1. INTRODUCTION

1.1. Objectives of the study

A number of previous workers have suggested that the Uitkomst Complex formed in a dynamic magma conduit setting (Gauert *et al.*, 1995; Maier *et al.*, 1998). This suggestion was based largely on the tubular shape of the Complex, the lack of fractionation trends in the central harzburgitic portion of the Complex and the relatively large mass ratio of sulphides to silicates. Most recently, it has been established that the Uitkomst and Bushveld complexes are coeval and of a common magmatic lineage (De Waal *et al.*, 2001). The present work aims to test and constrain these hypotheses by means of a detailed petrographic and geochemical investigation of borehole SH176 that provides a complete intersection of the Complex. Previous studies either focused on selected portions of the Complex or compiled a composite intersection through the Complex based on a lithological correlation of several short boreholes along the plunge of the body (Gauert, 1998). The new trace element and isotope data will also significantly expand the existing database. The following points will be used as guidelines to constrain the formation of the Complex:

(a) The composition of olivines and the distribution of the platinum-group elements (PGE) can be used to determine whether the Complex crystallized from successive surges of magma flowing through a dynamic conduit or whether it represents a closed system. In the case of a dynamic conduit setting, successive lithological units may have undepleted Ni-PGE signatures. In the case of a closed system there should be a trend of progressive Ni-PGE depletion with height.

(b) Ratios of highly incompatible trace elements (for example: Th, Hf, REE, Nb, Ta, Zr and Y) and Sm/Nd isotopes may be used to determine whether the various lithological units of the Complex crystallized from magmas of different lineage as might be expected in a dynamic conduit system (e.g. Noril'sk and Voisey's Bay). These ratios will further be used to constrain whether any of the units has a similar lineage to the parental magmas of the Bushveld Complex.

(c) Comparison of the trace element and isotope characteristics of the sulphide bearing samples with those of the country rocks can hopefully be used to determine if the sulphides segregated *in situ* due to localised contamination, or whether sulphide segregation occurred at depth, followed by entrainment of the sulphides and deposition in the Complex.

1.2. Regional geological setting

The Uitkomst Complex is a layered ultrabasic to basic intrusion with a $^{207}Pb/^{206}Pb$ zircon minimum estimate age of 2044 (+/-8) Ma (De Waal *et al.*, 2001). The Complex is situated in the Mpumalanga Province, about 25 km north of Badplaas (Fig. 1.1.) and about 50 km to the east of the eastern limb of the Bushveld Complex. The Uitkomst Complex concordantly intruded sedimentary rocks of the lower Transvaal Supergroup, with the Oaktree member forming its floor and the Lower Timeball Hill shale its roof (Fig. 1.2.(a)). Gauert *et al.* (1995) estimated that the Complex intruded the Transvaal Supergroup some 10 km below the level of the Bushveld Complex.

The Uitkomst Complex forms an elongate, tubular body with a relatively consistent lateral cross profile. The body forms three distinct troughs, a Deeper, Central and Upper Trough (Fig. 1.2.(b)). Near the base and the top there are significant sill-like lateral extensions of the intrusion (Von Scheibler *et al.*, 1995). Generally, the shape of the body is governed by the nature of the country rock in that the quartz-rich and dolomitic lithologies appear to be more resistant to thermal-chemical-mechanical erosion by the intruding magma than the shales. Some areas of the Complex are underlain by a "basal" shear zone that has been described as a pre-intrusive thrust zone in the country rocks extending laterally beyond the margins of the Complex (Gauert, 1998; Hornsey, 1999). Striations on the shear planes indicate a northwest-southeast movement (Gauert, 1998).

The total thickness of the Complex is about 860 m, but some 110 m of this consist of post-intrusive diabase sills. The intrusion plunges at an angle of about 8° to 10° to the northwest and is at least 12km long as established by boreholes on the farm Little Mamre (Fig. 1.1.) (De Waal and Gauert, 1997). To the southeast, the Complex is eroded and is overlain by a relatively thin gossaniferous cover of intrusive rocks (Gauert *et al.*, 1995).

