Exploration strategies for nickel sulphide deposits

By
David Charles Dodd

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Contents

Abstract

An overview of world class Ni-sulphide deposits (and two examples of African Ni-sulphide deposits/resources) namely Voisey's Bay, Noril'sk, Sudbury Igneous Complex, Jinchuan, Uitkomst and Kabanga shows they have a number of features in common. These characteristics which include tectonic setting, host lithologies and morphology may be used to generate targets for new Ni-sulphide projects.

After considering a combination of exploration techniques it was found that stream and soil geochemical surveys combined with airborne electromagnetic (EM) and ground EM surveys are the most appropriate for detecting Ni-sulphide deposits. It is important to discriminate between geochemical anomalies resulting from silicates and those attributable to sulphides. This may be done by identifying areas of coincident, elevated Ni and Cu anomalies or ratios such as Ni/MgO. Likewise with geophysics it is important to use a low frequency (such as 2,5 Hz) EM technique to discriminate between sulphides and conductive sediments or serpentinised ultramafics.

Data from exploration programmes needs to be continuously integrated and compared to the genetic model in order to assess the targets potential and know how to further evaluate it. Critical review stages must also be built into the exploration programme in order to ensure that the effort remains focused and that the exploration expenditure remains in balance with the potential outcome. Socio-political considerations as well as infrastructure are important considerations that need an initial assessment before commencing with groundwork and will need to be evaluated in greater detail if initial results are encouraging before embarking on a major drill programme, or when changes occur during the programme.

The application of geophysics, genetic models and drilling is illustrated in the case study of Insizwa (modeled on Noril'sk). Exploration results show this Karoo aged intrusion has little potential to host an economic Ni-sulphide deposit. The application of the deep penetrating mobile metal ion (MMI) geochemistry to a conceptual target analogous to the Sudbury Igneous Complex is given in an overview of the Morokweng Project. Analytical data from a single borehole and the MMI results show that Sudbury style mineralisation is unlikely to have formed at Morokweng.

Chapter 1 – Objectives, Limitations and Acknowledgements

1.1 Objective

A strategy for implementing Ni-sulphide exploration projects is derived by reviewing pertinent geological criteria and exploration techniques. Ni-sulphides are discussed as there is currently a strong demand for this commodity driven by growth in the stainless steel industry. Recent advances in the hydrochemical extraction processes have also highlighted the financial viability of Ni sulphides above Ni oxide deposits. Furthermore, Falconbridge (who the author works for) is well positioned in the world's nickel market as a substantial and reliable producer and it is within the companies direct interest to replace its depleting resources. By assessing which geological features are common to several world class Ni-sulphide deposits recommendations are made as to how these characteristics may be used to identify new Ni-sulphide targets.

The evaluation of identified targets is illustrated by reviewing geochemical and geophysical techniques and showing how these have been applied to two projects, namely Insizwa and Morokweng. The case studies show the steps involved in evaluating targets and synthesizing the results in order to assess the targets potential. No two targets are the same but by outlining the exploration strategy at Insizwa and Morokweng the reader can get a "feel" for how Ni-sulphide exploration projects are conducted and how the results are used to decide on the next phase of exploration. The Insizwa case study shows how geophysics, mapping and drilling were used to evaluate this target. The Morokweng case study shows how MMI soil samples were used to determine the presence or absence of underlying mineralisation.

The treatise therefore addresses the question: which are the diagnostic features of hypabyssally formed Ni-sulphide deposits that may be used in an exploration programme aimed at new discoveries; and how can these be used, together with exploration techniques, to implement a Ni-sulphide exploration programme? Hypabyssal refers to igneous rocks intruded at a depth intermediate between abyssal (plutonic) and surface.

1.2 Limitations

The treatise does not discuss all large Ni-sulphide deposits, but rather a selection deemed appropriate to illustrate the environment in which Ni-sulphides are formed. Komatiitic nickel deposits and other sulphide deposits where the nickel present is extracted as a by-product (e.g. the platinum group elements (PGE) deposits of the Bushveld Complex) are not discussed.

The review of geophysical and geochemical data is not exhaustive and is not intended to give a detailed account of every available technique. A review of geochemical techniques is given and discussed in light of the authors experience in implementing these surveys. The objective of this treatise is not to give a detailed account of how the individual surveys work or to explain the chemical reactions that cause anomalies. It is rather, to show the exploration geologist what techniques are available and to give some insight into interpreting the survey results.

1.3 Acknowledgements

I wish to thank Professor H. Theart for his encouragement, support, enthusiasm and guidance both in teaching and coordinating the M.Sc. in Earth Science Practice and Management course as well as overseeing this treatise.

I would also like to extend my sincere gratitude to my wife for her patience and understanding throughout my M.Sc. and Falconbridge for allowing me to use some of their data.

Chapter 2 - An Exploration Model for Hypabyssal Ni-Sulphide Deposits

2.1 Introduction

Ni, Cu, Co and platinum group elements (PGE's) i.e. the group VIII transition metals, are most strongly concentrated in the centre of the earth's core and become increasingly less concentrated towards the mantle and finally the crust. Ni needs to be concentrated by about eight times the typical mantle concentration to form an ore body of about 2% (the % Ni, not Ni equivalent, required to form a Falconbridge class deposit) whilst Pt needs to be concentrated by about 70 times from its mantle concentration to form an ore body (Naldrett, 1989).

Ortho-magmatic processes are dominant in allowing this process of concentration to take place. These processes may be divided into the following groups:

1) Intracontinental rifting resulting in flood basalts, anorthosites and PGE rich layered intrusions. This rifting may be the response to plume activity or meteorite impacts.
2) Rifted continental margins causing komatiite, tholeiite or PGE related intrusions/extrusions.
3) Komatiite-related flows in greenstone belts (not discussed further in this treatise).

Naldrett (1997) includes the additional categories of “Phanerozoic Orogenic Belts” and “Other” whilst Nutt (2002) - who categorizes the processes differently – includes ophiolite intrusions. Naldrett's “other” includes the Finland deposits and Selebi-Phikwe, Botswana.

These additional categories are not viewed by this author as being necessary, as deposits associated with orogenic belts are interpreted to have formed during the rifting phase and are therefore accounted for in the “Rifted continental margins” category. The same applies to the Selebi-Phikwe and Finland deposits which are also thought to have been emplaced during rifting processes even though the belts may have subsequently been closed/sutured, deformed and metamorphosed.

This treatise concentrates on the first category listed i.e. magmatic Ni-Cu- sulphide deposits (excluding komatiites) as these form the focus of most current Ni-Cu-PGE exploration. Examples of deposits that fall into this category are described in the ensuing paragraphs which outline: Geology, Mineralisation, Model for Ore Genesis, and “Key Aspects to Exploration” derived from each of these known deposits. This study excludes (but refers to) sulphide poor PGE-(Cu)-(Ni) mineralisation associated with mafic/ultramafic cumulate rocks such as the Bushveld and Stillwater Complexes. The following deposits are discussed:

Table 1 – Deposits discussed in treatise

Deposit	**Category**
Voisey's Bay	Intracontinental Rifting – Associated with anorthosite
Noril'sk	Intracontinental Rifting – Associated with flood basalts
Uitkomst	Intracontinental Rifting – Associated with the Bushveld Complex
Sudbury Igneous Complex	Astrobleme.
Kabanga	Intracontinental Rifting – Full Wilson cycle, intruded during late lateral collision related extension.
Jinchuan	Rifted Continental Margin

Emphasis is placed on the Intracontinental Rifting category which hosts the largest Ni-Cu-PGE deposits in the world namely the Bushveld Complex and, Noril'sk. This category of deposit displays considerable diversity (such as the difference between an astrobleme causing a melt sheet, plumes causing layered complexes and mafic/harzbugite and anorthositic intrusions such as Uitkomst and Voisey's Bay (which may also have resulted from plumes). The Kabanga and Uitkomst deposits have been included as examples of Ni-S deposits in Africa.

The intracontinetal rifts are thought to be related to hotspot or mantle plume activity and are often located at triple junctions and may be related to flood basalts (Piranjo, 2000). This association is not always clear, as in the case of the Bushveld Complex.

Once the deposits have been discussed individually the features they have in common will be outlined in order to determine how these may be used for exploration purposes. This will be preceded by a summary on the theory of Ni-Cu sulphide genesis. The following chapters will outline how the geological attributes initially discussed can be detected through exploration techniques such as geochemistry and geophysics. This will be followed by two case studies (of the geology and exploration) – one of a flood basalt type setting namely Insizwa and the second of an astrobleme type setting, namely the Morokweng Impact Structure.

The final chapters will give conclusions from the investigation and outline a series of steps suggested for Ni-sulphide exploration.

2.2 Theory of Magmatic Sulphide Deposit Formation

Magmatic sulphide deposits form as a result of the segregation and concentration of droplets of liquid sulphide from metal rich mafic or ultramafic magma. The solubility of sulphide in silicate melts is too low (<0,3%) to account for the large amounts of sulphides in giant magmatic sulphide deposits and the S content in the mantle (125-250 ppm) is too low to maintain sulphide saturation in most mafic/ultramafic magmas so a sedimentary sulphur source is required (Lesher, 2000 presentation). Various processes may trigger sulphur supersaturation such as:

1. The assimilation of sulphur rich sedimentary rocks such as anhydrite bearing evaporates and sulphur rich shales (Naldrett, 1999).
2. The assimilation of siliceous material may decrease the solubility of sulphur in the magma (Naldrett, 1999).
3. The extraction of iron out of the magma in the form of cumulus, early formed, mineral phases such as chromite will decrease the solubility of the remaining magma (Naldrett, 1999).

Lesher (2000 presentation) describes the process of contamination as following the following steps:

1) "The silicate and sulphide components will decouple.
2) The silicate component will dissolve into and be assimilated by, the lava/magma (silicate xenomelts are rarely preserved).
3) The sulphide component will melt to form an immiscible sulphide xenomelt.
4) A residual component (e.g. skarn, xenolith) may be "left behind."

As host lavas are only locally depleted in chalcophile elements it appears that the magmas remained sulphide undersaturated during ascent. After the sulphide droplets have formed their chalcophile metal content needs to be upgraded. These droplets then need to be concentrated in order to form a deposit of sufficient tonnage.

Moderate to high degrees of partial melting of the mantle are required to generate a metal rich magma as sulphides retain metals (especially PGE's and Cu) at low degrees of partial melting. Degrees of partial melting greater than 11% (in the so-called modern systems) or 16% (Archaean systems) require plumes (McKenzie and Bickle, 1988).

These plumes are believed to have formed in different time periods and through different means. This is determined as follows: If the magma's MgO content is greater than 11% but less then 18%, and was emplaced during Phanerozoic to Proterozoic times, then it is assumed to have been emplaced as a plume. This is because the maximum MgO content derived by adiabatic decompression of the "modern" upper mantle with a potential temperature of 1 280° C is 11% so magmas with higher MgO contents must come from mantle plumes. Likewise the maximum MgO content of Archaean upper mantle with a potential temperature of 1 380° C is ~ 16%, so magmas with higher MgO contents must also be derived from plumes. Picrites with a Ni content lower then 500 ppm but with an MgO content of ~15% are thought to have formed by wet melting above subduction zones (McKenzie and Bickle, 1988).

Lesher (2000 presentation) describes the properties of sulphides as follows: They remain molten at much lower temperatures (T_S = 1 050° C) than mafic magmas and are twice as dense ($\rho_{Sul} \approx 5,3$ kg/m^3, $\rho_{Sil} \approx 2,7$ kg/m^3). Molten sulphides are also ~ 10 – 10 000 times more fluid than silicate magmas ($\eta_{Sul} \approx 0,1$ g-cm/s, ($\eta_{Sil} \approx 1 - 1\ 000$ g-cm/s). Sulphides also have extremely high surface tensions. All of these factors cause sulphides to coalesce rapidly and to become physically segregated.

The process of forming magmatic sulphide deposits can therefore be summarised as follows:

Initially a fertile chalcophile rich magma must form from a moderate to high degree of partial melting. According to Mckenzie and Bickle (1988) this occurs as a result of plumes. As most deposits are associated with rifting, it is presumed that the plumes must initiate the rifting. Once this magma has formed it must reach crustal levels without reaching sulphide saturation levels. The magma must then be emplaced in such a manner that it assimilates S from country rocks and the segregated sulphides experience a high R factor (a large ratio of silicates to sulphides). This means the sulphides can strip chalcophile elements from a large volume of magma due to partioning factors favouring the sulphide. The sulphides then need to be concentrated in such a manner that they form an economic deposit.

This theoretical overview is now followed by an examination of six world class deposits in order to determine what common characteristics they display that can be used for exploration.

2.3 An Overview of Some of the more Important Deposits for Consideration in Exploring for Hypabyssal ores

2.3.1 Voisey's Bay Intrusion

2.3.1.1 Introduction

This 124 Mt deposit (1,66% Ni; 0,88% Cu and 0,05% Co) is one of the most famous recent mineral discoveries and is located in northern Labrador (Canada) – Fig 1. It was discovered by Diamond Field's exploration partner, Archaean Resources who initially began exploring for diamonds in 1993 before shifting interest to base metals during this same year.

The deposit was discovered by spotting a gossan from a helicopter and was later proven to be significant after sampling and drilling.

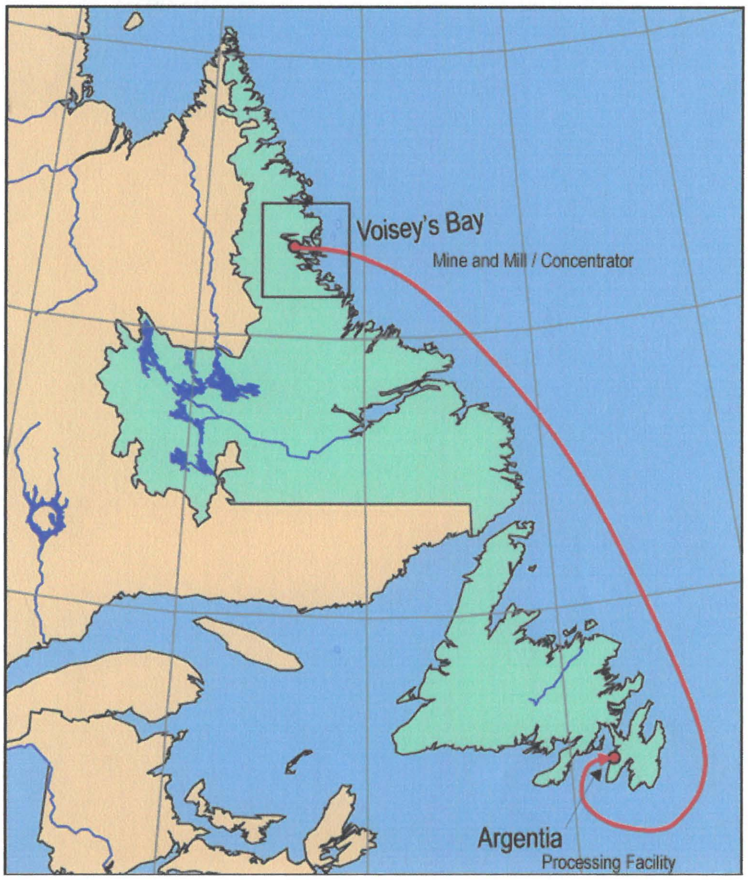


Fig. 1 – Location of Voisey's Bay Proposed Mine Site and Processing Facility (After www.l.ca/voiseys/images/sites_map)

2.3.1.2 Geology

The Voisey's Bay Intrusion belongs to the 1,34 to 1,29 Ga Nain Plutonic Suite. This consists of anorogenic anorthosite, ferrodiorite, troctolite, gabbro and granitoid intrusions which straddle the ~ 1,85 Ga suture which separates the Archaean aged Nain Province in the east and the Proterozoic-aged Churchill Province in the west (Li and Naldrett, 1997). The Churchill Province is comprised of interbanded garnet-sillimanite and sulphide as well as graphite bearing paragneisses collectively known as the "Tasiuyak gneiss" as well as enderbitic gneiss (Li and Naldrett 1997).

The Voisey's Bay Intrusion is a troctolite intrusion which forms part of the Reid Brook Complex (Fig 2) within the Nain Plutonic Suite. This intrusion consists of two chambers (the upper Eastern Deeps subchamber and the lower Reid Brook subchamber) which are connected with a gabbroic/troctolitic conduit. Mineralisation occurs mainly along the conduit starting in the Reid Brook chamber in the west and extending through to the Discovery Hill zones, through to the Mini-Ovoid, the Ovoid and the base of the Eastern Deeps subchamber.

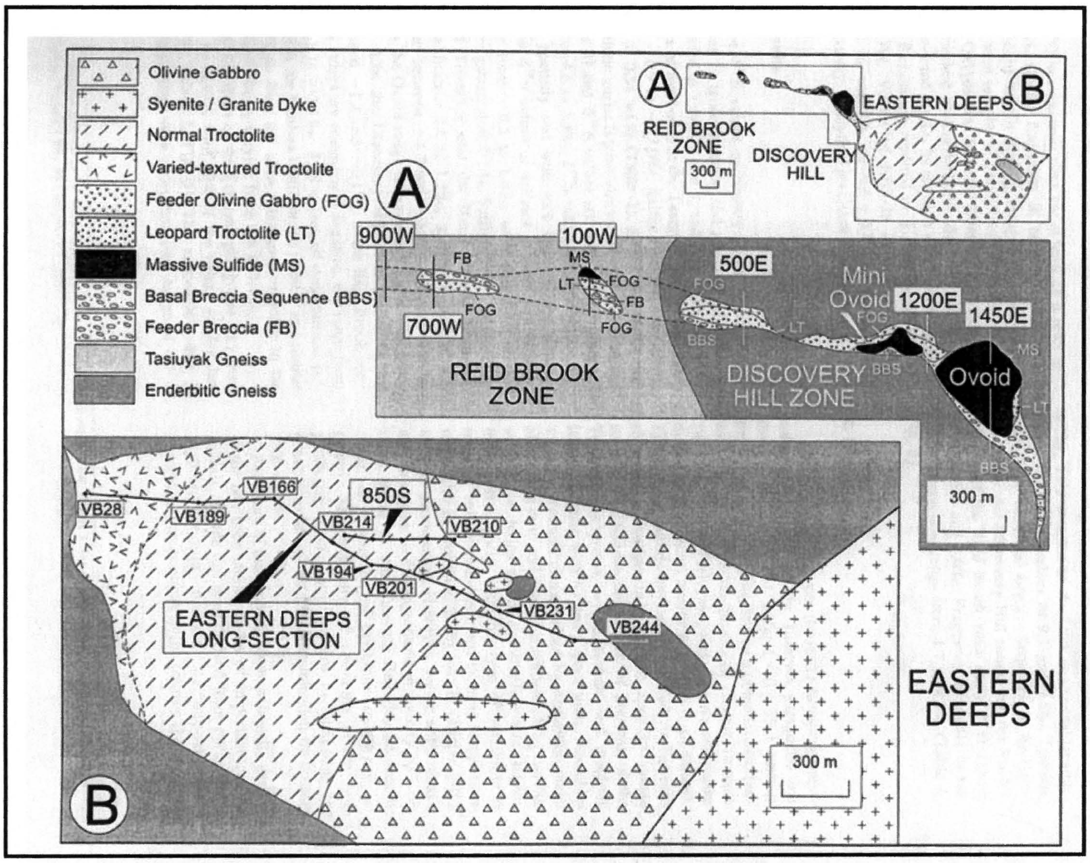


Fig. 2 – Cross-Section through Voisey's Bay (After Li and Naldrett, 1999)

The intrusion consists of the following lithologies:

Table 2 – Voisey's Bay Intrusion Stratigraphy

Lithology	Acronym	Location
Leuco-troctolite	LUT	Reid Brook Chamber
Feeder Breccia	FB	Reid Brook Chamber
Feeder Olivine Gabbro	FOG	Feeder Sheet
Leopard Troctolite	LT	Feeder Sheet
Basal Breccia Sequence	BBS	Feeder Sheet
Olivine Gabbro	OG	Eastern Deeps Chamber
Normal Troctolite	NT	Eastern Deeps Chamber
Varied Textured Troctolite	VTT	Eastern Deeps Chamber

Mineralisation has been discovered in several localities tabulated below:

Table 3 – Voisey's Bay Intrusion Mineralisation

Style of mineralisation	Location of Mineralisation
Massive stringers	In the gneisses flanking the feeder sheet
Massive sulphides	In the Ovoid (a 600 x 300 x 110 m^3 basin of massive sulphides)
Massive sulphides	Developed close to the entry of the feeder to the Eastern Deeps Chamber

The petrography of the major rock types is tabulated below and location of rock types shown in Fig. 2:

Table 4 – Voisey's Bay Intrusion Lithologies, Contamination and Mineralisation Summary (The rock type acronyms as explained on the next page) Information in table taken from Li and Naldrett, 1997.

Subchamber/ Conduit	**Rock Types**	**Evidence for Contamination**	**Mineralisation**	**% Sulphide**
Eastern Deeps	OG NT VTT BBS Minor ferrodiorite and ferrogabbro occur in places	Gneiss fragments and lesser amounts of ultramafic xenoliths are concentrated at the outlet of the conduit into the subchamber	At base	The NNT typically has < 3% sulphides
Conduit	Chilled Margin Rocks (ferrodiorite, ferrogabbro, ferrogabbronorite) FOG FVT LT BBS Ferrodiorite			The FOG and chilled margin rocks typically have < 5% sulphide but up to 5%.
Ovoid	MS separated from the footwall by thin layer of ferrodiorite or ferrogabbro.	Entry of conduit into the Ovoid chamber is marked by a breccia sequence containing gneissic inclusions of a few mm diameter and 2 to 20 mm diameter ultramafic fragments.		
Conduit in Reid Brook Zone	LT VTT OG Ferrodiorite and ferrogabbro FB	Towards the surface LT and VVT carry more gneiss inclusions. Fragments of the country rock paragneisses occur as multiple zones subparallel to the margins of the conduit.		VTT has 2-25%
Reid Brook	Variable troctolite	The variable troctolite		

Subchamber/ Conduit	Rock Types	Evidence for Contamination	Mineralisation	% Sulphide
Subchamber	LUT	contains inclusions of leucotroctolite and gneiss		

Leuco-troctolite/LUT

This is a medium to coarse-grained plagioclase ~olivine cumulate with oikocrystic olivine and augite. Li and Naldrett (1999) interpreted the LUT to have formed from the same pulse of magma as the OG in the Eastern Deeps chamber and the FOG conduit

Rock Type Descriptions (As described by Li and Naldrett, 1999, unless stated otherwise)

Feeder Olivine Gabbro/FOG

FOG is plagioclase (4- to 50 modal %) and olivine/augite cumulate (< 10 modal % each) which contains more intercumulus minerals (30 to 50 modal %) than either LUT or OG. The remainder of the rock is made up of minerals which include biotite, ilmenite and hornblende.

Leopard troctolite/LT

This has characteristic black spots of 0,5 to 1 cm diameter in a yellowish background of interstitial sulphides (Naldrett et al., 1996). The black spots consist of oikocrysts of olivine enclosing plagioclase or oikocrysts of augite enclosing both olivine and plagioclase. The leopard texture is not developed if the sulphide content decreases below 25%.

Basal Breccia Sequence/BBS

This rock contains abundant gneissic inclusions, minor ultramafic rock fragments and rare leucotroctolite and olivine gabbro fragments. The ultramafic fragments consist predominantly of melatroctolite along with minor dunite and wehrlite. The dunite and wehrlite are highly altered. The leuctroctolite and olivine gabbro fragments are sulphide free rocks and have compositions similar to the FOG of the conduit.

Olivine Gabbro/OG

There is an abrupt textural change between the NNT and the OG. The OG is medium to coarse-grained and mottled with abundant oikocrysts of augite (up to 20%).

The sharp textural change, which coincides with an abrupt change in olivine composition is sited by Li and Naldrett (1999) as evidence for the OG and underlying NTT and VTT as having formed from two separate pulses of magma.

Normal Troctolite/NT

The term “Normal Troctolite” is derived from its distinctive uniform texture which varies from the underlying rock due the presence of sulphides or gneiss inclusions in these rocks. This rock is an olivine plagioclase cumulate with discrete intercumulus minerals comprising up to 40% of the rock. The olivines sometimes enclose the pyroxenes and in other areas the reverse is true.

Varied Textured Troctolite/VTT

This differs from NT in that it contains up to 25 vol. % gneiss inclusions and some blotchy sulphide. Plagioclase varies from a few millimeters to several centimeters in length.Pegmatitic plagioclase laths frequently project into the sulphides. Interstitial hornblende, biotite and apatite is more common in VT than in the NT whilst augite oikocrysts are less abundant (Li and Naldrett, 1999).

2.3.1.3 Mineralisation

The mineralisation is located in the feeder sheet as massive stringers in gneisses flanking the feeder in the Ovoid. The Ovoid is a 600 x 300 x 110 m^3 basin of massive sulphide at surface and as a zone of massive sulphide that has formed at the entry of the feeder into the Eastern Deeps chamber (Li and Naldrett, 1999).

By July 1995 31,7 Mt of ore with grades of 2,83% Ni; 1,68% Cu and 0,12% Co had been discovered in the Ovoid and Mini Ovoid. In October 1995, a second major discovery, known as Eastern Deeps was made. INCO's current tonnage including reserves, indicated and inferred resources is 124 Mt at 1,66% Ni (Li and Naldrett, 1999).

The sulphides are composed of pyrrhotite, pentlandite, chalcopyrite, magnetite and minor cubanite. The mineralisation shows a close association with the Basal Breccia Sequence. Locality of mineralisation shown in figure 3.

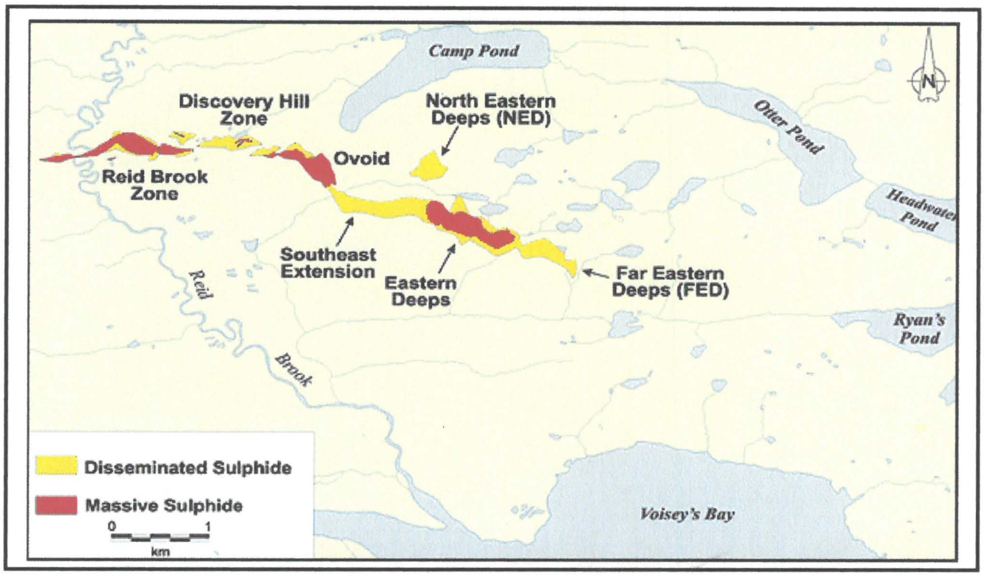


Fig. 3 – Locality of Voisey's Bay Deposits (After www.l.za/voiseys/images).

2.3.1.4 Model for Ore Genesis

The overall plunge of all parts of the Voisey's Bay Intrusion appears to be about 30° to the east. This causes different parts of the system to be exposed at different localities. The Eastern Deeps represents the upper chamber whilst the Discovery Hill represents an intermediate level forming part of a conduit. Li and Naldrett (1999) believe that the Ovoid is the base of the upper chamber whilst Lightfoot (1997) believes it is a swelling within the feeder conduit. Evidence exists for considerable reaction to have taken place between the gneissic fragments and the troctoloitic magma hosting them (Li and Naldrett, 1999).

There is a systematic relationship between the Ni and Fo contents of the olivines from the ultramafic rock inclusions in the feeder olivine gabbros at all localities, the olivine gabbro of the Eastern Deeps chamber and the leuco-troctolite of the Reid Brook chamber (the Ni content of the olivine decreases with decreasing Fo). This suggests that these rocks were all related to each other by the fractionation of a single magma (Li and Naldrett, 1999). Li and Naldrett (1999) suggest that this magma was sulphide saturated as there is a rapid decline in Ni with decreasing Fo content in the olivines as well as low whole rock Cu/Zr ratios for the same samples. These authors argue that the appreciably higher Ni content of olivine in the variably textured troctolite and normal troctolite of the Eastern Deeps as well as its high whole rock Cu/Zr ratios indicates that their parental magma was only partially fractionated and chalcophile depleted.

These differences can be explained if there were at least two inputs of magma, the first of which reached sulphide saturation early and crystallized in the lower chamber to form the mafic/ultramafic layers from which the other inclusions were derived. Before it fractionated further it progressed up the feeder to form the Feeder Olivine Gabbro lining the walls of the Eastern Deeps. Whilst in the lower chamber, this magma reacted with gneiss fragments falling from the collapsing roof. The addition of the gneiss resulted in sulphide immiscibility. Re-Os data from Lambert et. al. (1999) supports large scale interaction between the troctolite magma and enclosing gneiss. S-isotope data from Ripley et. al. (2002) indicates that at least some of the sulphur was derived from the gneiss and their oxygen isotope data supports this.

The injection of a fresh batch of magma may have been the cause for the original magma to have been swept up into the conduit and into the upper chamber. This magma was less fractionated than the original residual magma so it retained much of its original chalcophile elements. Where it came into contact with the segregated sulphides, it lost some of its Ni and Cu, enriching these sulphides in the process. Some of the earlier formed sulphides may have been "picked up" by the next input of magma and have been entrained in the magma flow resulting in the disseminated ores of the Leopard Troctolite and Varied Textured Troctolite and possibly some of the massive ores.

These processes are explained by Li and Naldrett (1999) as having occurred in the following steps which may help in understanding what has been outlined so far.

1) Magma rises to a lower chamber in the Tasiuyak gneiss and olivine crystallization starts and begins to react with gneiss fragments from the collapsed roof and becomes sulphide saturated.
2) New, Ni-undepleted magma enters the chamber and disrupts the early cumulates and pushes the early magma into the upper chamber. As the magma is pushed up sulphides become lodged in the feeder.
3) Continued input of magma picked up sulphides and partially reacted gneiss and transported them up the feeder into the lower part of the upper chamber.

These steps are illustrated in Fig. 4.

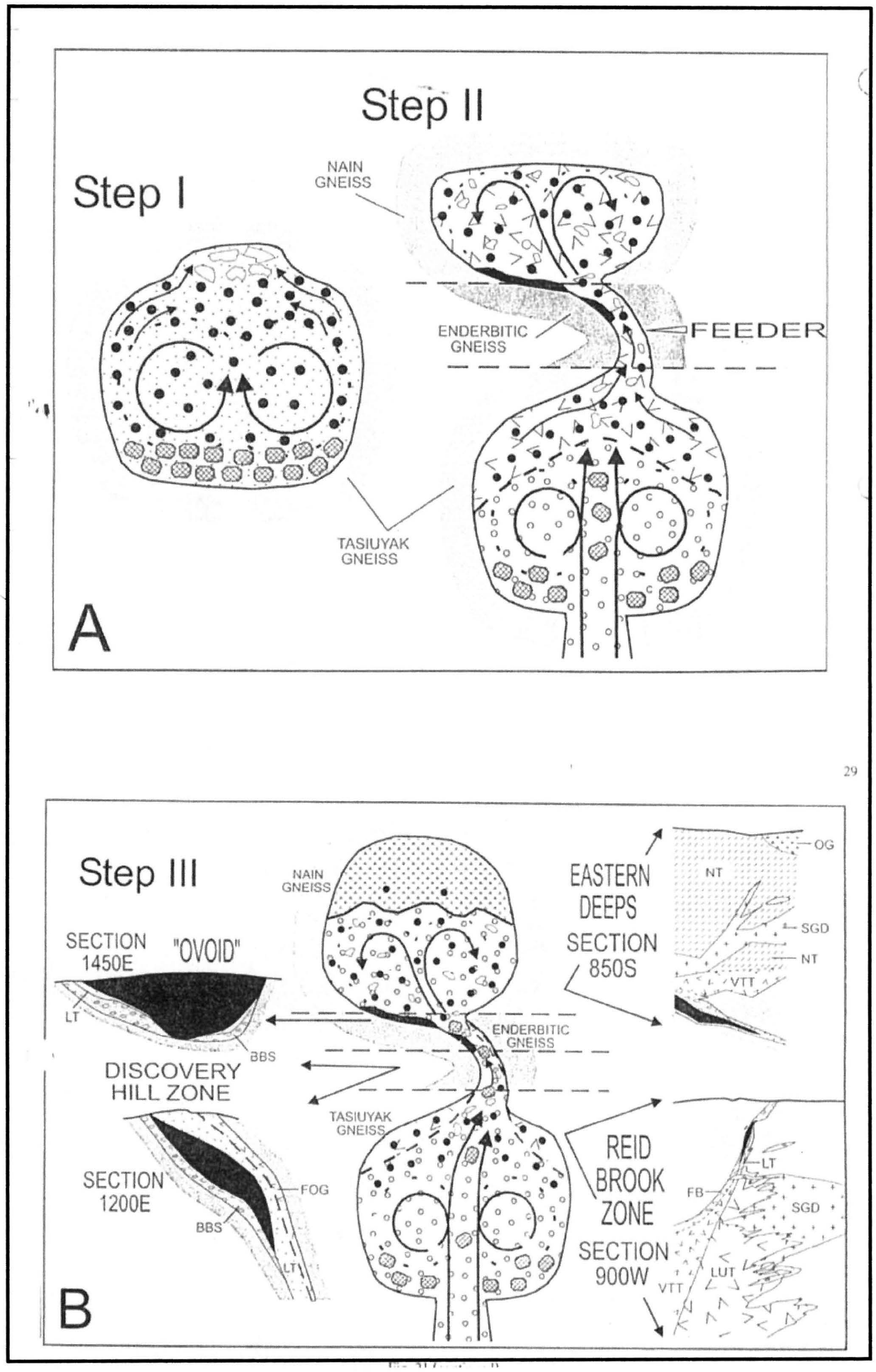


Fig. 4 Genetic Model for Voisey's Bay Deposit Formation, showing steps 1 to 3 (After Li and Naldrett, 1999). (Solid black indicates sulphides, cross hatch indicates xenoliths of gneiss).

Some mixing of the two magmas is expected and this would account for the two populations of olivine found in the lower chamber (Li and Naldrett, 1999).

This morphology of the conduit and Eastern Deeps chamber prior to erosion is interpreted by Naldrett (1997) to have looked as follows (Fig.5)

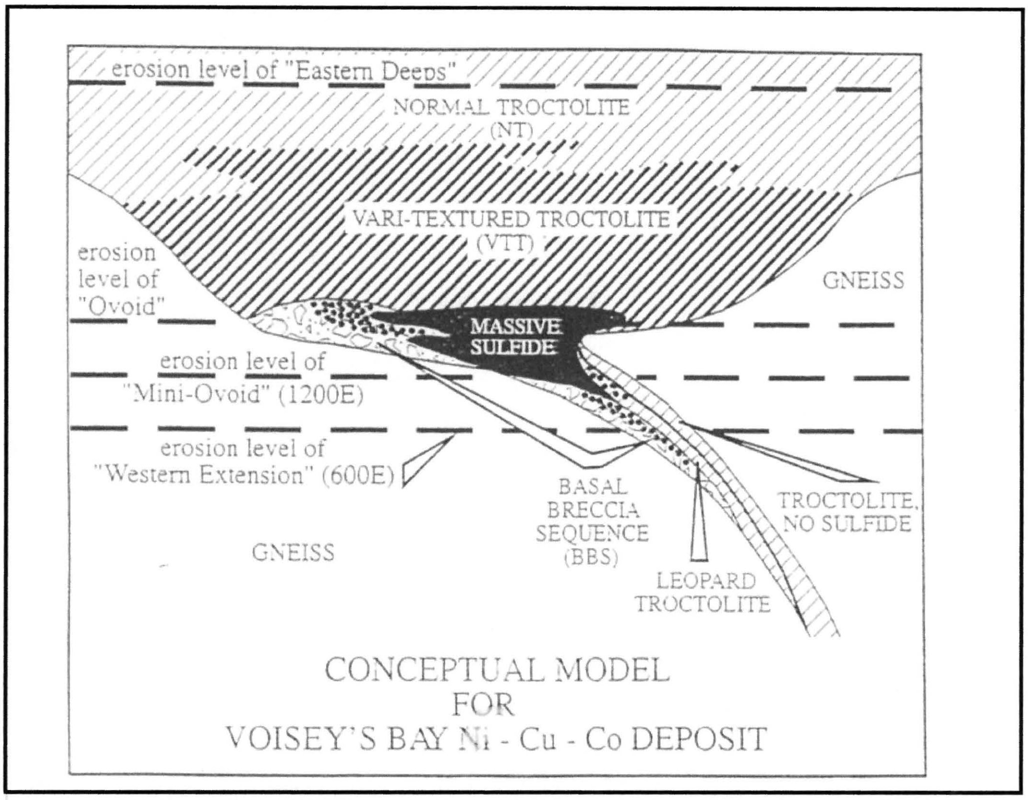


Fig. 5 Interpreted morphology of Voisey's Bay prior to crustal tilting and erosion after Naldrett, 1997.

2.3.1.5 Key Aspects of Deposit Relevant to Exploration

1) Discovered from a gossan showing. Such gossans could be detected through stream sediment surveys as they would cause elevated Ni, Cu and Co values.
2) Reported to be a strong EM conductor (Watts pers. Comm. 2003).
3) Dynamic system with "flow through" of magma meaning that dykes and sills may represent prospective targets.
4) Situated on a cratonic boundary. These boundaries can be detected using aeromag surveys and or publications outlining interpreted cratons and mobile belts. If the latter is used the interpretations usually reflects that latest tectonic overprinting which in Africa is usually Pan African tectonics Care should be taken to interpret where the boundary would have been located during the expected period of magmatic emplacement of the prospective lithologies (usually the proterozoic).
5) Shows evidence for assimilation of country rock.
6) Intrusions do not have a distinctive magnetic signature (Watts, pers. comm. 2003).

