction zone (Natal Thrust Belt and Natal Nappe Complex) involving a succession of mafic and ultramafic rocks (interpreted as comprising oceanic crust and forming parts of an ophiolite complex - Fig. 1, 25-28), together with metasediments and metalavas, thrust onto the stable foreland of the Kaapvaal Craton in a series of thrust nappes along a sole décollement known as the Mfongosi thrust.

Extensive, but discontinuous sheets of talc schist with pods of serpentinite occur along the basal slides of most of the major thrust sheets. The upper and most extensive thrust sheet (Tugela nappe, Matthews and Charlesworth, 1981) is composed almost entirely of amphibolites and a number of metamorphosed mafic and ultramafic intrusions with occasional serpentinites containing podiform segregations of chromite. In the west, approximately 10-30 km north and northeast of Kranskop, some of the intrusions include the Tugela Rand, Macala, Mambula, Ntulwane, Sitilo and Fort Yolland complexes. In the east the Mlalazi and Hlobane complexes are exposed between Eshowe and Empangeni.

Tugela Rand Complex

The Tugela Rand intrusion (Fig. 1.25) forms a layered, differentiated, mafic to ultramafic body intruding amphibolite gneisses of the Tugela Nappe (Tugela Terrane), about 10 km north of Kranskop. The intrusive mass has a basin-shaped “lopolithic” structure, is underlain by granite and gneiss, and is composed of peridotite in the centre, under which dips a pyroxenite-norite mass. Lambert (1962) and Harmer (1979) agreed with Du Toit (1931) who first suggested that the complex represents a multiple intrusion, the order of injection being peridotite-pyroxenite-norite-granite in a descending structural sequence. Dix (1979) added controversy by suggesting that the mafic-ultramafic components of the intrusion represent a structurally inverted sequence. He reported scour structures and several macro-rhythmic units with reverse zoning (downwards from dunite to websterite to gabbronorite) and attributed the inversion to the location of the complex within the inverted limb of a large recumbent fold thrust northwards above granitic and dioritic orthogneisses.

Lambert (1962) recognised two generations of serpentinite; an older primary serpentinite and a younger variety derived from the deuteric alteration of dunites and peridotites. Thomas *et al.* (1990) reported small, irregular, low-grade chromite ore bodies occurring within the serpentinite, as well as Cu, Ni, and Co sulphides disseminated within the lowermost pyroxenitic and peridotitic rocks.

The intrusion, also referred to as the Tugela Rand Layered Suite, represents the product of alkali basalt magmatism at *c*.1200 Ma and was intruded prior to the main deformation and metamorphism (Wilson, 1990).

Mambula Complex

The Mambula layered mafic-ultramafic complex (Fig. 1.26) intrudes amphibolites of the Tugela Terrane approximately 20 km east of Kranskop. The intrusion, which outcrops over an area of approximately 25 km^2, is circular and broadly funnel or saucer shaped, and consists largely of medium-grained gabbro with titaniferous magnetite layers, together with subordinate norite and websterite and coarse-grained to pegmatitic pyroxenite and anorthosite dykes (Du Toit, 1919, 1931; Schulze-Hulbe, 1979; Thomas *et al*., 1990). At least six vanadium-bearing titaniferous magnetite layers varying between 1 and 5m in thickness have been recognised (Reynolds, 1986a). The nature and occurrence of these ores, which contain Ti-magnetite, ilmenite and pleonaste, and 10-30% silicate phases (plagioclase, clinopyroxene and minor hypersthene), are consistent with them having formed by fractional crystallisation of a mafic magma from which the Mambula Complex crystallised. The more felsic and Fe-rich nature of the intrusion suggests it represents a higher part of a layered complex than the Tugela Rand body (Reynolds, 1986a), but it is uncertain whether both bodies are the result of the same magmatic episode. Deformation is mainly confined to the margins of the Mambula Complex and medium-grade metamorphism has affected the rocks. Foliated xenoliths of amphibolite also occur in the marginal zone. Matthews and Charlesworth (1981) suggested that the complex was a syntectonic intrusion and Thomas *et al*. (1990) stated that it was also dismembered by northward-directed thrusting.