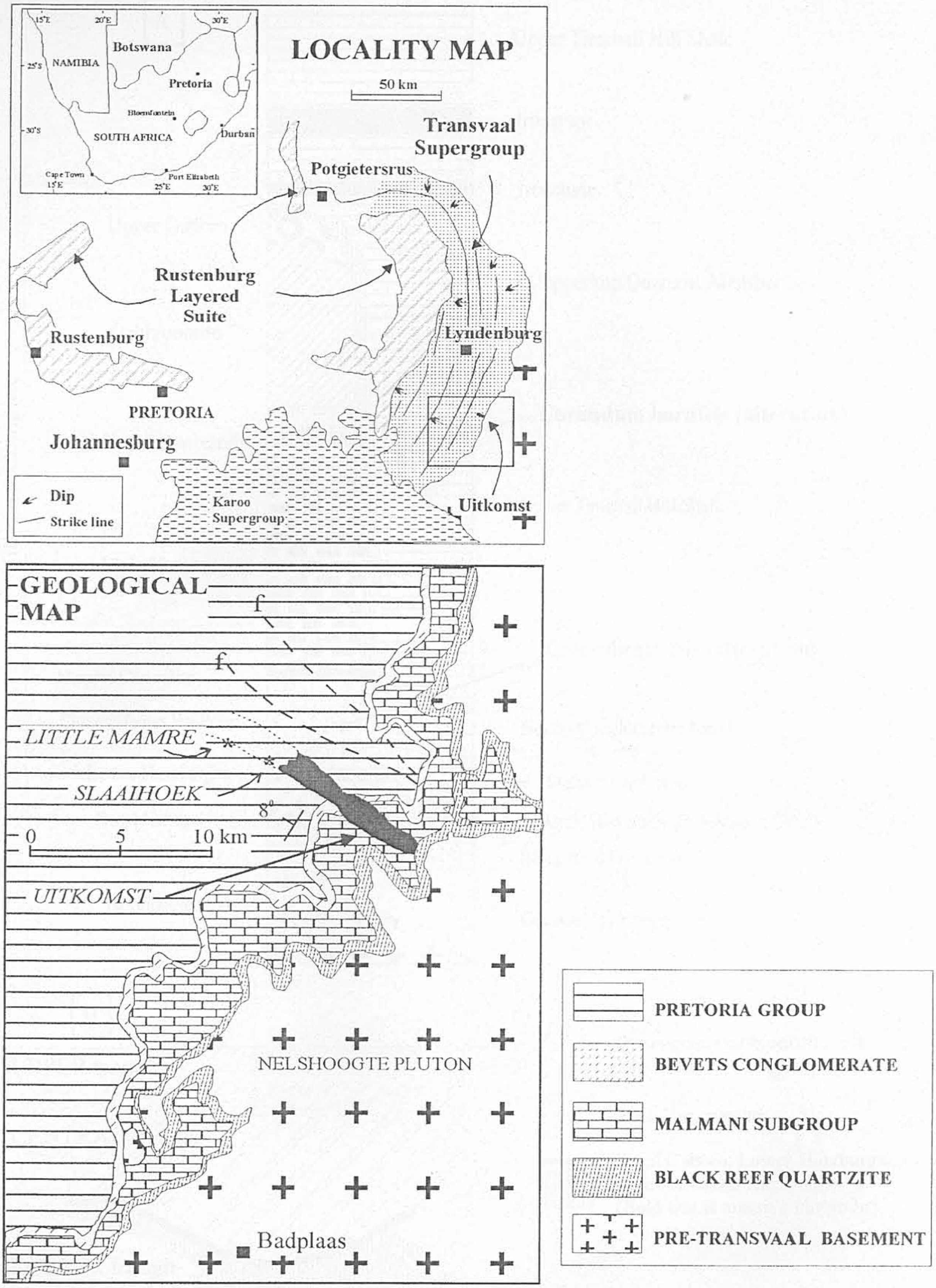

Fig 1.1. Locality and simplified geological map of the Uitkomst Complex (modified after Gauert (1997)).