2.3.2. Noril'sk

2.3.2.1 Introduction

These deposits are situated in the Arctic Circle in northern Siberia in the province of Krasnojarsk (Figs. 6 and 7) (von Gruenewaldt, 1991).

Fig. 6 – Locality of Norilsk (After www.mining-technology.com/projects/norilsk)

The mineralised Talnakh intrusion was discovered in 1961 as a result of a boulder tracing prospecting programme when massive sulphide boulders were observed. Follow-up diamond drilling intersected significant mineralisation. This deposit is mined by Mining and Metals Co. Noril'sk Nickel (MMC Noril'sk Nickel) and is one of the world's largest metal producers accounting for 50% of the world's Pd, 20% of the world's Pt and 15% of the world's Ni production (Mining Journal, London, 2001). It has a similar Ni content to that of the Sudbury intrusion and twice the Cu content, but five times the concentration of PGE's, being second only to the Bushveld Complex (BIC) (Naldrett et. al., 1996).

The Noril'sk-Talnakh magmatic Ni-Cu-PGE sulphide deposit formed as a result of a ~ 250 Ma plume which resulted in the Siberian Flood Basalt Province (SFBP), one of the world's largest and best preserved igneous provinces. Several eruptive centres contributed to the development of the SFBP which are in turn controlled by major regionally extensive and deep-seated faults.

The Nori'lsk deposits are located on the northeast margin of the Siberian platform along the prominent Noril'sk-Kharaelak fault. Russian literature describes this as the most important factor controlling the mineralisation at Norilsk and controlling the localization of mineralisation processes. This fault is a 50 m wide zone of fractured rock with a 75 to 80° west dip. The west side is downthrown 400 m relative to the east side (Nagerl, 2000).

2.3.2.2 Geology

This deposit is situated on the Siberian platform which is separated from the adjacent stable blocks, the Taimur Peninsula to the north and the Ural block to the west, by the Khatanga and Yenesei troughs respectively (von Gruenewaldt, 1991) – Fig 7.

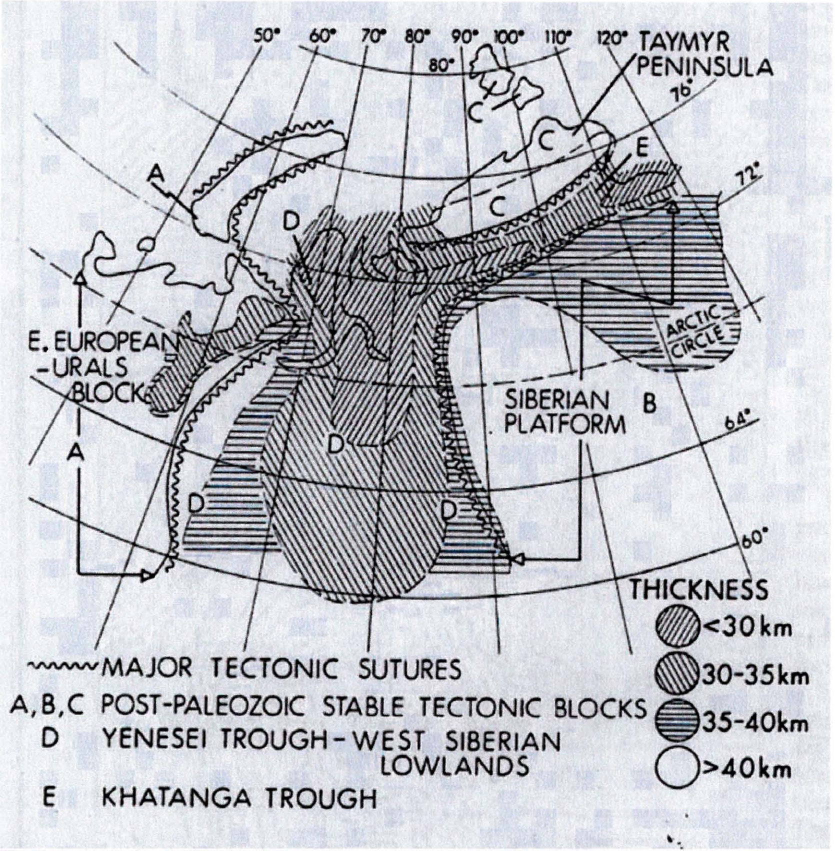


Fig. 7 Location of Noril'sk relative to tectonic features of northwestern Siberia (After Tamrazyn, 1971in Naldrett et. al., 1992)

In the western part of the Siberian platform the basement rocks are overlain by Silurian dolomites and limestones. These are overlain by sediments of the Tunguska Supergroup which consists of calcareous and dolomitic marls and sulphate rich evaporates of Devonian age, lower Carboniferous limestones and mid-Carboniferous continental sediments which include coal seams (von Gruenewaldt, 1991) – Fig 8.

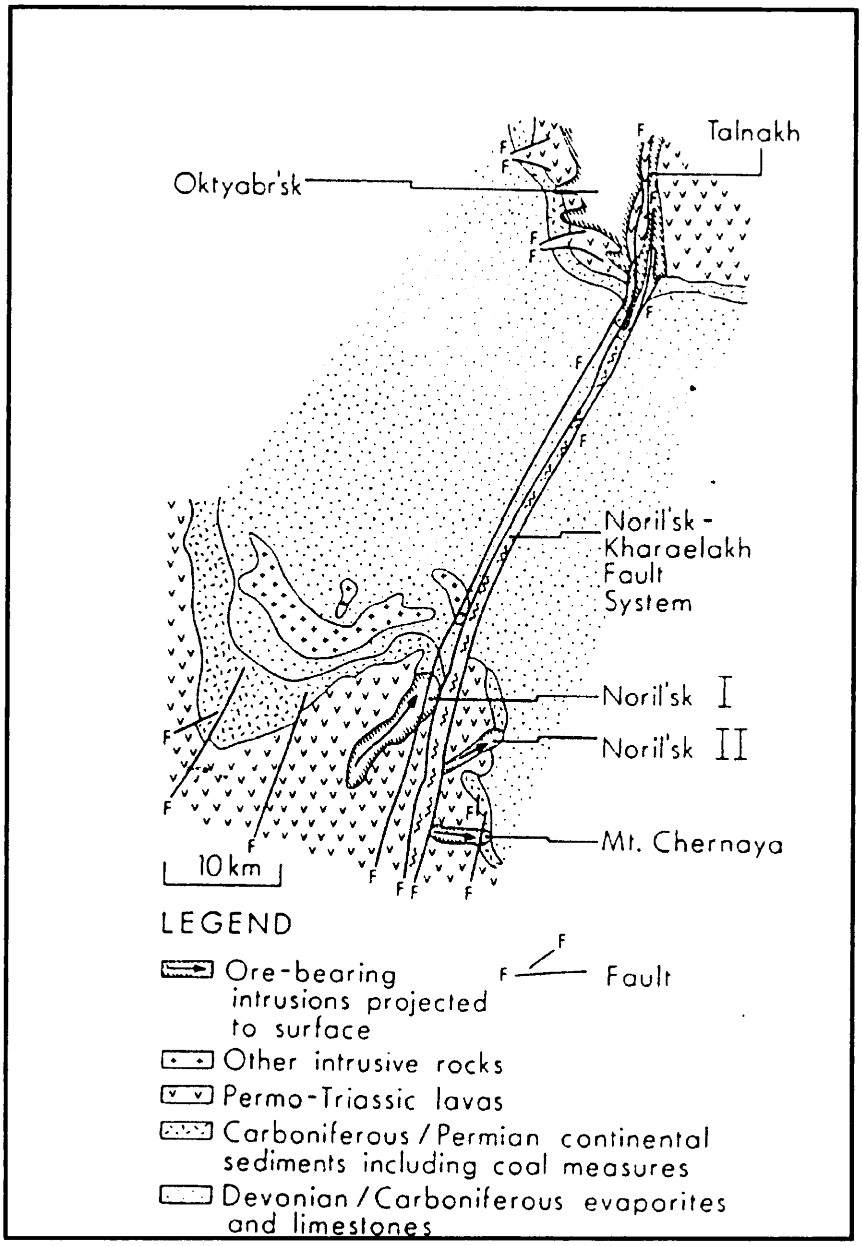


Fig. 8 – Regional Geological Setting of the Noril'sk Ore Bearing Intrusions (partially schematic) (After Smirnov 1966)

Large scale rifting followed the deposition of these sediments and extrusion of the flood basalt of the Siberian traps of late Permian to Triassic age. Continued subsidence of the troughs caused deposition of thick sedimentary sequences of early Triassic to mid-Tertiary age.

According to Naldrett (1992) the 3,8 km thick succession of flood basalts is formed by five principle magma types. From the base to the top these are:

1) A fractionated magma with alkalic affiliations (Ivakinsky and Syverminsky).
2) A Ni-rich suite including picritic basalt (Gudchichinsky).

3) A primitive but Ni-depleted suite including picritic basalt (Tuklonsky).
4) A light REE enriched, crustally contaminated suite (Lower Nadezhinsky, nd_1). Above this there is a transitional suite (Upper Nadezhdinsky, nd_2, and Morongovsky, mr_1 and $_2$).
5) A primitive suite without picrites (Mokulaesky) similar to the Tuklonsky type.

A cross section of the Noril'sk geology is shown below in Fig 9:

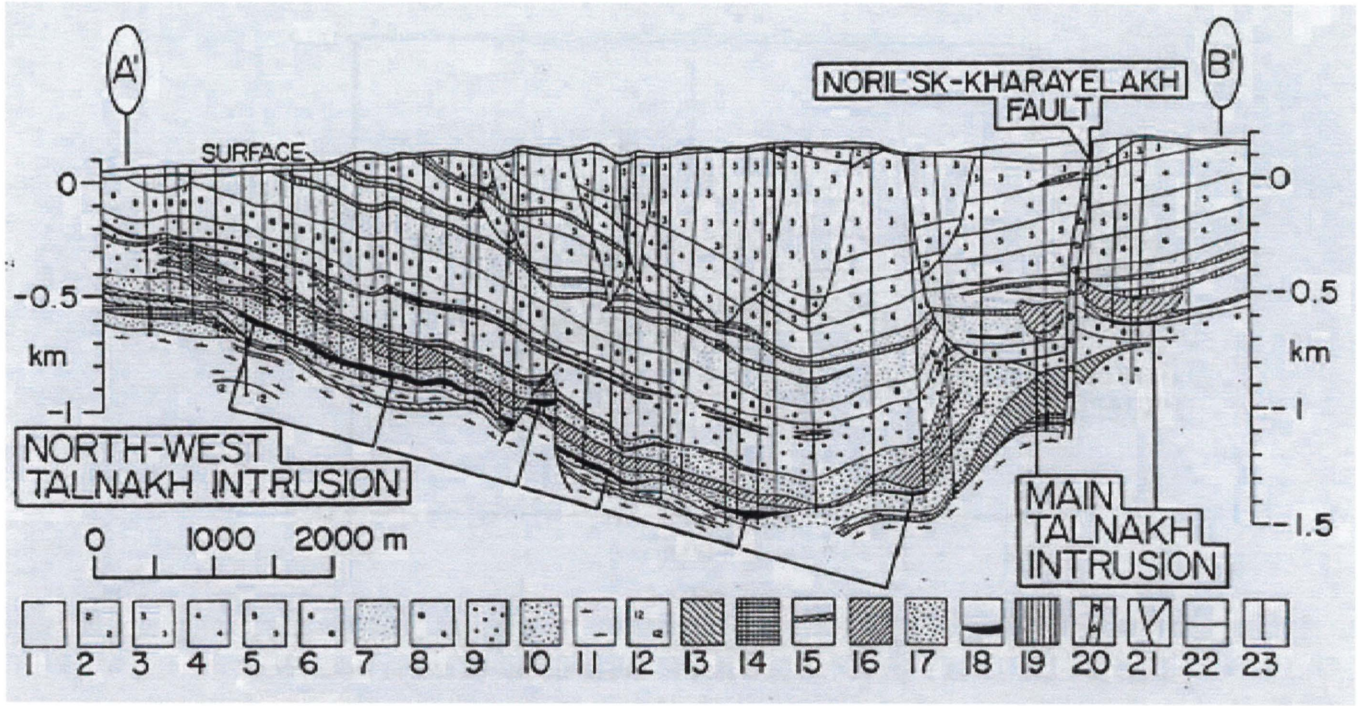


Fig. 9 East-west cross section through the southern part of the Kharayelakh basin, showing the Northwest Talnakh, Main Talnakh and Lower Talnakh intrusions. Patterns 1 = Quaternary cover; 2-6 = basalts; 7 = Tungusskaya Series (continental sediments); 8 = Yuktinsky, Nakokhozsky and Kalargonsky formations (Middle and Upper Devonian dolomites, limestones, marls, anhydrites); 9 = Manturovsky formation (Middle Devonian marls, anhydrites, argillites); 10 = Kureysky and Razvedochninsky formations (Lower Devonian argillites, marls); 11 = Zubovsky formation (Lower Devonian marls, anhydrites); 12 = Silurian dolomites, limestones; 13, 14 = Lower Talnakh Intrusion; 15 = Talnakh Sill; 16-18 = Northwest and Main Talnakh intrusions, 16 = gabbro-dolerite, 17 = picrite and taxitic gabbro-dolerite; 18 = massive sulphide; 19 = trachy-dolerite and dolerite sills; 20 = Norilsk-Kharayelakh fault; 21 = other faults; 22 = formation boundaries; 23 = drill hole locations (After Naldrett 1992).

The Noril'sk type mineralised intrusions are considered to be part of the feeder system of the primitive, Ni depleted picritic basalts. von Gruenewaldt (1991) points out that there are a large amount of intrusions in the Noril'sk area and yet only the Noril'sk type intrusions are mineralised. This he ascribes as being partly due to these intrusions being emplaced within, or in close proximity to, the Noril'sk-Karealakh fault. This may be because the fault acted as a conduit for the more primitive Noril'sk type intrusions. It is these olivine rich magmas that then experienced sulphide segregation and became depleted in Ni (Naldrett, 1992).

The main Talnakh intrusion crosscuts its sedimentary hosts in an area where the sedimentary package changes from terrestrial to marine type sediments rich in sulphates. The intrusion is 15 km west of the Norilsk-Kharaelak fault and is exposed at surface to the south-southwest of the Mayak mine.

The western portion of the mineralised Talnakh intrusion (Oktyabr'sky and Taimyr mine areas) has a concave lopolith shape and occurs at a depth of 400 m and dips to the north. A typical stratigraphy of the differentiated Talnakh-type intrusions is as follows:

Upper contact of “eruptive” breccia
Leuco gabbro and gabbro dolerite
Non olivine-bearing gabbro dolerite
Olivine picrite and gabbro dolerite with taxitic texture

The position of these sills relative to the Noril'sk Kharayelakh fault is shown in Fig. 10.

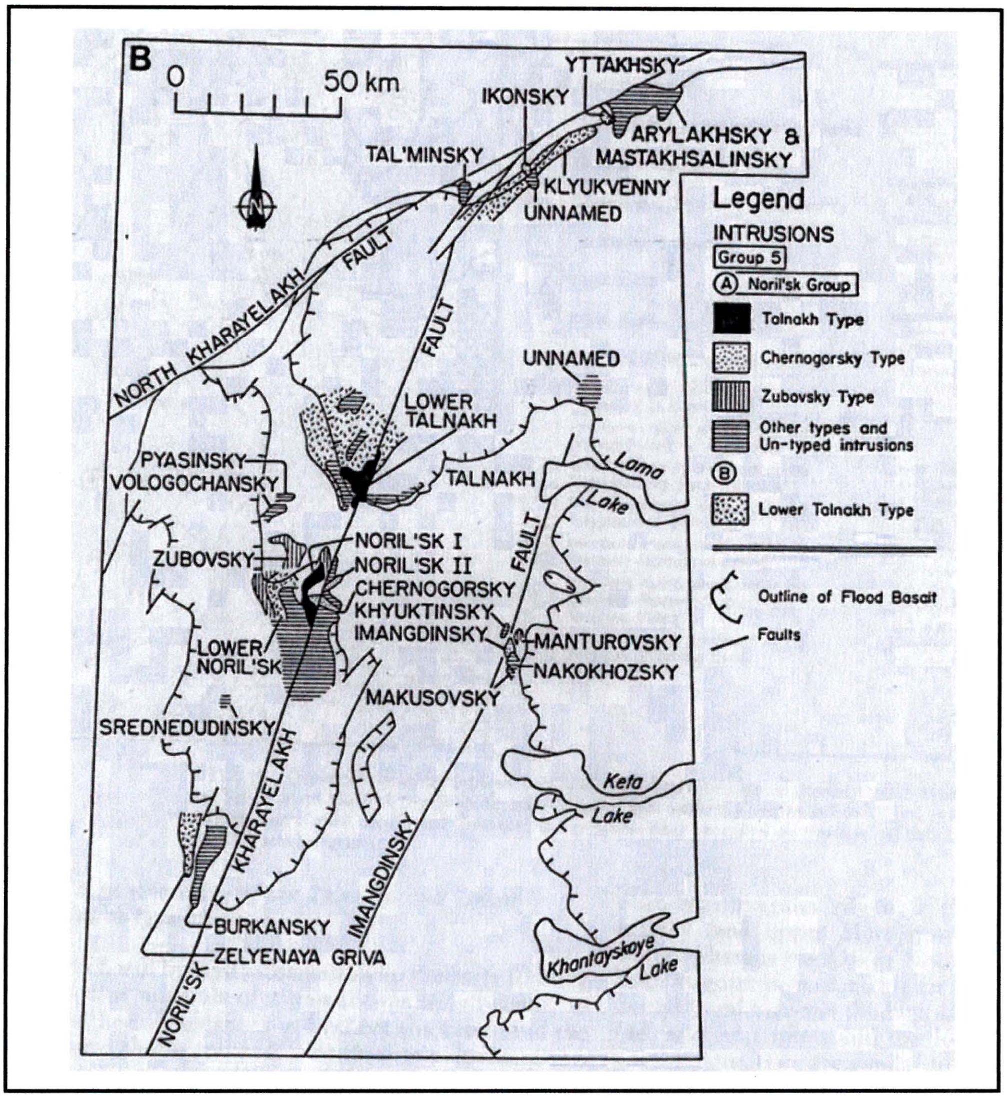


Fig. 10 Talnakh intrusions on west side of Norilsk-Yalnakh fault (After Naldrett et. al., 1995)

2.3.2.3 Mineralisation

Ore Deposits

There are currently three deposits that are being mined:

Noril'sk 1, Talnakh and Oktyabr'ksy west.

Noril'sk 1 Deposit

This deposit is mined by the Medvezhy Ruchey (Bear Pit) and Zapolyarny (U/G) mines. The mines have been in operation since 1948 and only disseminated ore remains, the massive ore reserves were depleted in 1960. The disseminated ore is hosted in taxitic gabbro.

Talnakh Deposit

This is mined by the Mayak and Komsomolsky mines and the new Skalisty mine. This deposit was discovered in 1961 on the eastern side of the fault.

The intrusions are hosted in Permian and Carboniferous rocks.

Oktyabr'sky Deposit

This deposit, the most significant within the Noril'sk region, was also discovered in 1961 and is mined by the Komosomolsky, Oktyabr'sky and Taimyr mines. Reserves are quoted as 200 Mt massive ore, 200 Mt Cu ore and 400 to 600 Mt disseminated ore. Only 30% mooihoekite and cubanite massive ore remains – refer to "Ore" section. These copper rich ores have very high PGE contents (refer to Table 5).

The intrusion is hosted in Devonian rocks and is surrounded by a feldspathic halo. The disseminated ore contains 9 g/t PGE's.

The nature of the Noril'sk ores

The ore is divided into four types namely massive ore, copper ore, disseminated ore and a low sulphur PGE ore (Nagerl, 2000), all hosted in differentiated intrusions. The massive ore deposits are zoned.

These ores are centred on the Noril'sk and Talnakh ore junctions and are located within the intrusions in the following manner as outlined by Naldrett et al. (1996):

1) Massive ore typically occurs at or beneath the lower margin of intrusions.
2) Disseminated ore in taxitic or picritic gabbrodolerite which form in the lower parts of intrusions.
3) Copper ore forms as impregnations into the hornfelsic country rock adjacent to massive ore or occupies the matrix of breccia zones that have developed at the front and upper contact of the intrusions.
4) The low sulphur PGE ore is related to a "eruptive breccia" zone above the disseminated zone in the Noril'sk 1 intrusion.

von Gruenewaldt (1991) notes that the massive ore is frequently separated from the mafic intrusion by sediments and displays intrusive relations to the sediments and the mafic intrusion. This author also describes a breccia ore which he states suggests extensive mobilization of the ore as it consists of fragments of host rock in a sulphide matrix.

Grinenko (1985) believes that this may have occurred as a result of the sulphides having a lower melting temperature than the ultramafic cumulates of the Talnakh body. After this body solidified and then fractured on-going tectonic movements squeezed the sulphides higher up the stratigraphy and into the fractures.

It is only the Noril'sk type intrusions i.e. only those that show well-defined differentiation that have significant amounts of mineralisation associated with them.

Table 5 - The grades of the ores are as follows (Falconbridge Ventures presentation, 2000):

Ore Type	**Sub-Type**	**Ni (%)**	**Cu (%)**	**PGE g/t**
Massive	Pyrrhotite	2,8 – 3,5	4 - 5	8 – 9
	Cubanite	2,8 – 3,5	10 - 15	
	Mooihoekite	> 2,8	20 - 30	40
Copper	Breccia	1 – 1,2	2 - 10	10
Disseminated		0,3 – 1,5	1	5
Low S[6]	Reef Type	0,1	0,1	5- 6

The various ore types are described below as outlined by Nagerl (2000).

Massive Ore
Subdivided into three sub types of ore that occur as a zoned mass:

Cpy-mooihoekite 5 –10% of massive ore in central part of ore body with up to 100's g/t PGE. This ore is 70% mined out.
Cpy-cubanite 20 – 25% of massive ore surrounds mooihoekite ore and averages 3,15 – 3,2% Ni.

The total size of the massive sulphides body prior to mining is estimated to be about 509 million tones.

Copper Ore
This ore looks like a breccia and may have possibly formed by metasomatism of sulphides superimposed on country rock and appears as a sulphide cement to the country rocks. Grinenko (1985) offers an alternative explanation given above.

Disseminated Ore
The taxitic lower gabbro zone contains disseminated sulphides throughout the intrusion. The disseminated ore forms 81,9% of the total ore reserves and is currently mined from the Noril'sk # 1 deposit.

Reef-type Ore (Also referred to as low sulphide ore).
This occurs above the disseminated ore but is also hosted in a taxitic gabbro (with brecciated fabric) in the upper part of the Talnakh intrusion. The reefs are 3 m wide and has reserves of about 12 Mt at 7 g/t PGE. It is only found in association with the disseminated ore and never occurs outside of disseminated ore contours. It is interpreted as a "cap" to the disseminated ore.

A Detailed Stratigraphy of the Talnakh-type intrusions showing the distribution of mineralisation is given below in table 6 (After von Gruenewaldt, 1991).

Table 6 - Detailed Stratigraphy of the Talnakh-type intrusions showing the distribution of mineralisation

UPPER GABBRO SERIES	Contact Gabbronorite	⬛
	Equigranular and pegmatoidal chromite-bearing anorthosite gabbro with inclusions of picrite, troctolite and clinopyroxenite	🟩
	Equigranular and taxitic gabbro	⬛
	Gabbrodolerite and quartz-bearing gabbrodolerite	⬛
LAYERED SERIES up to 100 m	Diorite with micropegmatite	🟨
	Gabbrodolerite grading downward into	🟩
	Olivine biotite gabbro dolerite grading into	🟩
	Picritic rocks (picritic gabbrodolerite, picrite, troctolite, plagioperidotite) with disseminated sulphides globules (~ 25 m)	⬛
LOWER GABBRO SERIES 30-35 m	Taxitic rocks (gabbrodiorite, olivine and gabbrodolerite and contact gabbrodolerite) with disseminated sulphides	⬛
Massive sulphides 0 – 40 m		🟥

Heavily disseminated sulphides are hosted in the taxitic lower gabbro zone usually as irregularly shaped, large sulphides patches. The texture of this taxitic gabbro varies from coarse-grained pegmatitic patches, plagioclase rich segregations, fragments of gabbroic rock, etc.

The picrite overlying the lower taxitic gabbro has numerous sulphides globules displaying fractionation with the upper part consisting chalcopyrite and the lower half composed of pyrrhotite. Interstitial sulphides occur throughout this type of mineralisation.

These sulphides spheres decrease in abundance upwards making way for weak sulphide disseminations.

Chalcophile Elements

Comparisons of the MgO and Ni content of the Nadezhdinsky (nd 1 and 2) formations show it to be highly depleted with average Ni values of 25 and 41 ppm respectively (Naldrett et. al., 1995).

2.3.2.4 Model for Ore Genesis

The Nadezhdinsky lavas (nd) reach their maximum thickness of ~ 500 m where they are closest to the Noril'sk-Kharayelakh fault indicating this structure was an important eruptive centre during Nd time. The magma is interpreted to have been fed into staging chamber(s) at depth below the lower Talnakh intrusion. These chambers then emptied to form the Lower Talnakh and Lower Noril'sk sills (Naldrett, 1997). This magma and new pulses of magma continued from here to the surface to form the Nd suite lavas. This process is illustrated in Fig. 11.

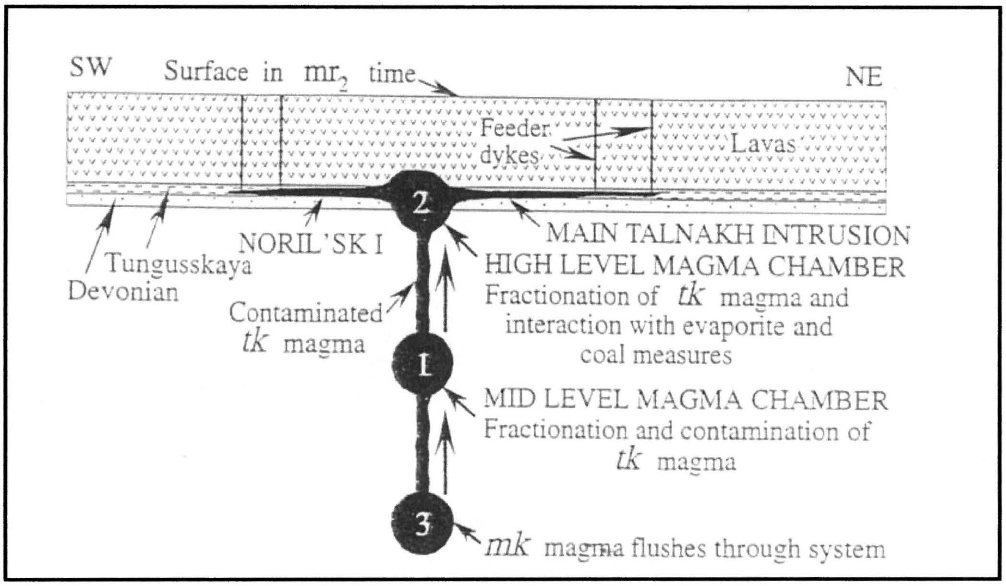


Fig. 11 Conceptual model for Ore Genesis after Naldrett (1997)

Elevated La/Sm, radiogenic Sr and unradiogenic Nd isotopic signatures of the Nd lavas provide clear evidence for the process of crustal contamination having taken place (Falconbridge presentation, 2000). Naldrett et. al. (1995) describe the contamination as resulting from magma rising beneath a keel of a developing volcanic basin where its ascent to the surface would be obstructed. Here it would be forced to pond and then spread out within the hosting sedimentary strata where it assimilated crustal sulphur. Further evidence for this lava been related to the underlying mineralisation is that it shows significant chalcophile depletion e.g. elevated Cu/Pd, Y/Pd and low Cu/Zr, Cu/Y (Falconbridge presentation, 2000).

Grinenko (1985) was able to detect a correlation between the sulphur content and the average $\delta^{34}S$ values of the sulphides in barren and un-economic mineralised intrusions. Grinenko also calculated the average $\delta^{34}S$ values for mineralised intrusions and related these $\delta^{34}S$ values to the contamination processes.

Barren intrusions with no sulphides generally occurred in sulphur-free clastic sediments of the Tunguska super-group and in the overlying flood basalts. Where uneconomic sulphides had formed these resulted from contamination caused by sulfate-bearing sediments which have relatively high sulphur contents. These rocks showed isotopic inhomogeneity and the contamination was interpreted to have occurred in-situ as a result of assimilation of the wall rocks.

Grinenko (1985) calculated from mass balance calculations that 20 to 36% sulphur had been added to the uneconomic mineralisation. She assumed an initial magmatic isotopic composition of 0 and an initial sulphur content of 0,12 to 0,23 wt%.

The economically mineralised intrusions are interpreted to have been contaminated by the evaporates/anhydrite bearing sediments prior to final emplacement. This is because of the isotopic homogeneity of the rocks.

The chambers were replenished with Morongovsky (Mo) like magma which emptied in a dynamic manner resulting in the formation of the Kharayelakh, Talnakh and Noril'sk 1 mineralised intrusions. The significant (~ 250 m) thick contact metamorphic contact metamorphic aureoles associated with the intrusions show that significant "flow-through" took place. The envisioned dynamic process would have caused sulphides to have been entrained in the silicate melt causing a high R factor. Changes in the flow regime would have caused the more dense sulphides to settle out and pool in axial depressions. These pools then fractionated to form Cu-rich liquids enriched in Pt and Pd whereas the mss cumulates preferentially retained Ni, Ir and Os.

The Noril'sk-Talnakh intrusions are described in the Falconbridge (2000) presentation as "a series of stacked, transgressive, composite sills with mineralisation hosted in enlarged zones that represent axial flow regimes".

Naldrett et. al. (1995) interpret this process to have occurred in three stages (based on the chalcophile elements in the Nd magma). They propose that intitial contamination took place in the mid to upper-crustal level where Ni, Cu and Cr were reduced to 50 to 70% of their concentrations in the Tuklonsky Formation (tk). During the third stage the Cr in nd2 continued to decrease but sulphide removal has ended. The second and third phases are interpreted to have occurred in a shallow magma chamber that was emplaced at the level of the Devonian-Carboniferous evaporates and coal measures.

The model outlined above is supported by the several factors evident in Noril'sk type intrusions as mentioned by Naldrett et. al (1995) namely:

1) They contain a large proportion of sulphides ranging from 2 to 10% of their total mass.
2) The sulphides contain a high proportion of PGE which according to Naldrett et. al. (1992) was formed by at least 200 times more magma then that represented by the intrusions.

3) The mineralised intrusions are surrounded by an intense metamorphic aureole. This is reported to extend into the country rock for the same thickness as the intrusions themselves, in some cases up to 400 m.
4) The sulphur displays very heavy isotopic compositions for mantle-derived sulphur with $\delta^{34}S$ ranging from +8 to +12.

2.3.2.5 Key Aspects of Deposit Relevant to Exploration (Nagerl., 2000 – unless otherwise stated)

1) The deposit has a significant metamorphic aureole (Naldrett, 1995).
2) The deposit has a surface expression and was found by boulder prospecting.
3) Coal seams preclude EM as an effective exploration tool.
4) The regional aeromagnetic and gravity anomaly is not attributed to sulphides but rather to the intrusions although according to Watts (2003, pers. comm.) the signature produced by the intrusions is also weak.
5) The deposit occurs on a craton margin in the vicinity of the junction of the E-W and N-S rift.
6) On a smaller scale, the ore is associated with a major N-S fault on the flanks of an anticline. The nose of this anticline is eroded.
7) The ore-hosting and non-ore hosting intrusions thicken near the ore.
8) The ore-hosting intrusions are olivine and plagioclase-rich and are the most Mg-rich in the province.
9) The intrusions are not large (in the order of 10's of kms).
10) Ore hosting intrusions are horizontal and pipe-like, they are not flat sheets.
11) Ore-hosting intrusions are differentiated.
12) Ore is associated with taxitic gabbro suggesting a high volatile content in sulphides; perhaps from the carbonates.
13) Ore has a complex sulphide mineralogy; > 150 minerals.
14) The deposit formed on the 248 Ma Paleozoic-Mesozoic boundary and may be related to this geological event.
15) The deposit occurs at the top of a carbonate-evaporate sedimentary pile and at the base of a volcanic pile.
16) Host sedimentary rocks have favourable physical-mechanical and chemical properties for the formation of ore.

2.3.3 Uitkomst Complex – Nkomati Mine

2.3.3.1 Introduction

This Bushveld-aged (2 044 Ma, De Waal et. al., 2001), layered mafic-ultramafic complex hosting the Nkomati Mine is situated about 20 km north of Badplaas contains Ni, Cu, Co and PGE mineralisation (Fig 12). It was first discovered by unknown asbestos prospectors and recorded for the first time in 1929 by Wagner (Theart 1999). Anglo American first realized its Ni potential in 1970. The complex is exposed in a broad valley which dissects the Transvaal Sequence orthogonally to the escarpment. The complex is a long linear shaped intrusion which has a keel shaped base and is concordant to the Transvaal sediments with a dip of about 4° to the northwest located on the edge (about 60 km from the closest contact) of the Bushveld Complex (Fig. 13).

Fig. 12 Locality of the Nkomati Mine after Woolfe, 1998.

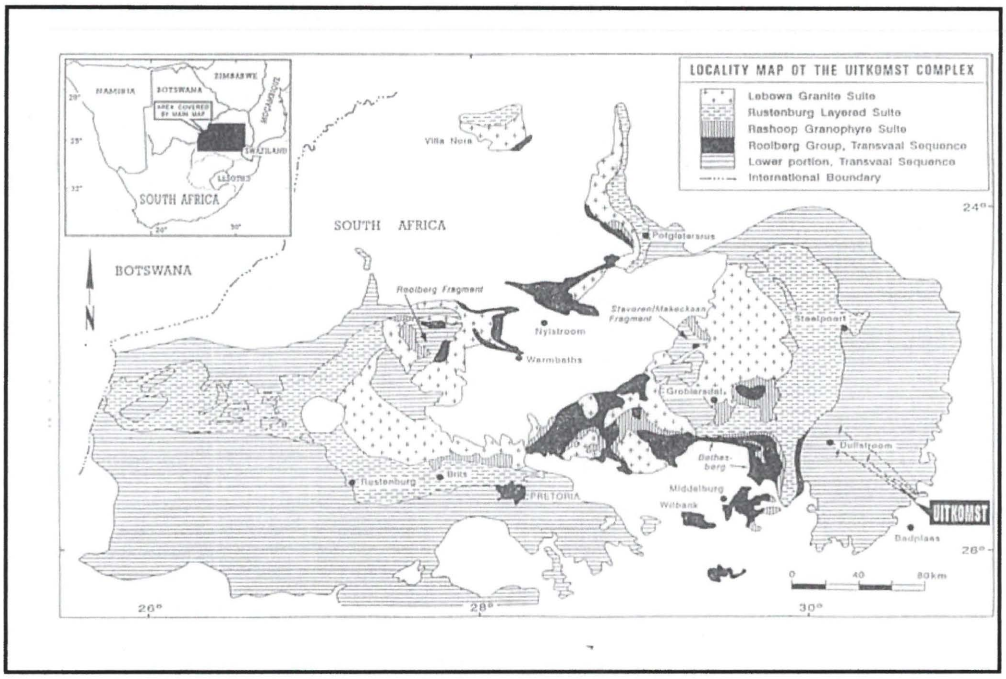


Fig. 13 Position of Uitkomst relative to the Bushveld Complex, from Gauert et al., 1996

Anglovaal Minerals Ltd. (Avmin) has a 75% interest and Anglo American Corporation Ltd. (Anglo), 25%. The Nkomati Joint Venture was established between these two groups in order to explore and exploit the Uitkomst body. The Nkomati mine which extracts the metals from Uikomst is currently the only primary Ni mine in the Republic of South Africa (Gauert et. al. 1995).

2.3.3.2 Geology

The complex is comprised of stratiform mafic and ultramafic units that from bottom to top are comprised of gabbro, sulphide-bearing harzburgite, unmineralised harzburgite, pyroxenite, gabbronorite and gabbro (Fig. 12). The body is hosted by the Timeball Hill Shale, Rooihoogte Formation and Malmani Dolomite and has Black Reef Quartzite as footwall rock (von Scheibler 1995). The layering is sub-parallel to the sedimentary layering i.e. 3,5 to 4, 0° W- northwest.

The average cumulative thickness of the sill is 670,5 m (Theart and Nooy, 2001), the complete stratigraphy is shown below (J. Woolfe, 1998) with the mineralisation and petrography columns taken from Li et. al. (2002).