Sithilo Complex

The Sithilo ultramafic intrusion (Fig. 1.27), like most others in the Tugela Valley, intrudes amphibolites of the Tugela Terrane about 27 km west of Eshowe. The complex, which has a strike length of approximately 3 km, varies in width from 0.5 to 1 km. It consists largely of serpentinised dunite, harzburgite and orthopyroxenite and in places displays veins of good quality chrysotile asbestos and at least four low-alumina chromite ore bodies. The chromite is characteristically developed in lensoid bodies that grade along strike from massive chromite with a plus 60% Cr_2O_3 content and a Cr/Fe ratio of 3 to disseminated chromite grading less than 5% Cr_2O_3 (Lambert, 1962; Wuth and Archer, 1986; Thomas *et al*., 1990). Wuth and Archer (1986) also reported the presence of a pipe-like body of chromite 15 m in diameter and discordant to the surrounding host rocks. The Sithilo body is cut by several late-stage aplite dykes and asbestos mineralization occurs in the sheared serpentinites immediately adjacent to the dykes.

Although tectonism has influenced the present disposition of the chromite at Sithilo primary magmatic differentaiation played a significant role in the early localisation and concentration of the mineralization (Lambert, 1962; Wuth and Archer, 1986). These authors further concluded that in terms of lithology, structure and tectonic setting the Sithilo body shows affinities with the ultramafic portions of typical chromite-bearing, alpine-type, podiform ophiolitic ultramafic complexes like those described by Thayer (1967).

Other ultramafic-mafic complexes in the Tugela Terrane

In addition to the Tugela Rand, Mambula and Sithilo intrusions there are numerous other ultramafic-mafic bodies in the Tugela Terrane about which little has been published. Most of the bodies are podiform in character and have been tectonised, metamorphosed and serpentinised. Most also contain showings of chromite. The Macala intrusion situated about 20 km northeast of the Tugela Rand body consists primarily of metagabbro, whereas serpentinites and talc schists make up most of the smaller occurrences near Middledrift about 8 km northwest of Mambula. The

Ntulwane and Fort Yolland complexes located approximately 2 km and 5 km northeast of Sithilo, respectively, also consist dominantly of serpentinites and talc schists with stringers of chromite and thin seams of chrysotile asbestos (Charlesworth, 1981).

In the east, between Eshowe and Empangeni (Fig. 1.28), the Mlalazi and Hlobane ultramafic-mafic complexes occur adjacent to the Frontal Thrust Belt (Natal Thrust Belt) and have been described by McCarthy (1961) and Charlesworth (1981). The Mlalazi Complex, about 6 km due east of Eshowe, comprises three units, namely: the Emtilombo serpentinite and subordinate metapyroxenite body, the Mpumazi ultramafic schists made up predominantly of talc-amphibole-chlorite rocks, and the Tanjane metagabbros, which in places contains deformed lenses, rafts and sheets of amphibolite. The Hlobane Complex, located about 12 km west of Empangeni, consists predominantly of large pod or lens-like bodies of metagabbros, the compositions of which vary from medium- to coarse-grained olivine norites, troctolitic gabbros and leucogabbros. Gradational contacts occur and thin anorthositic bands are present in places and an impersistent lens of serpentinite occurs on Hlobane Hill (McCarthy, 1961; Charlesworth, 1981). As with all the other ultramafic-mafic intrusive bodies occurring along the northern margin of the Natal Metamorphic Province these complexes are regarded as having resulted from the differentiation of ultramafic-mafic magmas that were intruded and subsequently deformed and metamorphosed at the time of ophiolite obduction and nappe development adjacent to the southern margin of the Kaapvaal Craton approximately 1250-900 Ma.

East Namaqualand Belt (Kakamas Terrane)

Oranjekom Complex

As with the Tugela Terrane (Natal Tectonic Belt) in the eastern sector of the Namaqua-Natal metamorphic belt, the Namaqua sector of the belt (Kakamas Terrane) also possesses a number of small, ultramafic-mafic to anorthositic, layered intrusions or plugs that were emplaced early in the evolution of the Namaqua Front and have subsequently been deformed and metamorphosed to amphibolite grade (Poldervaart and Von Backström, 1950; Vajner, 1974; SACS, 1980; Geringer *et al*., 1990). The ultramafic-mafic bodies occur in different stratigraphic horizons, including the Marydale and Kaaien Groups, the Korannaland Supergroup and the calc-alkaline granitoids of the Keimoes Suite. Southwest of Prieska are the Waterkop and Plat Sjambok complexes (gabbro, anorthosite, syenite), while to the east of Kenhardt are the Brakboschpoort (olivine gabbro, gabbronorite) and Irene (gabbro) intrusives. Vajner (1974) also reported two small serpentinite bodies near Putsonderwater located midway between Prieska and Upington.