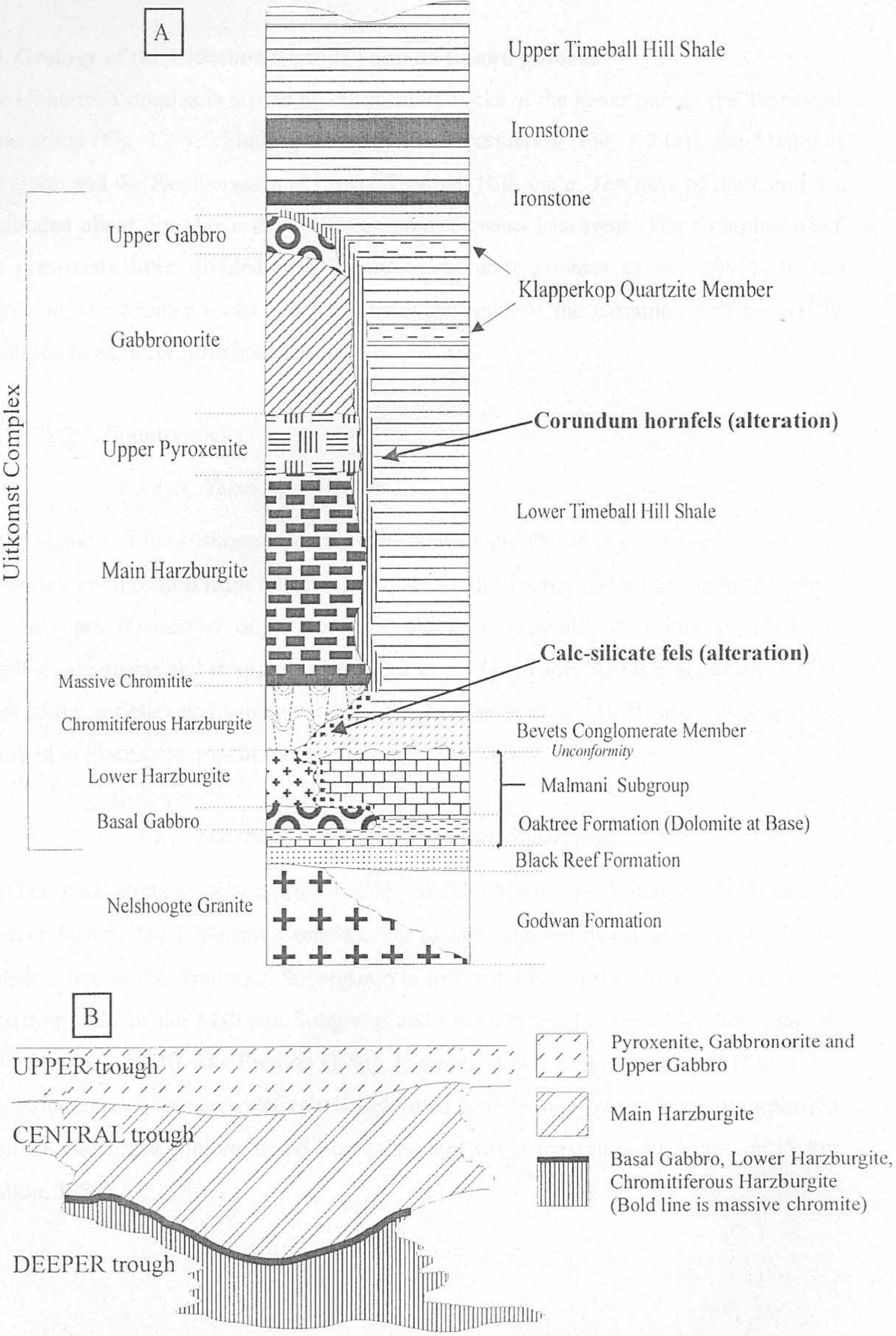

Fig.1.2. **A.** Schematic profile and contact relations of the Uitkomst Complex (after Hornsey, 1999; Gauert, 1998).
B. Cross section from Slaaihoek-Little Mamre boundary illustrating the trough-like nature of the Complex (from De Waal and Gauert, 1997).

1.3. Geology of the Uitkomst Complex and its Country Rocks

The Uitkomst Complex is hosted by sedimentary rocks of the lower part of the Transvaal Supergroup (Fig. 1.3.), including the Black Reef Formation (Fig. 1.2.(a)), the Malmani Subgroup and the Rooihoogte and Lower Timeball Hill Shale. The base of the Complex is situated about 5m above the Archaean granite-gneiss basement. The Complex itself has previously been divided into 7 lithological units (Gauert *et al.*, 1995). In the following, the country rocks and the lithological units of the Complex will be briefly described in an order from base to top.