Table 7 - Uitkomst Stratigraphy

Unit	Thickness (m)	Petrography	Sulphide Mineralisation
Upper Gabbro	10 – 20	Subhorizontal modal layering	Mostly sulphides barren
Norite	250 – 300	Massive to integranular	Mostly sulphides barren
Upper Pyroxenite	60 – 80	Intergranular with cumulus augite	Sulphur barren to weakly disseminated
Peridotite	200 – 300	Olivine + minor chromite cumulate	Weakly disseminated
Massive Chromitite	0 – 5		
Chromititic Peridotite	30 – 65	Olivine + Chromite orthocumulate	Weakly disseminated
Lower Harzburgite/ Lower Pyroxenite (stratigraphic name, does not imply genesis)	20 – 40	Variable between feldspathic harzburgite to olivine websterite with cumulate olivine and chromite	Disseminated to net-textured
Basal Gabbro	0 – 7	Phaneritic with plagioclase, augite and olivine	Blotchy sulphides to massive veins

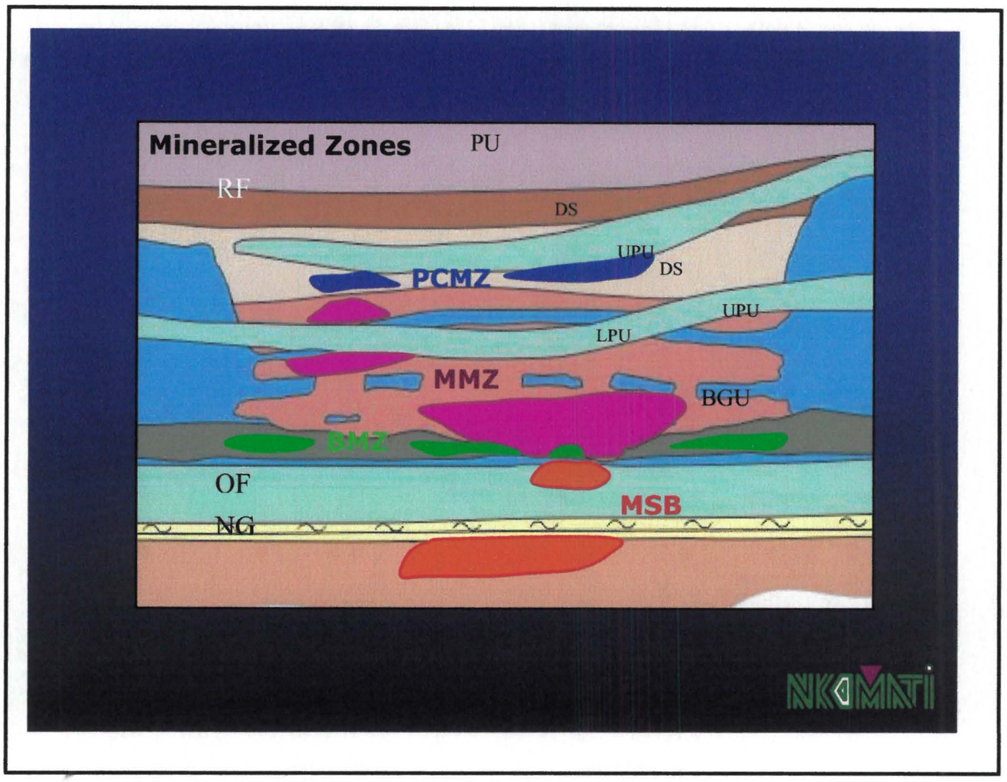


Fig. 14 (After Woolfe, 1998). Cross section through Uitkomst Intrusion; MSB = Massive Sulphide Body; BMZ = Basal Mineralised Zone; MMZ = Main Mineralised Zone, PU = Peridotite Unit; RF = Rooihoogte Formation; PCMZ = Chromititic Peridotite Mineralised Zone; DS = Dolerite Sills, UPU = Upper Peridotite Unit; LPU = Lower Pyroxenite Unit; BGU = Basal Gabbro Unit; OF = Oaktree Formation; NG = Nelshoogte Granite (After Woolfe, 1998).

Li et. al. (2002) report that there are altered dolomite xenoliths of variable sizes ranging from a few centimeters to 1 mm diameter in the lower part of what they describe as the lower harzburgite unit which corresponds to Woolfe's (1998) lower pyroxenite unit. von Scheibler (1995) proposes that quartzite layers including the Rooihoogte and Klapperkop Quartzites controlled the prorogation of the Uitkomst magmas during emplacement. He states that this is proof that the melts were derived from a downdip direction to the W-northwest. This is in agreement with de Waal et. al. (2001) who shows from major and trace element data that the parental magma of the Uitkomst harzburgite is similar to Bushveld B1 magma (which implies the magma flowed out from the Bushveld Complex).

Gauert et. al. (1996) provide further evidence (in addition to the presence of xenoliths) for sources of contamination from δ^{34} S isotopic data. Their data is tabulated below. These authors conclude that the mineralisation is largely due to local assimilation of sulphur from country rocks.

Table 8, Data from Gauert et. al. (1996)

Lithology	δ^{34} **S**	**Interpretation**
Main Harzburgite	- 7,4 to 1,2 (Mode – 6 per mil)	
Lower Harzburgite	Ave – 4,5 +/- 1,8 per mil (Mode – 6 per mil)	Large degree of homogenization between sedimentary and magmatic sulphur. Mass balance calculations (assuming B1 type magma and dolomite indicate that only 10% dolomite assimilation is necessary)
Basal Gabbro	-19,5 to 1,8 per mil (Modes at 0 and –6,0 per mil	Evidence for magmatic, sedimentary and mixed sulphur
Country Rocks	-11,5 to 15,5 per mill	

The compositions of the olivine and the Ni contents of the olivine varies considerably between the different units (Li et. al., 2002). There are two variations of olivine namely an Fe rich and a MgO rich olivine. The Mg rich olivine occurs in all harzburgite and pyroxenite units whilst the Fe rich variant is restricted to the upper gabbro unit. Li et. al. (2002) further divides the Mg rich unit into three subtypes based on their Ni content namely:

1) A Ni rich olivine containing 3 000 ppm Ni which occurs in the unmineralised harzburgite and pyroxenite. These lithologies have a δ^{34} S of - 0,2 to 2,8% which is similar to mantle derived sulphur which has values of ~ 0 +/- 3%).
2) Moderately Ni-depleted olivine containing 1 300 – 2 300 ppm Ni which is located in the sulphides mineralised harzburgite (> 1 wt. % total sulphides). The δ^{34} S values for this unit are – 2,6‰ to – 7,1‰.
3) Highly Ni-depleted olivine containing < 500 ppm Ni which occurs in the upper portion of the pyroxenite unit.

Olivine forsterite (Fo) content vs. Ni content also show the various subtypes also plot in different fields showing they probably crystallized from different magmas (Li et. al., 2002). The negative δ^{34} S values of the (-3 to 7%) of the sulphide mineralised harzburgite units suggest the addition of crustal sulphur which would have caused the formation of sulphide liquid.

Li et. al. (2002) state that (despite the subdivisions previously outlined) the olivine compositions throughout the sequence are fairly similar. This they ascribe to a high ratio of magma to cumulus olivine which would be achieved through repetitive replenishments of fresh magma into a large chamber or by continued flow of magma though a dynamic conduit. The former scenario does not account for the variations in the S isotopes between the various lithologies. It is therefore, concluded by Li et. al. (2002) that the mineralised harzburgites were flow cumulates that formed in a tabular magma conduit as per Norilsk and Voisey's Bay. de Waal et.l al. (2001) reach the same conclusion.

2.3.3.3 Mineralisation

The mineralisation has not been badly disrupted by structures although it is cut by a number of steep northeast-south west directed faults as well as flat-lying thrusts. The steep faults have caused negligible displacement whilst the thrust faults have caused duplication in places.

There are four zones of sulphides mineralisation (Fig 14) namely:

Massive Sulphide Body (MSB)

This is a localized high-grade orebody which is exploited by the current Nkomati mine (refer to Fig. 14). The Co is mostly in solid solution in the pentlandite whilst the PGE's occur in a number of telluride, arsenide and alloy species (Theart and De Nooy, 2001).

Basal Mineralised Zone (BMZ)
This is a copper rich zone hosted by the Basal Gabbro Unit.

The sulphides are composed essentially of pyrrhotite, with the Ni and Cu sulphides being pentlandite and chalcopyrite.

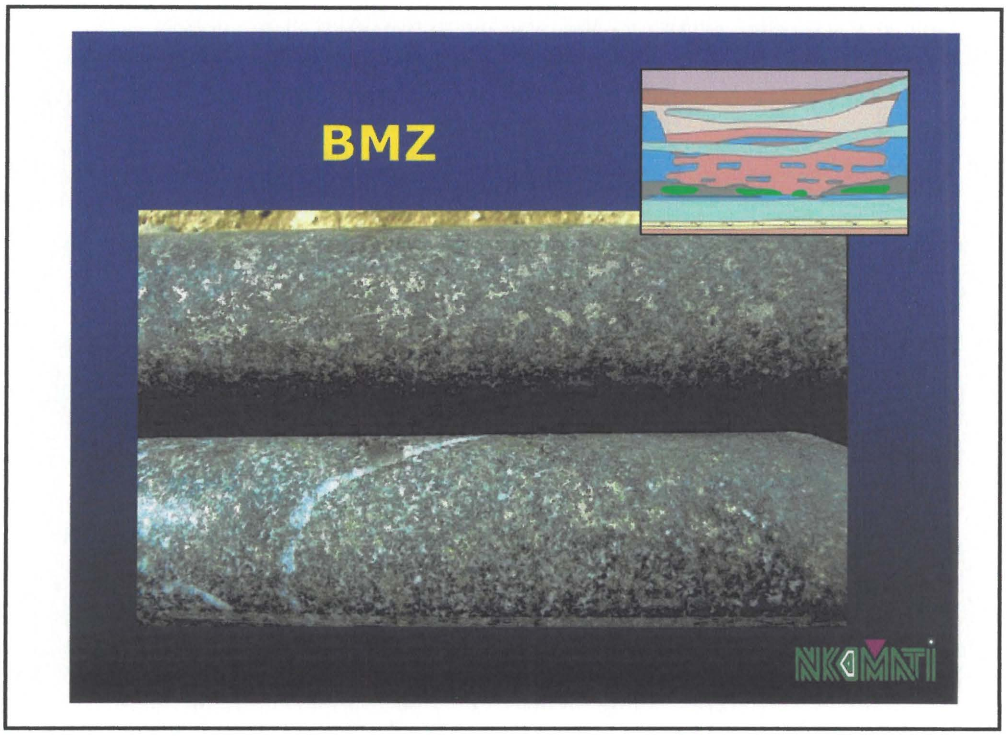


Fig. 15 Basal Mineralised Zone (After Woolfe, 1998)

Table 9 (Nkomati Mineralisation, After Maier et. Al., 2004)

MMZ	Mt	Ni (%)	Cu (%)	Co (%)	Pt (g/t)	Pd (g/t)
	72	0,60	0,22	0,03	0,30	0,82
PCMZ						
	22,0	0,43	0,14	0,02	0,25	0,62
MSB						
	2,9	2,04	1,13	0,10	1,65	4,18
BMZ						
	3,9	0.54	0,60	0,03	0,36	4,18

The Main Mineralised Zone (MMZ) – Figs 16 to 18
This is located in the Lower Pyroxenite Unit and is a continuous unit dilated by sills giving it the appearance of being a number of flat-lying lenses (Theart, pers. comm.; 2003) extending up to 3 km long and 400 m in cross-section. The thickness of the high grade lenses averages about 8 m with a maximum of 47 m.

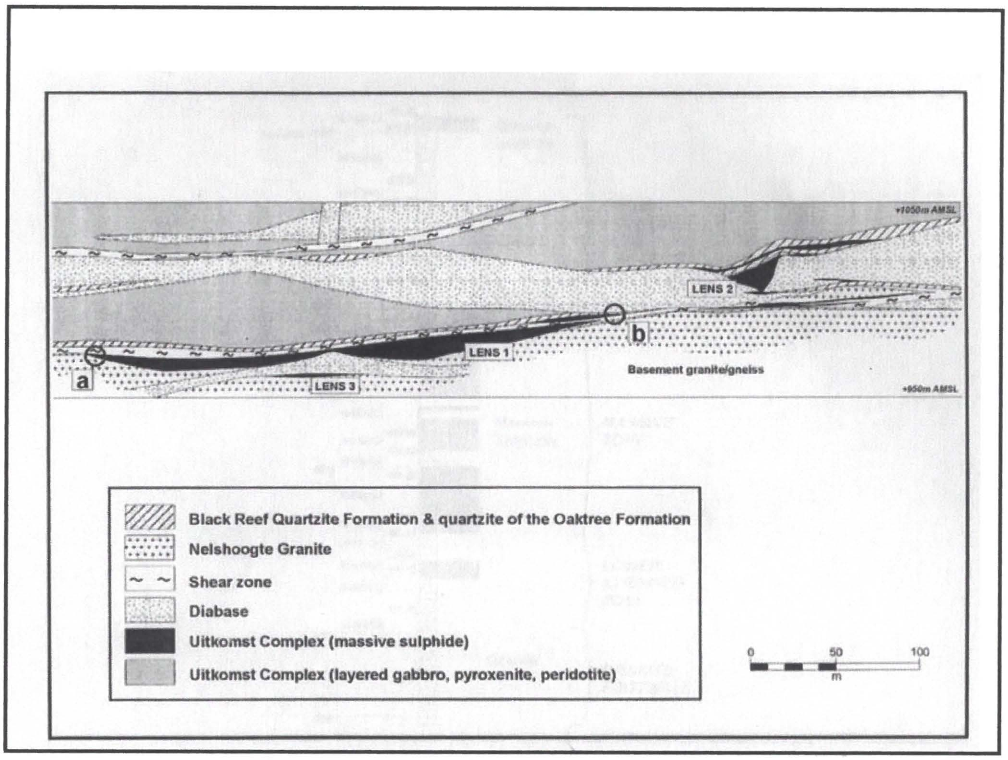
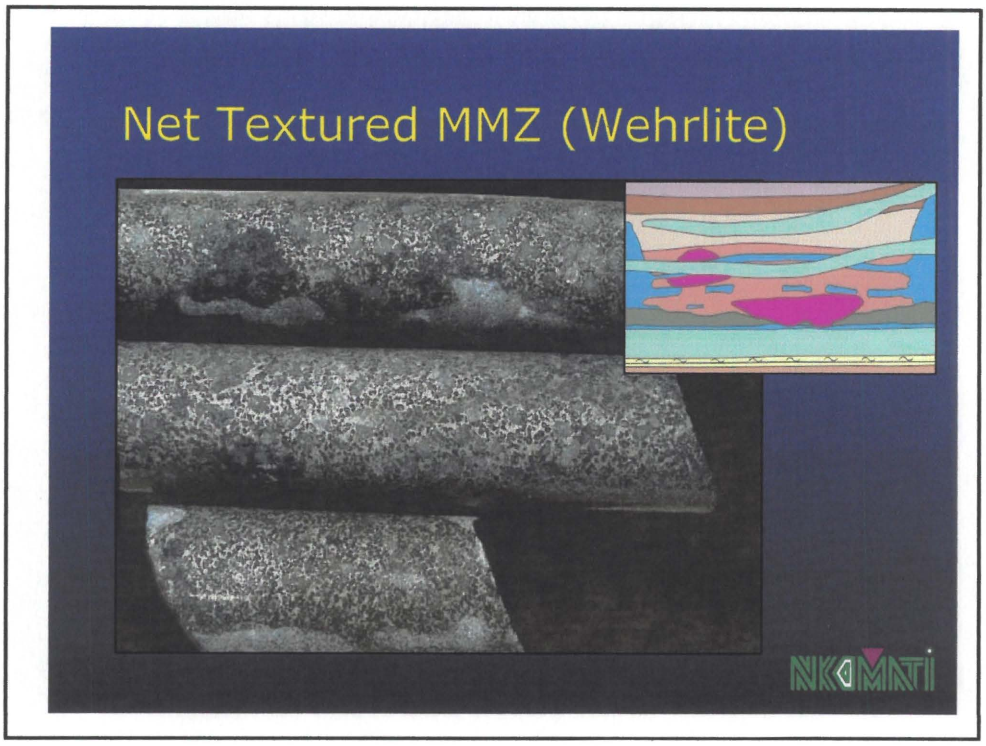


Fig. 16 (After Theart and Nooy, 2001) Cross-Section showing ore lenses


Disseminated/Blebby MMZ

Fig. 17 Disseminated/blebby sulphide of the Main Mineralised Zone

(After Woolfe, 1998)



Net Textured MMZ (Wehrlite)

Fig. 18 Net Textured Sulphides of the Main Mineralised Zone (After Woolfe, 1998)

The Chromititic Peridotite Mineralised Zone (PCMZ)
This is hosted by the chromititic peridotite unit which has a slightly lower grade then the MMZ.

2.3.3.4 Model for Ore Genesis

Gauert et. al. (1995) conclude from field, petrography, mineral and whole rock geochemistry that the following sequence of events occurred.

1) The original emplacement of magma took place from northwest to southeast.
2) The intrusion was bounded between two major fracture zones that gave rise to an elongated body, which acted as a conduit for later magma emplacement.
3) The original emplacement of magma was derived from the Bushveld Complex. The chilled margins show chemical affinities to a micropyroxenite described from the Bushveld Complex.
4) The Lower pyroxenite/harzburgite and chromiteferous harzburgite units originated from crystal settling of a contaminated basic magma.
5) The Main harzburgite crystallized from a magma of basic composition that flowed through the conduit after formation of the other three lithological units.
6) At a late stage of emplacement, after replenishment in the conduit came to a standstill, closed system conditions developed in the upper part of the complex resulting in a magma fractionation trend of increasing incompatible elements towards the top of the intrusion.

7) The mineralisation in the lower three units was caused by oxidative degassing of the dolomite resulting in the segregation of the sulphides liquid.

Discussion

The Uitkomst body is reported to be fault bound by Gauert et. al. (1995) although the dominant structure controlling the emplacement of this body appears to be the major fault running from Amsterdam in the southeast across the entire Bushveld Complex to the northwest (detectable from aeromagnetic plots). Bushveld Complex magmas have been shown by de Waal et. al. (2001) and Gauert et. al. (1995) to have been the source of the Uitkomst magma. These magmas flowed updip and were possibly controlled by the three quartzite formations (Rooihoogte, Black Reef and Klapperkop) as described by von Scheibler (1995). It is also thought by the author that the contact between the Transvaal Supergroup sediments and the basement granite was instrumental in controlling the emplacement of the conduit. The presence of xenoliths, and negative δ^{34} S isotopic values for the basal gabbro and lower harzburgite show contamination of these magmas took place. Cawthorn (1999) describes the contamination as resulting from the assimilation of pyritic and graphitic shales which were interlayered with the quartzite units controlling the emplacement of the magma. He also mentions degassing of dolomite where the magma broke through the footwall and formed a "channel" in this lithology as been important in the contamination process. Cawthorn (1999) also attributes the origin of the chromitite to an increase in oxygen fugacity resulting from degassing dolomite.

The apparent inverted stratigraphy of pyroxenite overlain by peridotite is explained by Cawthorn (1999) as being the result of decreasing assimilation and not reversed differentiation. This he explains as resulting from the addition of SiO_2 and K_2O to olivine which would cause pyroxene crystallization and sulphide segregation. The overlying subsequent magma pulses were less contaminated and hence had less sulphide and crystallized sulphide poor peridotite.

The initially emplaced basal gabbro experienced partial contamination as the sediments were not well homogenized within the melt which cooled relatively quickly. The subsequent pulse of magma, the lower pyroxenite, cooled somewhat slower and so the sediments were well homoginised within this layer (table 7). This would have resulted in sulphur saturation and precipitation which would have accumulated at the base of the conduit to form the MSB. The ratio of cumulate olivines to melt indicates that there must have been a much higher volume of melt flowing through the system then is currently preserved. This magma could potentially have "fed" a chamber that is now eroded. This flow of magma would have caused a high R factor which would have resulted in an increased tenor of the sulphides as they "strip" the chalcophile Ni and Cu from the entrained olivines. The sulphides that did not precipitate prior to the crystallization of the lower pyroxenite unit became trapped to form the disseminated mineralisation. The upper pyroxenite would have "lost" its Ni to the underlying sulphides causing it to be Ni depleted (Li et. al., 2002).

2.3.3.5 Key Aspects of Deposit Relevant to Exploration

1) No distinct aeromagnetic signature possibly because it is largely masked by the overriding signature created by Timeball Hill Shales which also covers a large part of the intrusion with scree.
2) Detectable through stream sediment sampling (reported in INCO unpublished 1977 report,) to leave an anomaly up to 2 km downstream with anomalous values of 700 to 800 ppm Cu and 900 to 1 100 ppm Ni.
3) The ultramafic igneous rocks weather preferentially resulting in a topographic "low".

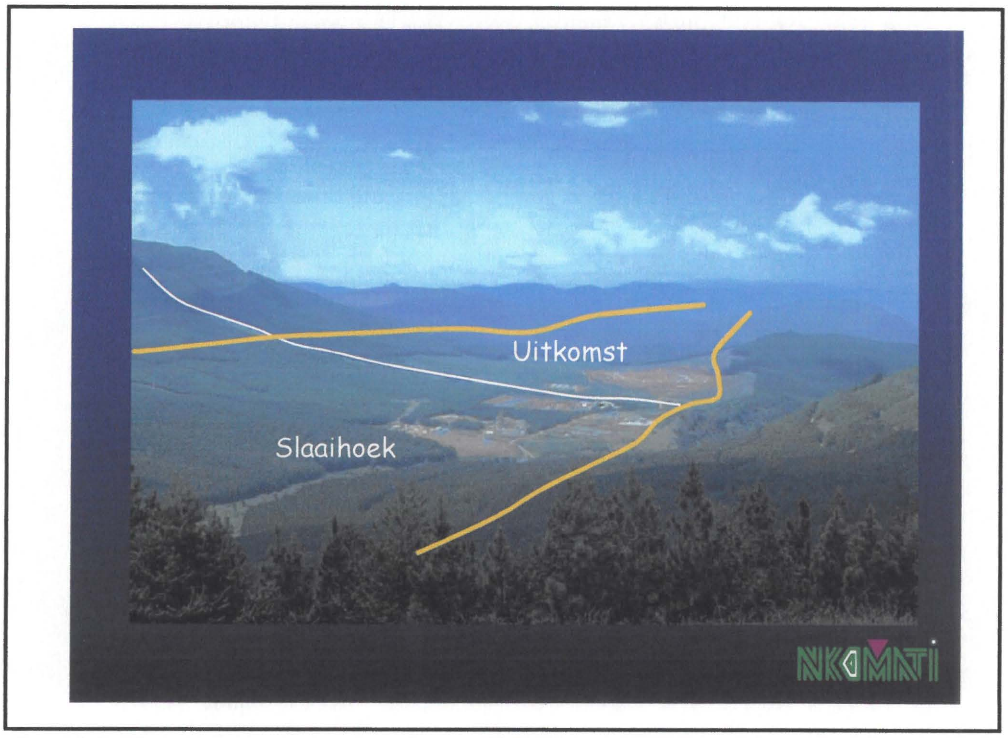


Fig. 19 Surface Depression caused by preferential weathering of primitive lithologies. The yellow line shows the surface expression of the Uitkomst Body. Slaaihoek and Uitkomst are farm names. (After Woolfe 1998).

4) Emplaced along a major lineament and possibly along the contact between the Transvaal Supergroup sediments and the basement granite.
5) Magma sourced from the Bushveld Complex which is possibly an intracontinental rift (origin of the Bushveld Complex discussed by Pirajno, 2000).
6) System was dynamic, i.e. was a conduit which experienced significant “flow-through”.
7) Uitkomst body shows evidence for Ni depletion and enrichment in olivines.
8) System shows evidence for contamination both in the presence of xenoliths and negative δS^{34} isotope values.
9) Body contains ultramafic and mafic rocks.
10) The lower part of the body is not sill-like but restricted to a subhorizontal tube-like intrusions.
11) Associated with a metamorphic aureole indicating high temperature melt and sustained “flow through”.

2.3.4 Sudbury Igneous Complex

2.3.4.1 Introduction

The Sudbury Igneous Complex is located near the junction of the Superior, Southern and Grenville provinces of the Canadian shield (Dressler, 1984) although this boundary is not related its genesis. The Ni-Cu ores of the Sudbury district were discovered in 1883, during the construction of the Canadian Pacific trans-continental railway (Naldrett et. al. 1997). The Sudbury Igneous Complex is a layered intrusion ranging from quartz norite at the base, through gabbro to a granophyric cap. Its related Ni ores are currently being mined by INCO and Falconbridge.

2.3.4.2 Geology

The structure is believed to be the remnant of a large, 1 850 Ma meteorite impact which had an original rim diameter of approximately 220 km (Stoffler et. al., 1994). It is situated at the contact between the tonalitic gneisses and intrusive quartz monzonites, all of Archaean age (>2,5 Ga) to the north and rocks of the Proterozoic Southern Province to the south. The Sudbury Igneous Complex is more than 2 500 m thick and the related ore deposits were produced by impact melting of the upper and lower crust and subsequent differentiation of the melt, whose original volume was in excess of 12 500 km^3. The impact produced a transient cavity of about 110 km diameter that collapsed to a 220 km wide shallow ring or multi-ring basin which subsequently became filled with pelitic sediments (Pye et. al., 1984).

The term Sudbury Structure includes the ring-shaped Sudbury Igneous Complex, the surrounding brecciated and shocked basement rocks (Archaean and Proterozoic igneous and metamorphic rocks) (Pye et. al. 1984).

Generalised stratigraphy of the broader stratigraphic divisions tabulated below.

Table 10 (Naldrett, 1997)

Stratigraphic Unit	**Description**
Onaping Formation	This is a breccia composed of fragments of country rock and recrystallised glassy material set in a matrix of glassy shards. It is interpreted as fall-back breccia.
Sudbury Igneous Complex	Described below.
Footwall Breccia	A breccia of country rock that forms a layer 10 to 50 m thick between the Sudbury Igneous Complex and the footwall gneisses and monzonites along the north range of the Sudbury Igneous Complex. It extents a further 10 m into these rocks as apophyses. It is also present along the South Range but much less common.
Sudbury Breccia	This is a breccia composed of country rock fragments which range from microscopic to more than 10 m in diameter. They occur as dykes and irregular masses in all pre-Sudbury Igneous Complex rock types outside of the Sudbury structure.

The Sudbury Igneous Complex is composed of the following lithologies:

Table 11 (After Mccormick et. al. 2002 and Stoffler et. al 1994)

Stratigraphic Unit	**Description**	**Thickness (m)**
Chelmsford Formation (Hanging Wall)	Turbidites – sand and siltstone.	800
Onwatin Formation (Hanging Wall)	Pelagic shales, siltstones and minor greywacke.	600
Onaping Formation	Polymict breccias containing shocked rock and quenched "recrystallised" melt particles.	1 600
Granophyre	Main mass mafic norite, felsic norite, quartz gabbro, and granophyre in the north range; and quartz rich norite, South Range norite, quartz gabbro and granophyre in the South Range	2 400
Quartz Gabbro		
Felsic Norite		
Sublayer Dark Norite Breccia & Light Gabbro Breccia	A discontinous, xenolith bearing, gabbroic to noritic unit (the sublayer),.	0 - 50
Footwall		

The Sudbury Igneous Complex is usually divided into three units (Naldrett et. al., 1984) namely:

1) an upper Main Mass of noritic, gabbroic and granophyric rocks.
2) The Contact Sublayer
3) The offset Dykes composed of noritic and dioritic rocks. These dykes are radial to the Main Mass and Sublayer and extend for up to 15 km from the Sublayer.

These three units are described below:

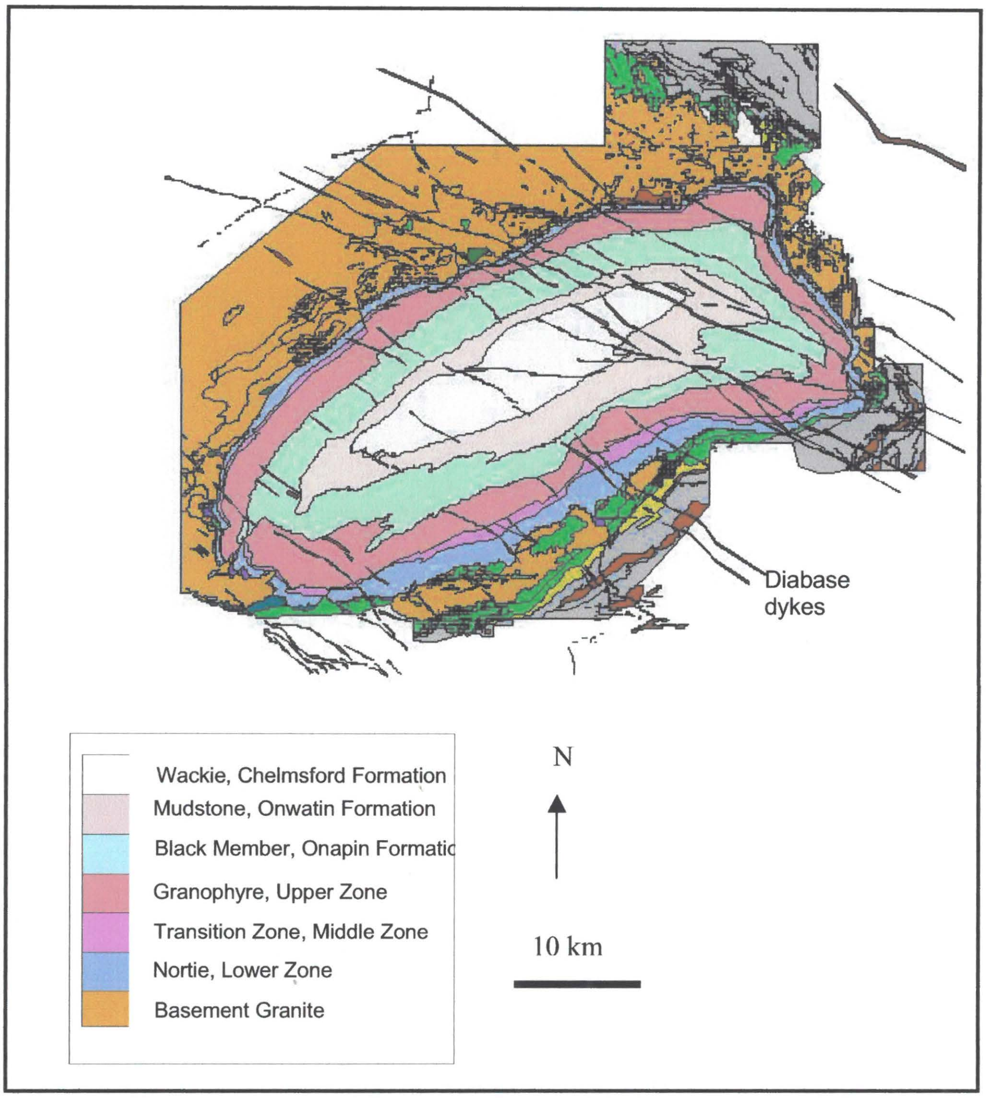


Fig. 20 Sudbury Igneous Complex Geology – (From Falconbridge Database)

Main Mass - These norites are plagioclase-orthopyroxene-clinopyroxene cumulates that have cryptic Mg/(Mg+Fe) ratios in the pyroxenes and An content of the plagioclase which are consistent with fractional crystallization (Naldrett et al., 1970).

Sublayer - This layer consists of a suite of medium-grained norites and gabbros that are distinguished from the Main Mass felsic norite and quartz gabbro by their lower quartz content in relation to pyroxenite (Naldrett et. al., 1972).

Evidence for an impact origin for the Sudbury Igneous Complex includes:

1) The basin shape of the structure.
2) The upturned collar around the basin, particularly evident in the Huronian rocks along the southern margin.
3) Shock metamorphic features in the country rocks around the structure.
4) The Sudbury breccia (which is similar to the pseudotachylite of the Vredefort and Ries structures) in the country rocks around the structure and the footwall breccia beneath the complex (Dressler, 1984).
5) Evidence for shock metamorphism in country rock inclusions in the Onaping Formation.
6) The 1 800 m of the Onaping Formation itself, the lower half of which is interpreted to be fall-back breccia or an ignimbrite (Peredery and Morrison, 1994).

Structure

Work by structural geologists (Shanks and Schwerdtner, 1991) and from high resolution seismic data (Milkereit et. al., 1992) have show the following with regards to the structure and morphology of the Sudbury Igneous Complex.

1) The Sudbury Igneous Complex was originally circular and bowl shaped and has been deformed during the Penokean orogeny (1,7 to 1,9 Ga) by northwest directed thrust faulting.
2) The Sudbury Igneous Complex is not funnel shaped with an extension to deeper levels of the crust.
3) There is no need to invoke a large deep-seated ultramafic-mafic pluton to explain the Sudbury Igneous Complex.

2.3.4.3 Mineralisation

There are three main types of orebodies (Fig. 19) namely: contact mineralisation, offset dyke ore deposits and footwall mineralisation.

Contact-Type Deposits

These occur the base of the Sudbury Igneous Complex within the Sublayer which contains xenoliths of the underlying footwall material and mafic as well as ultramafic inclusions not derived from the immediate footwall. The footwall exhibits considerable compositional diversity ranging from being quartz free to quartz rich or from noritic to gabbroic with textural variation ranging from poikilitic to diabasic (Morrison et al., 1994). The Sublayer is thickest in areas that contain footwall depressions and is absent in other areas.

Mineralisation styles vary from disseminated to massive with the major portion of the sulphides occurring below the Sublayer in the Footwall Breccia. The Footwall Breccia is more distinct in the North Range than the South Range. This is partly because there is a greater colour contrast in the North Range between the inclusions (leucocratic gneiss) and the host rock (which has a dark colour) than in the South Range where the melanocratic sediment and mafic inclusions differ only slightly in colour from their host rocks. The South Range rocks have also undergone a greater degree of deformation resulting in the original distribution of the ores having being altered (Morrison et al., 1994).

The greatest concentrations of massive sulphide occur at the base of the Footwall Breccia. The Cu/Ni ratios in Contact-Type deposits vary from Low ratios of 0,1 to 0,5 in Sublayer norite-hosted deposits. Some of the Footwall Breccia hosted contact deposits have similar Cu/Ni ratios although if these deposits overlie footwall-type deposits they have ratios of 0,7 to 1,0). These different ratios are useful in detecting footwall type deposits. The contact type deposits are pyrrhotite rich and contain trace amounts of chalcopyrite (Jago et al., 1994).

Offset Dyke Deposits

Offset dykes are radial or concentric to the contact of the Sudbury Igneous Complex and have sharp contacts with the wall rock. The dyke deposits are hosted in a Sublayer matrix which is sometimes mixed with a component of Footwall Breccia (Morrison et al., 1992) and can extent up to 10 km or more into the basement (Jago et.al., 1994). An e.g. of an Offset Dyke deposit is the Copper Cliff offset dyke in the south range.

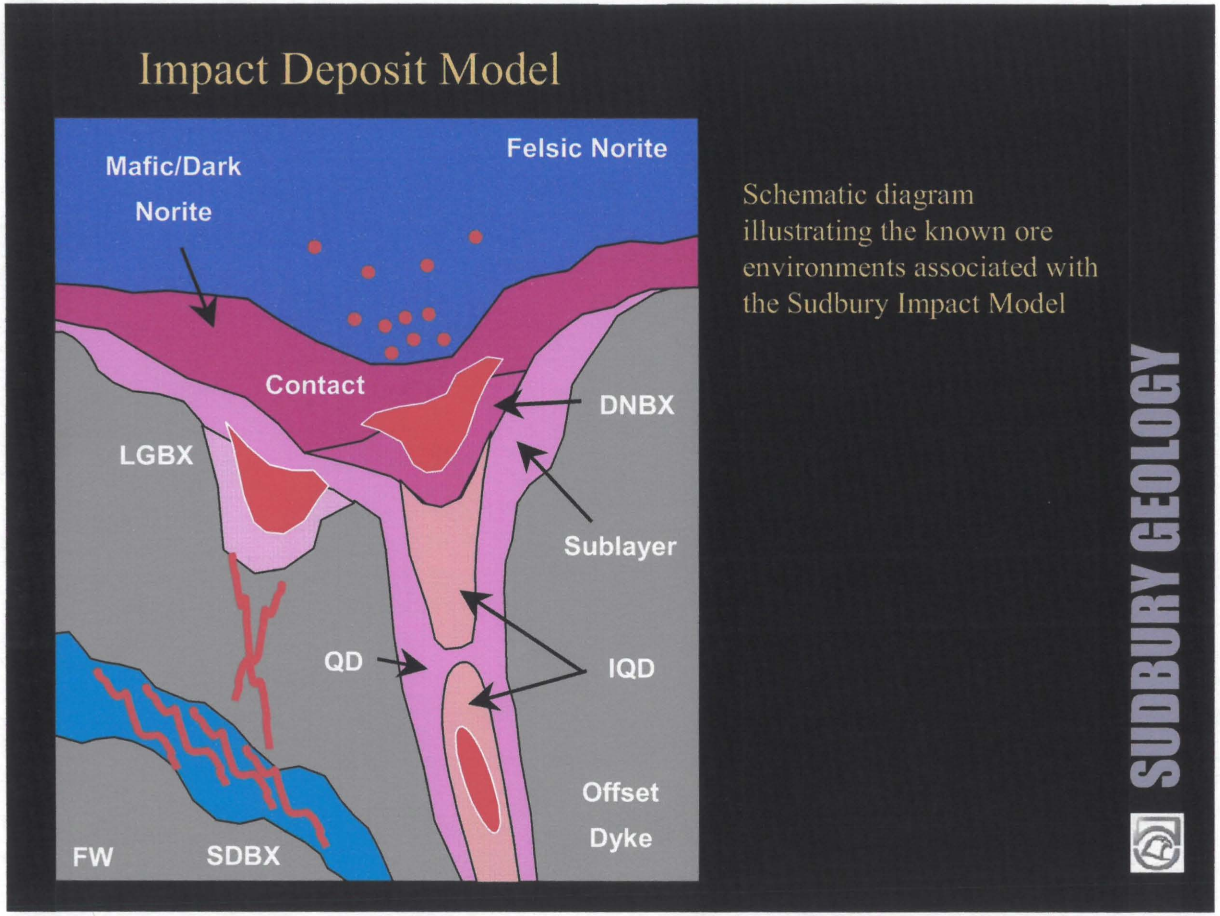
The geochemistry of inclusion poor and rich varieties of quartz diorite that the offset dykes are composed of shows them to have very similar compositions which also approximates that of the bulk composition of the complex (Tuchscherer and Spray, 2002). This indicates that they were probably emplaced at an early stage before any significant fractionation took place. Uplift would have caused extension of impact generated fractures and gravity would have caused impact melt and sulphides to have been driven into these causing the mineralisation in these dykes. Lightfoot and Farrow (2002) interpret that the amount of sulphides in these dykes is related to the thickness of the overlying melt sheet injected into these dykes. The melt sheet would have been thickest in Copper Cliff and Frood Stobie and thinner in the Worthington, Manchester and Foy offset dykes.

Footwall-Type Deposits

Occasionally sulphides migrate from the Footwaal Breccia into wall rocks in the form of veins, sheets and/or disseminated sulphides. These sulphides are highly fractionated with Cu/Ni ratios greater than 1. This mineralisation is considered as Cu +Au+Ag deposits as the sulphides generally contain an 28 g/t PGE's plus Au and Ag (Jago et. al., 1994) which increases the value per tonne of ore. Ni grades are in the order of 2% over several metres in drill intersections (Jago et. al., 1994). Whilst the offset dykes contain Sudbury Igneous Complex material that cuts the footwall stratigraphy the Footwall-Type deposits are composed mainly of massive sulphides and/or Footwall Breccia and contain little, if any Sudbury Igneous Complex silicates.

Footwall deposits are emplaced within or in close association with large zones of Sudbury Breccia that are in general proximity to contact type ore which occurs within troughs. Their petrographic characteristics indicate that they have formed under extensive thermal recrystallisation in response to the migration of hot fluids. The breccia zones are thought to have been conduits for the contact ore which then migrated into the footwall. Examples of Footwall-Type Deposits include McCreedy West, McCreedy East and Victor.