Another cluster of gabbro-anorthosite intrusions occurs southeast and northwest of Kakamas (Geringer *et al*., 1990). Of these, the Kakamas South Complex, situated approximately 10 km southeast of Kakamas is the largest (*c*. 8 km long and 1-2 km wide). Other intrusions still further southeast include the Middel Post and Koegab bodies. Northwest of Kakamas are the Kakamas North, Oranjekom and Zeekoesteek bodies.

The Oranjekom Complex (Fig. 1.29), about 28 km northwest of Kakamas, is the best exposed, preserved and most accessible of the intrusions and has been studied in detail by Geringer *et al*. (1990) and Kruger *et al*. (2000). The intrusion has a strike length of over 8 km and is approximately 1.4 km wide. It comprises a deformed, layered suite of rocks and small plugs consisting of metamorphosed gabbro, leucogabbro, anorthosite and subordinate bronzitite, intruded into pre-tectonic gneissic granite and metasediments. The rocks were named by Geringer *et al*. (1990) according to estimates of the modal percentages of plagioclase, orthopyroxene, clinopyroxene and amphibole: gabbro (50-60% plagioclase); leucogabbro (60-80% plagioclase) and anorthosite (> 80 % plagioclase).

The Complex according to Kruger *et al*. (2000) has a *Marginal Zone* consisting of fine-grained metagabbro interpretted to be a chilled margin, a *Transitional Zone* dominated by leucogabbro, megacrystic leucogabbro and anorthosite, and a *Central Zone* consisting mainly of massive metagabbro with subordinate meta-leucogabbro. Although recrystallisation and deformation has occurred the rocks preserve a high proportion of their original mineralogy, textures and small-scale layering features.

A Rb-Sr isochron plot indicates that the Oranjekom Complex was intruded and metamorphosed at *c*. 1095±70 Ma ($^{87}Sr/^{86}Sr$ initial ratio of 0.70395) and is within error of the Sm-Nd errorchron age of 1221±249 Ma (Kruger *et al*., 2000). Field evidence and isotope data indicate, however, that the Complex predated the intrusion of the Keimoes Suite batholith dated between 1150and 1200 Ma (Barton and Burger, 1983). The intrusion appears to have had a MORB-like source with an age of *c*. 1230 Ma, but was emplaced into crust thickened by subduction or thrusting and subvertivcal movement at a later stage (*c*. 1100 Ma) and was affected by a second metamorphism at *c*. 944 Ma (Geringer *et al*., 1990; Kruger *et al*., 2000).

UMKONDO IGNEOUS PROVINCE

Large-scale magmatism, responsible for the emplacement of huge volumes of mantle-derived magmas over an area of 2 million km^2, occurred approximately 1106-1112 million years ago in southern Africa (Allsopp *et al*., 1989; Hanson *et al*., 2004a). This event gave rise to the term *Umkondo Igneous Province*, named for the extensive diabase sills, up to hundreds of metres thick, intruded into Palaeoarchaean to Mesoproterozoic formations and cratonic basement rocks on the Kaapvaal Craton and areas beyond. Included in this group are the sill-like intrusions, such as the Timbavati Gabbro (Figs. 1.30, 24) and the Anna's Rust Gabbro (Figs. 1.3, 18) described below, and the sills of diabase and gabbro that were injected into the Umkondo, Palapye and Waterberg Groups in Zimbabwe, Botswana and South Africa (Hanson *et al*., 2004b).

Timbavati Gabbro intrusion

The Timbavati Gabbro (Fig. 24) comprises a number of igneous bodies of mafic to ultramafic composition intruded into granitic, gneissic and migmatitic Archaean basement rocks of the Mpumalanga Lowveld The predominantly gabbroic rocks crop out in a series of koppies and ridges in the western half of the Kruger National Park and extend southwards from the Shingwedzi River in the north to the Crocodile River in the south – a distance of approximately 270 km (Brandl, 1985a; Walraven, 1986, 1989; Walraven and Hartzer, 1986). The discontinuous outcrops appear to represent remnants of an extensive sill or laccolith and follow a roughly zig-zag type pattern which is particularly irregular south of the Olifants River in the centre of the Park (Saggerson and Logan, 1970). Pre-existing basement structures influenced the emplacement of the gabbroic rocks since there is a close correlation between trends of the dyke and sill sections and faulting, jointing and regional foliation noted in the basement granitoids (Bristow *et al*., 1982). The highly irregular surface pattern of the outcropping sills was described by Walraven (1984b) as arcuate – the rocks having been intruded along conical fractures dipping inward at shallow angles of about 20-30˚. Estimates of the thickness of the gabbro sills vary from around 200 m to between 300 and 480 m (Walraven, 1984b).