1.3.1. Country rocks

1.3.1.1. Nelshoogte Pluton

In the vicinity of the Uitkomst Complex the Nelshoogte Pluton is comprised of gneisses of varying composition from feldspar and quartz-rich varieties to biotite and hornblende-rich subtypes (Gauert *et al.*, 1995). The pluton is generally described as a biotite trondhjemite gneiss and is approximately 3.2 to 3.5 Ga in age (Anhaeusser *et al.*, 1981). Most of the varieties and subtypes mentioned by Gauert *et al.* (1995) are sericitised and silicified in places and are cut by quartz and chlorite veins.

1.3.1.2. The lower part of the Transvaal Supergroup

The Transvaal strata are approximately 2550 to 2080 Ma in age (Eriksson, 1993) and, in the area hosting the Uitkomst Complex, dip towards the northwest at about 8°. In the Badplaas region the Transvaal Supergroup is incomplete with the Chuniespoort Group consisting only of the Malmani Subgroup and the Oaktree Quartzite Member (Gauert, 1998; Hornsey, 1999). The Pretoria Group, however, is completely developed (Fig. 1.3.). The sedimentary rocks are relatively undeformed comprising low-grade metamorphosed mudrock, sandstone, dolomite and iron formation with a maximum thickness of 15 km (Button, 1986).