This style of mineralisation is dominated by chalcopyrite, cubanite and pentlandite with local concentrations of millerite and bornite (Jago et al., 1994). These authors conclude that the mineralogical and metal zonation patterns formed by crystal fractionation of a relatively primitive, pyrrhotite-rich sulphide melt from the contact environment.



Impact Deposit Model

Schematic diagram illustrating the known ore environments associated with the Sudbury Impact Model

SUDBURY GEOLOGY

Fig. 21 Sudbury Igneous Complex Styles of Mineralisation, DNBX = Dark Norite Breccia, LGBX = Light Granite Breccia, FW = Footwall, QD = Quartz Diorite. The diagram shows the contact mineralisation and associated disseminated sulphides having formed in a trough above Footwall Type mineralisation. The photograph shows borehole core drilled into a fractionated Cu rich Footwall Type sulphide vein. (after Falconbridge Presentation, 2001)

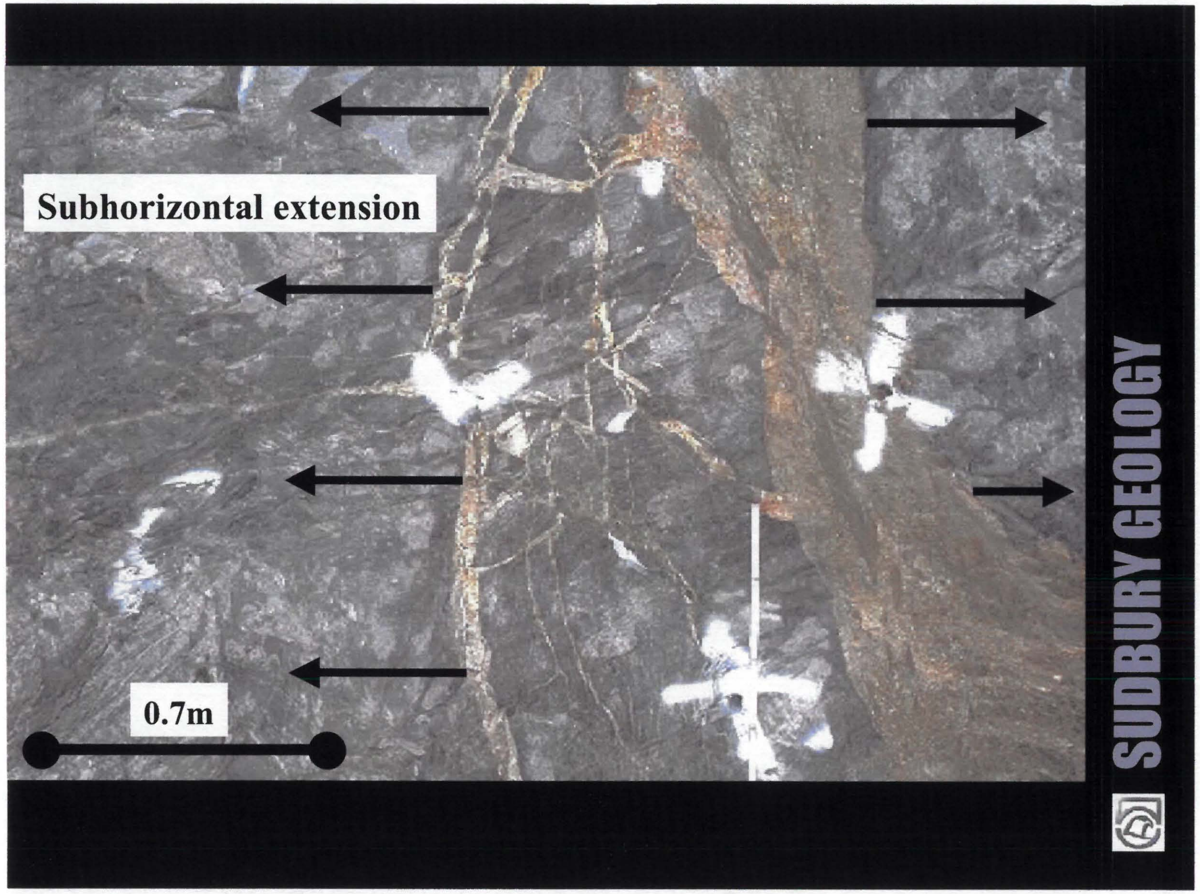


Fig. 22 Footwall Style Mineralisation (after Falconbridge Presentation, 2001)

2.3.4.4 Model for Ore Genesis

Possible sequence of events as outlined in a presentation by INCO staff (2003)

1) Impact event and formation of superheated melt sheet and breccias.
2) Injection of sulphide undersaturated quartz diorite melt into Offsets.
3) Cooling and sulphide saturation of the superheated melt sheet.
4) Sulphide segregation and concentration in depressions at the base of the melt sheet.
5) Injection of sulphide-laden quartz diorite into Offsets.
6) Cooling, and segregation of melt sheet into convecting mafic and felsic layers.
7) Continued sulphide segregation and accumulation.
8) Localisation of sulphides, country rock inclusions, and xenoliths in depressions.
9) Crystallisation of the noritic matrix, the formation of the Sublayer.
10) Cooling of the melt sheet from the roof down and the base up.
11) Orthopyroxene and sulphide accumulation; Ni+Cu-depletion of the upper noritic melts.
12) Sulphide liquid separation; post magmatic modification.

Discussion

The granophyre is depleted in Ni and Cu (INCO presentation, 2003) but there is a sharp increase in Ni values in the melt sheet directly above the mineralisation in the Sublayer. This indicates that the Ni has been stripped from the overlying granophyre and concentrated at the base of the melt sheet (Fig. 23)

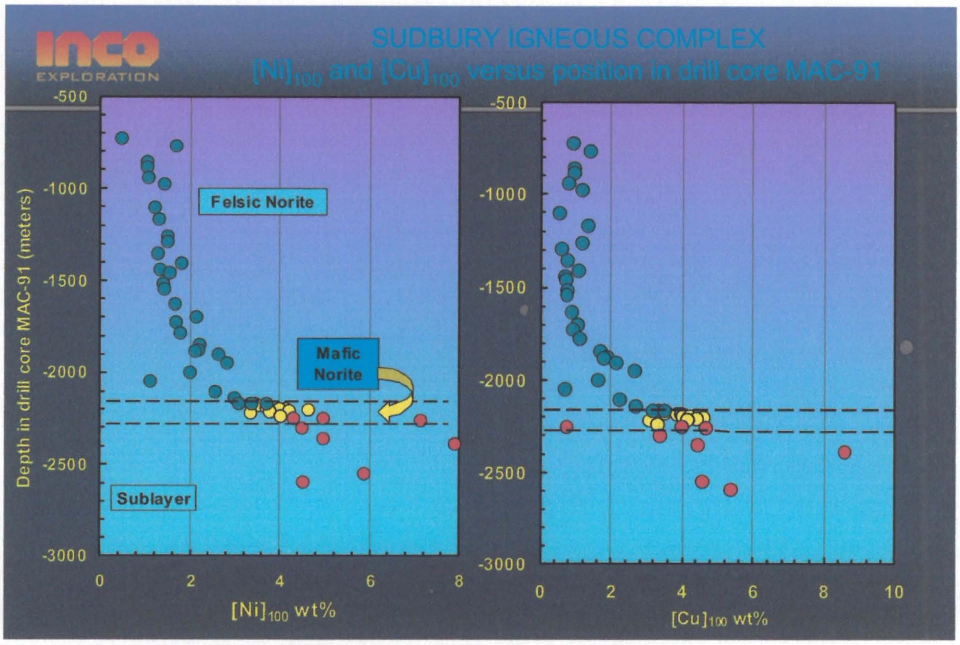


Fig. 23 Ni and Cu plotted through the Sudbury Igneous Complex showing the depletion through most of the melt sheet and the marked increase in the felsic norite and mafic norite overlying massive sulphides (caused by disseminated sulphides) (After INCO, presentation acquired in 2003)

Recent theories (MacEachern, pers. comm. 2002) have shown that sulphides concentrate in embayments because these offer greater surface areas which allows for greater cooling. This causes them to become the focus for the “downward flow” of convective currents. The entrained sulphides have SG’s too great to be moved back up by the convection cells and precipitate out of the melt at the point of the embayment. As the melt sheet cools further the last entrained sulphides are "frozen" above the embayment forming disseminated sulphides. These disseminated sulphides cause the increase in Ni values towards the base of the melt sheet above the Sublayer. Empirical observations of reserves and tonnages (Falconbridge data) overlain on a contoured image of the Sudbury Igneous Complex's thickness show that most medium to large deposits have formed where the melt sheet is at least 2 km thick. This implies that in these areas the convective cells were large enough to have scavenged sufficient metal to form economic deposits.

2.3.4.5 Key Aspects of Deposit Relevant to Exploration

1) Large meteorite impact site with a melt sheet thicker than 2 km, in places and an original diameter of ~ 250 km, i.e. a thick melt sheet is required.
2) Evidence for a meteorite impact includes radial fractures, shatter cones, presence of suevite, brecciated host rocks and enrichment in siderophile elements.
3) Mineralisation is extensive with individual sulphide bodies forming "footprints" of elevated Ni and Cu values in the order of 25 km radii.
4) Radial embayments, formed as a result of the impact, host the mineralisation.
5) The melt sheet shows Ni depletion through the majority Main Mass but is enriched in Ni towards the base of the Main Mass directly above the sublayer as a result of disseminated sulphides.
6) The melt sheet is well homoginised i.e. it has undergone significant convective overturn.
7) The ore is formed at the base, within the footwall and in the offset dykes.

2.3.5. Jinchuan

2.3.5.1 Introduction

The Jinchuan Ni-Cu deposit is situated in the central Gansu province, northwest China (Fig. 24) and is easily accessible via railway or air followed by rail transport. It is the second largest Ni-Cu deposit (after Sudbury) and contains 500 Mt of ore at grades of 1,2 wt% Ni and 0,7wt% Cu (Chai, 1989).

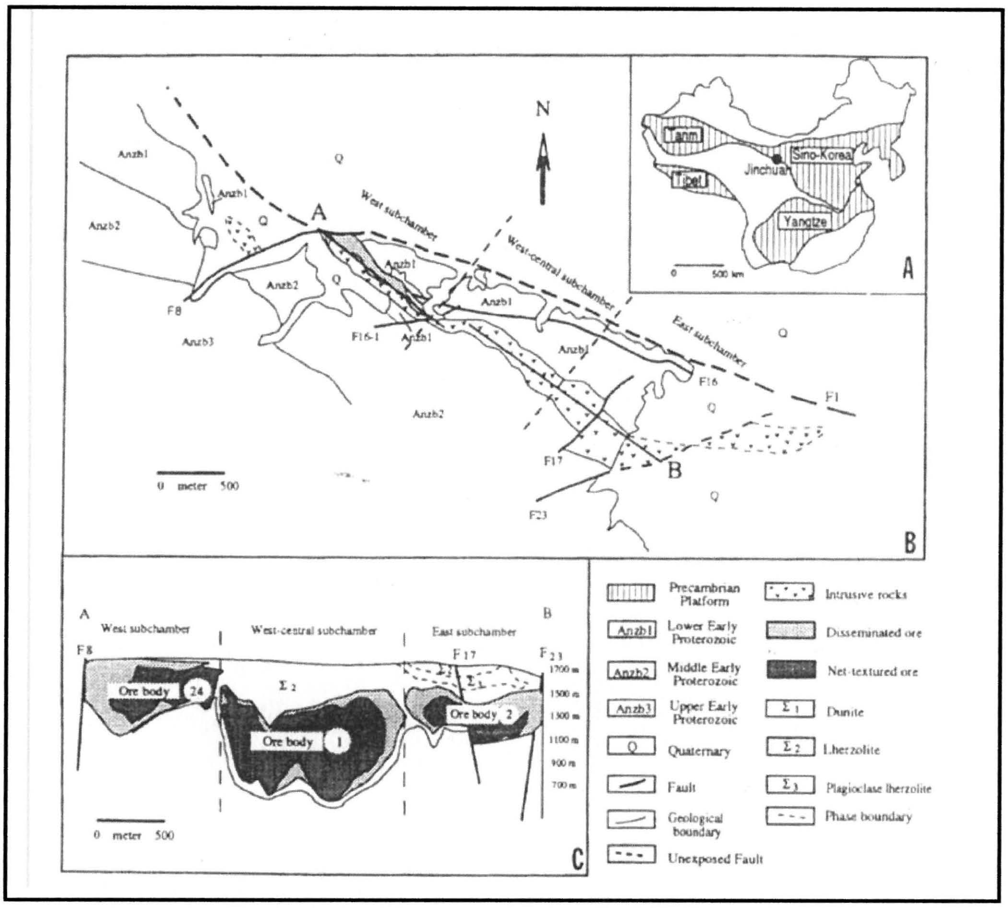


Fig. 24 Location, Geology and Ore Body Morphology of Jinchuan (After Chai and Naldrett, 1992)

The original discovery was made from a surface gossan showing on the western part of the Jinchuan ultramafic intrusion which is now the location of an open pit mine. The discovery was made by a coal prospecting team in 1958. The shaft was sunk in 1960 (which is now the Longshou mine – Mining Area 1) after intensive drilling at 50 m intervals on northeast trending lines across the deposit. The drilling delineated a 100 Mt reserve with a a grade of 1% Ni. The first open pit started in 1966 on the western part of the deposit.

An exploration programme in 1969 concentrated on the eastern part of the intrusion and delineated a 400 Mt deposit with a grade of 1% Ni in Mining Area 2 (Chai, 1989). Construction started on this part of the mine in 1974.

2.3.5.2 Geology

The deposit is close to the southern margin of the Sino-Korean craton and is hosted in one of a series of mafic-ultramafic bodies that have intruded a marginal, northwest-trending, uplifted Longshoushan belt (Naldrett, 1999). Chai and Naldrett (1992) conclude that the host intrusion was emplaced in a rift zone that formed at the boundary between the Sino-Korean craton and a developing Proterozoic ocean. This basin was later closed. The intrusion is thought by Chai (1989) to have intruded between 1 719-1 339 Ma (based on dating of intrusion (1 505 and 1 529 Ma from biotite) and cross-cutting dykes dated at 1 339 Ma as well as intrusive relationships).

The intrusion is divided into two parts namely a lateral zoned western section (which consists of two subchambers) and a vertically layered eastern part (Chai and Naldrett, 1992). The respective lithologies are tabulated below:

Table 12 Jinchuan Geology

Western Section (Zoned)	**Eastern Section (Vertical layering)**
	Lherzolite
Olivine pyroxenite (margins)	Plagioclase lherzolite
Lherzolite (around core)	Lherzolite
Dunite (core)	Dunite

The Ni, Cu and PGE values also show zonation and increase in grade from the outside to the centre of the intrusions (Chai and Naldrett, 1992). The lithologies show the intrusions were very primitive and their MgO contents confirm this with values being mainly > 35 wt%. The Jinchuan intrusion is 6 km long and has an average width of 300 m and is more than 1 000 m deep in its central part.

The ultramafics have intruded early proterozoic marbles and gneisses of the Baijiazhuzhi formation

The igneous lithologies are described as follows:

Table 13 - Description of Jinchuan Lithologies

Lithology	**Description**
Olivine Pyroxene	This accounts for less than 10% by volume of the rock. Olivine forms 10 to 40% of the rock and the rest consists of pyroxene, mostly clinopyroxene. This rock contains trace amounts of sulphide.
Plagioclase lherzolite	This lithology is distinguished as it forms a distinctive marker horizon. It contains 3 – 10% plagioclase which is an interstitial phase along with pyroxene.
Lherzolite	This makes up about 80% of the rock. Usually massive with what appears to be little layering (although this could be due to alteration). Modal percent of olivines varies from 40 – 85%, pyroxenes form 10-50% of the rock and plagioclase is usually less than 2%. Chromite ranges from 0,5 to 2%.
Dunite	This is sulphide bearing with 8 – 30% Ni-Cu sulphides. Modal abundance of olivine ranges from 70-90%, pyroxene modal abundance ranges from 70-90% (mostly orthopyroxene) whilst plagioclase is generally < 1% and there is 1-2% chromite. Magnetite (1-3%) is mainly associated with sulphides. The olivine is always intensely altered to serpentine and magnetite.

Although the bulk of the intrusion is very primitive it is thought to originally have been a largely gabbroic intrusive and the gabbroic part has now been eroded (Chai and Naldrett, 1992).

Structure

The Precambrian terrain hosting the Jinchuan deposit is bound by major northwest trending faults which are named F1 and F2 and have mapped strike distances in excess of 100 km. There is a set of secondary faults which are parallel to the first and increase in frequency closer to the main faults. The magmatic intrusions are associated with these areas of fairly intense faulting. There is a later set of southeast trending faults which cuts across the former.

2.3.5.3 Mineralisation

The ore reserves for the deposit are 510 Mt with grades of 1,07% Ni and 0,67% Cu (this excludes the "Deep Ore Zone" where an additional resource of approximately 100 Mt at 1% Ni has been identified. Ni and Cu reserves in the different mining areas are split as follows by Chai (1989):

Table 14 - Tonnage in Mining Areas

Mining Area	**1**	**2**	**3**	**4**
Ni (Mt)	0,93	4,11	0,21	0,19
Cu (Mt)		2,64		

There is also a Co resource of 139 000 t.

The Ni and Cu reserves can also be split according to ore type as indicated below (data from Chai, 1989)

Table 15 – Tonnage according to Grade

Ni Grade	**Low (0,5-1%)**	**High (1-2%)**	**Extra High (>4%)**	**Metasomatic Ore (0,5-2%)**
Ni	0,63	4,65	0,03	0,11
Cu	0,42	2,91	0,04	0,05

The ore has been divided into the classification system tabulated below which was devised by the Beijing Institute of Non-Ferrous Metallurgy, based on the economic conditions of mining, ore processing and refining.

Table 16 Ore Classification after Chai (1989) -Classified as Sulphide, Mixed or Oxide Ore)

Ore Type	**Percentage of total Tonnage**
Sulphide Ores	
Sulphide Ni Ore	Sulphide Ni/Total Ni = 60%
Sulphide Cu Ore	Oxide Cu/Total Cu = 10%
High Grade Ore	Ni content > 1%
Low Grade Ore	Ni content 0,5 – 0,99%
Low Grade Mineralisation	Ni content 0,3 – 0,49%
Sulphide Cu Ore	Same standard as sulphide Ni ore. If both Cu and Ni have reached a particular grade the ore will be graded as Ni ore
Mixed ore	
Mixed Ni Ore	Sulphide Ni/Total Ni 45 – 60%
Mixed Cu Ore	Oxide Cu/Total Cu > 30%, Cu content > 0,8%
Oxide Ore	
Oxide Ni ore	Sulphide Ni/Total Ni < 45%, Ni content >1%
Oxide Cu ore	Oxide Cu/Total Cu >30%, Cu content >0,8%

PGE Mineralisation

PGE enrichment is reported by Chai (1989) to occur in the net-textured ore but no tonnages are available. PGE enriched zones are reported to be 10-100 m long, 1-7 m wide and 20-40 m deep. The highest values reported from Mining Area 1 are 81,67 and 11,80 ppm Pt and Pd respectively. The massive ore is reported to have much lower values than the net textured ore, which also has higher Cu values.

2.3.5.4 Model for Ore Genesis

The lateral zonation in the west and vertical zonation in the east indicate that that the two formed through different processes (Chai and Naldrett, 1992). The lateral zonation is interpreted to be the result of flow differentiation processes (Barker, 1983) whilst the lateral layering in the east is attributed to cumulus settling under gravity resulting in a layered sequence (Fig. 25). Chai and Naldrett (1992) explain the reappearance of lherzolite as resulting from a new influx of magma.

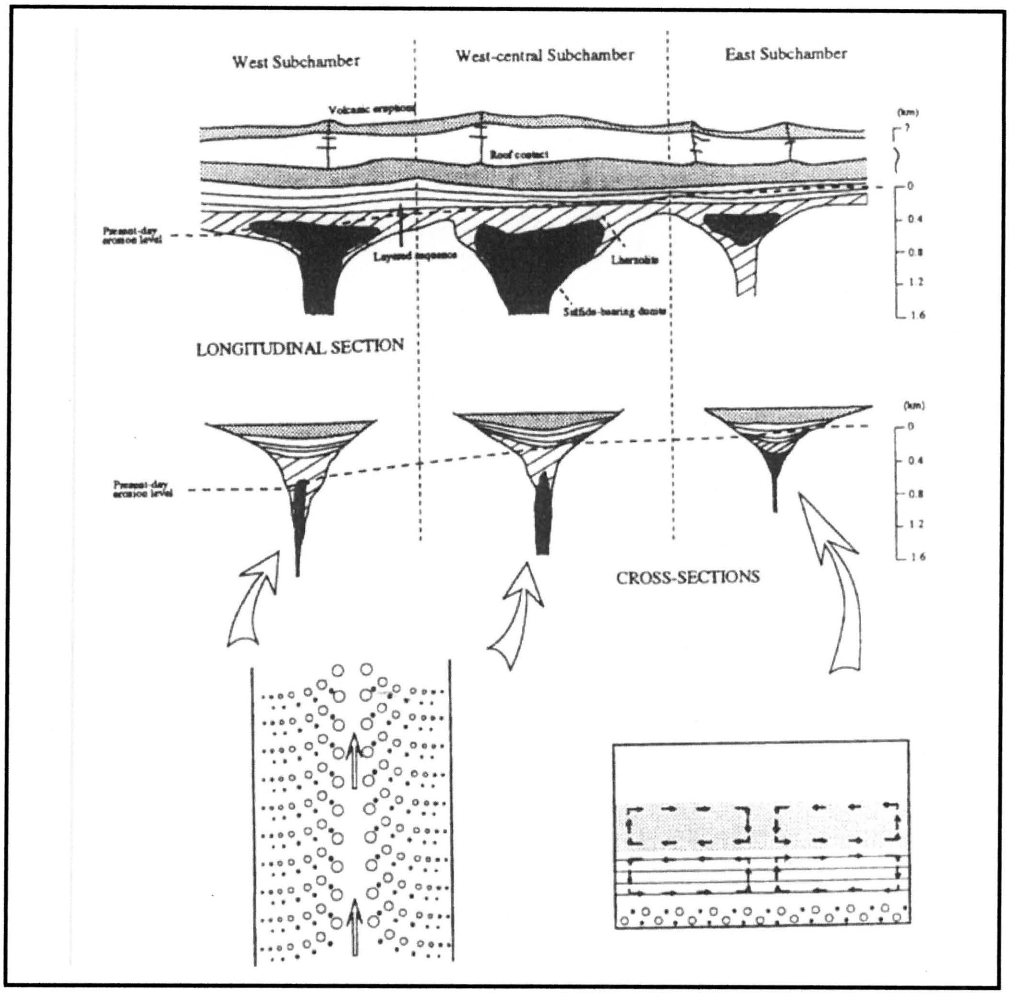


Fig. 25 Schematic representation of the formation of Jinchuan showing the formation and later erosion of gabbro (After Chai and Naldrett, 1992)

The sulphur in the ores appears to have a magmatic origin. This is because it is enclosed within intrusive rocks and the δ S ^{34} gives mantle type signatures of –2 to +3 per mil.

Textural evidence indicates that some sulphide droplets had segregated prior to the crystallization of the olivine and that sulphide continued to settle after the last olivine cumulates. Plagioclase and pyroxene had not crystallized during sulphide segregation (Chai and Naldrett, 1992). This indicates that the sulphide crystallized from a large amount of magma.

Chai (1989) postulates that mafic magma with around 10-15% MgO content intruded into a weak structural zone and formed a trumpet shaped chamber similar to the Great Dyke. He postulates that the magma was sulphur saturated or almost saturated when it was emplaced and that cooling of the magma triggered crystallization and sulphide segregation. With constant influxes of fresh magma a lower high grade and upper lower grade ore zone formed. Sulphides were then squeezed into breccia zones and fractures as a result of pressure from overlying silicates or because of tectonic compression.

2.3.5.5 Key Aspects of Deposit Relevant to Exploration

1) Discovered as a result of the recognition of a gossan.

2) Is associated with a northwest trending magnetic anomaly.
3) Hosted on a craton margin.
4) Emplaced in a rift zone.
5) Mineralisation associated with primitive rocks.
6) Dynamic system operative which upgraded the sulphides.
7) Occupies a major northwest striking fault.
8) Is 6 km long and 300 m wide.

2.3.6 Kabanga

2.3.6.1 Introduction

The intrusions hosting the Kabanga deposits are situated on the border between Tanzania and Burundi (Fig. 26) and forms a considerable resource which has not been exploited yet because of socio-political conditions.

Fig 26 Locality map of Kabanga

2.3.6.2 Geology

The intrusions related to the Kabanga deposits are hosted in the Karagwe-Ankolean system (also known as Burundian Supergroup in Burundi and Rwanda). This is part of a large mesoproterozoic Kibaran mobile belt which stretches from southeastern Congo (DRC), through Burundi, Rwanda and Tanzania to southwestern Uganda. The Tanzanian part of the belt is considered to be the marginal facies east of the main orogenic belt (the external domain). The belt reaches upper amphibolite-facies metamorphic grade in the eastern DRC, Burundi and Rwanda with abundant generation of synkinematic granitic plutons (Tack et. al., 1994).

The age of the Kibaran metasedimentary rocks is poorly constrained with a maximum of 2 050 Ma being the age of the deformation of the underlying basement rocks. The minimum age is given as 1 370 Ma, which is the age of the early synorogenic granites in Burundi (Cahen et. al., 1984).

Tectonism

Possible eastward directed thrusting has been identified by interpretation of aeromagnetic data which Tack et. al. (1994) interpret to imply a collision event from the west and a possible repetition of sedimentary stratigraphy in this "foreland" belt. Tack et. al. (1994) have divided this region, on that basis, into a more intensely metamorphosed Western Internal Domain in western Burundi and Rwanda and an Eastern External Domain in Tanzania and eastern Burundi.

Way up indicators such as fractionation cycles show the metadolerite sills and the ultramafics intruded sub horizontally into the sediments and were later folded.

Sediments

The sedimentary rocks of the Karagwe-Ankolean system in Tanzania are arenites and pelites with relatively few greywackes or carbonates (Grey, 1967). These sediments have a basal sequence of conglomerates and sandstones with some amygdaloidal basaltic volcanic rocks passing into more siliciclastic cycles made up of shales and arenites at their base. The shales are often interbanded with thin siltstones and sandstones and also contain significant amounts of sulphide and graphite. The arenaceous sandstones preserve weak evidence of grading (coarsening upwards and downwards) and of cross-lamination. Grey (1967) considered the sedimentary rocks to have formed as fluvial and shallow marine deposits within an intracratonic basin with several cycles of uplift and sagging. Evans et. al. (2000) suggests that a more modern interpretation would be one of cycles of progradation and regression in a foreland basin with a subduction zone located to the west.

These sedimentary rocks have been metamorphosed by the Kibaran orogeny between approximately 1 370 – 1 310 Ma. This caused low to medium-grades of metamorphism.

The metasediments that host the Kabanga mafic/ultramafic intrusions are comprised of quartzites, muscovite-andalusite schists, biotite-staurolite schists and muscovite-biotite schists which together form what has been termed the third sedimentary cycle (Evans at. al., 2000). These rock types have varying proportions of detrital quartz and fine-grained clay minerals of the original sedimentary rocks. The most prominent quartzite unit (Q2 or Rubona Quartzite) is about 500 m thick and forms a ridge of high ground striking NE. Drilling has shown this unit to be made up of many individual quartzite bands 1 to 50 m thick with interleaving thin bands of muscovite-andalusite schist. Around the Kabanga deposit almandine garnet is found in only one of the mica schists which makes it a useful marker horizon.

The aforementioned mineral assemblages are typical of mid-amphibolite-facies high-T/low-P regional metamorphism. It appears that the peak regional metamorphism was enhanced at Kabanga by the intrusion of a large synkinematic batholithic granite intrusion 5 km to the west (the Bushubi Granite).

Sulphides occur in all the above sedimentary rocks and vary from trace amounts in the quartzite up to 10% in some of the mica-rich layers. Pyrrhotite is the dominant sulphide in the mica schists below the base of the weathering, but minor pyrite is present as small cubes in quartzites to great depths.

Within all rocks, at all scales, overturned folding is present which show moderate plunges to the south west. Sedimentary structures (graded bedding and cross-lamination) identified on the surface and in orientated drill-core within the quatzose bands consistently show the younging direction to be to the east.

Mafic intrusive magmatism

Gabbro-norite and metadolerite sills

Jung and Meyer (1990) record a multitude of thin mafic sills as metadolerites which occur in the more fissile metapelitic lithologies but have also been noted in the quartzites. Some of the sills have been differentiated to form more primitive bases (melanorite and olivine-pyroxenite) and more felsic upper parts (leucogabbro and granophyre). The sills have been folded along with the metasedimentary rocks. Most of the sills have been modified to greenschist retrograde assemblages of tremolite-actinolite and saussuritised plagioclase although they often retain igneous textures (Jung and Meyer, 1990).

The metadolerites are broadly concordant with sedimentary layering and vary from 0.1 to 20 m in thickness. They appear to have a regional extent, having been mapped at the same broad stratigraphic level for at least 30 km along strike. Similar metadolerite sills have been located at this same stratigraphic level throughout the Kagera region.

Mafic-Ultramafic cumulate intrusions and their mineralisation

These bodies occur close to the boundary of the internal and external domains (known as the boundary or transition zone) of the Kibaran Orogenic Belt in Burundi and Tanzania and have collectively been called the Kabanga-Musongati alignment of intrusions (Tack et. al., 1994). The ultramafic bodies are crudely defined by the position of magnetic anomalies. The anomalies are not negative because of remnant magnetism, but because of their position relative to the equator (Watts., 2003, pers. comm.)

Olivine and orthopyroxene cumulates dominate within the intrusive bodies with marginal and upper zones composed of norites to gabbronorites (Deblond and Tack, 1999). These groups of bodies are broadly concordant to the sedimentary layering on a regional scale but on a local scale their side contacts cut across sedimentary layers.

The ultramafic bodies are crudely layered and differentiated with olivine cumulates dominating the western side and gabbroic rocks the eastern side. The bodies are pod-like and the orientation of the internal layering and differentiation is roughly coincident with the younging-up direction to the east.

Stratigraphy of Intrusives (Data taken from Evans et. al., 2000)
Table 17 – Kabanga Main

Unit	**Thickness (m)**	**Description**
Kabanga Main		
Olivine-pyroxene cumulates	?	Contain 1-5 modal % sulphides
Main Rhythmic Unit 2		
The Main Gabbronorite (subunit 2c)	?	Contains cumulate plagioclase and orthopyroxene with lesser clinopyroxene (5 –10 modal %). Quartz is present up to 15 modal %, usually as a micrographitic intergrowth with k-feldspar forming a granophyric texture.
Medium-grained olivine-sulphide cumulate called the Main Peridotite-pyroxenite (subunit 2b).		Contains minor plagioclase and coarse orthopyroxene. As well as 15 – 25 modal % throughout in an interstitial net-texture sulphides.
Fine-grained feldspathic harzburgite named the Main Harzburgite (subunit 2a)	?	Plagioclase and poikilitic orthopyroxene are the dominant interstitial minerals (5-10 modal % each) and sulphide may reach 5%.
Main Cumulate Rhythmic Unit		

Unit	**Thickness (m)**	**Description**
Kabanga Main		
Gabbronorite to Norite called the Main Gabbro-norite subunit of the Main Rhythmic Unit	?	Contains abundant plagioclase and has similar texture and composition to the marginal gabbronorites. Contains quartz-rich xenolith blocks within it and patchy aggregates of granophyric quartz and k-feldspar. Sulphide is coarse and patchy in this unit
Pyroxene-sulphide cumulates	5-10	Olivine is a common accessory mineral but rarely reaches more than 10 modal %. Interstitial sulphide varies from 10 –30 modal %.
Olivine cumulates - Olivine pyroxene cumulates know as the main peridotite-pyroxenite subunit.	50- 60	An orthocumulate texture with more abundant interstitial sulphides and 1-10 modal % plagioclase.
Olivine cumulates - Olivine cumulates	?	Repetitive cycle or rhythmic pattern of olivine cumulate layers (0,5 –3 m thick) grading upwards into much thinner layers of olivine pyroxenites. Sulphides distributed in small quantities throughout this unit ranging from 1 – 10 modal %.
Olivine cumulates - Feldspathic harzburgites	Up to 40	Variations from olivine being the dominant cumulate (50-65 modal %) to more pyroxenitic rocks.
Gabbronorite	0,1 – 2	Unmineralised. 40 – 70 modal % orthopyroxene and 30 – 50 modal % plagiocalse with minor olivine (0-2 modal %) and 5- 10 modal % clinopyroxene.
Massive Sulphide		
Kabanga North		
NRU1 (North Cumulate Rhytmic Unit)		
Gabbronorite	20 – 40	The pyroxene is dominantly orthopyroxene where preserved (40-60 modal %) with 5 –15 modal % clinopyroxene. Plagioclase is co-dominant (40-50 modal %)
Norite	?	
Olivine pyroxene cumulates	?	
Sulphide poor olivine cumulate or feldspathic pyroxenite	30-50	20 – 30% modal orthopyroxene and 5 – 15% interstitial plagioclase. 0,5 to 5 modal % disseminated sulphides
Sulphidic picrite		Olivine (now largely serpentinised) and lesser orthopyroxene are surrounded by a network of 20-30 modal % interstitial sulphides
Olivine-pyroxene-sulphide cumulates (sulphidic peridotite)	15 to 25	
Massive Sulphide		

The Ni laterite resources at Burundi, namely Musongati, Waga and Nyabikere are developed over such olivine-pyroxenite cumulate intrusive bodies (Deblond and Tack, 1999).

The Kabanga group of ultramafic intrusions hosts Ni sulphide deposits. Similar small ultramafic bodies are located at Kanyautenge, Kibamba, Ruiza and Burigi in Tanzania.

Sulphide mineralisation occurs to a greater or lesser extent in all the mafic-ultramafic intrusions at Kabanga but most mineralisation is confined to Kabanga Main and Kabanga North.

Tack et. al. (1994) report an age of 1 275 +/- 11 Ma (from U-Pb isotopes) in zircon fractions for the intrusion at Musongati.

Mineralogical Investigations

Chromite and olivine are texturally the earliest cumulate minerals. The olivine cores have compositions (Fo_{79} to Fo_{91}) consistent with the marginal rocks having being derived from a high Mg basaltic magma. Olivine and chromite compositions of these minerals overlap with those of the Great Dyke (Zimbabwe) and Bushveld Complex (South Africa) (Evans et. al., 2000). The olivine is moderately to strongly depleted in Ni relative to its MgO content as shown in table 18 (Evans et. al., 2000)

Table 18

Sample	A	B	C
Mineral	Olivine	Olivine	Olivine
Rock Type	Olivine melanorite	Feldspathic Harzburgite	Feldspathic Harzburgite
MgO%	45.66	47.73	48.40
NiO%	0,06	0,07	0,18

Contaminants

The Kabanga-Musongati type intrusions have a siliceous, high Mg basalt parental composition similar to several other large Ni-Cu and PGE deposits such as the Bushveld Complex, Great Dyke and Jinchuan.

The similarity of geochemical ratios and patterns of Kabanga-Musongati magmatism to those of the Karagwe-Ankolean sedimentary rocks, as well as the abundance of sulphide in some of the sedimentary rocks, implies that sulphide segregation resulted from assimilation of these sediments. As the geochemical ratios are consistent over varying lithologies it appears that the contamination did not occur locally but rather somewhere where it could affect the whole magma volume. Initial Sr isotope ratios of 0,7069 to 0,7097 recorded by Tack et. al. (1994) are consistent with contamination by upper crustal material.

2.3.6.3 Mineralisation

Mineralsation occurs in two bodies, the Kabanga North and Kabanga Main intrusions (Fig. 27). These are described below. The mineral inventory of both is given in table 19.

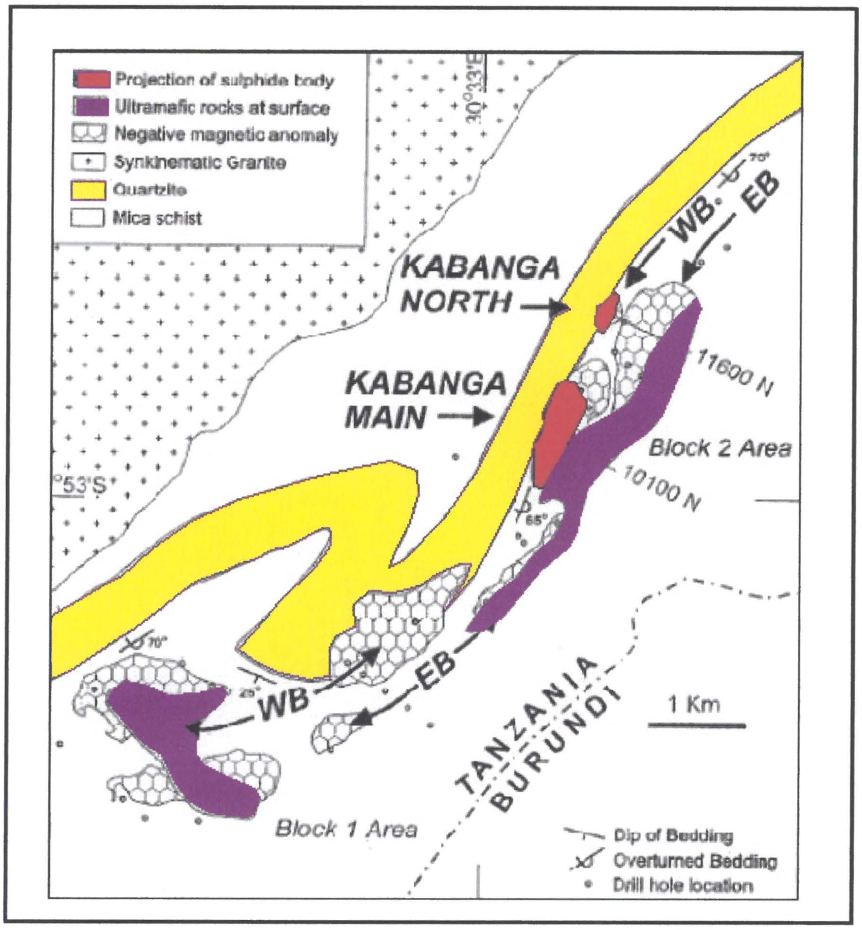


Fig 27 Geology of Kabanga showing the Kabanaga Main and Kabanga North sulphide bodies projected to surface (After Evans et. al., 2000).