Early investigations of the Timbavati Gabbro led to the conclusion that it represented a single, differentiated intrusion, but a geochemical study undertaken by Walraven (1984b) led him to conclude that the magma was emplaced as a number of separate intrusive pulses involving at least three different rock types. These include: (1) quartz gabbro (comprising clinopyroxene and plagioclase accompanied by smaller grains of orthpyroxene and lesser amounts of quartz, amphibole, biotite, ilmenite, magnetite, chalocopyrite and pyrite); (2) a coarse-grained, quartz-free gabbro with large grains of orthopyroxene and smaller clinopyroxene grains (together with lesser amounts of olivine, plagioclase, biotite, ilmenite, magnetite, chalcopyrite and pyrite); and (3) medium-to coarse-grained olivine gabbro consisting of olivine, clinopyroxene, plagioclase and orthopyroxene (with minor magnetite, ilmenite, biotite and chromite).

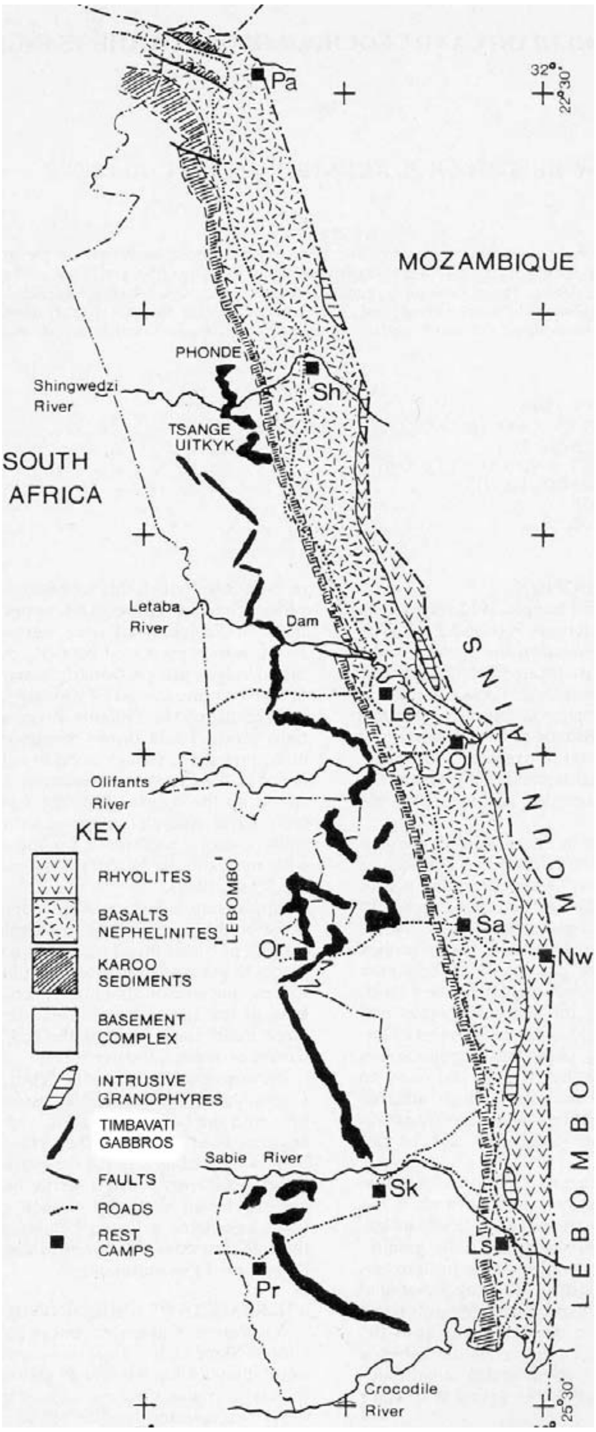

Figure 24. *Simplified geological map of the northeastern part of the Kaapvaal Craton showing the distribution of the Timbavati gabbro intrusion in the Archaean basement granitoid gneisses of the Kruger National Park. Abbreviations signify rest camps in the park (e.g., Pr= Pretorius Kop; Sh= Shingwedzi). The distance between the Shingwedzi and Crocodile Rivers is approximately 270 km (map after Bristow et al., 1982; Brandl, 1985a, Walraven, 1986; Walraven and Hartzer, 1986).*