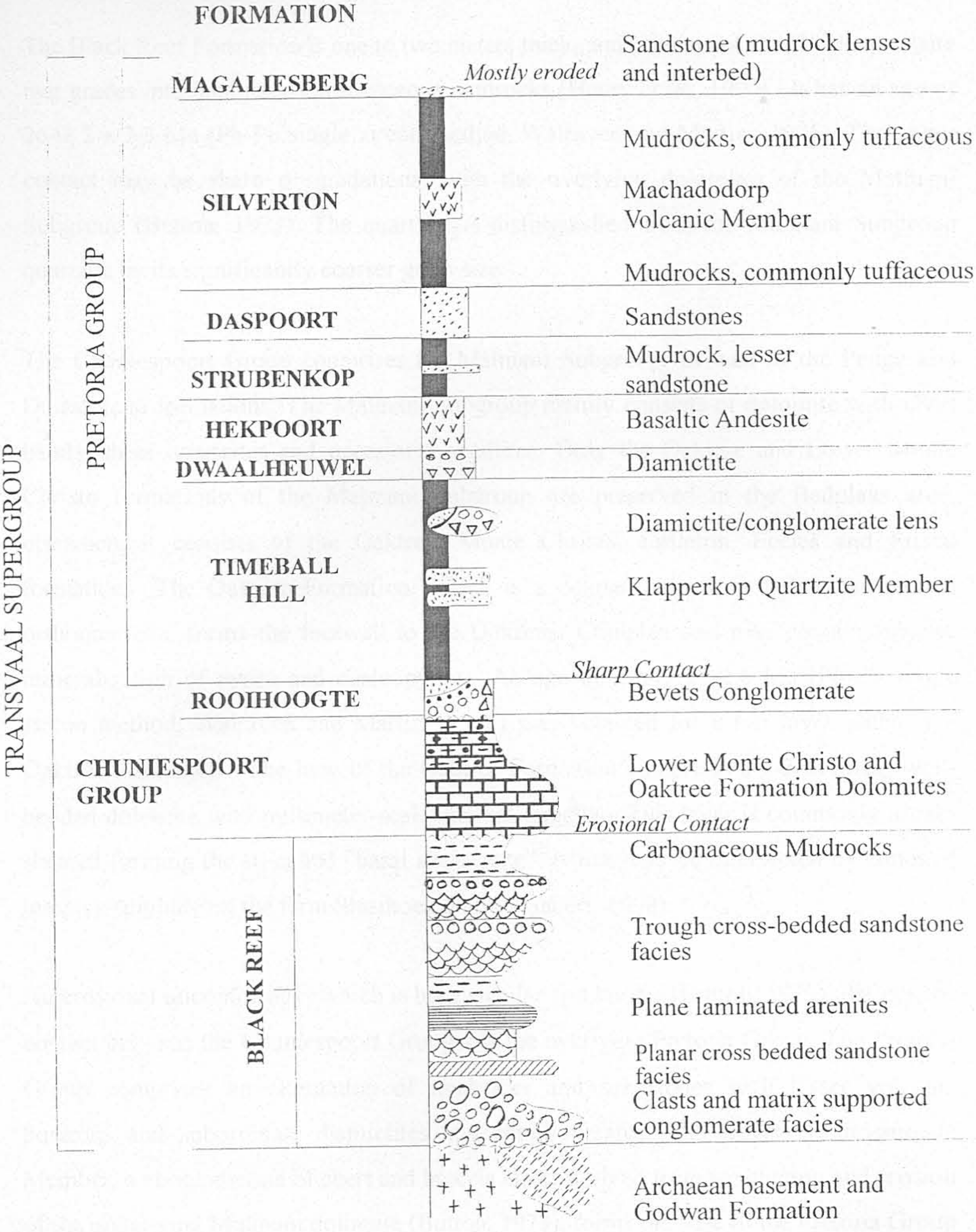

Fig.1.3. Simplified lithostratigraphy of the Eastern Transvaal basin. Vertical scale not proportional. Modified after Eriksson *et al.*, (1993).

The Black Reef Formation is one to two meters thick, and consists of an arkosic quartzite that grades into laminated carbonaceous mudrocks (Henry *et al.*, 1990). It has an age of 2642.2 ± 2.3 Ma (Pb-Pb single zircon method, Walraven and Martini, 1995). The upper contact may be sharp or gradational with the overlying dolomites of the Malmani Subgroup (Button, 1973). The quartzite is distinguished from the Malmani Subgroup quartzite by its significantly coarser grain size.

The Chuniespoort Group comprises the Malmani Subgroup, as well as the Penge and Duitschland formations. The Malmani Subgroup mainly consists of dolomite with chert bands, sheet quartzites and occasional argillites. Only the Oaktree and Lower Monte Christo formations of the Malmani Subgroup are preserved in the Badplaas area, elsewhere it consists of the Oaktree, Monte Christo, Littleton, Eccles and Frisco formations. The Oaktree Formation, which is a coarse grained, trough cross-bedded orthoquartzite, forms the footwall to the Uitkomst Complex and may contain stringer mineralization of pyrite and chalcopyrite. An age of 2 549.9 ±2.6 Ma (Pb-Pb single zircon method, Walraven and Martini, 1995) was obtained for a tuff layer within the Oaktree Formation. The base of the Oaktree Formation comprises a 2-3 m thick, well-bedded dolomite with millimeter-scale internal lamellae. This layer is commonly highly sheared forming the so-called "basal shear zone", which may be intersected by zones of massive sulphide on the farm Slaaihoek 540JT (Gauert, 1998).

An erosional unconformity, which is both angular and karstic (Button, 1973), defines the contact between the Chuniespoort Group and the overlying Pretoria Group. The Pretoria Group comprises an alternation of mudrocks and sandstones with lesser volcanic horizons and subordinate diamictites and conglomerates. The Bevets Conglomerate Member, a conglomerate of chert and breccia clasts derived from weathering and erosion of the underlying Malmani dolomite (Button, 1973), forms the base of the Pretoria Group in Mpumalanga. In general, the conglomerate consists of quartz clasts in a fine-grained matrix of clay minerals (Eriksson, 1988). However, at Uitkomst the Bevets Conglomerate consists of quartz gravel set in a dark quartzitic matrix (Hornsey, 1999) and is sharply overlain by the Timeball Hill Shale.

The roof of the Uitkomst Complex is situated within the Timeball Hill Formation, just above the Klapperkop Quartzite Member. The Timeball Hill Formation is divided into a lower and upper portion (Button, 1973; Eriksson, 1973). The Klapperkop Quartzite acts as a 10 m (Gauert, 1998) thick marker horizon separating the two portions of the Formation. The basal rocks of the Timeball Hill Formation are mainly carbonaceous mudrocks containing micro-algal fossils (Nixon *et al.*, 1988), with a poorly constrained age of 2224 ±21 Ma (Rb-Sr whole rock method, Burger and Coertze, 1976). They grade upwards into interbedded ferruginous mudrocks and fine-grained sandstones (Button, 1973; Eriksson, 1988). The Upper Timeball Hill Member comprises carbonaceous and ferruginous mudrocks locally enriched in pyrite (Eriksson, 1973). Ironstone is present as discrete beds within the Upper Timeball Hill Member. The shale becomes increasingly enriched in silt grading through ferruginous shale into oolitic ironstone.