Kabanga North

This is a steeply dipping, tabular massive sulphide body associated with a small, subvertical ultramafic pipe. It has a strike of 420 m and narrows to ~ 250 m in deeper portions (based on Anglo Amercan's current model).

Kabanga Main

This is an irregular, arcuate massive sulphide horizon that wraps around the western contact of a large ultramafic sill and occurs in a basal shear several metres away from the intrusion. It has a strike length of 650 m.

Table 19 Kabanga Mineral Inventory
(Barrick resource calculation – from Falconbridge presentation 2003)

Deposit	Type	% Ni	% Cu	% Co	Tonnes	Intrusion type
*Kabanga (North and Main)	Massive and DisseminatedSulphide	1,66	0,23	0,14	21 Mt	"Feeder" conduit

2.3.6.4 Model for Ore Genesis

The siliciclastic sedimentary sequence of the Karagwe-Ankolean sediments in the vicinity of the Kabanga resource is similar to other Proterozoic sedimentary basins such as the upper formations of the Transvaal Supergroup in South Africa and Botswana.

The sequence is dominated by siliciclastic sedimentary rocks, particularly alternating arenaceous sandstones and shaly units typical of a foreland basin. The lower parts of the sequence contain conglomerates and basaltic volcanic rocks with amygdaloidal features characteristic of sub-aerial eruption. Higher up the shaly units have deep sea or closed basin affinities and are abundant in graphite and sulphide.

The alternating sequence of arenaceous and shaly material is interpreted to have resulted from intermittent uplift followed by rapid erosion causing deposition of arenaceous material. This was followed by slower subsidence causing the deposition of the shaly rocks.

After the deposition of the sediments basaltic rocks intruded as ultramafic/mafic bodies as well as laterally extensive concordant dolerite to gabbronorite sills. Some of the sills differentiated after intruding. The mantle derived magma was able to intrude to crustal levels by utilizing the boundary between the Tanzanian craton and Palaeoproterozoic Buganda-Toro Mobile Belt. The sills and intrusions are broadly conformable to the sediments and are thought to have been intruded in a layer parallel fashion exploiting thrust planes and the more fissile shaly layers adjacent to quartzite layers. Folding in the area is ascribed by Evans et. al. (2000) to bedding parallel deformation resulting from gravity sliding within the accumulating basin.

During or before emplacement S and other incompatible elements were assimilated from the pelitic rocks by the magma causing sulphur saturation and the formation of an immiscible sulphide melt. The ultramafic/mafic intrusions have concordant upper and lower margins but discordant sidewalls which form narrow magma conduits much like Uitkomst (although narrower). The Kabanga intrusion is interpreted to have fed more voluminous gabbro and gabbronorite sills and intrusions higher in the sequence (Evans et. al., 2000). The physical flow processes during the transport of the magma in relatively small conduits feeding larger more evolved intrusions above would have led to the upgrading and concentration of sulphide within the lower cumulate ultramafic bodies.

2.3.6.5 Key Aspects of Deposit Relevant to Exploration

1) Hosted within S-rich sediments.
2) Magma flow confined to conduits.
3) Magmatic sulphides are associated with mafic/ultramafic rocks.
4) Dynamic "flow through" system.
5) Isotopic evidence for contamination.
6) Craton boundary.
7) Intrusion has a magnetic signature.
8) Extensional tectonic setting.

9) Mid-proterozoic age (1.27 Ga)

2.4 Significant features of the Ni deposits reviewed.

Characteristics of major Ni-sulphide deposits are summarised in table 20. Features that all the deposits have in common include the following:

1) Host rock is a mafic/ultramafic intrusive consisting of a largely gabbroic upper part and a peridotitic lower section. Intrusions therefore show changes in lithology from the base to the top, but this is not due to in-situ fractionation. It rather results from a flow of magma from an underlying, fractionating chamber. This highlights two important points the first being that primitive lithologies are required as a source of Ni to upgrade the sulphides. The second is that dynamic flow through systems are required in order to meet the high R factors required to upgrade the sulphides. This point is supported by the shape of the magma systems hosting the deposits. Most deposits are located in tubular intrusions (or where these open into chambers) and not flat lying sills or large layered complexes (there are some exceptions such as Noril'sk and the Sudbury Igneous Complex but this differs in that it lacks repetitive lithological layering). Other exceptions include Thompson and Pechenga which intruded as subvolcanic sills. Examples of deposits that fit these criteria (not the exceptions) are the Uitkomst intrusion, Voisey's Bay and Jinchuan.
2) The former point means that deposits are frequently associated with large outpourings of magma which may results from: meteorite impacts (e.g. Sudbury Igneous Complex in Canada), flood basalts (e.g. Dufek Intrusion in Antarctica, Duluth Intrusion in Minnesota and the Norilsk-Talnakh intrusion in Siberia) or feeder systems to/from large magma chambers (interpreted setting for the Uikomst body).
3) Dynamic "feeder systems" result in metamorphic aureoles (e.g. Jinchuan, Norils'k' Voisey's Bay and Uitkomst).
4) Intrusions are frequently located along the borders of Archaean cratonic blocks, emplaced within Proterozoic sedimentary sequences. These belts include the Circum-Superior belt which comprises the Thompson belt, the Fox River belt, the Labrador trough, the Kemi and Koillismaa belts and the Kabanga-Musongati belt. Igneous intrusions in these settings are associated with rifting events that coincide with continental or former continental margins. Duluth, Kambalda and Mt. Keith were formed in Intracontinental rift settings whilst Jinchuan, Pechenga, Raglan, Thompson and Voisey's Bay were all formed in rifted continental settings.
5) Craton boundaries/mobile belts will all have undergone several periods of deformation and so intrusions will not have their original shape or orientation (e.g. Kabanga). This needs to be remembered when exploring in these areas as the flow direction, type of intrusion and base of intrusion may be substantially different from what it was during emplacement. In these terrains it is also necessary to distinguish intrusions emplaced during rifting (which are prospective) from ophiolites (which are not prospective) and are frequently isolated serpentinsed dunite slithers that have been tectonically emplaced.
6) Deposits vary in age but many were emplaced during the Proterozoic and are related to rifting that took place during this period (examples include Pechanga, Thompson, Duluth, Jinchuan, Voisey's Bay and Kabanga).
7) Deposits formed from any high Mg magma types. Norilsk and Voisey's Bay formed from picritic basalt whilst Pechenga fromed from a ferropicrite. None appear to have fromed from mid-ocean ridge tholeiitic basalts.
8) Intrusions are frequently associated with major fault systems such as the Norilsk-Talnakh deposits, radial faults in the Sudbury Igneous Complex, the F1, F2 and F3 faults at Jinchuan and the major (interpreted) northwest-southeast trending fault thought to have controlled the Uitkomst intrusion.

9) Silicates higher in the sequence well above the deposits, such as overlying flood basalts are often depleted in Ni. This is because the Ni has been stripped from the silicates into the sulphides.
10) The main target at Ni-Cu-sulphide deposits is massive sulphide mineralisation. This is relevant as sulphide bodies are conductive and can be detected through the use of airborne and ground EM. Sulphides also weather to form gossans at surface which is how Voisey's Bay and Jinchuan were discovered.
11) The massive sulphides are located at the base of the intrusives (Sudbury, Jinchuan, Thompson, Voisey's Bay, Uitkomst) or around the periphery of pipe-like bodies (such as Kabanga).
12) Analyses of core (samples including silicates and sulphides) directly above massive sulphides usually show elevated Ni values because of disseminated haloes of sulphides above the massive sulphide deposits. These disseminated sulphides increase the "footprint" of the target. Examples of deposits associated with disseminated haloes include Uitkomst (area of planned opencast mining), Sudbury (the Sublayer), the footwall breccia of Voiseys Bay and Jinchuan.
13) Sulphides generally contain elevated Ni, Cu, Co and sometimes PGE's. As deposits are associated with primitive intrusives the silicates will cause elevated Ni values in overlying soil profiles or regoliths, but only the presence of sulphides will cause coincident elevated Ni, Cu, Co and possibly PGE's.
14) Most deposits show direct (isotopic signatures) evidence or indirect evidence (inclusion of xenoliths) for crustal contamination. Most deposits discussed in this treatise show some indication of crustal contamination. Norilsk was contaminated by evaporites, Voisey's Bay and Kabanga by sulphidic shales (Pechenga also contaminated by sulphidic shales) and Uitkomst by carbonates.
15) Intrusions classed as Alaskan type, alpine type, ophiolites and zoned intrusions are not associated with Ni-Cu-sulphide deposits.
16) Meteorite impact sites are prospective if the melt sheet is thick (> 2 km). Mineralisation is located at their base, in the footwall and offset dykes. The Ni in the melt sheet is depleted and the disseminated sulphides cause large footprints (2 000 x 2 000 m).
17) Deposits frequently found in belts or camps e.g. deposits hosted in the Sudbury Igneous Complex and those at Noril'sk.

2.5 Discussion and recommendations for Ni-sulphide exploration.

It can, therefore be seen that these deposits have a number of features in common that can be used for Ni-Cu sulphide exploration. Firstly areas of continental or intracontinental rifting can be defined as prospective. It is in these areas that mantle tapping of the required primitive lithologies has taken place. Within these areas ultramafic/mafic intrusions should be identified, or inferred from geophysical surveys or survey products (to be discussed later). Intrusions that are associated with major lineaments should be rated as higher priority targets as should those that are known to be intruded into S bearing sediments i.e. contaminant horizons. If known/inferred intrusions are associated with a Ni-Cu sulphide showing these should be given the highest rating. In these areas the process of sulphide segregation has taken place and so many of the requirements to form a deposit are known to be met.

Areas associated with a high "flow through" of magma such as flood basalt provinces should also be identified as being prospective. Metamorphic aureoles around intrusions are one way of identifying this as fairly small intrusions can cause considerable heat if they have experienced substantial "flow through" Intrusions with shapes that show they could have been feeders (such as conoliths) should be looked for, as opposed to sills, lopoliths or bodies that have undergone "passive" fractionation processes.

Once targets have been identified from these steps i.e. once the desk top project generation phase has been completed then follow up work can be done on the ground to determine if further criteria are met. This includes detailed mapping and sampling to identify shapes and types of lithologies, presence of sulphides and Ni depletion in silicates. Soil and stream sediment sampling may be done to identify ultramafics (elevated Ni, Cr and MgO values) and also to identify areas of coincident elevated Ni, Cu, Co and PGE's. Airborne and ground geophysics may be done to determine the presence of conductive massive sulphide ore bodies. The exploration techniques and their application to identifying the salient features of Ni-Cu deposits will be discussed in later chapters. It should be borne in mind that the massive sulphide bodies are located at the base of intrusions so exploration programmes should target this area, i.e. intrusives should not be ignored because they do not have sulphides on surface and drilling programmes need to be designed to penetrate the footwall.

These factors all pertain directly to the geological potential of an area. It is however, necessary to evaluate political and fiscal risk prior to embarking on an exploration programme. Once (or before) targets have been identified (depending on company policy) factors such as security of tenure, country politics, royalties, cost of operating in a country, available infrastructure, particular sensitivities such as aboriginal rights etc. need to be assessed and local communities in the area of the project need to be consulted.

The "Index to Economic Freedom" is a publication issued annually which outlines the "economic freedom" of a large range of countries. Economic freedom is defined as "the absence of government coercion or constraint on the production, distribution, or consumption of goods and services beyond the extent necessary for citizens to protect and maintain liberty itself" (Beach and O'Driscoll, Jr., 2003). Below is a list of factors they deem as affecting economic freedom and which need to be considered before exploring in new areas:

1) "Corruption in the judiciary, customs service and government bureaucracy."
2) "Non-tariff barriers to trade, such as import bans and quatas as well as strict labeling and licensing requirements."
3) "the fiscal burden of government, which encompasses income tax rates, corporate tax rates and government expenditures as a percent of output."
4) "The rule of law, efficiency within the judiciary, and the ability to enforce contracts".
5) "Regulatory burdens on business, including health, safety and environmental regulation".
6) "Restrictions on banks regarding financial services, such as selling securities and insurance".
7) "Labour market regulations, such as established work weeks and mandatory seperation pay".
8) "Black market activities, including smuggling, piracy of intellectual property rights and the underground provision of labour and other services".

Prior to implementing any ground work contact should be made with the local community. They need to be informed of what work will be taking place and, if possible work should be provided to some of the local inhabitants. Involvement with the local inhabitants is not only the onus of a responsible company, but is a statutory requirement in Tanzania, Malawi and South Africa. It is also important to maintain good relationships with the local community because of the problems that could be encountered with them if mining starts and they are not co-operative especially if relocation is required or if their consent is required as at Voisey's Bay where INCO has had ongoing issues with the Inuits. At Insizwa community meetings were held on a regular basis and an effort was made to inform all inhabitants of when and where the meetings would be held.

Table 20 – Characteristics of Selected Ni-Cu-Co sulphide Deposits

Deposit	**Ni (%)**	**Cu (%)**	**Co (%)**	**PGE (g/t)**	**Resource (Mt)**	**Major Lithology**	**Age (Ma)**	**Tectonic Setting**	**Contamination**	**Type of Intrusion**
Noril'sk	2,7			3,9	900	Gabbro	180	Intracontinental rifting.	Addition of sulphur from sediments.	Feeder Conduit
Voisey's Bay	1,66	0,95	0,08		124,4	Gabbro	1 350	Magmatic hotspot after continental collision.	Magma mixing with silica and S addition from host rocks.	Feeder Conduit
Sudbury	1,20			1,0	1 650	Gabbro	2 100	Meteorite Impact	Superheated magma homoginising with host sediments	Melt Sheet
Duluth	1,20			1,0	4 000	Gabbro		Rifting	?	?
Stillwater				19,5		Gabbro		Intracontinental hot spot	?	?
Jinchuan	1,06	0,7	0,12		515,0	High Mg basalt	1 508	Rifting		
Kambalda	2,96	0,22	0,07	1,1	66,0	Peridotite	2 800	Rifting – back arc basin	Assimilation of S bearing gneisses	Feeder Conduit
Agnew	0,22	0,08			52,0	Peridotite	2 800	Rifting – back arc basin	?	?
Bushveld						Gabbro	2 440	Intracontinental hot spot. Crustal attenuation, contamination and magma mixing.		Layered Complex
Merensky	0,22	0,08		5,0	>1 500					
UG2				4,7						
Platreef				5,0						
Great Dyke	0,18	0,16	0,04	4,0	1 200	High Mg basalt	2 500	Extensional/Intracontinental rifting	?	?
Kabanga Resource	1,66	0,23	0,14			Gabbro/ dunite	1 270	Extensional/Intracontinental rifting	?	

Chapter 3 – Exploration Techniques

3.1 Introduction

Chapter 3 provides an outline of how geochemistry and geophysics may be used in exploration for magmatic Ni-sulphide deposits. This discussion does not pretend to replace standard reference works on geochemical and geophysical exploration techniques. The intention is rather to briefly introduce those methods most applicable to the exploration of magmatic nickel deposits.

These chapters outline some of the available tools for exploration. These would be applied once a project area was chosen. The criteria used to select suitable project areas have been covered in the preceding chapters.

3.2 Geochemistry

3.2.1 Designing Surveys

3.2.1.1 Soil Surveys

Soil and stream sediment surveys are useful in detecting mineralisation and/or detecting ultramafics that may host Ni-sulphides. According to Thomson (1986) these surveys can be divided into three parts namely sampling, analysis and interpretation. Sampling is the most costly and its effectiveness is determined by the survey design. The author's experience in designing soil surveys has shown that the following to be important:

1) Ensure that surveys are orientated perpendicular to the expected, or known, strike of the geology, and or potential mineralisation. If the geology of the area is not known it should be mapped. Regolith mapping is also useful and can be done with the aid of landsat and verified with field checks.
2) Sample spacing should be determined from the size of the "footprint" (mineralisation halo) expected from the ore body. A massive sulphide body of about 20 Mt would be several hundred metres in each direction and depending on the host lithologies and dispersion of disseminated sulphides its footprint would be significantly larger. Surveys should be designed so that at least three continuous samples on at least three adjacent traverse lines are taken over the potential anomaly. According to Amor et. al. (1998) it is only necessary to intersect expected anomalies on two adjacent lines so they state that the sample spacing should be no more than one third of the strike length of the expected feature.
3) A physical grid with wooden stakes, involving line cutting and traditional surveying need not be implemented. The grid can be designed on the computer and the waypoints downloaded onto a GPS. When samples are taken the geographical co-ordinates are then recorded with their corresponding sample numbers as well as any other pertinent information such as soil type and colour, float geomorphology etc. The sample number can also be recorded on the GPS and then downloaded into a browser table of a GIS. This data can later be merged with an imported spreadsheet of the sample results in order to plot the data digitally and overlie features such as magnetics, geology and geochemistry using the GIS. Data can then be queried for instance all Ni values overlying a particular lithology could be selected.
4) Ideally samples should be taken at regular intervals in both directions such that samples are taken evenly over the sample area, e.g. a 50 x 50 m grid would be

preferable to a line spacing of 100 m and a sample spacing of 30 m. This ensures that later when the data is "gridded" using processes such as inverse distance weighting the influence of each sample is equal throughout the sampled area. Gridding can be done using a GIS, Oasis Montaj or other software.

5) Sufficient samples should be taken over each lithotype to get a representative suite.
6) Sample lines should always start and end in background values i.e. traverses should not start or end in areas that are known or expected to be mineralised. If the sample results show this has occurred additional samples need to be taken. Thompson (1986) states that a survey should be designed to maximize the contrast between background and mineralisation taking the following into account:
    a. The primary contrast between mineralised and unmineralised rocks.
    b. The relative mobility of elements in the secondary environment.
    c. Dilution caused by barren material.

According to the author these factors are of greater significance when interpreting the data and do not affect the design of the survey.

7) The same horizon (usually the B-horizon) should always be sampled i.e. different samples should not be taken from different soil horizons. This means that samples should not simply be taken at a consistent depth. If the soil horizon is poorly developed in places then exceptions will need to be made.
8) The correct sample size should be taken. It is recommended that sufficient sample material is collected to use in duplicate and confirmatory analyses. Some samples at Morokweng (chapter 4.2) were analysed 3 times due to laboratory discrepancies between batches. Generally only 30 g is required for fire assay and less than a gram for ICP (Amor et. al., 1998).
9) If possible an orientation survey should be done across known mineralisation to determine background and threshold values, the depth to sample as well as the effectiveness of the sampling to detect mineralisation. In the absence of mineralisation samples can be collected across different lithologies and contrasts noted. Surveys across mineralisation should be conducted on two traverse lines which are located in the same geomorphic environment and hosted in the same rock types as expected in the survey area. Bradhsaw (1975) recommends the following procedure for soil orientation surveys:
10) At least four or five samples should be collected over the mineralisation as well as over background values.
11) The character of different soils should be evaluated so samples should be collected in different physiographic positions such as steep slopes and bogs. Variation between soil horizons at different depths should also be checked.
12) A number of different size fractions should also be analysed, Bradshaw (1975) suggests the following are checked.

Table 1 – Soil fractions to test in an orientation survey (After Bradshaw, 1975)

Mesh (ASTM)	**Aperture (Microns)**
-35 +80	-500+177
-80	-177
-80+140	-177+63
-140+230	-105+63
-230	-63

- Bradshaw (1975) also recommends preparation of a heavy mineral fraction if a detrital resistate fraction is suspected. All samples should be analysed using a total extraction technique as well as other techniques deemed appropriate.

13) Any geochemical survey should include a well designed control programme to assess the confidence in the sampling and the analytical methods employed. For this reason field and laboratory standards are submitted in order to check

laboratory accuracy and precision. Samples taken close to each other will help in determining soil inhomogeneity, which will assist in determining the acceptable error margin when results are received.

14) It is very important to determine the most appropriate analytical technique for the survey. Special care needs to be taken where wet chemical processes are involved to ensure that the required elements go into solution. This will be discussed later.

3.2.1.2 Stream Sediment Surveys

This has become an established method of mineral exploration at both the reconnaissance and more detailed scales in many parts of the world. It allows a preliminary evaluation of large areas at relatively low cost. It is also a direct measurement of the metals being explored for, as opposed to geophysics in which for e.g. the conductivity of the metal being explored for is measured. Drainage geochemistry also has the advantage of being used for geochemical mapping and detection of potential hosts rocks to ore bodies, even if the mineralisation is not directly detected itself.

A stream retains the same order until it meets another stream of the same order at which point the order of the downstream confluence increases by one (Amor et. al., 1998). It is useful when planning a stream sediment sampling programme to colour code streams according to their order. A preliminary programme should concentrate on higher-order streams as they represent larger catchment areas and access to sampling sites tends to be easier (Amor et. al., 1998).

The catchment areas covered by a stream, at the area where a sample is collected, should be used to assign polygons to the areas represented by the samples. In this way potentially unsampled areas can be detected.

According to Amor et. al., 1998 an appropriate sampling density for reconnaissance purposes is from one to three samples per square kilometer, concentrating on second order streams although this depends on the nature of the drainage pattern. For more detailed surveys, e.g. on a property scale, a density of six samples per square kilometer is more appropriate.

Sample material should be collected from active streams and not from collapsed banks. It is also best to collect finer material and not coarse sandy or gritty material. Organic material should also be avoided.

For panned concentrates the best material to collect is stream gravel so low order streams are not particularly suitable. Panning is facilitated by pre-sieving –first through a 1 cm sieve and then a 1 mm sieve.

The results of regional stream sediment surveys conducted by public institutions are available in many countries. These surveys could be used during target identification exercises and could provide information that is critical to the design of any closer spaced programme.

3.2.2 Sample Decomposition/Dissolution Techniques

This is the process whereby analytes are released and is brought about by digestion and leaching with concentrated or dilute acids, fusion with acid or alkaline fluxes, liberation of volatile components by pyrolysis, or by partial or selective extraction by a variety of reagents. The decomposition process allows the chemist to determine all or only a fraction of the analytes.

The decomposition step is required for many of the standard multi-element techniques such as atomic absorption spectrometry (AAS), induced coupled plasma spectrometry (AAS), induced plasma spectrometry (ICP) and ICP-mass spectrometry. Methods such as neutron activation analysis, fire assay and x-ray flouresence-spectrometry analyze solids and report total metal concentrations.

Factors to consider when choosing appropriate decomposition techniques (as outlined by Amor et. al., 1998) are:

1) The analytical method and the need to avoid interferences.
2) The ability to determine several elements in the same solution.
3) The ease with which a large number of samples can be economically processed.
4) The availability of equipment and reagents.

The two broad groups of decomposition techniques are:

1) Total extraction: Strong decompositions which release the majority of analytes from metal lattices.
2) Partial extractions: Partial decompositions intended to remove only the weakly bonded elements such as the primary ore minerals.

The Analytical Techniques/Instrumentation commonly used for rock and mineral analysis are:

1) X-ray fluorescence spectrometry (X.R.F).
2) Atomic absorption spectrometry (A.A.S).
3) Inductively coupled plasma spectrometry (I.C.P).
4) Inductively coupled plasma spectrometry-mass spectrometry (ICP-MS).
5) Neutron activation analysis (NAA).
6) Fire assay.

The advantages and disadvantages of these techniques are given in table 2.

Table 2

Pros	Cons
X-Ray Flouresence Spectrometry (XRF)	
Non-destructive fusion beads and pressed powder disks may be returned and re-analysed.	Sample preparation requires fusion and pulverization to make pressed powder disks.
Relatively small amount of sample required.	Care should be taken to ensure that the material used remains representative.
Multi-element analyses including many useful elements for Ni-sulphide exploration such as the trace elements Ni, Cu, Co and the major elements MgO, CaO, K_2O, Na_2O, SiO_2.	
Total analyses	Not geared for partial analyses esp. where

	solutions need to be analysed.
Atomic Absorption (A.A.S.)	
Partial analysis possible	Single element analyses – wet chemical dissolution.
	Sample material is destroyed.
Inductively Coupled Plasma Atomic Emission (ICP)	
Suitable for a large spectrum of elements.	Possibilities of incomplete dissolution with wet chemical dissolution.
Multi-element analyses.	Partial analysis possible for ICP Mass Spectrometry (ICPMS) and ICP optical emission spectrometry (OES).
Relatively cheap.	Analytical error greater than XRF.
Partial analysis possible..	ICP OES may suffer from inter-element interference problems.
ICPMS has very low detection limits.	
Quick turnaround time.	
Enzyme Leach – followed by AAS or ICP. Enzyme Leach is a selective partial dissolution technique that extracts only weakly adsorbed elements, especially from clay particles.	
Deep penetrating to allow detection of deep seated mineralisation.	Poor repeatability of results
Low detection limits.	Not likely to “miss” mineralisation but not always easy to determine the quality of anomalies.
Anomalies can be detected using a number of anomaly patterns such as “rabbit” ears and apical anomalies.	Large number of false anomalies generated.
	“Black box” technique not fully understood.
	Lack of understanding of processes involved means consultants expertise in interpreting results is sometimes needed.
Results are not dependant on sampling the same soil horizon or a particular soil horizon. This is useful if a thick “cotton” soil has developed above the ultramafic being explored.	
Estimates of the depth of the mineralisation can be made by consultants by assessing the strength of apical anomalies relative to oxidation halos.	The technique used for depth detection is not disclosed and is not substantiated by case studies.
Mobile Metal Ion (MMI) MMI is a selective partial dissolution aimed at releasing only the weakest held elements that were deposited by migrating groundwater.	
Deep penetrating, apparently down to about 800 m (R. Fripp, pers. Comm.).	Poor repeatability of reuslts
Any soil horizon or type can be used providing the soil is indurated.	“Black box” technique not fully understood.
Small amount of sample material required (about 30 g).	Large degree of analytical error.
Low detection limits (few ppbs).	

The different techniques are appropriate in different environments and sometimes a combination of techniques is required e.g ICP and XRF on core samples.

3.2.3 Surface Environments

Elements are dispersed above deposits so that they leave a significant halo of indicator minerals. The dispersion process is broadly divided into mechanical and physical dispersion processes (Thomson, 1986). Distinctions are also made between the primary and secondary geochemical environments. The primary dispersion environment is normally taken to be below the zone of weathering and is, therefore, characterized by high pressure and temperature and a low free oxygen content. The opposite applies to the secondary weathering environment (Thomson, 1986).

Conditions in the surface environment represent a complex interplay of climatic, physiographic, biological, anthropogenic and geological factors and are, therefore, highly variable from the local to the continental scale (Plant and Raiswell., 1994). Climates have also changed substantially since the mid-Tertiary (Plant and Raiswell., 1994).

The temperate and higher latitudes are dominated by effects of Pleistocene glaciation whilst the warmer, lower latitudes have regoliths associated with past or present periods of deep weathering and laterisation under seasonal tropical conditions (Plant and Raiswell, 1994). Although there are complex variations on a local scale Plant and Raiswell (1994) state that conditions are sufficiently similar over extensive regions to develop general models and exploration methods. An example are the cool climates in northwest Europe.

These are characterized by relatively high rainfall and high levels of organic activity. Here two types of surface environment can be distinguished. The first consists of those areas with impervious crystalline rock. In these areas water is in contact with the rock for short periods of time leading to low concentrations of cations and anions in surface water. Concentrations of H+ ions generally exceed those of Ca 2+ ions and surface conditions are predominantly acid (partly as a result of organic activity) and there are large areas of peat bogs and/or acid soils. Oxidation of organic detritus in cool, wet climates is generally slow and accumulations of peat and poorly drained soils give rise to reducing conditions. The acidity may also be increased by the precipitation of industrial gases.

These acid reducing conditions cause Fe and Mn to be soluble but they do precipitate near to the surface in iron pans and in streams in equilibrium with atmospheric oxygen resulting in the formation of hydrous Fe and Mn oxides.

The weathered products of chalcopyrite are enriched in Cu, Ag and to a lesser extent Sn, Mn and Cd whilst those of pyrrhotite have high Ni and Co (Levinson, 1974). The size of dispersion anomalies is determined by the mobility of the elements released. Ni, Cu and Co have moderate mobility under oxidizing conditions and high mobility under reducing conditions. These elements become immobile under neutral conditions.

3.2.4 Interpretation

3.2.4.1 Statistical processing of geochemical survey results

Statistical interpretation initially focuses on two aspects of the data set namely its central tendency and dispersion (Stanley and Sinclair., 1987). When interpreting data it is important to distinguish between data sets. The most obvious are the different soil horizons (if different horizons have been collected during the same survey), different soil types and samples collected over different underlying lithologies. Stanley and Sinclair (1987) mention additional discriminatory factors such as:

1) Possibility of contamination by man.
2) Presence of coloured chemical precipitates.
3) Amount of organic material present.
4) Sand/clay ratio of sample.
5) pH at sampling sites.
6) Parent material from which sample was derived.
7) General physiographic description of environment around the sample site (e.g. steepness of slopes).
8) Vegetation type.

Basic statistics that can be used to describe central tendency include the arithmetic mean, median, mode and geometric mean. Dispersion can be described using the range, variance, standard deviation and percentiles (Stanley and Sinclair, 1987). More complicated statistical interpretation involves the use of probability graphs, correlation coefficients, chi squared distributions and two way contingency tables. These statistics help in defining different populations groups, identifying correlations between data sets, defining thresholds and identifying anomalous values.

To identify anomalies it is necessary to determine what background values are. Typical background values for Ni are given in table 3.

Table 3 – Typical Ni values in various lithologies

Rock Type	Ni (ppm)
Granites	8
Shales	20-100
Mafic Rocks	160 (fairly uniform)
Ultramafic Rocks	1 200 (but varies widely)

3.2.4.2 Models

As case studies of different geochemical surveys show such diversity models can be used to help synthesize the existing data and provide an overall understanding of geochemical dispersion and a framework into which further data can be fitted or upon which the data can be interpreted. These models are constructed from an understanding of landscape geochemistry. Fortesque (1980) identifies six fundamental concepts which determine the landscape geochemistry in a particular environment namely:

1) The abundances of elements in a given medium.
2) Element migration – the mobility of elements and the form in which this movement takes place.
3) Geochemical flow – the pathways along which element migration takes place.
4) Geochemical gradients – the rate of change in the abundance of elements. This is often descriptive of changes in substrate, geochemical flow and geochemical barriers.
5) Geochemical barriers – these are caused by changes in conditions usually related to migration (Eh, pH, etc.) or flow (permeability, porosity etc.).
6) Historical development – the position in time in the evolution of the landscape such as partial or complete development of a process with a defining end point, overprinting by a change in conditions, pollution etc.

These fundamentals are used to interpret geochemical data as an expression of the landscape. In this way recognizing patterns of element abundances allows interpretation of underlying controls such as geochemical barriers, gradients, flow and migration.

These patterns can then be used to create idealized models which pictorially represent the general conclusions relating to the dispersion of economic minerals. According to Hoffman and Thomson, 1987 every model should include the following features:

1) A body of mineralisation or a rock type, etc. representing mineralisation.
2) The relative distribution of bedrock, overburden, soil groundwater, surface water, vegetation etc.
3) Dispersion pathways related to mineralisation and anomaly formation which are highlighted.

Integration with aeromagnetic data is useful in delineating major lineaments and unexposed intrusives.

3.2.4.3 Enzyme Leach Anomaly Recognition

For the interpretation of enzyme leach data three types of anomalies are recognized (De Schutter and Tailleffer, 1997):

1) Mechanical/hydromorphic dispersion anomalies which are formed in basal till as mineralised bedrock is smeared down ice glaciation.
2) Oxidation halo anomalies are produced by the gradual oxidation of buried reduced bodies (e.g. massive sulphide) and are distinguished by an asymmetrical halo or partial halo formed around the reduced body by the "oxidation suite" (central depressions or lows over the mineralised body for elements such as Cl, Br, I, As, Sb, Mo, W, W, Re, Se, V, U and Th).
3) Apical anomalies – these are formed by the diffusion of elements away from a concentrated source which they develop directly over and provide a high contrast with background values. Elements that form these anomalies include Ni, Cu, Pb, Zn, Au, Ag.

Since amorphous MnO_2 makes up a minute portion of the total MnO_2 in a soil sample the results of the trace elements released are reported in ppb. Most anomalies are defined as being at least 10 x above background although evidence for movement within the electrochemical cell for relatively immobile or insoluble elements (e.g. Cd, Sn, Ga, Au and Hg) is considered to be very significant.

The following points relating anomaly recognition are taken from De Schutter and Tailleffer's (1997) report which is drawn from a two day workshop held with Dr. R. Clark. Many of these points have also been discussed with Dr. Clark by the author when evaluating enzyme leach results from the Falconbridge Ventures Tekwane Project in Botswana (close to Francistown).

1) Single element anomalies especially Cu only anomalies are not very significant. Multi element anomalies are much more significant (as with conventional geochemistry).
2) Variable ground conditions (such as wet vs. dry) can cause shifts in the background values of some elements especially Cu. There is also some evidence for seasonal variance in results.
3) Elevated REE (particular elements not listed) values coincident with Zr are highly indicative of faults and usually appear directly above the suboutcrop of faults.
4) The type of response such as apical/oxidation etc. is supposed to give an indication of the depth of the target but this is not substantiated by case studies.
5) Enzyme leach anomalies do not make it possible to identify the size of the target.

In the author's experience enzyme leach anomalies (both apical, oxidation halos and combinations of these) are frequently coincident with faults and merely occur where there is abundant fluid movement. It is important to distinguish between fault induced haloes and those indicative of mineralisation. Drilling and mapping of float by the author on two projects where enzyme leach sampling was conducted showed the technique is very effective in delineating the underlying geological contacts (more so than conventional geochemistry).

3.2.5 Application to Ni-sulphide Exploration

Soil and stream sediment surveys should always be designed with the size of the target in mind. Orientation surveys are useful in both instances in determining the sample interval required to detect the mineralisation. These will show factors such as the length of the dispersion trail of elements such as Ni and the types of values expected over mineralisation. The factors to consider when designing a survey have been covered in section 3.2.1.

For soil samples once data has been received and has passed quality control procedures it may be useful to divide it into subsets according to the lithologies the samples overlie. In order to detect anomalous values it is then necessary to know what background values to expect above the different lithotypes for the specific analytical technique being used (table 3 gives the Ni values for various rock types which will give an indication of the difference in Ni levels expected in the different subsets). Anomalous values in each subset are normally defined as those that are in excess of two standard deviations. This technique may appear too simplistic but works well for Ni-sulphide exploration. If Ni and Cu anomalies are coincident the target is highly prospective. Elevated Ni alone could be due to silicates but if Cu is also elevated this indicates the anomaly may be due to sulphides.

Anomalies should also reflect the size of the exploration target. In the Morokweng case study (chapter 4) anomalous values were detected, but the anomalies did not cover a wide enough area to reflect the size of the target that Falconbridge was wanting to discover. The application of enzyme leach is discussed above in section 3.2.4.3 and that of MMI is illustrated in detail in the Morokweng case study (chapter 4, section 4.3.1).

The procedure to follow with stream sediment data is outlined in Appendix 1 under the heading “Orientation Survey” (which was undertaken at the Insizwa Complex) and is briefly outlined here. The –75 micron material analysed using XRF was found to be the most suitable. The main task is to discriminate between silicates and sulphides. Dividing Cu and Ni by MgO proved to be the best way of doing this. Thresholds of 40 for Cu/MgO and 150 for Ni/MgO proved useful in separating the two and gave dispersion trails of up to 1 000 m below known mineralisation. Variations of this technique could be more generally applicable.

3.3 Geophysics

3.3.1 Introduction

The aim of geophysics is to identify "blind" geological features (especially mineralisation) that are obscured by overlying lithologies or unconsolidated sediments. The appropriate survey needs to be chosen that will identify the features that the geologist is wanting to delineate. This will depend on the physical properties of the geological features under investigation. A survey has to be designed, quality data collected and then reduced in order to give an optimum or approximation of the geology. The data is reduced using either quantitative or qualitative means. Quantitative interpretation results in an interpretation of the depth, dip, strike and geometry of a body whilst qualitative interpretation uses filters, image processing and pattern recognition to interpret lithologies and structures. A brief overview of the application of geophysics to Ni-sulphide exploration is given in the following section, section 3.3.2.

For gravity and magnetics the physical properties that control the outcome of the survey are susceptibility and density respectively. If an image of either gravity or magnetic data is plotted what is shown are anomalies arising from sources at different depths which have different wavelengths. The physical property contrast of gravity images is relatively low (mostly 15% or less density variation) whereas with magnetics there are up to four orders of magnitude variation in susceptibility. Gravity can be used to detect bodies at greater depths whilst magnetic data is limited by the Curie isotherm for magnetite (~20km) but is mostly suitable for the upper 3 to 5 km.

Ambiguity can arise in interpreting either gravity or magnetic data if the geometry, depth and density (or magnetic susceptibility) are all unknown. Knowledge of one or more parameters allows for interpretation of the others. Remnant magnetism can also be a source of ambiguity in data interpretation.

3.3.2 Application to Ni-Sulphide Exploration

Initially regional geophysical surveys are used to help identify targets. Regional gravity and aeromagnetic surveys can be used to identify prospective terrains. These images can help in interpreting craton boundaries, mobile belts and major lineaments. Once a prospective area is located, the discrete magnetic and gravity highs can be identified which may be indicative of "hidden" mafic/ultramafic intrusives. Massive sulphide ore bodies cannot be detected using these regional surveys. Identifying these geological features using geophysical products is known as qualitative interpretation. The results of qualitative interpretation are shown in section 4.3.6.2 which illustrates how regional aeromagnetics was used to delineate the interpreted extent of a melt sheet. Useful features for Ni-sulphide exploration that can be identified during this process include:

1) Linear features indicating dykes, faults, steeply dipping strata etc.
2) Ultramafic rocks unless remnantly magnetized show as magnetic highs as they generally have high concentrations of magnetite.
3) Unmetamorphosed sediments generally produce low amplitude anomalies.
4) Basement granite also produces low amplitude anomalies.

When applying quantitative interpretation it is important to use the most useful derivatives to show the features one is trying to identify. With each increasing order of differentiation the resolution between adjacent, closely spaced anomalies increases and deeper (long wavelength) features disappear relative to shallower (shorter wavelength) features (Corner, 2000). This is useful as it gets rid of overriding large deep-seated features and allows one to detect the smaller intrusions that are targeted during Ni-sulphide exploration.