In view of the fresh nature of the gabbroic rocks the Timbavati Gabbro was initially considered to be related to the Karoo age dolerites (Visser and Verwoerd, 1960), but later investigations revealed that Karoo strata overlie the gabbro. Published radiometric ages (Burger and Walraven, 1979, 1980) range from 1072 ± 4 Ma to 1123 ± 5 Ma ($^{40}Ar/^{39}Ar$) to 1454 ± 50 Ma (Rb-Sr; Bristow *et al*., 1982). Studies by Hargraves *et al*. (1994) led to the discovery that the palaeomagnetic pole of the Timbavati Gabbros coincides closely with others obtained from coeval mafic igneous rocks in Zimbabwe, Botswana and elsewhere in South Africa, confirming the wide areal extent (~1200 x 800 km) of the *c*. 1100 Ma Umkondo (Kibaran) igneous event (Allsopp *et al*., 1989; Hanson *et al*., 2004a).

Anna's Rust and Vredefort Mafic Complexes

As noted earlier, a suite of mineralogically and chemically related mafic intrusions of late Mesoproterozoic age, occur in the core and collar of the Vredefort Dome (Nel, 1927a, b; Bisschoff, 1972a, b; 1999). Included among these bodies is the Anna's Rust Sheet and related gabbroic intrusions collectively referred to by Reimold *et al*. (2000) as the Vredefort Mafic Complex (Fig. 18). The Anna's Rust Sheet (Anna's Rust Gabbro; Hanson *et al*., 2004a) comprises an undulose, subhorizontal, sheet-like intrusion, ~120m thick, exposed to the east of the Vaal River and extending from the core-collar transition in the north to the region a few kilometres east and south of Parys. Exposures of the Vredefort Mafic Complex occur in the centre of the dome, close to Vredefort, and at various localities to the east of the town. Boreholes drilled at a number of widely separated localities in the central parts of the dome have intersected gabbroic rocks that, on geochemical grounds, are also considered to form part of the complex (Pybus, 1995). The gabbros are also devoid of any shock deformation effects, pseudotachylite veins or breccia (Reimold *et al*., 2000) and their widespread development on the dome suggests that they represent a shallow, sill-like intrusion, only partially exposed in places, as at Anna's Rust (Reimold *et al*., 2000).

The gabbroic rocks consist of plagioclase, clinopyroxene, minor orthopyroxene, titanomagnetite, ilmenite and some biotite. Chemically the rocks possess high-Ti values, show ophitic textures and can generally be distinguished from other mafic bodies in the region (such as Karoo dolerites) by the presence of glomeroporphyritic plagioclase. Rb-Sr and ^{40}Ar-^{39}Ar age dating suggest the rocks were intruded into the Kaapvaal Craton approximately 1200-1000 Ma ago, and are seen by Friese *et al*. (1995) and Reimold *et al*. (2000) to be part of the Kibaran (Umkondo/Grenville) orogenic cycle. More recently, Hanson *et al*. (2004b) referred to the intraplate magmatism as part of the Umkondo Igneous Province.

Greenlands dykes and sills

Three different populations of mafic dykes and sills were recorded by Minnitt *et al*. (1994) in the Greenlands Greenstone Complex situated approximately 27 km from Parys in the southeast quadrant of the Vredefort Dome (Fig. 1.31). In addition to Karoo-age dolerite intrusives these authors reported dykes and sills with occasional pseudotachylite veining, together with others chemically and petrologically similar to the high-Ti tholeiitic rocks of the Anna's Rust Sheet and Vredefort Mafic Complex, intruded into Archaean ultramafic-mafic lavas (komatiites, komatiitic basalts and tholeiites). No direct ages are available for the Greenlands dykes and sills (or the mafic intrusions on the farms Hester and Oceaan to the northwest of Greenlands - Fig. 18), but they are also believed to form part of the Umkondo magmatic event (Minnitt *et al*., 1994; Reimold *et al*., 2000).

Majuba Gabbro intrusion

A sill-like intrusion of gabbroic rocks, mineralogically and chemically similar to the Anna's Rust and Vredefort Mafic Complex rocks in the Vredefort Dome, occurs in the Majuba Colliery near Amersfoort in Mpumalanga Province (Fig. 1.32). The Rb-Sr isotopic whole rock age calculated for the Majuba gabbros is 1052 ± 11 Ma, with an initial ratio of 0.70517 (Reimold *et al*., 2000). Together with the mafic intrusions associated with the Timbavati, Anna's Rust and Vredefort Mafic Complexes, the Majuba intrusion also appears to represent part of the Umkondo magmatic event on the Kaapvaal Craton.

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