1.3.1.3. Alteration of the Transvaal Supergroup by Intrusive Rocks

Within a contact zone of about 50 m surrounding the intrusion, the dolomites of the Malmani Subgroup have been transformed to a calc-silicate hornfels grading to a talc- and tremolite-bearing carbonate rock further from the contact. Dolomite xenoliths are common in the intrusion and are in some cases metamorphosed to skarns of diopside, epidote, calcite and tremolite. Extensive underground exposures of the dolomite and dolomitic xenoliths are exposed in the Nkomati Mine on the farm Slaaihoek 540JT. The Bevets conglomerate Member is transformed into a resistant fine-grained quartzite at the contact with the Uitkomst Complex. The pelitic roof rocks in contact with the Uitkomst Complex underwent medium to high-grade metamorphism, forming a 10-50 m thick rim of corundum-andalusite-hornfels.

1.3.2. The Uitkomst Complex

The Uitkomst Complex has been intruded by a large number of sills that constitute up to 10% of the total thickness of the Complex and are generally of a broadly concordant nature to the host rock lithologies. They probably represent several ages of intrusion (ref. in Hornsey, 1999). They are generally fine- to medium-grained and of gabbroic composition.

1.3.2.1. The *Basal Gabbro Unit* (BGAB)

This constitutes the base of the Uitkomst Complex and generally overlies the quartzitic floor rocks of the Oaktree Formation. In the Slaaihoek area this Unit overlies, and is deformed by, the basal shear zone. The BGAB is, on average, 5.6 m thick with a maximum thickness of about 15 m but it may also be absent in places. The width of the BGAB is relatively variable due to common sill-like offshoots. The rock type is a variably altered, equigranular, fine-grained gabbro with a distinct chill zone at the base and a gradational contact to the overlying unit. The BGAB is laterally more extensive than the overlying Lower Harzburgite Unit (Fig. 1.2.(a)).

1.3.2.2. The *Lower Harzburgite Unit* (LHZBG)

This forms the central portion of the deeper trough (Fig.1.2.(b)), but in places the LHZBG appears to have eroded the underlying BGAB to form the base of the Complex (Hornsey, 1999). The average thickness of the LHZBG is about 35 m with a maximum thickness of 90 m (Gauert *et al.*, 1995). The LHZBG is a relatively heterogeneous unit consisting mainly of poikilitic harzburgite, but locally including feldspathic lherzolite and feldspathic wehrlites (Gauert *et al.*, 1995). The most primitive rocks, i.e. the wehrlites, are the main sulphide bearing lithology (Hornsey, 1999). The LHZBG contains abundant xenoliths of dolomite and quartzite that may be up to tens of meters in diameter. Notably, the xenoliths appear to have experienced little rotation, as their layering is commonly sub-parallel to the igneous layering of the host rock.

1.3.2.3. The *Chromitiferous Harzburgite Unit* (PCR)

This forms the upper portion of the deeper trough (Fig.1.2.(b)), with an average thickness of 60 m (Gauert *et al.*, 1995), comprising abundant layers, lenses and schlieren of massive chromitite in a predominantly harzburgitic matrix. The chromitite becomes increasingly more massive towards the top of the Unit with a 0-15 m thick massive chromitite layer marking its upper contact. The silicate rocks are heavily altered to an assemblage comprising talc, carbonate, phlogopite, chlorite and serpentine.

1.3.2.4. The *Main Harzburgite Unit* (MHZBG)

This forms the central trough (Fig. 1.2.(b)), and is the thickest unit of the Complex at an average thickness of 330 m. The MHZBG is comprised of mainly harzburgite that locally grades into dunite. It lacks mineralization except for minor disseminated sulphides in the lowermost 10 m and some relatively thin horizons in its upper portion. There is a distinct macro layering on a centimeter to meter scale caused by modal and grain-size variations. The rocks are moderately altered to serpentine, but in most cases, relict olivine is preserved.

1.3.2.5. The *Pyroxenite Unit* (PXT)

This forms the lower part of the upper trough, extending laterally in the direction perpendicular to the plunge direction for about 1200 m. There is a gradational contact with the upper part of the Main Harzburgite Unit. The PXT is on average 60 m thick (Gauert *et al.*, 1995) and, according to Gauert (1998) can be subdivided into 3 sub-units i.e.:

- A lower olivine-orthopyroxenite portion,
- A central orthopyroxenite with minor accessory chromite and sulphide, and
- An upper norite to gabbronorite showing increasing amounts of plagioclase, clinopyroxene and minor quartz with height.