Quantitative interpretation can also be conducted by using the wavelength of the body to give an indication of the depth to, and the causative source of magnetic anomalies. This is useful at an early stage of project generation as it can show if a body is too deep to explore for. There is a large degree of error involved in the interpretation of these depths due to the ambiguity involved in interpreting the data so features that are interpreted to be a little too deep to explore for should not be excluded. Some features can, however, be interpreted to definitely be below a certain depth for instance a feature may be interpreted to be below 2 000 m and then does not warrant any further work as most Ni-sulphide targets below 500 m are generally considered uneconomic.

On a more detailed project level it is common to fly an airborne EM survey when looking for Ni-sulphides. Massive sulphides are conductive and show up clearly in an EM survey (depending on their depth). DIGHEM and VTEM surveys penetrates to only about 60 m (or at most 120 m depending on ground conditions), but MEGATEM and GEOTEM surveys are able to penetrate to about 600 m. These surveys need to be followed-up with field mapping in order to identify what the magnetic highs are indicating. Most magnetic highs are caused by dolerite dykes but some may be more prospective resulting from primitive intrusions. The source of EM anomalies needs to be field checked and could be anything from graphitic sediments to serpentinised ultramafics to sulphides. These EM conductors will need to be followed-up with ground surveys if they are coincident with mineralisation or if they are hidden.

Detailed gravity surveys may be used to delineate the extent of the intrusion being explored, this was done at Insizwa and is discussed in Appendix 1.

Ground EM surveys suitable for Ni-sulphide exploration utilizes the low frequency range and discriminate between massive sulphides and other conductive material. UTEM is particularly suitable for this (and was implemented at Insizwa (Appendix 1), and slow decaying, late channel UTEM conductors should be drill tested. EM targets can be modeled in three dimensions but the author has not had exposure to this and it will not be discussed here.

Pros and cons of different geophysical surveys in their application to Ni-sulphide exploration are outlined below:

Table 4 – Pros and Cons of Various Geophysical Techniques

Pros	**Cons**
Regional Aeromagnetic Surveys	
Data relatively easily accessible and affordable from government geological surveys.	
Lineaments, craton margins and mobile belts identifiable	
Large intrusions identifiable.	If there is a deep-seated large-scale feature this may mask even large intrusions but its effects can be reduced by using derivatives.
Images such as the analytical signal are useful for mapping as they directly overlie their causative source.	
Allow intrusions to be identified that can then be field checked and may become targets if found	End up field checking many barren dolerite intrusives. Checking the mag highs against

Pros	Cons
to be primitive or associated with sulphides.	government maps can help but the scale of these and the lack of detail means that many outcrops mapped as dolerite still need to be field checked as they are often more primitive olivine gabbros or other prospective lithologies.
Detailed EM (Ground and Airborne) Surveys	
Provides conductors which may be indicative of mineralisation.	Conductors can arise from several sources such as graphitic sediments and may not necessarily be indicative of mineralisation. Disseminated sulphides may mask massive sulphides.
Gravity Surveys	
Provides details of an intrusions dimensions useful for targeting specific areas within a complex such as where a "feeder" opens into the complex	Is costly and requires a large project and large target area.
	Data can be skewed by lack of sample points.
	Terrain correction in mountainous areas can be problematic.
	Does not provide direct targets like EM.

Chapter 4 - Two Case Studies

4.1 Introduction

Two case studies are provided in the ensuing chapters. These are included to show the integration and application of principles discussed in the preceding chapters (geology, geochemistry, geophysics). It is hoped that the reader will grasp an understanding of how conceptual ideas, mapping, geophysics, geochemistry, research and drilling can be applied to a target and how the data can be synthesized to decide on whether the target warrants further work or not.

The Insizwa target is modelled on the Norilsk deposit (chapter 2) and displays many of the features discussed under the heading "Overview of All Deposits Discussed – Discussion and Recommendations for Ni-Cu-Co-PGM Exploration" (chapter 2). Much of the work conducted at Insizwa was geophysical and the application of the techniques discussed in the geophysical chapters is shown here and discussed further in Appendix 1.

The author worked on the Insizwa project for last two years of Falconbridge Venture's involvement there (1999 and 2000). This case study is a summary of the work conducted there over a five year period (1995 to 2000). This study starts with a summary of the results and then continues with an introduction and explanation of the geology. This is followed by sections on the geochemical and geophysical work conducted. A summary of the drilling results is included. The case study ends with a discussion, conclusion and recommendations.

The second case study is of the Morokweng Project. This target is modeled on Sudbury (chapter 2). The case study will show why the area was thought to be prospective, how it was evaluated (largely using geochemistry) and why it was ultimately decided not to pursue the project further.

4.2 Insizwa Complex

4.2.1 Introduction – Locality and conceptual motivation for selection

The Insizwa Complex is situated in the vicinity of Mount Ayliff, Eastern Cape Province, approximately 200 km southwest of Durban and 90km from the Indian Ocean, centred on 30°45'S and 29°15'E (Fig. 1). The area is bisected by a national highway (N2) and is serviced by regional roads and rough tracks. The nearest railway line is at Kokstad, 30 km north of the Project area. Eskom grid electricity is available at Mount Ayliff, central to the Project area.

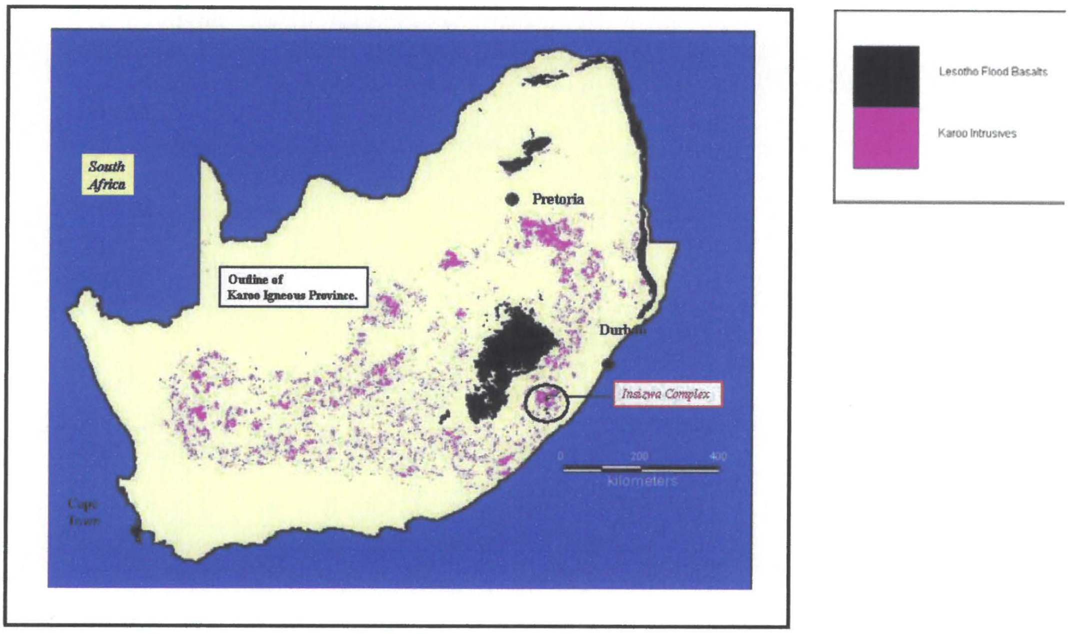


Fig. 1 Geographical locality of the Insizwa Complex and position relative to the Lesotho Flood Basalts and karoo Igneous province

Falconbridge Ventures started work at Insizwa in 1995 and this continued through to the end of 2000. The exploration target was a Ni-Cu-Co-PGM massive sulphide deposit of +/- 30 million tonnes with economic grades sufficient to sustain a mining operation of at least fifteen years.

The work conducted by Falconbridge Ventures on the Insizwa Complex from 1995 to 2000 is outlined here as a case study. The objective is to show how the geological characteristics described in Chapter 2 as well as the exploration techniques described in the ensuing chapters were applied to an exploration project.

The first objective is to show why the area was thought to be prospective (in light of the features described as being favourable for the formation of a Ni-sulphide deposit, as outlined in chapter 2 of the treatise). A summary of this is given in the following points which shows the Insizwa Complex has:

1) A thick package of ultramafics/mafics providing a potential source of Ni.
2) The presence of sulphide showings indicates that the formation of sulphide took place.
3) Olivines depleted in Ni indicate that a sulphide phase enriched in Ni may have segregated.
4) Large volumes of magma flowed through the system as evidenced by the 800km^2 area of the Insizwa Complex and 27 000 km^2 of exposed Lesotho basalts. This increases the potential for any sulphides that may have formed to be upgraded.
5) The high ^{87}Sr/^{86}Sr ratios and presence of granophyric veins (melted sediments) indicate the possibility of contamination, which would aid in sulphide precipitation.
6) Overall similarities to the Noril'sk Ni-Cu-PGE sulphide deposit in Russia, with the same genetic model being invoked for the Insizwa Complex show a favourable setting for a Ni-sulphide deposit.

Surveys implemented included ground and airborne geophysics, mapping, soil geochemistry and drilling. Regrettably this did not result in the discovery of any significant mineralisation. The sequence of their implementation is given below:

1) Firstly the area was identified as being prospective for Ni-sulphides (based on the criteria described above).
2) Secondly extensions of known mineralisation were explored for using airborne and ground geophysics. This involved using airborne EM/Mag to identify extensions of known footwall mineralisation. Targets were followed-up with ground TDEM, reconnaissance geochemical traverses across targets and finally with drilling.
3) The second phase of exploration concentrated on the Ndzongiseni-Sidakeni area of mineralisation (Fig. 5). IP surveys and drilling were conducted.
4) The final phase concluded the work at Ndzongeseni which included systematic trenching and drilling as well as mapping of the "Off-lobe" areas to identify "feeder dykes. ("Off-lobe" areas are those areas between the lobes). Potential targets both along the footwall, and in "off-lobe" areas were evaluated with UTEM surveys and conductors were then drill tested.
5) Research work was conducted at various stages of the exploration to help verify the genetic model, identify areas for potential exploration and to gain a better understanding of the geology.

4.2.2 Geology

The Insizwa Complex is the largest intrusion within the Beaufort Group (which consists predominantly of shale with subordinate sandstone) of the Karoo Sequence and one of the largest Karoo aged intrusions within the Central Flood Basalt Province of Southern Africa (P.C. Lightfoot et. al., 1984) Fig. 2.

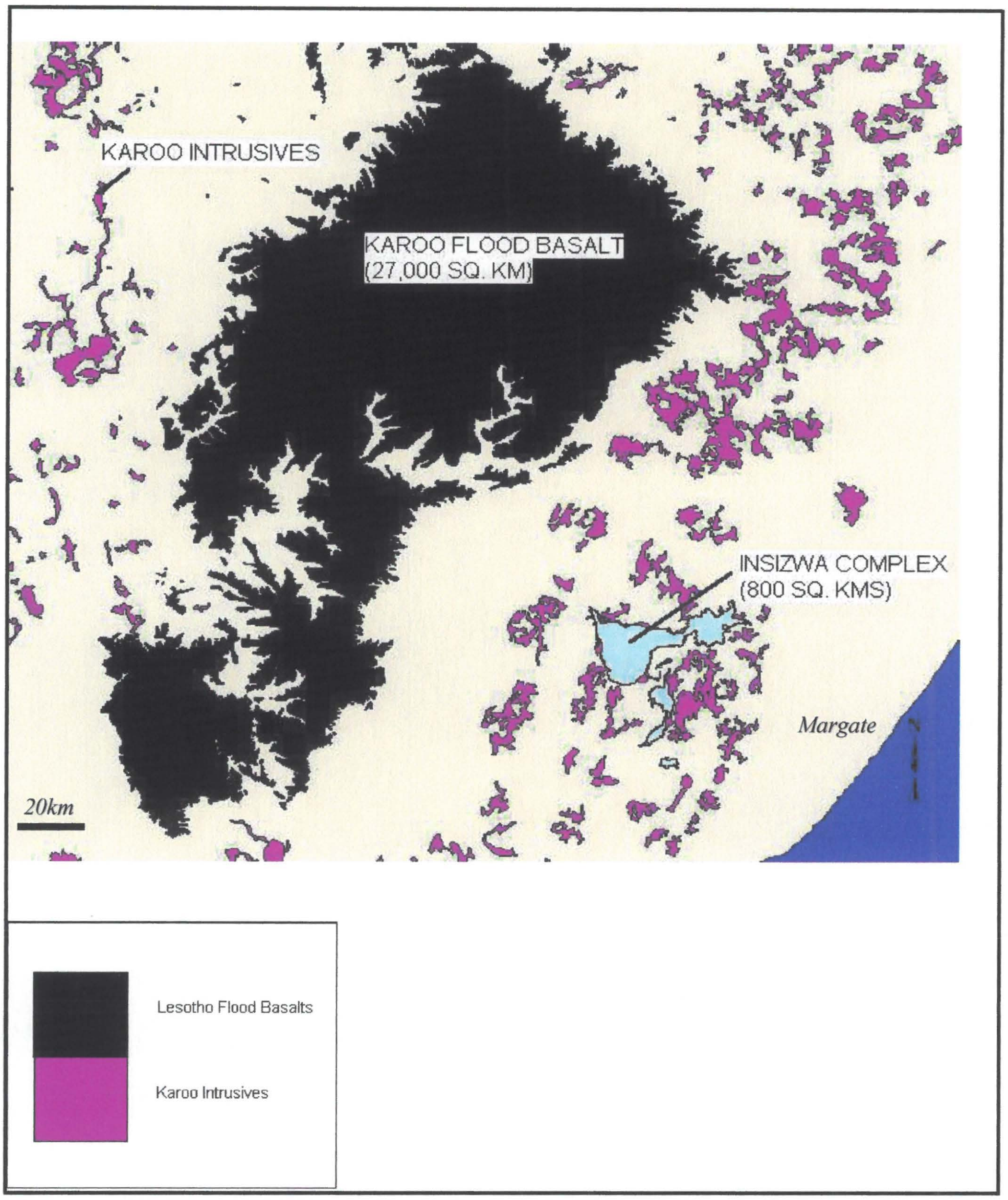


Fig.2. The size and position of the Insizwa Complex relative to the Lesotho Flood Basalts (After government 1:1 000 000 South Africa Geology Sheet)

It extends over a 300 km strike length and reaches a maximum thickness in excess of 1 200 m. The complex also contains the thickest known sequence of ultramafic/mafic intrusives within the Karoo Igneous Province (KIP) which outcrops in five lobes; Insizwa, Tonti, Tabakulu, Ingeli and Horseshoe (Fig. 3)

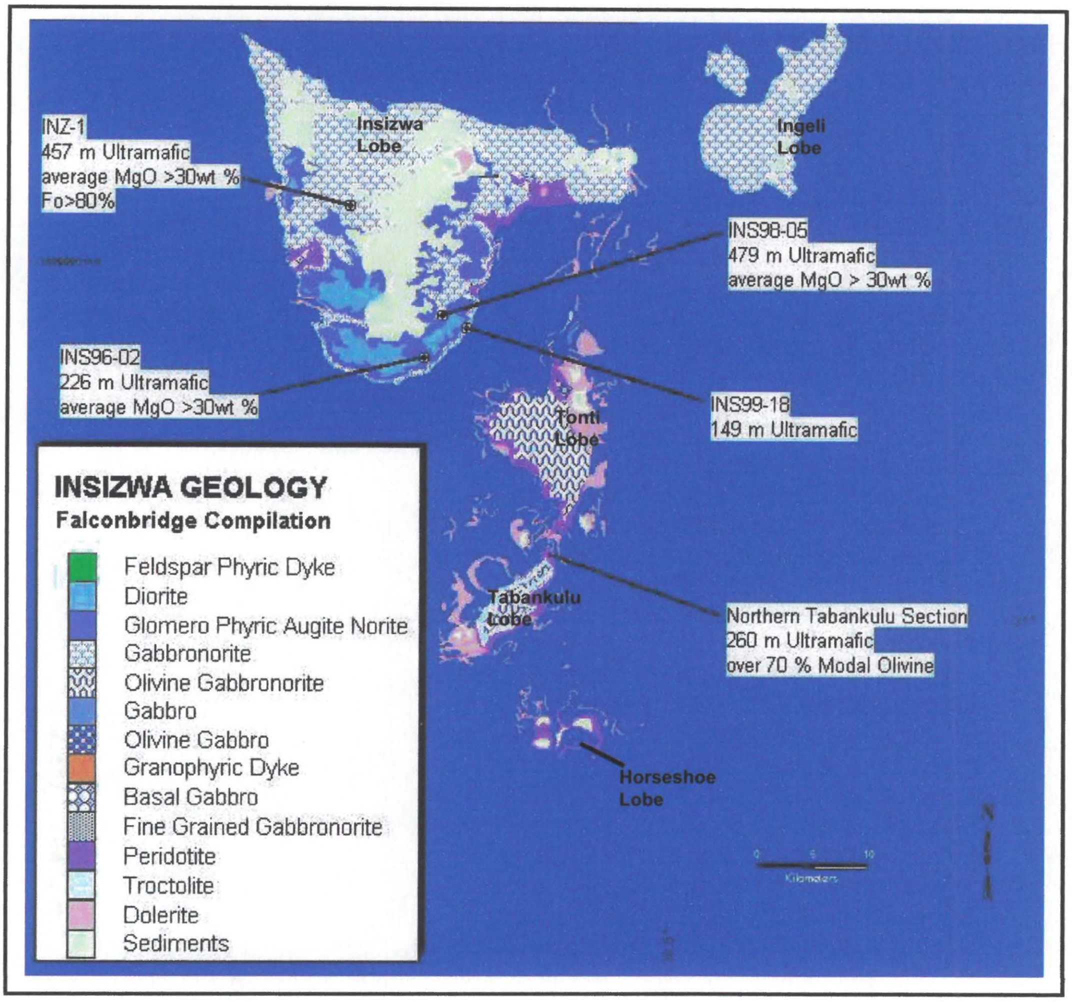


Fig. 3. The geology of the five lobes of the Insizwa Complex (Falconbridge geological compilation, 2000)

There are numerous high tenor sulphide showings (up to 13,7%Ni and 5,75% Cu in sample 36651 – at Ndzongiseni within the Insizwa Complex, the largest of which is the old Waterfall Gorge mine. This site contains 466 253 tonnes grading at 0,69% Ni + Cu and 0,43 g/t combined PGE (Pt, Pd + Au, indicated and inferred within 50 m from the surface) defined by Gencor in 1992 and up to 13,7% Ni and 5,75% Cu in grab samples (Falconbridge, 1999 Annual Report).

The Insizwa Complex is a layered, differentiated mafic to ultramafic intrusive complex consisting of five exposed, sheet-like lobes named earlier (Fig. 3). Each lobe of the Insizwa Complex appears as a relatively flat-lying igneous sequence consisting of basal gabbros, peridotite and varying upper gabbros resulting from a multiple intrusive history. Igneous layering has resulted from in-situ fractionation, as well as from various "injections" of compositionally contrasting magmas (Marsh, 2000).

The stratigraphy of the Insizwa Complex as described by Lightfoot et al. (1984) is shown in Table 1.

Table 1 – Stratigraphy according to Lightfoot (1984)

Unit	Description
Roof Zone	Diorite – Cumulus plagioclase with intercumulus quartz, K-feldspar, hornblende and biotite.
Upper and Top Gabbronorite	Olivine plagioclase cumulate with variable proportions of intercumulus augite and bronzite, with intercumulus olivine in some horizons.
Upper and lower Peridotite	Composed predominantly of olivine cumulate with intercumulus augite, bronzite and plagioclase.
Basal Gabbronorite/ Gabbro	Cumulus olivine in a chilled groundmass of augite, bronzite and plagioclase.

Marsh (2000) has made stratigraphic divisions based on Cu/Zr and Cu/Ni ratios and according to him the stratigraphy (from base to top) is as follows:

Top Gabbronorite
CuO poor Gabbronorite
Upper Gabbronorite
Upper Lherzolite
Picrites and gabbros
Lower Lherzolite
Picrites

The distinction between lherzolites and picrites is not made elsewhere in the text, all ultramafics with >30% olivine are referred to as picrites. The rocks named picrites by Marsh (2000) have been referred to in the text as basal gabbro as per Lightfoot's 1984 stratigraphic divisions.

4.2.3 Genetic Models (Fig. 4)

Initially exploration concentrated on locating sulphides along the footwall and below the lobes, particularly at the Insizwa Lobe between Waterfall Gorge and Ndzongizeni. This work was based on the model described below.

Deep-seated fractures would have provided conduits for picritic magma to be tapped from the mantle and brought to the surface. Segregation of a sulphide phase is postulated to have occurred, possibly after contamination by the host sediments. This would have taken place in a zone with relatively less confining pressure, such as chambers or where a dyke feeds a sill (Fig.4).

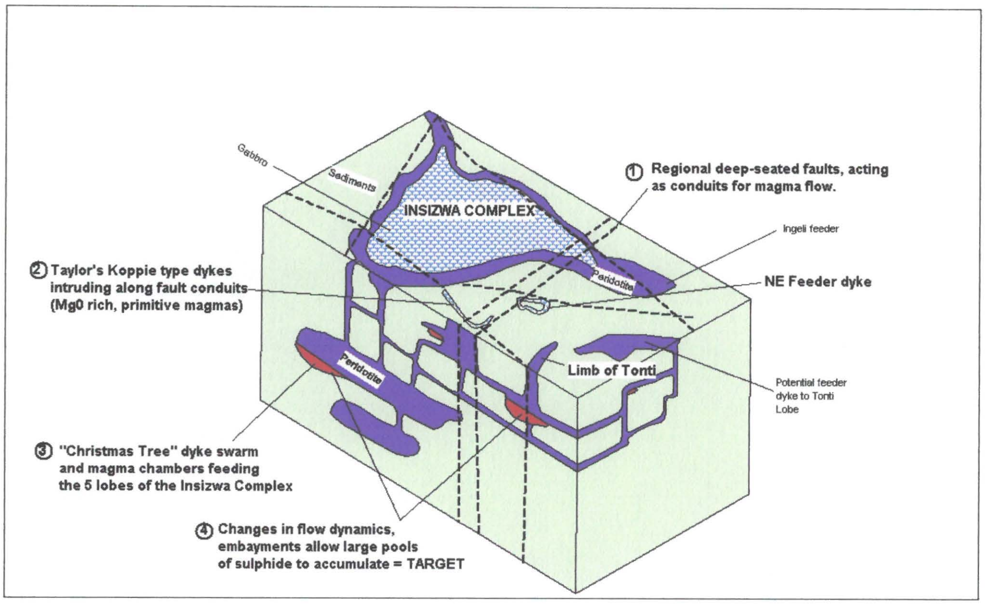


Fig. 4 – Schematic representation of the Insizwa genetic model

Field observations supporting this model are as follows:

1) Old adits at the Insizwa Lobe, (including the Waterfall Gorge mine) are located along the footwall of the lobes, especially between Waterfall Gorge and Ndzongizeni indicating the potential for further down-dip mineralisation.
2) These lobes contain thick packages of ultramafic rock (in excess of 400m) suggesting a primitive parental magma rich in Ni.
3) Brecciated xenoliths and sulphides at Waterfall Gorge suggest the sulphides at the mine were derived from a distal source and represent remobilized mineralisation, possibly from a larger body.
4) Structural analyses (identification of lineaments from SPOT) indicate the presence of large, possibly deep-seated structures at Insizwa, which may represent conduits for potential "feeder dykes" to the Insizwa Complex.
5) The following indicate evidence of contamination:
    a. Presence of sedimentary and igneous xenoliths within massive sulphide, granophyric veins and metamorphosed footwall sediments which host significant isolated sulphide at Waterfall Gorge.
    b. High $^{87}Sr/^{86}Sr$ ratios.

Field evidence and research did not disprove the model. Polished section analyses from Ndzongizeni did, however, indicate that the high PGE values obtained from the trenching programme, grab samples and the INS98-04 mineralised borehole intersection probably resulted from localised hydrothermal processes.

The discovery of the Taylor's Koppie dyke led to a change in focus from the lobe margins to possible feeder dykes. Taylor's Koppie dyke is thought to represent a "feeder dyke" to the Insizwa Complex and could, therefore, host a sulphide deposit. Evidence for this hypothesis includes:

Zoning showing evidence of several pulses of magma identified in stream exposure. The "zones" identified are:

1) Complex contact zone with partly assimilated sedimentary material in a fine-grained mafic host.
2) Olivine norite containing large sulphide blebs of pyrrhotite and chalcopyrite (up to 5 cm in diameter) and disseminations.
3) Coarse-grained olivine norite with disseminated and small sulphide blebs.
4) Central barren (no sulphide) olivine gabbronorite.
5) The presence of sulphide confirming that the process of MSS had occurred.
6) The extent of thermal metamorphism is consistent with extensive magma flow (large hornfels ridges are preserved).
7) The dyke appears to "enter" the Complex between Waterfall Gorge and Ndzongiseni – the area of best mineralisation.
8) Structural control on the dyke is evidenced by the 90° change in strike.
9) Anisotropy of magnetic susceptibility studies and the geochemical similarity to the complex point towards Taylor's Koppie having formed from magma flowing from depth up towards the complex.

This evidence for a "feeder dyke" led to a shift in focus to the "Off-Lobe" areas between the lobes where other potential "feeder dykes" could possibly be discovered. Feeder dykes were thought to hold more potential to host a deposit from a genetic point of view as outlined in the chapter giving an overview of factors favourable for Ni-sulphide formation which shows that conduits with a high R-factor show greater economic potential than layered complexes.

The basis of the genetic model remained the same – picritic magma depositing sulphides possibly through contamination. The difference, however, lies in the target areas that were now dykes and sills between the lobes. These could potentially be closer to the "throat" of the system and hence to potential deposits.

Results of field work and research at Insizwa has shown the following regarding the geology of the complex:

Formation of the Insizwa Complex

1) It is suggested, by Marsh (1999), that a thick peridotite pile, with constant olivine compositions, such as at the Insizwa Complex could not have nucleated, grown, and settled in situ. It is proposed that the peridotite, which varies in thickness, as does the underlying basal gabbro, formed by the propagation of an intrusion with varying composition. "At the sharp end of the dyke we have normal Karoo doleritic magma but trailing behind we have a wide core of phenocrysts-charged magma"(J.Marsh, 1999).
2) The basal gabbro would have formed from the more typically Karoo type magma whilst the overlying peridotite would have resulted from the phenocryst charged magma.
3) The overlying gabbros formed from more "typical Karoo magma".

Basal Gabbro

The basal gabbro could have formed from solidification of the "sharp end" of a propagating sill as described above. This unit varies in thickness from being absent in some boreholes to up to ~90 m thick (INS99-14).

Peridotite

This unit could have formed by the process described above, i.e. by the continued settling of olivine from large volumes of phenocryst charged magma dropping crystals out as they flowed. It varies from being absent (INS99-14) to up to ~480 m thick (INS98-05). The lack of variation in the composition of the olivines indicates the olivine in these rocks would already have had to have been in existence in the magma at the time of intrusion (Marsh, 1999, Bulletin S 494, internal report).

An interesting feature of the peridotite is its "geochemical split". The lower peridotite is characterised by upward declining Ni/Cu (from values of 10 to 6) and Ni/MgO (from values of 50 to 30) in INS96-02. The upper peridotite shows an upward increase in these ratios from 6 to 10 and 30 to 50 respectively. These trends are also observed, to a lesser extent, in boreholes INS98-05 and INS98-09 indicating it is an extensive feature in the SE part of the Insizwa Lobe (there is little data from other parts of the lobe).

Another interesting feature of the peridotite is the Cu enrichment in the uppermost part of the peridotite. The high Cu, Cu/Zr and Cu/MgO ratios in the upper peridotite suggest some Cu concentration by sulphide accumulation. This high Cu/Zr correlates with high Ni/MgO. This enrichment is observed in all the boreholes studied by Marsh (1999), namely INS96-01, 02, INS98-05, 08 and 09.

Upper and Top Gabbronorite

Marsh (2000) concluded the following with regard to the upper and lower gabbronorites:

1) Gabbronorites in INS96-02 can be separated into two units – the Top Gabbronorites and the Upper Gabbronorites. Separation is based on a geochemical "break" marked by the discontinuity in the Cu/Ni and Sr/Al_2O_3.
2) The Insizwa Complex formed by an open system magmatic process (shown by the variation in the Sr isotopes with depth).
3) The Insizwa Complex shows a high degree of lateral and vertical heterogeneity with regard to Sr isotopes and formed from several influxes of compositionally different magmas.
4) High $^{87}Sr/^{86}Sr$ ratios are suggestive of significant contamination. Doleritic magma would have had to assimilate up to 50% of its mass of sandstone to provide sufficient contamination. Alternatively assimilation took place at deeper levels with contaminants that have higher $^{87}Sr/^{86}Sr$ ratios, which may be the more likely scenario.
5) The Upper Gabbronorites are depleted in Ni, possibly due to sulphide segregation.
6) The Cu depletion of the Top Gabbronorites suggest they formed by the injection of a Cu poor magma.

Roof Zone

No work has been done on this zone.

"Off-Lobe" Area

These were mapped to distinguish typical Karoo dykes from potential "feeder dykes" to the Insizwa Complex and to follow-up on AEM conductors. Discriminating "feeder dykes" from other intrusives was based on identifying dykes with:

1) Sulphides.
2) High MgO contents.
3) Compositions similar to the Insizwa Complex.
4) Structures that could potentially trap sulphides.

Within the eastern margin of the Insizwa Lobe only Taylor's Koppie exhibits potential as a "feeder dyke" because of its geochemical affinity to the Insizwa Complex (based on Marsh's work – Bulletin S 491, internal report, 2000). Additional research by Maier (2000, Bulletin S 543, internal report)) has shown this may not be the case because of the more metal depleted nature of Taylor's Koppie relative to the Insizwa Complex.

Mapping and geochemical research of the intrusions in the western margin of the Insizwa Complex show they all (except for one) have compositions typical of Karoo dolerite. The one exception is thought to be an "off-shoot" from the Insizwa Comlpex. The lack of significant Cu depletion shown by Cu/Zr ratios indicates that sulphide segregation is unlikely to have occurred in these intrusions. No targets were discovered in this area that warrant follow-up with ground geophysics.

The best airborne conductor on the western margin of the Insizwa Complex, from the 1999 AEM survey, named 1999 Zone A is located in a "bowl-like" depression which is bound on three sides by poikilophytic olivine bearing dolerite with MgO contents of 6.27%, 6.29% and 8.11%. The anomaly itself is covered by red soil and float from the surrounding intrusions. According to Watts (Falconbridge Ventures in-house geophysicist) pers com. (2000) the spatial confinement of the conductor may indicate its association with a diatreme/breccia pipe.

A NE trending dyke, on the eastern side of the Insizwa Complex, named the "NE Feeder" has MgO values that are slightly elevated above those of typical Karoo intrusions (~12% MgO as opposed to 6 to 8% MgO) and hosts minor disseminated sulphides. It is not thought to be a worthy target due to the minor sulphide content and lack of olivine rich rocks.

The only other intrusion of interest in the "Off-Lobe" area is the Taylor's Koppie. The potential of Taylor's Koppie as a "feeder dyke" possibly hosting mineralisation has previously been discussed.

4.2.4 Mineralisation

Mineralisation is hosted along the footwall within the basal gabbro and underlying hornfels. Most exposures of gossan/sulphide are located between Waterfall Gorge and Ndzongiseni.

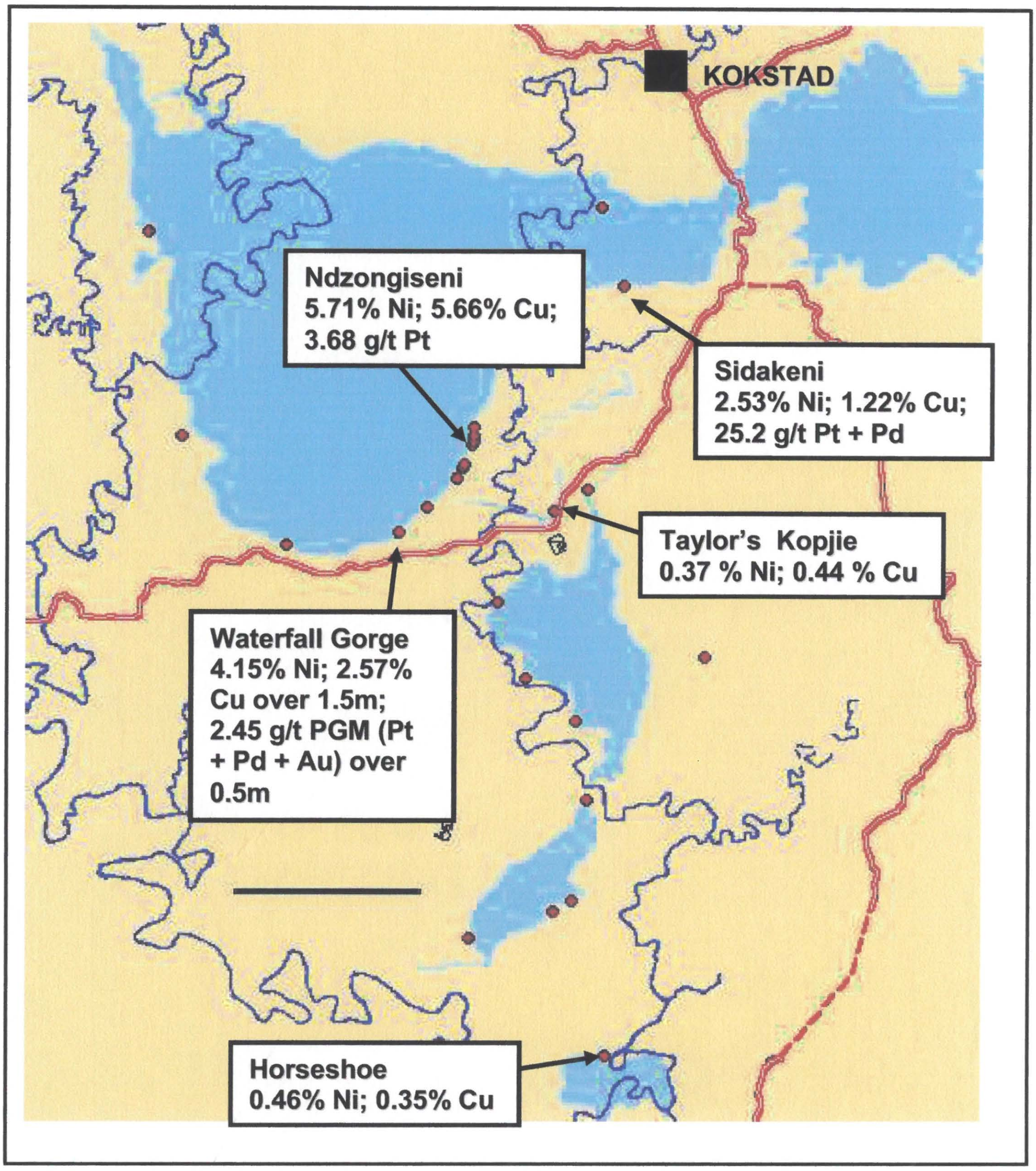


Fig. 5 Insizwa Complex mineralisation with grab sample values (Falconbridge sample data used)

There are four distinct styles of mineralisation at Waterfall Gorge namely disseminated, blebby, vein type and massive (Figs. 6 and 7). Brecciation at Waterfall Gorge indicates mineralisation may have been "transported", possibly derived from a distal, larger ore body.

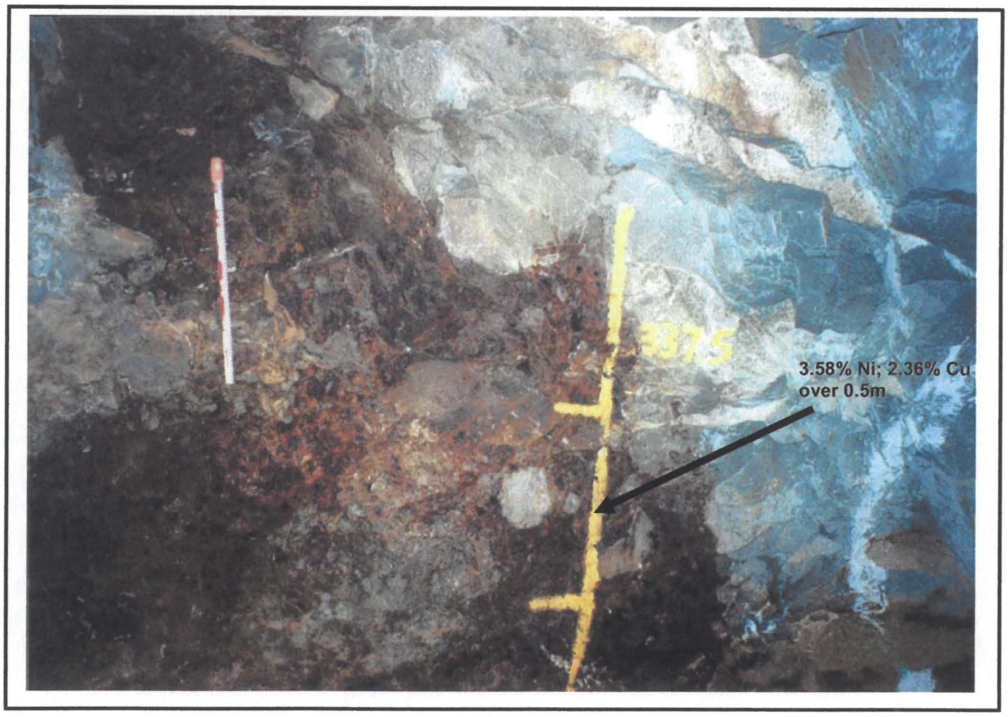


Fig. 6 Massive Sulphide at Waterfall Gorge

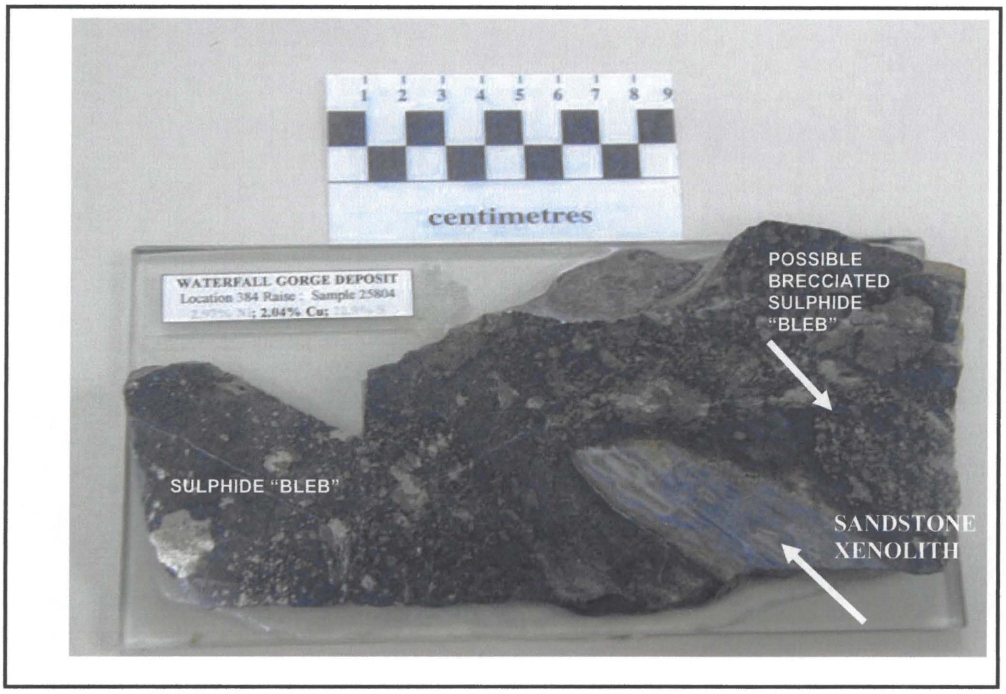


Fig. 7 "Blebby Sulphide and Xenolith from Waterfall Gorge

Results from polished section analyses (Bulletin S 546, internal company report) which are described below, isotope work (Bulletin S 490, internal company report), trenching and mapping suggest that the showings at Sidakeni, Marwaqa, Ndzongiseni and Malusi are derived from small, localised, possibly hydrothermal systems. This mineralisation generally occurs as veins along the footwall and has Ni to Cu ratios of 1:1 to 1:2 with elevated PGE values.