However, in the SH176 borehole intersection, orthopyroxenite grades very rapidly (over a distance of approximately 1 m) into gabbronorite of the overlying Gabbronorite Unit.

1.3.2.6. The *Gabbronorite Unit* (GN)

This Unit is approximately 250 m thick (Gauert *et al.*, 1995) forming the bulk of the upper trough. The GN may have sill-like lateral extensions of at least 1.4 km (Von Scheibler *et al.*, 1995). The Unit shows vertical compositional layering, with more melanocratic noritic and gabbronoritic rocks at the base grading into relatively leucocratic gabbros at the top. The uppermost 10 m are formed by diorite, which appears to intrude into the overlying Upper Gabbro Unit (PLATE 1).

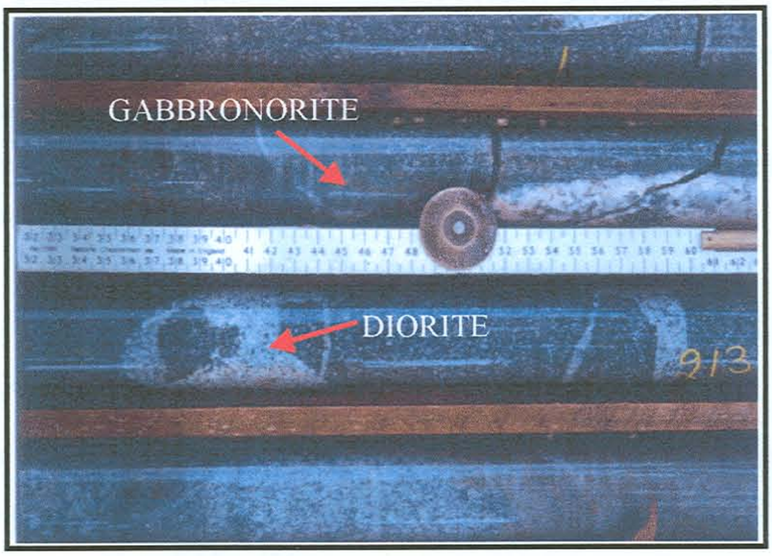

PLATE 1. Gabbronorite section near 123m showing diorite intrusion into gabbroic rock.

1.3.2.7. The *Upper Gabbro Unit* (UGAB)

This Unit constitutes the uppermost unit of the Uitkomst Complex with a thickness of approximately 50 m (Hornsey, 1999). The basal contact is intruded by diorite of the Gabbronorite Unit and the upper contact with the Timeball Hill Shale is distinctly chilled. The Unit grades from melanorite to gabbronorite at the top.

1.3.3. Sulphide mineralization

Sulphides occur within four lithostratigraphic units (Hornsey, 1999). These are (i) the Basal Mineralized Zone (BMZ) within the BGAB, (ii) the Main Mineralized Zone (MMZ) within the PXT, (iii) sulphide rich zones in the PCR (PCMZ) and (iv) several massive sulphide bodies (MSB) on the farms Slaaihoek and Uitkomst, stratigraphically situated in the footwall sediments to the Uitkomst Complex and within the basement granite gneiss. The MSB consists of three broadly lenticular bodies, predominantly of massive sulphide separated by other lithologies. The size of the deposit is about 500 by 200m with a maximum thickness of 20m (Hornsey, 1999). The sulphide mineralization is present as massive ore and stringers although the distinction between the two is governed by economic rather than geological parameters.

The sulphides consist mainly of pyrrhotite with lesser pentlandite, chalcopyrite, pyrite, magnetite and a range of PGE-bearing minerals (Theart and DeNooy, 2001). Both the MSB and MMZ are closely associated with numerous thrust faults and shear zones and with later intrusions of diabase sills. The sulphide bodies contain few xenoliths of country rock, except for in the marginal zones and where the sulphides intrude the basal Malmani dolomites.

1.3.4. Dolerite and Dykes

These make up about 13% of the total thickness of the Complex. They are composite in nature and are commonly concordant to their host. The basal sill, with a broadly uniform thickness of between 20 and 40m (20m in borehole SH176) is a fine-to medium-grained dolerite with a sharp contact to the massive sulphide and a 10-15cm chilled margin. The PCR contains about 57% of the total thickness of diabase sills, the MHZBG 30%, the GN 8% and the UGAB contains about 5%.