Merkle (2000, e-mail correspondence) studied polished sections from a mineralised intersection in borehole INS98-04 at Ndzongiseni between 260,03 m (sample 53268) and 261,22 m (sample 53272).

The objectives of this study were to help determine the genesis of mineralisation based on the sulphide mineralogies and the relationship between the various sulphide phases.

Table 2 – INS98-04 Mineralisation

Sample No	Sample Length (cm)	Ni %	Cu %	Pt+Pd+Au g/t
53268	26	-	0,14	2,05
53269	31	-	0,22	19,66
53270	27	7,08	10,8	7,99
53271	35	-	-	4,34
53272	30	-	-	0,235

Merkle's (2000, e-mail correspondence) work shows that there were several generations of fluids of variable temperatures (mostly below 250° C) and compositions that infiltrated along veins and fractures.

He states that the high Ni to Fe ratio in the massive ore is indicative of a hydrothermal and not a magmatic system.

Six samples from the Insizwa Complex (five from Waterfall Gorge) were submitted to the Sudbury Metallurgical Technology Centre for polished section analysis, image energy dispersive systems and scanning electron microscope analyses to determine the sulphide phases.

The total volume percent of sulphide in each polished section was determined by a Kontron image analyser and proportions of each sulphide determined by manual point counting.

Whittaker (pers. Comm. 2000 - from the Sudbury Metallurgical Technology Centre) concludes that pyrrhotite is the main sulphide in each sample with lesser amounts of chalcopyrite. Pentlandite has the lowest abundance. The pentlandite is mainly equigranular, which makes it amenable to liberation.

Ten rock samples from Waterfall Gorge were submitted to Ted Thatcher from which eighteen polished sections were prepared and analysed.

The objectives of this study were to:

1) Identify the different sulphides present and in particular the nickel sulphides, i.e. pentlandite, millerite etc.

2) Determine whether the different sulphide phases i.e. blebby, disseminated, massive etc. have a common or separate source.
3) Determine if there is any zoning of the sulphides.
4) Identify any replacement of the original sulphides by nickel sulphide.
5) Identify the dominant habit of the nickel sulphides.
6) Identify the different host rocks.
7) Identify any obscure minerals (e.g. Insizwaite) and the mafic mineral, which rims some of the sulphides.
8) To determine the volume percent and composition of the various sulphides present.

The polished sections were analysed under a SEM. Sulphide phases were then identified using an EDS. The mineralogical and textural characteristics of the sulphides were then studied and described using transmitted and reflected light.

Thatcher's (1996, internal report) observations of Waterfall Gorge mineralisation are as follows:

1) The dominant sulphide phases in the basal gabbro and the hornfels are 41% pyrrhotite, 34% chalcopyrite and 25% pentlandite.
2) The different styles of sulphides have formed from a common immiscible sulphide liquid of magmatic origin.
3) The sulphides may have been transported as immiscible liquid either laterally or upward to their present position. The host magma may have been peridotite or the basal gabbro but appears to be the peridotite, which pre-dated the basal gabbro and initiated melting of the country sediment rock.
4) There is no evidence of zoning or replacement of earlier sulphides by nickel sulphides, although chalcopyrite crystallisation post-dates that of pyrrhotite and pentlandite.
5) Pentlandite occurs as coarse, anhedral grains and not as the usual flame structures.
6) Host rocks to the sulphide include pelitic to semi-pelitic sediments, contaminated and uncontaminated gabbro and olivine gabbro.
7) Uncommon minerals include cubanite, millerite, mackinawite, hauchecornite/badenite, violarite, bravoite, bornite, galena, gersdorffite, tetradymite/grülingite, hessite/stützite and amalgam.
8) Pyrrhotite, pentlandite and chalcopyrite show normal compositions for these minerals.

T. Thatcher's observations of hornfels mineralisation show the following:

1) The thermally metamorphosed argillaceous sediments appear to have been somewhat unusually iron and sulphide rich.
2) The sulphide mineralisation in these metasediments is considered to have been essentially syngenetic but has been remobilised to some extent during the thermal event.
3) Hydrothermal sulphide mineralisation occurs in the vein/segregation material and one of the dolerites.
4) There is no obvious variation in the degree of thermal metamorphism of the sediments. The presence or absence of cordierite is probably controlled by the primary composition of the sedimentary layers.

The mode of formation of the "thermal veins" or segregations is not entirely clear. They could be; a) thermally metamorphosed calc-pelitic sedimentary horizons, b) cross-cutting hydrothermal veins, c) veins forming parallel/subparallel to bedding in advance of emplacement of thin dolerite sheets.

Ground follow-up work to detect mineralisation consisted of mapping, sampling, trenching, ground geophysics and drilling, details are given in Appendix 1.

Mapping generally either commenced after an airborne electromagnetic (AEM) survey, in order to identify magnetic features, or concentrated on identifying footwall mineralisation.

Two distinct morphological domains were identified as described above:

- The footwall
- The "Off-Lobe" areas (between the lobes)

The Footwall

This represents the prospective horizon where the footwall is exposed. The eastern margin of the Insizwa Complex has been mapped in the most detail and contains the greatest number of sulphide showings. Table 4 outlines the mineralisation between Waterfall Gorge and Sidakeni.

Table 3: Highlights of values obtained during 2000 mapping of Eastern Margin mineralisation together with values from Waterfall Gorge and Ndzongiseni obtained from previous workers.

***Sample No.**	**Mineralisation Style**	**Ni (%)**	**Cu (%)**	**Co (%)**	**Ni:Cu**	**Pt (g/t)**	**Pd (g/t)**	**Total PGM [Pt,Pd+Au] (g/t)**
71878	Malachite stained hybrid	0,52	1,71	0,0126	1:3,288	0,97	10,22	11,76
71890	Small sulphide vein in hybrid matrix	0,13	1,26	0,0031	1:9,692	3,08	10,13	14,22
71891	Malachite stained hybrid	0,4	0,47	0,0119	1:1,175	0,26	1,67	2,06
	Hornfelsed sediments	2,53	1,22	-	1:0,4822	-	-	-
71958	Malachite stained hornfels	0,25	1,69	0,0089	1:6,696	<0,02	0,21	0,38
71959	Gossan within peridotite	1,21	0,59	0,0205	1:0,4876	0,22	0,57	1,01
71956	Fractured massive sulphide	1,9	30,6	0,07	1:16,11	0,24	0,57	1,03
	-	1,4	1,09	-	1:0,7786	-	-	-
	-	0,24	0,46	-	1: 1,9167	-	-	0,43

* Sample No: All surface grab samples collected during mapping.

[1] Waterfall Gorge values were derived from the Gencor 1992 Waterfall Gorge resource estimation and from a 1938 bulk sample (45 tons)

One mineralised showing – the KwaKanya showing - was mapped on the western side of the Insizwa Complex, its values are given in Table 5.

Table 4 - KwaKanya Mineralisation

SAMPLE No.	Ni (%)	Cu (%)	Pt (g/t)	Pd (g/t)	Au (g/t)	PGM (Pt,Pd+Au)	ROCK TYPE
71201	0,41	0,80	1,91	2,00	0,57	4,48	Hornfels
71202	0,46	0,76	1,96	3,03	0,43	5,42	Hornfels
71203	0,32	0,18	0,55	0,84	0,11	1,50	Hornfels

4.2.5 Work Conducted

The work conducted at Insizwa including geochemistry, geophysics, trenching and drilling is reviewed in Appendix 1.

4.2.6 Discussion

Exploration concentrated on finding possible extensions to known mineralisation as well as endeavouring to discover previously undetected deposits. Two distinct morphological domains were recognised, the Lobe or footwall and "Off-Lobe" sites.

The known mineralisation is located within the former and initial exploration concentrated on the lobe margins, the area down-dip of Waterfall Gorge and the exposed footwall between Waterfall Gorge and Ndzongiseni. Subsequent work focussed on discovering potential "feeder dykes" in the "Off Lobe" area. Research was undertaken during both phases of work to help formulate genetic models for mineralisation.

Footwall

Geological mapping confirmed the presence of the historic sulphide showings along the FW. Airborne and ground geophysics provided weak to moderate conductors but when drill tested proved not to be attributable to massive sulphides.

Geochemical ratios show the potential for sulphide segregation is largely restricted to the peridotite unit. This unit probably formed from a magma highly charged with phenocrysts that mixed with other magmas of slightly different compositions causing minor sulphide segregation resulting in the mapped showings.

The largest known concentration of these sulphides is at Waterfall Gorge. It does not represent a significant deposit in itself but provided positive indications that significant sulphide segregation may have taken place and a larger deposit could possibly have formed elsewhere in the Insizwa Complex. Alternatively its brecciated nature indicates it is a distal representation of a larger, nearby deposit. Drilling and geophysics has shown the Waterfall Gorge mineralisation does not extend down-dip or along strike.

The numerous showings along the footwall, namely; Sidakeni, Marwaqa and Ndzongizeni show that sulphide segregation is widespread. Furthermore the values from these showings reveal the sulphides have a high tenor, particularly the PGE's. Results from isotope work, drilling, trenching and polished section analyses, do, however, indicate that the various showings are the result of small, isolated, localised, hydrothermal mineralising systems. They are not vectors to a large, magmatic, massive sulphide ore body.

“Off Lobe” Areas

The identification of Taylor’s Koppie as a potential “feeder” dyke led to the focus on the areas between the lobes where other potential “feeder” dykes could possibly be discovered. These dykes would be closer to the “throat” of the system so the potential for the target being at an economically exploitable depth is higher.

Mapping was conducted in the areas east, south and west of the Insizwa Lobe. Airborne EM surveys were conducted prior to mapping, and, on the eastern side, UTEM surveys and drilling were also undertaken. Drilling of UTEM conductors did not result in the intersection of any massive sulphide deposits.

- Taylor’s Koppie was the only “feeder” dyke identified (although tenuous geochemical correlations can be made between other intrusions and the Insizwa Complex) but Maier (2000) dismissed even this dyke as not having “fed” the Insizwa Complex. Whilst the idea of locating “feeder” dykes remains valid, the exploration work focussing on discovering these has borne no fruit and research by Marsh has shown most intrusives have average Karoo compositions. Furthermore, Marsh pers com. (2000) feels that the Karoo Igneous Province is not a favourable target for Ni deposits. This is because of the geochemical homogeneity of nearly all intrusives (with relatively low MgO and Ni contents), as well as the overall lack of field evidence for contamination.

Surveys and Results

Of the fifteen anomalies identified from the 1996 Dighem (see Appendix 1) survey only eight were deemed worthy of follow-up with ground magnetics and moving loop TDEM. From these surveys three targets were identified (L, C and A) of which the best two (A and C) were drill tested – holes INS98-06 and INS98-07. No mineralisation was intersected.

Interpretation of the 1996 UTEM survey testing down-dip extensions of the Waterfall Gorge mineralisation resulted in the identification of two targets namely, AU and R. The stratigraphic hole INS96-01A was drilled in the vicinity of AU whilst R was drill tested by INS98-05. No mineralisation was intersected.

The weak TDEM conductors identified from the 1996 survey were drill tested with INS98-03 and 04. The former intersected no significant mineralisation whilst the latter, INS98-04 intersected the best mineralisation drilled to date at Insizwa (see Appendix 1 for details).

The 1998 helicopter-borne EM survey identified five new conductive anomalies to follow-up (targets 98-A and 98-C were identified during the 1996 Dighem survey). These targets (98-D, 98-E, 98-F, 98-G and 98-H as well as 98-A and C) were followed-up in 1999 with UTEM surveys that confirmed the presence of these conductors.

The 1999 UTEM conductors and geological targets at Ndzongiseni were drill tested later that year but no significant mineralisation was intersected as many were attributed to conductive scree.

General

Mapping and sampling have confirmed the process of sulphide segregation took place as there are several sulphide showings. Some of these have high Ni, Cu, Co and PGE tenors which was originally thought to be due to upgrading resulting from a high throughput of magma. At Ndzongiseni, however, the high grades appear to be due to hydrothermal processes.

Waterfall Gorge is thought to have resulted from magmatic processes but drilling and geophysical surveys show there are no extensions to this deposit, either along strike or down-dip. Surveys (geophysical, mapping and drilling) in the area where most of the showings are located (between Waterfall Gorge and Ndzongiseni) have not detected any significant deposits.

Ndzongiseni is an area with several old adits and sporadic outcrop of gossans along a strike length of approximately 1,2km. This area has been explored in detail, including IP, HLEM, TDEM surveys, detailed mapping, trenching and drilling. Results have shown the mineralisation is sporadic and discontinuous and does not represent a deposit that is economically exploitable.

Research at Ndzongiseni has included Pb-Pb isotope studies and polished section analyses. These have both confirmed the survey results and shown the mineralisation to have resulted from a small, hydrothermal system (e-mail from R.Merkle, 1999).

Work in the "Off-Lobe" area has not been successful in identifying a "feeder dyke" hosting massive sulphide. Dighem surveys, followed up with moving loop TDEM and magnetics around Tonti, Tabankulu and Horseshoe Lobes as well as mapping at the Horseshoe Lobe has not resulted in any discoveries in these lobes.

4.2.7 Conclusion

The basic geological conditions at the Insizwa Complex for the formation of a Ni, Cu, Co, PGE massive sulphide ore body appear favourable as outlined below:

1) The thick package of ultramafics/mafics.
2) The evidence for large volumes of magma having flowed through the complex.
3) The evidence of several magmas, of differing composition having formed the Insizwa Complex.
4) Presence of sulphides showing that sulphide segregation took place.

The various surveys have, however, not resulted in the discovery of any significant sulphide body. The best drill intersection was in INS98-04 (1,62% Ni; 2,55% Cu; 4,2g/t Pt and 3,3g/t Pd over 1,19m which included 7,08% Ni and 10,8% Cu over 0,27 m from 260,60 to 260,87 m), but this could not be followed along strike or up-dip and is thought to have resulted from very local hydrothermal processes.

So whilst the geology shows strong potential for the formation of a deposit, the various surveys have not detected one. The footwall on the eastern margin of the Inisizwa Complex has been extensively evaluated, down to a depth of 500 m where the UTEM surveys have been implemented. The Dighem surveys flown around the four lobes south of the Insizwa Lobe have the ability to detect sulphides to a depth of 60 m. Poor coupling may mean that there is still some potential for discoveries in these lobes, particularly below 60 m. Maier's work does, however, indicate that sulphide precipitation resulted from mixing of magmas of similar composition, a process that would not cause significant sulphide segregation. The lobes are thought to have formed from the same magma source/chamber/connected chambers so Maier's (2000) interpretation would apply equally to all lobes.

It is concluded that the more obvious targets around the Insizwa Complex have been fully evaluated. The geological conditions are conducive to sulphide formation but according to Maier's (2000) studies perhaps not to the extent of forming a significant sulphide body.

Further work, possibly involving the deeper "seeing' UTEM surveys around lobes where it has not been used still has the potential to detect a deposit. The survey results, and research indicate that the point of diminishing returns on exploration costs versus possibility of a discovery has been reached. The Insizwa Complex may host a massive sulphide deposit but Falconbridge Ventures work and research during this programme show this is unlikely.

Exploration work shows that an undetected deposit, if present may be at one of the following localities:

1) Along the western footwall of the Insizwa Lobe below a depth of 60 m.
2) Along the FW of Tonti, Tabankulu or Horseshoe, below a depth of 60 m.
3) At depth, within a lobe, possibly where a "feeder dyke" opens into the overlying lobe.
4) A picritic dyke within the Karoo Igneous Province, probably related to a deep seated, mantle tapping conduit, i.e. an intrusion similar to the Insizwa Complex that has not yet been mapped.

It can be seen from this discussion and the details given in the Appendix 1 how the exploration was conducted and what surveys were implemented. The area was initially identified as prospective mainly because of its analogies to Noril'sk, its sulphide showings and relatively thick ultramafic units. Government geological and aeromagnetic maps were used to identify the extent of the lobes and the their geology. Work shifted from first assessing the down-dip or along strike extensions of known mineralisation to evaluating the possible "feeder-dykes" in the off-lobe areas. Regional surveys included the Dighem airborne EM around the lobe margins, airborne EM in the off-lobe areas and a gravity traverse across the Insizwa lobe. Detailed work included TDEM soundings, UTEM surveys, trenching at Ndzongiseni and drilling of UTEM conductors as well as systematic drilling at Ndzongiseni. Research work entailed AMS, polished section analyses and Pb isotope studies.

The combined evidence from the various surveys indicates that the Insizwa Complex has a low potential to host an economic Ni-sulphide deposit.

4.3 The Morokweng Impact Structure

4.3.1 Introduction

This second case study is included as it shows the evaluation of an impact model (Sudbury analogue). This is outlined in chapter 2 as a favourable setting for a Ni-sulphide target. Whilst the first case study of Insizwa utilized geophysics to a large extent to evaluate the Insizwa Complex, work on this target by Falconbridge Ventures was almost entirely geochemical making this an informative example of the use of MMI although aeromagnetic surveys were also extremely useful in delineating the extent of the Mororkweng melt sheet.

The ring structures of the Morokweng Impact Stucture were first recognised by M. Andreoli in the middle 1980s from a regional aeromagnetic survey of the Ganyesa district, conducted by the Bophuthatswana Geological Survey (BGS) which has been part of the South African Council for Geoscience since 1994.

Core from four shallow holes drilled by the BGS was recognised by M. Andreoli to be norite of impact origin in 1991. This was confirmed by detailed petrographic and chemical analysis. In particular, the considerable enrichment of siderophile elements and the intersection of impact related breccias were cited as firm evidence for an impact origin. Further evidence includes large scale domal uplift (the Ganyesa dome) with associated radial faults and injection of dykes resulting from differential uplift of a heterogeneous basement.

The impact has been dated by the age of the melt rocks at 145 million years +/- 2 million (Reimold., 2002).

Limited exploration work has been conducted by De Beers (for diamonds) and by Business Venture Investments 33 (Business Venture Investments 33) - for a massive Ni-Cu sulphide body - prior to Falconbridge Venture's involvement.

The area was believed to be analogous to the Sudbury Igneous Complex (as outlined later) and therefore offered a prospective target for Ni, Cu, Co and PGM exploration.

4.3.2 Location/Infrastructure (Fig 8)

The Morokweng Impact Structure is located 30 km SW of the town of Morokweng in the Northwest Province of South Africa (Fig. 8).
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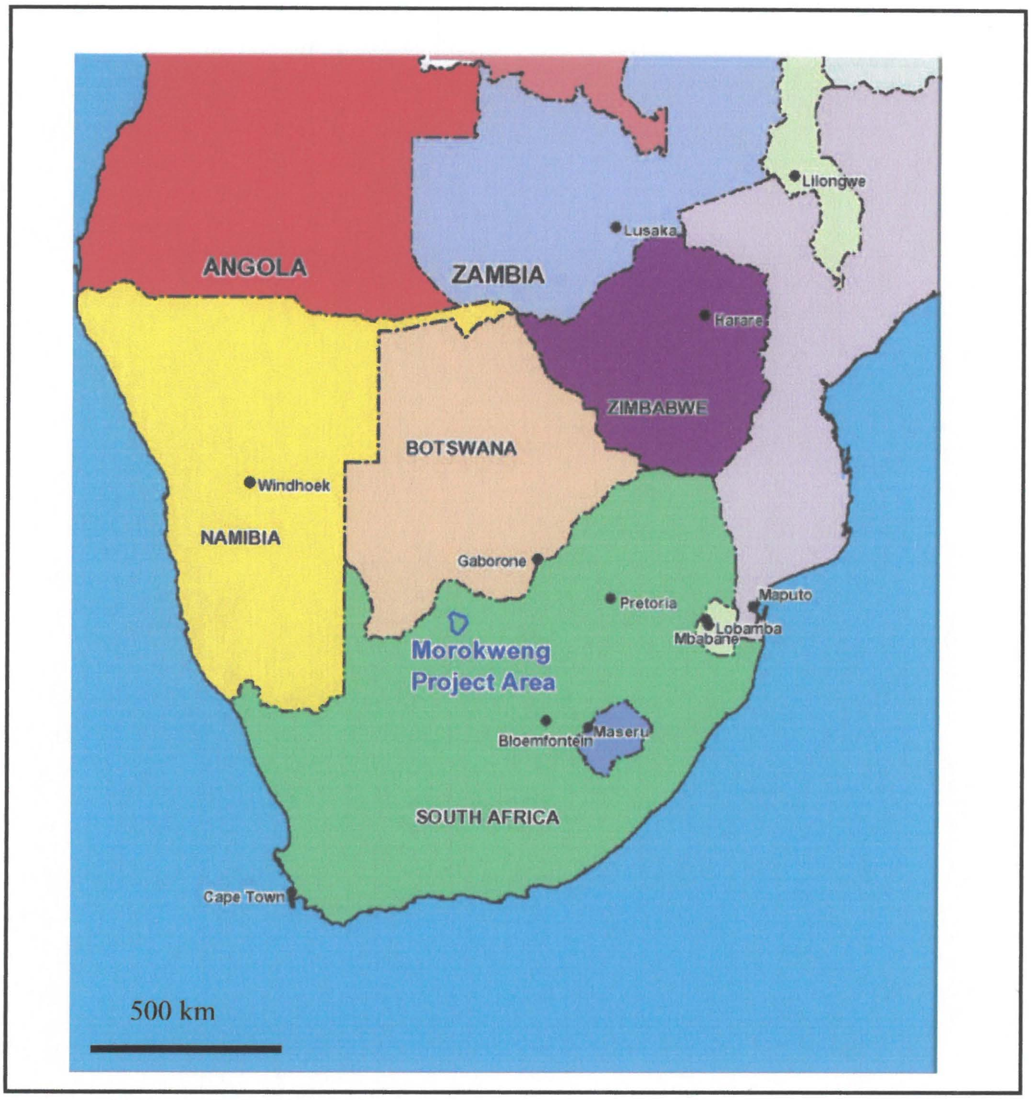


Fig. 8 Morokweng Impact Structure Locality Map

Morokweng is accessible by a good tar road connecting with the National Route N 14 at Vryburg, 120 km to the south. From the town, the area of interest is accessible by well-constructed calcrete surfaced roads and finally un-surfaced sand roads. The latter can be problematic for two wheel drive vehicles and after rain.

The area is just within the limits of the Kalahari region and is typified by uniformly flat topography. There is no surface drainage except for flash flood sheet wash and channels after heavy rain during summer months.

Soils are very poorly developed and stabilised wind-blown sand supports low scrub and trees. Beneath 8-12 centimetres this sand is indurate and is not affected by present day wind-blown material, whereas close to the surface the sand is generally loose and prone to movement in high winds. There is no exposure of bedrock within the project area.

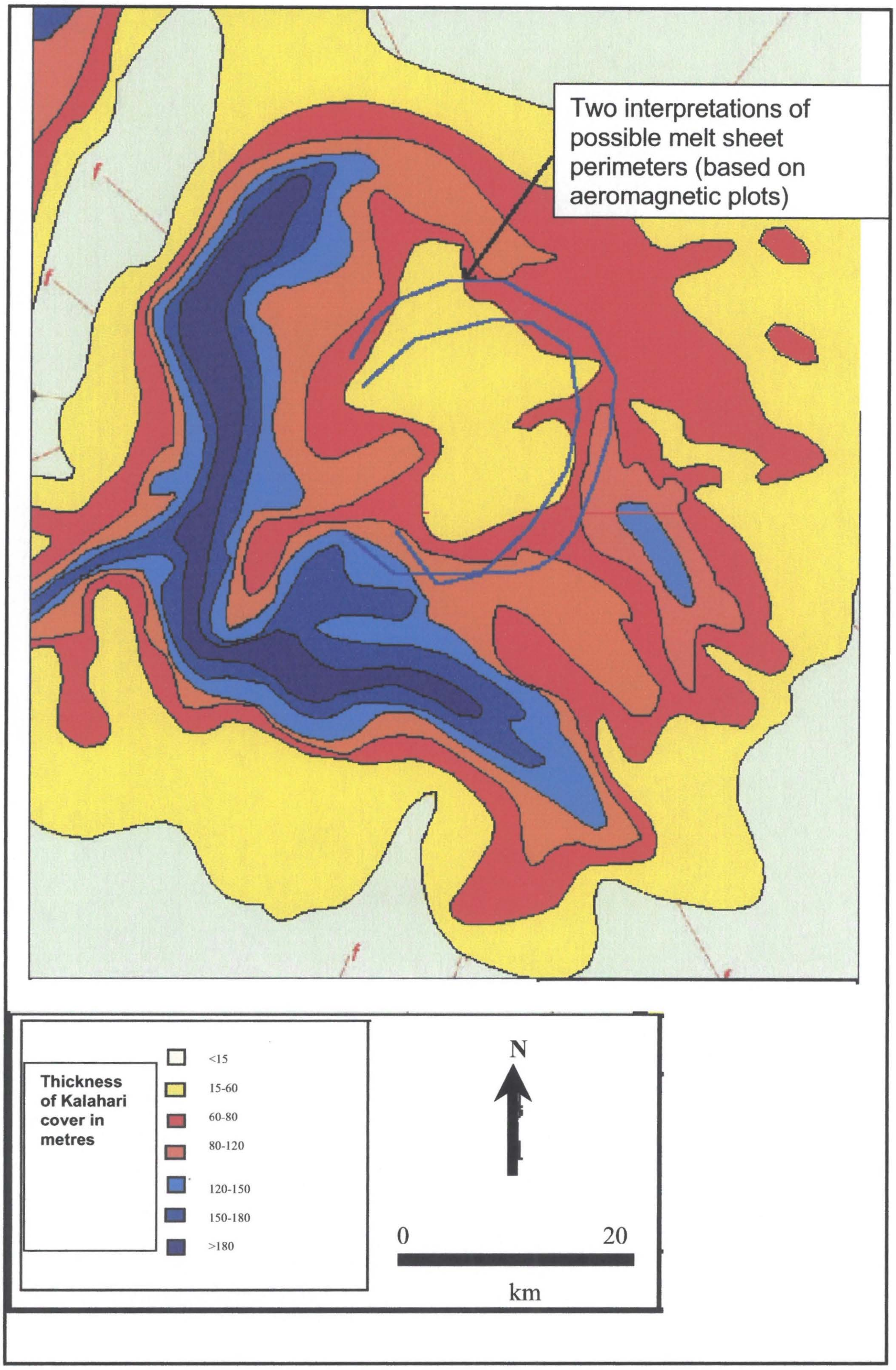
4.3.3 Regional Geology

Tertiary and Quarternary (Figs. 9 and 10)
Most of the area is covered by a thick sequence of Tertiary and Quaternary aged continental sediments of the Kalahari Group. This sequence, up to 180 metres thick, is comprised in its lower portions of fluvial and lacustrine sediments including well-developed and extensive evaporite layers.

Higher up in the Kalahari Group the fine sands and clays of lacustrine sediments are replaced by windblown sands and calcrete layers that developed in response to increasing aridity into the Quaternary. The calcretes form a continuous unit beneath the surface cover of sand.

The Kalahari Group varies in thickness across the melt sheet from less than 60 metres at its centre to over 120 around the edges.

The sediments lie directly over the norite of the melt sheet where present. This is marked by an unconformity which is identifiable by incision and development of boulder beds representing the end of a period of considerable peneplanation.



Two interpretations of possible melt sheet perimeters (based on aeromagnetic plots)

Fig. 9 Thickness of Kalahari Cover over the Morokweng Impact Structure

Archaean to Proterozoic

Knowledge of the nature and distribution of Archaean and Proterozoic rocks beneath the Kalahari Group cover has been gained from very limited exposure, chips from rotary percussion boreholes drilled for water, and interpretation of regional geophysical data.

Most of the basement is comprised of Proterozoic aged sediments of the Transvaal Supergroup. These are a thick sequence of marine and continental sediments including dolomites, Banded Iron Formations (Banded Iron Formations), quartzites and conglomerates.

Archaean granite gneisses and greenstones are reported by M. Andreoli (bulletin S 883, S 884, internal reports) to have been intersected by some of the boreholes in the area. Their distribution is, however, largely inferred from aeromagnetic data.

There are poor records of a borehole intersecting mafic and ultramafic lithologies to the west of the melt sheet, over the area currently mapped as greenstone rocks of the Linopen Lineament. This lineament forms a prominent magnetic high and has been drilled by Anglo American. They conclude that the lineament is caused by Banded Iron Formations of uncertain age possibly associated with mafic to ultramafic rocks.

Granite gneiss is demagnetised around the melt rocks; an effect of the impact and the associated intense thermal event.

The Molopo Farms Complex (a large, layered ultramafic-mafic intrusion of Bushveld age and affinity) is situated 80 km to the north, along the Botswana border.

4.3.4 Morokweng Geology and Similarities to the Sudbury Igneous Complex.

Knowledge of the nature of the melt rocks is from available core; the distribution of these rocks is largely indicated from regional aeromagnetic data. A simple interpretation of the melt sheet is shown in Fig. 10, Fig 18 of Chapter 2 shows the Sudbury geology.

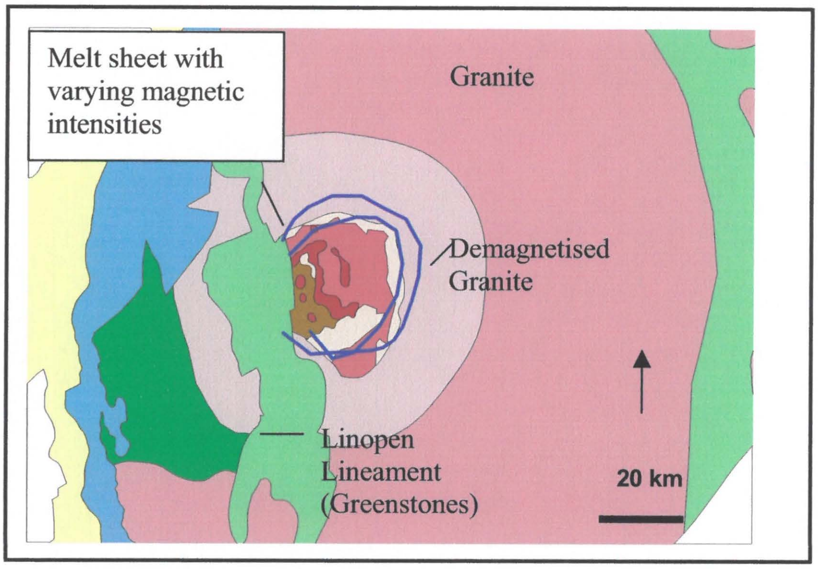


Fig. 10 Bell's (2001) qualitative geophysical interpretation of the geology under the Kalahari cover based on regional gravity and aeromagnetic data and detailed aeromag. over the centre of the melt sheet.

The melt rocks are thought to have a diameter of 40 to 50 km (Fig. 10). A change in the intensity of the magnetic field has been used to interpret the perimeter of the melt sheet (as has more detailed interpretations done by J. Bell a, consulting geophysicist). Two possible outer perimeters of the melt sheet have been identified on this basis (Fig. 12). The stratigraphy at Morokweng is outlined in table 9 (according to M. Andreoli's logging) and compared to Sudbury Igneous Complex in Fig. 9 below.

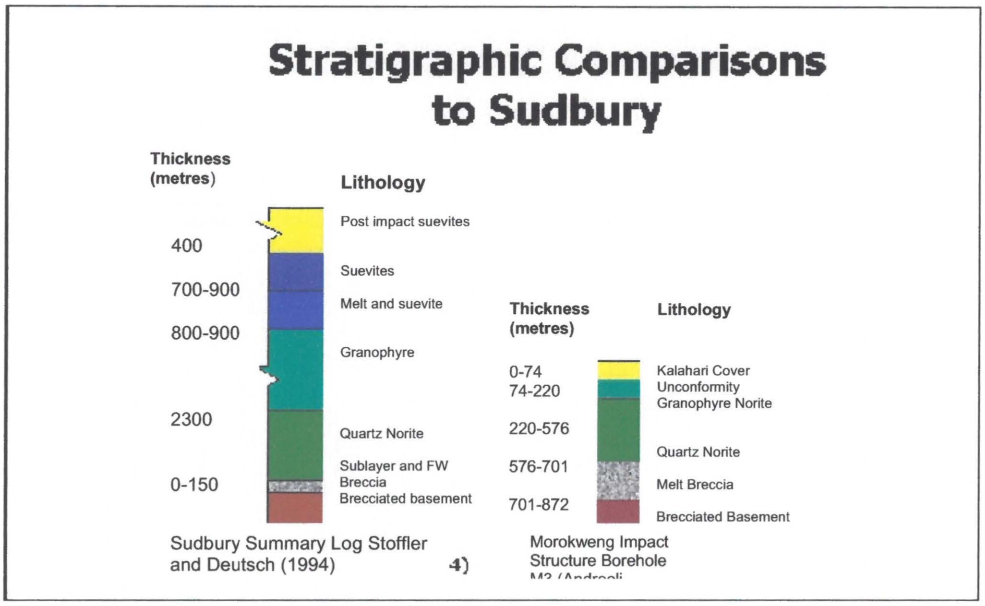


Fig. 11 Comparison of Sudbury and Morokweng Impact Structure Stratigraphies

An alternative Morokweng stratigraphy is given in table 17 of section 4.3.6.3.

As is shown below, the Morokweng melt rocks have high levels of nickel. This most likely reflects incorporation into the melt of large amounts of metals from the impacting bolide. This is supported by iridium levels, which average at 20 ppb, twenty times higher than at Sudbury. Iridium and nickel are both enriched relative to crustal levels in meteorites.

Table 5: Comparison between whole rock compositions: Morokweng and Sudbury

	SiO_2 (%)	**MgO (%) Ave.**	**Ni**
Morokweng melt rocks, quartz norite to gabbronorite	66,61 within quartz norite, 61,6 within gabbronorite and 73 within the clast rich gabbronorite	3,65 over quartz Norite, 5,60 over Gabbronorite and 4,79 over clast rich Gabbronorite	420 ppm within the quartz norite, 740 within the Gabbronorite and 694 within the clast rich gabbronorite
Sudbury melt rocks Mafic and Felsic Norite	63,14 - ave. over entire stratigraphy 55,16 – Sudbury Norite	4,4 to 14, 6 through mafic and felsic norite	15 to 40 ppm within felsic Norite and 40 to 1 000 ppm within dark mafic breccia

SiO_2 values from Collins, 1934. Sudbury MgO and Ni data from Lightfoot et. al. (2001), Morokweng stratigraphy and the equivalent Sudbury stratigraphic units are shown in table 6. Alternative stratigraphic comparison shown in Fig. 11

Geochemical data shows that the Morokweng quartz norite is less depleted in metal than the Sudbury felsic norite (420 vs. 15 to 40 ppm Ni). The clast rich gabbronorite at the base of the Morokweng stratigraphy is also less enriched in metals (694 vs. 1 000 ppm Ni) and more evolved than the Sudbury sublayer. This indicates that the felsic norite may not have been stripped of its Ni as would be expected if it equilibrated with massive sulphides. Likewise the clast rich gabbronorite is not as enriched in Ni as the dark mafic breccia is, indicating it does not contain as many disseminated sulphides. In the case of the dark mafic breccia the disseminations are indicative of the massive sulphides they overlie. There are no significant disseminations of sulphides within the Morokweng Impact Structure clast rich gabbronorite.

Sulphides are very rarely seen above the Sublayer at Sudbury yet at Morokweng minor disseminated sulphides are relatively common well above the basal contact. This could indicate that cooling took place too rapidly for sulphides to settle from the melt but does not entirely dismiss the possibility of this occurring.

Based upon relatively consistent estimates of 80 km for the diameter of the transient cavity of Morokweng Impact Structure, a probable original melt volume of 10^3 km^3 is obtained based upon observations of relative dimensions of other impact structures. Some comparisons of the estimated dimensions for Morokweng and Sudbury are as follows:

Table 6: Comparison of Dimensions of the Morokweng and Sudbury Impact Structures

	Morokweng	**Sudbury (reconstructed)**
Diameter of impact melt sheet (km)	40 – 50	200 (Grieve, 1992)
Thickness of melt (m)	799	2 500
Diameter of transient cavity	80	175 to 240
Volume of melt (km^3)	10^3	10^4

The deep levels of erosion at Morokweng mean the larger parts of the basal contact may be at prospective depths. The Jagersfontein kimberlite pipes 395 km S of Morokweng are interpreted to have experienced 825 m of erosion whilst the Kimberley pipes are expected to have undergone 1 225 m of erosion. (This is based on unpublished work by Lynne, M.D. on the Kimberlite facies presently exposed and knowledge of which facies have already been eroded). It is anticipated that Morokweng would have experienced a similar amount of erosion, i.e. in the order of 1 000 m.