The sills are accompanied by faulting, the most persistent fault being represented by the Basal Shear Zone, a well-developed mylonitic talc-schist between 1 and 4m thick. This shear zone contains rare boudins of relatively undeformed country rock. Other shear zones throughout the Complex are about 20cm thick. Quartz veins and jogs are interspersed throughout the shear zones. Strike slip faults are also present with a general strike of 0.50 and 0.60^0N (Hornsey, 1999) and are characterized by 10-20cm thick zones of clay gouge. This faulting episode crosscuts all other structural features evident in the study area.

1.4. Methodology

Sixty half-core samples of borehole intersection SH176 were selected for petrographic and geochemical investigation. The interval between samples is on average about 20 m, depending on the degree of alteration. Highly altered, sheared or faulted rocks and diabase sills were avoided where possible and lithological contacts were always sampled where visible.

Polished thin sections were prepared from all samples and used for petrographic description. Mineral modes were determined for the relatively unaltered samples only using point counting. CIPW norms were calculated for all silicate rocks using MINPET (Mineralogical and Petrological Data Processing System version 2.02 by L.R. Richard). Forty of the 60 samples were investigated for olivine compositions (Li *et al*, 2002). The mineral chemistry of the samples was not determined, partly in view of the previous detailed mineral compositional study by Gauert (1998).

Quarter-core samples were crushed in a jaw-crusher and milled in a C-steel mill. To minimize possible PGE cross contamination during milling and crushing the samples were sorted prior to crushing; the magnetite rich samples were crushed first followed by samples with increasing sulphide content. Cleaning the mill between runs involved crushing one or more aliquots of clean quartz.

For X-Ray fluorescence (XRF) analysis the sample powders were dried at 100°C and then roasted at 1000°C to determine the absorbed water (H_2O^-) and the percentage loss on ignition (the volatile content of the samples), respectively. Major elements, except for Na_2O, were determined on fused beads, following the standard method used in the XRF laboratory of the University of Pretoria, as adapted from Bennett and Oliver (1992). The beads were made with one gram of sample powder together with about six grams of flux (Lithium Tetraborate) and a single crystal of Bromide as a non-wetting agent. The trace elements and Na_2O were analyzed on pressed powder pellets compacted at 5 kN. To increase their strength and stability the sample powders are pressed into aluminum cups. Less than 1 vol% of Mowail glue was used as a binder to the sample powder due to its low mass absorption coefficient (MAC), which, at these levels, results in no significant dilution. Sulphide-rich samples were not fully analyzed due to problems encountered during the preparation of fusion discs, i.e., sulphides can destroy the platinum crucibles. All whole-rock data are listed in Appendix II.

PGE and gold were determined by instrumental neutron activation analysis (INAA) after fire-assay collection of a Ni-sulphide bead at the University of Québec, Chicoutimi (UQAC). As an assessment of the accuracy of the analyses, results for the international standard SARM-7 are listed in Table 1. Platinum-group elements were also determined on the in-house standard AX90, and the relative standard deviations indicate precisions varying from 4 to 23% (Table 1). The PGE data are listed in Appendix II.

Sulphur contents were determined for all samples at UQAC by LECO titration. Thirty-eight selected samples were sent to the laboratories of Professor D. Reid at the University of Cape Town, for trace element analysis using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). Thirteen of these samples were additionally analyzed for Sm/Nd isotopes at the Hugh Allsopp Laboratories, University of the Witwatersrand. The author carried out the sample chromatography and Dr. S. Prevec carried out the electromagnetic analysis of the samples.

Table 1. Accuracy and precision of PGE analysis (values in ppb)

	1	2	3	4	5
Os	63(±7)	62	2.7	22.9	<0.5
Ir	74(±12)	74.5	2.75	4.8	<0.01
Ru	430(±57)	439	18	8.8	<1
Rh	240(±13)	232	10.3	6.8	<0.1
Pt	3740(±45)	3486	126	5.9	<2
Pd	1530(±32)	1551	305	4.3	<2
Au	310(±15)	332.9	4	13.1	0.3

1.International reference sample SARM-7; **2.** UQAC result of SARM-7; **3.** In-house standard run with every batch of 20 samples at UQAC (n=4); **4.** Relative standard deviation on in-house standard in %; **5.** Blank; results obtained when 50 g of reagent silica is used in place of sample.