1) A number of well-defined concentric highs stand out on aeromagnetic data. Work by Bell (2001) indicates that these highs could be attributed to shallower depths of gneiss beneath the melt sheet, which is more magnetic than the norite itself.
2) It is possible that there may be structures (as are frequently associated with meteorite impacts such as impact rings and listric subsidence faults) that would have given rise to significant relief along the basal contact. These structures would have provided an abundance of suitable trap sites for liquid sulphides.

4.3.5 Previous Work (Fig. 12)

The figure below shows the extent of previous work as well as that done by Falconbridge Ventures during 2002. The Total Magnetic Field Image (TMI) was acquired from the government and the more detailed aeromagnetic survey covering the centre of the Morokweng Impact Structure was flown by Business Venture Investments 33. All boreholes were drilled prior to Falconbridge Venture's involvement in the project.

The black outline in Fig.12 shows where a regional helicopter borne sampling programme was conducted by Falconbridge Ventures and the black and red squares in both figures indicate where more detailed sampling was conducted. The red circles indicate the interpreted extent of the melt sheet (based on aeromagnetic signature) and lines show interpreted lineaments.

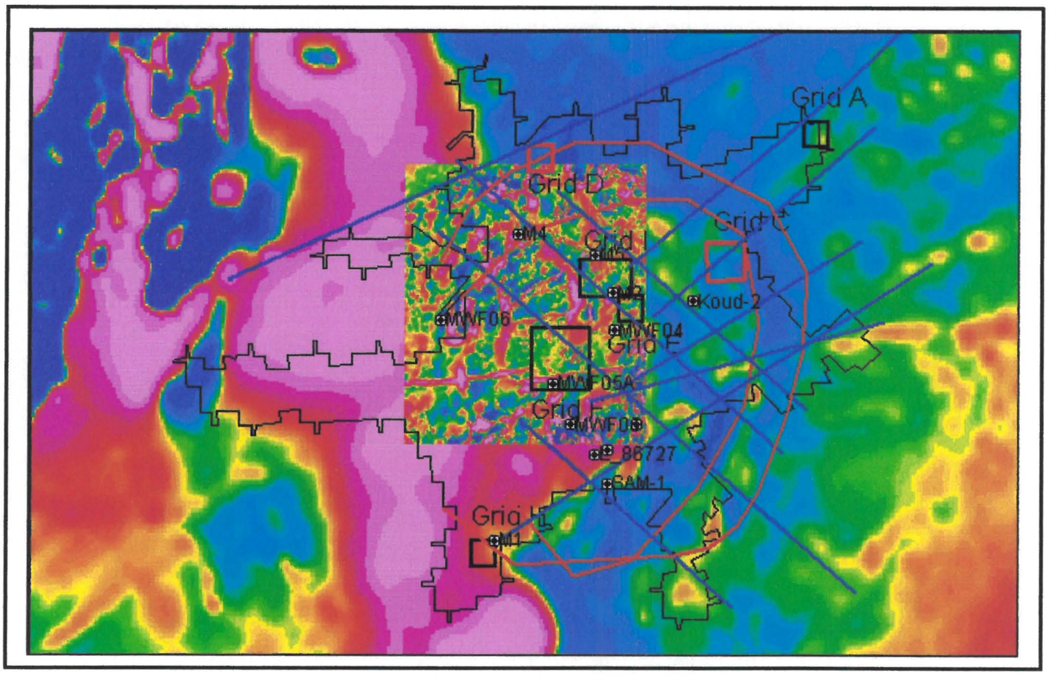


Fig. 12 Regional Government TMI (total magnetic intensity), detailed Business Venture Investments 33 aeromag (TMI), borehole collar positions, 2 interpreted perimeters of the Morokweng Impact Structure, interpreted lineaments based on regional aeromag. and black and red squares show the areas of the detailed grids.

Drilling

Results of previous drilling tabulated below and borehole positions are shown in the figure above.

TABLE 7: BOREHOLE DETAILS

EOH = End of Hole

Borehole	**Depth of basal Kalahari unconformity (m)** **EOH (m)**	**General Geology**	**Comments**
WF 03	EOH 130,25	"Melt rocks"	
WF 04	EOH 198,20	"Melt rocks"	Occasional presence of Ni-rich minerals at various depths.
WF05	EOH ~230	Terminated in a large xenolith of shocked and recrystallised granite.	The norite included a narrow, ~30-50 cm mineralised zone with disseminated high-grade Ni and Cu sulphides, Ni oxides and Ni silicates. The oxides and sulphides phases locally form a small vein (>6 cm long, 0,5 to 3 cm thick).
WF 06	?	Ultramafic, olivine rich rocks intersected with high (up to 1%) Cr.	
MWF 03	24,7 EOH 130,25	Medium-grained quartz norite.	Two samples yielded 8 and 22% Fe_2O_3 respectively.
MWF 04	43,5 EOH 198,3	Medium-grained, brown quartz norite intruded near the top by granite veins, with occasional pegmatoidal pockets.	A suite of analysed samples reveals a steady increase in Fe and Ni from the top to the bottom of the hole, as well as minor anomalous Ni enrichments, in Kalahari calcretes. In addition to the gradual increase in Ni with depth within the quartz norite, the analyses record 2 sharp Ni anomalies, 1 is less pronounced and matches an anomalous Fe content, the other is more pronounced and lacks a corresponding increase in Fe. These anomalies are thought to reflect local increases in trevorite and millerite.
MWF 05	98,04 EOH 271,29	The upper sheet consists of brown, medium-grained quartz norite with some coarse Ni sulphide and oxide segregations at 170 m. At 170 m the upper sheet is intruded by finer-grained, heterogeneous quartz norite. The heterogeneous rock consists of blebs of more melanocratic norite in very acidic pyroxenite granophyre and grades with depth into homogeneous, fine-grained quartz norite with scattered inclusions of coarser-grained quartz norite and ultramafic rocks (serpentinite, pyroxenite). The lower contact of this	It is possible that the borehole reflects 3 melts of different compositions, namely: a) High Ni, medium-grained quartz norite parental melt b) Low Ni, fine-grained to chilled quartz norite. c) Heterogeneous acidic granophyre

Borehole	Depth of basal Kalahari unconformity (m) EOH (m)	General Geology	Comments
		homogeneous rock is extremely fine-grained.	
MWF 06	Unknown but <110 EOH Unknown but >124,5	Unknown	This borehole was only sampled by Anglo American who provided Business Venture Investments 33 with 2 descriptions of peridotite specimens at 110 and 124 m. The sample at 100 m was serpentinised and included traces of sulphide, the deeper sample had traces of mica. These are thought to be samples of a clast or of a cumulate rock formed at the base of the impact sheet.
MWF05-A	Unknown EOH Unknown	Percussion chips of brown quartz norite scattered around the hole.	Percussion hole drilled to provide water for MWF 05.
13-86727	Unknown EOH Unknown	Complex suite of percussion chips consisting of shocked, strongly recrystallised granite, less shocked gabbro, mineralisation consisting of Zn and Mn oxides, plus unspecified oxides and sulphides and mafic impact melt with well developed spinifex quench textures.	The association of Mn and Zn rich oxides with sulphides and other oxides of undetermined composition may indicate the inclusion of Zn rich country rock in the melt sheet.
M1	~150	Intersected granitic gneiss close to the edge of the body and was terminated. Either the causative source is in the basement or the borehole intersected a xenolith. The latter is thought most probable as the degree of shock metamorphism is low.	
M2		Hole was lost due to caving Kalahari overburden. Between 35 and 50 m the percussion chips were of sandstone, a few of red clay. Below ~50m the rock became unusually hard and drilling yielded a fine white powder consisting of quartz and feldspar with traces of orthopyroxene.	It is possible that the drill penetrated a gravel/boulder bed at the base of the Kalahari Group and then intersected an acidic impact melt sheet below, or that the altered granite represents the basement.
M3	1 076	Peaks of magnetic susceptibility are associated with millerite and trevorite mineralisation (See table 5).	~ 15 m wide intersection of disseminated Ni-sulphide, Ni-oxide (+PGMS) sulphides associated with breccia bands between 350 and 365 m.
M4	370	Highly magnetic mafic to ultramafic rocks.	Disseminated sulphides hosted within the mafic to ultramafic rocks.

In the late 1970s Anglo American drilled a 650 m deep borehole (NEV1) to test the mineralisation potential of an airborne magnetic anomaly on the Linopen Lineament (Fig. 10). This hole is 35 km SW of the centre of the Morokweng Impact Structure and it intersected structurally disrupted banded iron formations beneath highly brecciated dolomite (presumably representative of the Griqualand West Stratigraphy), Andreoli, 1998.

Anglo American then drilled a further 15 holes to test similar airborne anomalies. The percussion holes did not intersect any significant mineralisation but anomalous Cu and Ni values are reported. Limited data is available for some of these boreholes and is outlined in Table 1. The observations recorded are those of Andreoli (1998). Borehole locations are shown in Fig. 12.

Several boreholes were drilled (probably by De Beers) in the Morokweng Impact Structure in search of kimberlite pipes. Business Venture Investments 33 reports these boreholes to have intersected highly brecciated and shocked mafic to ultramafic rock and amphibolite with occasional small sulphide crystals in thin hydrothermal veinlets.

Percussion drilling by the Department of Agricultural Engineering provided an additional source of information although the chips were often scattered and had to be sieved from the sand surrounding the boreholes. Two of these boreholes (13-86727 and BOS-1) yielded occasional chips of Ni and Zn bearing sulphides.

Modelling of the detailed aeromagnetic survey commissioned by Business Venture Investments 33 showed the crater floor was at a depth of 300 to 400 m (Andreoli 1998). Various magnetic anomalies that could not be explained in terms of stratigraphy were identified at depths of 100 to 200 m. These were termed "rosettes" or "honeycombs" and were attributed to highly magnetic rock containing millerite or trevorite and were therefore targeted during the ensuing drill programme.

Four vertical to subvertical holes were sited to intersect specific rosettes. Borehole M 3 was the deepest of these holes and the stratigraphy of this hole is tabulated below.

Table 8: Business Venture Investments 33 Borehole M3 (Log produced by M. Andreoli)

Depth (m)	Description
0 – 74	Kalahari sediments
74 – 220	Granophyre, granophyric quartz norite; millerite-trevorite clusters rare <200 m. Gradational lower contact.
220 – 576	Leucocratic, medium-grained, homogeneous quartz norite with scattered millerite-trevorite nodules. These are disseminated sulphides commonly associated with basement inclusions between 344 and 360 m; sulphide grains become rarer >540 m.
576 – 701	Mesocratic to melanocratic, fine to medium-grained, in places heterogeneous quartz norite with rare sulphide-trevorite nodules. ~633 m is the lower limit of millerite-trevorite nodules.
701 – 872	Heterogeneous, fine-grained and clast-laden (30-60%) leucocratic melt rock with occasional ultramafic clasts associated with pentlandite and lesser millerite. Sharp lower contact.
872 – 1 076	Pyroxenite gneisses intermediate to mafic with intrusive tonality veins and locally brecciated. At 1 000 m is a subvertical vein of impact melt with <5% sulphides (pyrrhotite). EOH 1 076 m.

Five percussion holes (M5 to M9) were drilled to target magnetic bodies (identified from a downhole survey conducted on M3) at depths of ~150 to 250 m between ~75 and 180 m north of M3. These percussion holes were used for pole-dipole induced polarisation (IP), radial down-hole IP, resistivity and down-hole Time Domain Electromagnetic (TDEM) surveys with a central loop configuration. A surface IP and ground magnetic survey was conducted across boreholes M3, M5 and M6.

Geophysics

1) Anglo America conducted a 1 x 1 km ground magnetic survey across the South-West sector of the Morokweng Impact Structure. It is thought that this survey covers the area of an earlier borehole (SAM-1) which is reported to contain sulphides. There is no log of this borehole available, but it is thought to have been sited in the vicinity of MWF 03.
2) Genmin conducted an airborne magnetic survey across the SE part of the Morokweng Impact Structure, results of survey not available.
3) Business Venture Investments 33 commissioned a higher resolution aeromagnetic survey in the central core of the Morokweng Impact Structure, Fig. 12. 420 km^2 was covered with a line spacing of 200 m and a sensor elevation of 75 m (Fig 12). Data has since been interpreted by J. Bell (2001).
4) A wire-line magnetic survey of M3 to a depth of ~285 m showed the presence of several shallow, magnetic, causative bodies in proximity to the hole. These were drill tested, no significant mineralisation was intersected, source expected to be magnetic millerite, borehole results tabulated in table 9.
5) The lack of TDEM anomalies near M3, M5 and M6 was taken to indicate that there are no massive sulphide intrusions proximal to these holes. (The down hole surveys were only conducted down to a maximum of 300 m so the possibility of mineralisation below this depth remains).
6) An isolated IP anomaly was located in borehole M3. The nature and exact position of this anomaly is not described in available reports.
7) Interpretation of ground magnetic traverses by GAP geophysics across boreholes M3 and 4 showed the magnetic anomalies probably resulted from stratigraphic Banded Iron Formation horizons. The boreholes did not intersect any Banded Iron Formation but may not have been orientated correctly to intersect these horizons.
8) The results of a surface IP survey across borehole M3 are reported as “not completely convincing” by Spectral Geophysics who suggest that the survey specifications were not ideal.

4.3.6 Falconbridge Ventures Exploration

4.3.6.1 Introduction

In the following section the author’s own work, or work commissioned by the author is discussed following the account of earlier exploration programme provided above.

The Morokweng Impact Structure offers a challenging exploration environment.

1) There are saline waters towards the base of the Kalahari Group, which hinder electromagnetic surveys.
2) The thick Kalahari sand means that conventional soil geochemistry would not detect covered mineralisation.
3) Calcrete layers in the Kalahari Group would form a chemical barrier severely restricting the mobility of path finder elements.

The Mobile Metal Ion (MMI) technique was chosen as a means of “seeing through” the Kalahari. Given the size of the target i.e. Sudbury style of mineralisation it was decided that 1 x 1 km grid spacing should be able to detect mineralisation during a regional survey that could later be followed-up with more detailed sampling.

An orientation programme involving the collection of five samples at 1 m spacing, at a number of localities, demonstrated the reproducibility of the values from these sites.

The sequential exploration programme at Morokweng was designed as follows, with the implementation of each step being dependant on the results of the previous one.

Geophysical interpretation to define the interpreted area of the melt sheet.
Regional 1 x 1 km helicopter supported soil sampling programme over the interpreted extent of the melt sheet.
Detailed 200 x 200 m sampling of targets selected from the regional programme.
Drill testing of best targets.

4.3.6.2 Geophysical Interpretation Conducted by Bell, - Fig. 10

Results

J. Bell, a consulting geophysicist was contracted to interpret available geophysical data covering the Morokweng Impact Structure. The aims of his study were to:

Interpret the regional geophysical setting of the Morokweng Impact Structure and interpret its perimeter.
Interpret the high resolution aeromagnetic data over the centre of the impact structure, including depth to source modeling over specific magnetic targets.

Data used included regional gravity and aeromagnetic data (surveys conducted by the Council for Geoscience and Gold Fields) as well as high resolution aeromagnetic data over the centre of the melt sheet (survey conducted by Business Venture Investments 33).

Bell (2001) produced an interpreted geological map based on the gravity and aeromagnetic surveys and supplied a DTM, Bouguer Gravity image, Aeromagnetic Reduced to Pole image, Aeromagnetic First Vertical Gradient Image and image showing depth to source modeling (quantitative interpretation) over the Business Venture Investments 33 detailed aeromagnetic survey (Bell, 2002).

Bell's work on the more detailed Business Venture Investments 33 image shows that the magnetic response of the melt sheet indicates that it is made up of at least three different domains which he labeled M1, M2 and M3. The depths of these features vary from 200 to 400 m (Bell, 2002).

Conclusions

Interpreted extent of melt sheet delineated with a diameter of approximately 40 km.

A N-S trending gravity and magnetic high on the western side of the Morokweng Impact Structure (called the Linopen lineament) is interpreted to be a greenstone belt.

The extent of the Molopo Farms Complex was identified from the regional aeromagnetic data so that its magnetic signature was not confused as being part of the Morokweng Impact Structure.

The very high magnetic anomalies within the melt sheet were interpreted to be xenoliths derived from the Linopen greenstone belt.

4.3.6.3 Soil Geochemistry

4.3.6.3a 2001 Helicopter Supported Regional Sampling Programme (1 km^2)Survey Parameters

1) A helicopter-supported programme was conducted involving the collection of 1 080 samples at a 1 km^2 interval over a period of six days. This survey covered the extent of the melt sheet (Fig. 12 – area of helicopter survey).
2) Samples of 300 g of indurate soil (below the windblown material) were collected at a depth of 10 cm.
3) Initially adjacent samples were composited in order to save analytical costs. 245 composites were submitted and analysed for Cu, Zn, Pb, Pt, Cd, Se (MMI A) and Ni, Co, Pd, Au, Ag (MMI B) by XRAL of Toronto. MMI A and MMI B are different patented leaching solutions designed to dissolve the elements indicated.
4) The results showed the technique was able to identify discrete anomalous areas within the melt sheet.
5) As the technique appeared to work it was decided to analyse all the samples in order to get a clearer picture of the anomalous zones.
6) The MMI B suite was chosen as the MMI A technique was unable to detect significant levels of Cu.

Interpretation of Results

Methodology

1) Lithofire geological consultants and MMI recommend that MMI results are interpreted by calculating response ratios. The response ratios are calculated by dividing each value by the threshold for that element. The threshold is defined as the average of all values below the lower 25th percentile (values below detection limit are halved) for that element.
2) Response ratios's were calculated for each element and plotted as circles proportional in size to the response ratios (figs. 13 to 15).
3) It was decided that the most useful elements were Ni, Pd and Co which largely returned values above the detection limit and showed some spatial coincidence of anomalous responses. These elements are also directly related to the style of mineralisation expected. Unlike Ni and Co, Au and Pt mostly returned values below the detection limits.
4) Three factors were used to detect areas of interest namely:

    a. Elevated response ratios
    b. Clustering of elevated response ratios
    c. Coincident elevated response ratios between elements

5) In order to be able to stack the response ratios and to compare the different elements the response ratios were normalised. This was done by recalculating the response ratios back to a scale of 1 to 10.
6) Targets were identified and rated based on the combined maximum response ratios for Ni, Co and Pd. Targets were also identified that would test different parts of the melt sheet namely the centre, periphery and possible offset dykes.

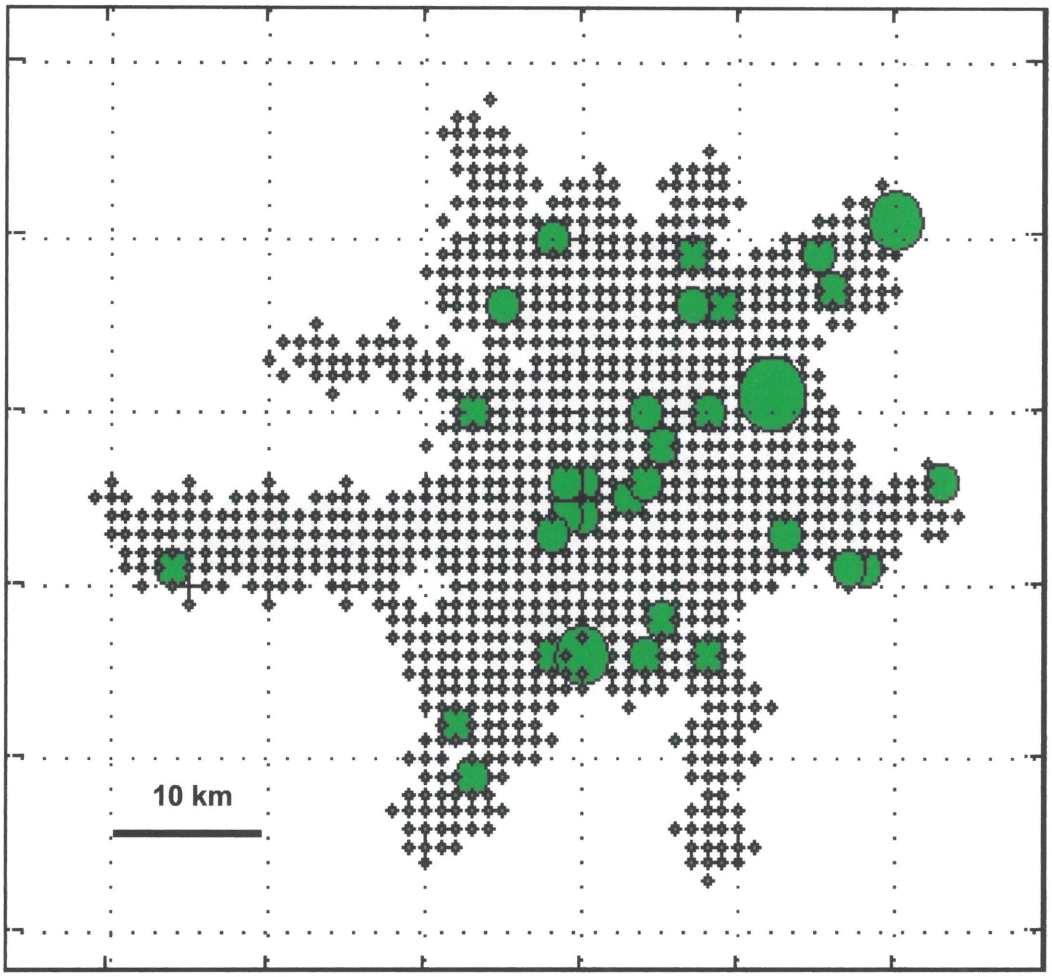


Fig. 13 – Ni Normalised response ratios

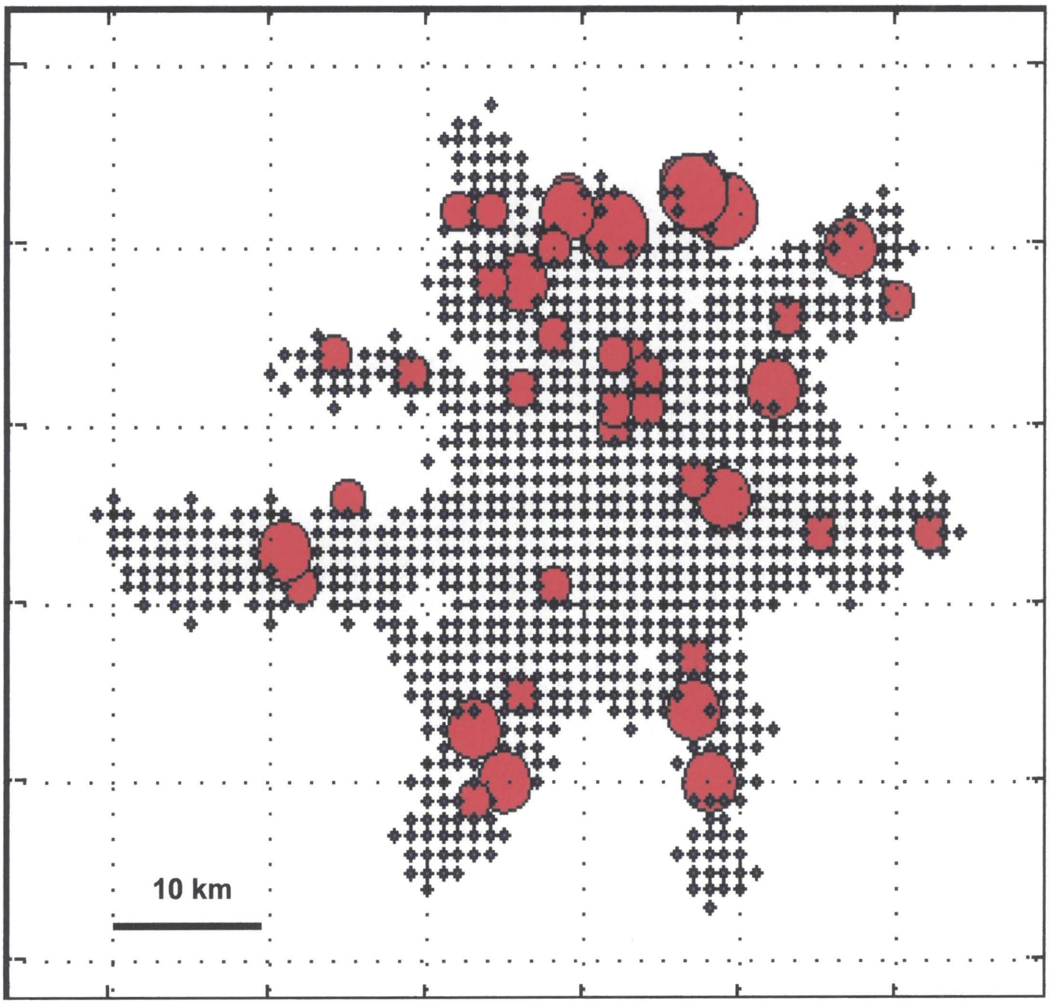
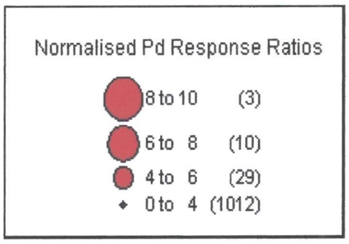


Fig. 14 Normalised Pd response ratios



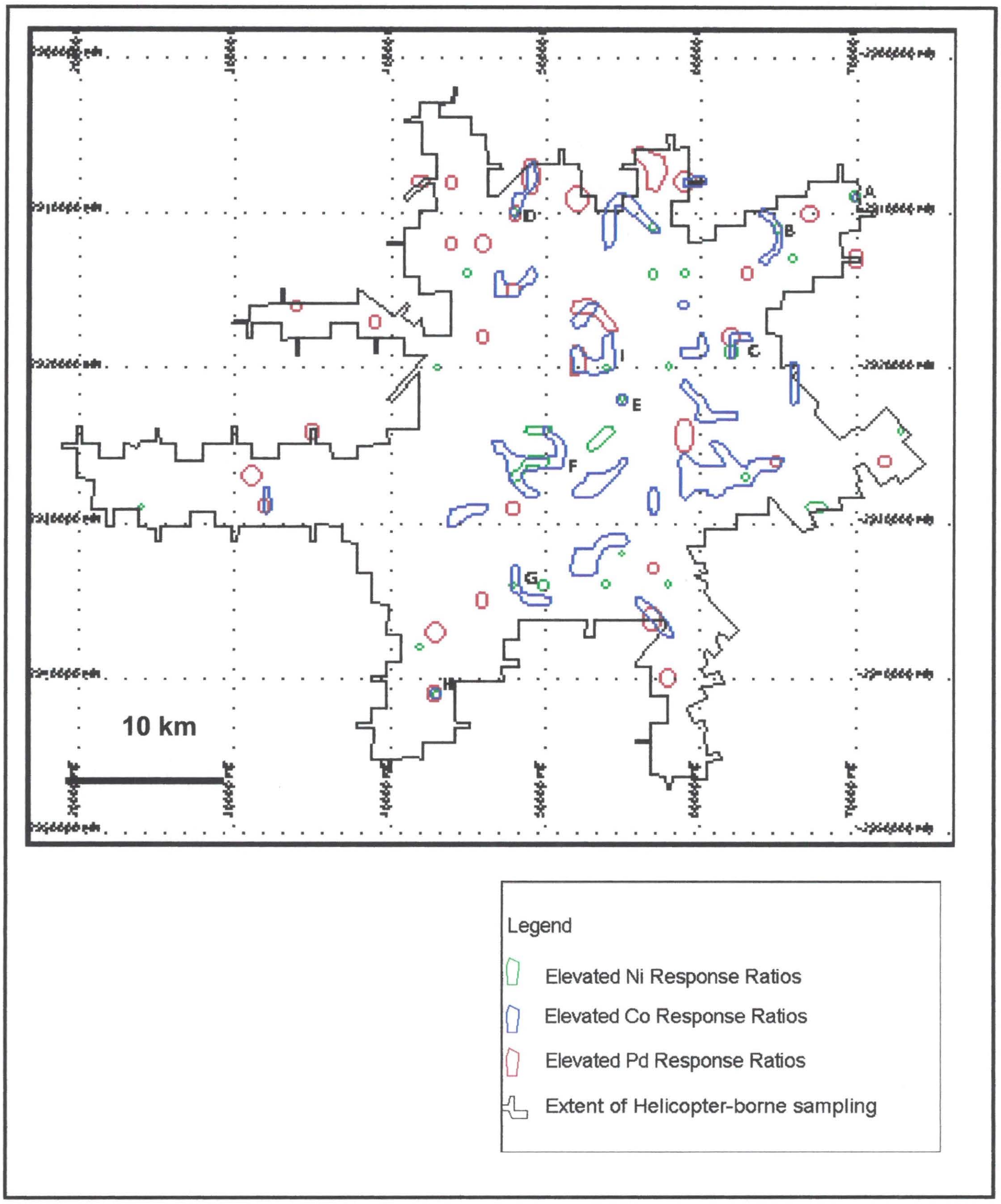


Fig. 15 – Elevated response ratios of different elements circled to show where coincident elevated response ratios are

Observations

The factors that characterized the potential targets as possibly overlying mineralisation have already been discussed. Position of targets that were followed up with detailed gridding are shown in Fig. 16. Table 10 outlines the positive features identified at the various targets A to G (positions of these shown in Fig. 15).

Table 9 Regional Helicopter borne Soil Sample Targets

Target	Rating	Coincident Elements	Ni response ratios Norm	Co response ratios Norm	Pd response ratios Norm	Combined Ni, Co, Pd	Position Relative to Melt sheet	Position Relative to Structures	Position Relative to Mag Features	Comments
C	1	Ni, Co, Pd	10	4	7	21	In outer region of interpreted melt sheet.	On southern part of a NE-SW trending lineament.	Located (along with targets A, E and F) on edge of a NE-SW trending mag feature defined by the Reduced to Pole image.	3 approximately coincident elevated elements. Elevated Co values over 3 sampling points, Ni and Pd cover 1 sample each. C has the highest combined response ratios, highest Ni response ratios, along a structure hosting other elevated Ni values. Hosted on the edge of J. Bell's interpreted melt sheet. Located along a circular structure which either forms the perimeter of the outer melt sheet or represents an undulation within the outer melt sheet.
I	2	Ni, Co. Pd,	5	7	6	18	Centre of Melt Sheet.	Bound by lineaments	Located between "mag highs".	1 coincident point of elevated Ni and Co, 6 elevated Co sampling points and 2 elevated Pd sampling points coincident with Co. Area is bound by lineaments and may be a down-faulted block that could form a favourable structural trap for any potential sulphides that may have formed. Regional aeromagnetic survey (Reduced to pole) indicates mineralisation may be located in an embayment.
D	3	Ni, Co, Pd	4	5	6	15	Close to perimeter of melt sheet.	Alongside a NW-SE trending lineament in NW part of melt sheet	No associated mag structure.	3 directly coincident elevated elements over 1 sample point and coincident elevated Co and Pd over 3 additional sample points. Outside of J. Bell's interpreted melt sheet area, within a broad, circular, ill defined mag low that may be indicative of part of the melt sheet. This target is along strike from anomalous Pd values and may represent distal, fractionated Cu/PGM rich sulphide veins associated with a more massive body.
H	4	Ni, Pd	4	5	6	15	Perimeter of interpreted melt sheet.	Edge of a NE-SW trending lineament	On edge of a mag high interpreted to be part of Kraaipan group.	3 directly coincident elevated elements. Single point anomaly. Outside of JBell's interpreted melt sheet area. Thought to possibly be on the perimeter of the melt sheet.
E	5	Ni, Co	4	8	2	14	Centre of melt sheet.	Along NW-SE lineament hosting target C.	See target C. Along break between mag high and mag low.	2 coincident elevated elements (Ni, Co). Located within intersection of lineaments in centre of melt sheet.
A	6	Ni, Co	6	5	2	13	Outside of interpreted melt sheet perimeter, possible offset dyke.	Targets A, B, C, E & F all constrained within the same, parallel NE-SW trending structures.	See target C.	2 coincident, elevated elements (Ni, Co). Located outside of outer melt sheet along a structure that may represent an offset dyke. Has a fairly high Ni response ratios. May be hosted in zone of brecciated melt rock.
F	7	Ni, Co	4	5	3	12	Inner part of melt sheet.	Hosted between NW-SE and SW-NE trending lineaments.	See target C. Located in a "relative low" possibly indicating a "trough" hosting both F and G.	Elevated coincident Ni and Co over 3 sample points with elevated Co over 9 sample points. Target has the largest number of elevated Ni sample points.
G Not sampled	8	Ni, Co	6	5	3	14	Close to perimeter of inner melt sheet.	G & H hosted between two diverging lineaments in the SW part of the melt sheet.	Relative" low Possibly indicating a "trough" hosting both F and G.	2 coincident, elevated elements (Ni, Co). Located on edge of inner melt sheet. Rates higher than B as it has higher response ratioss.
B Not Sampled	9	Ni, Co	5	5	1	11	Close to perimeter of melt sheet	On northern NE-SW structure.	No associated mag features.	Elevated Ni and Co over 1 sample point, elevated Co over a total of 4 sample points.

Results

Nine targets were identified of which seven (grids A, C, D, E, F,I and H) were followed-up with more detailed 200 x 200 m sampling.

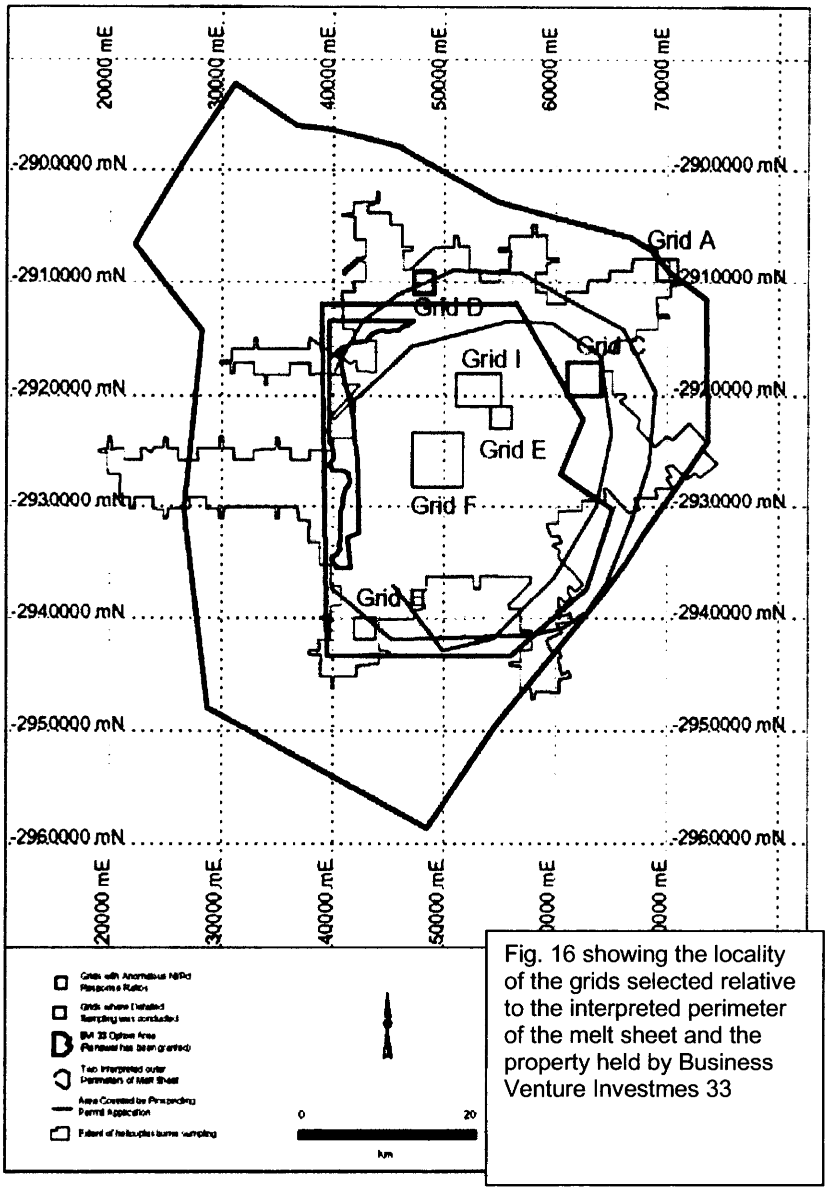


Fig. 16 showing the locality of the grids selected relative to the interpreted perimeter of the melt sheet and the property held by Business Venture Investmes 33

Conclusions

The regional survey was successful in detecting areas for more detailed follow-up work. Gridded images of the MMI results mimic the regional lineaments detected from the aeromagnetic surveys indicating that MMI is reflecting the underlying geology.

4.3.6.3b Detailed Grid Sampling (200 x 200 m)
Survey Parameters

1) 1 800 samples were collected from seven grids on a 200 x 200 m basis.
2) Approximately 500 g of sample material was collected at each sample site. The laboratory only requires 50 g so this amount of material allows sufficient soil to have samples re-analysed if there are quality control problems (as there originally was with the regional data set) and also provides enough material to be analysed by the A-dissolution method, if required.
3) 98 samples were taken over areas of elevated Pd to see if Cu could be detected using the A-Suite in these environments. Cu was detected so 525 samples from two of the most promising grids, as well as a third grid (to establish background levels) were submitted for A-solvent analyses which enables the detection of Cu, Pb, Zn and Cd.
4) All samples were collected by two geologists using plastic equipment (to avoid contamination). Wooden stakes were not used and sample sites were located using GPS's. No line cutting or field clearance was necessary.

Interpretation of Results

Methodology

1) The same methodology as used for the regional data set was applied to the samples collected from the grids. The response ratios were calculated for the three elements Ni, Co and Pd, these response ratios were also normalised and stacked.

a) In addition, for the detailed grids, the response ratios were calculated using three different methods namely:

- Calculating response ratios using results from each grid individually i.e. for grid A only the results from grid A were used to calculate its response ratios.
- Calculating the response ratios using results from all the seven grids i.e. combining the data for grids A, C, D, E, F, I, H and then calculating the lower quartile.
- Calculating the response ratios using the results from all grids plus the 2001 helicopter results.

b) For each method used the response ratios were plotted (on a 1:50 000 scale) as circles proportional in size to the response ratios. This was done for the normalised data and in the case of the response ratios calculated from individual grids also with the unnormalised response ratios.

c) In order to be able to overlay two thematic maps the unnormalised response ratios calculated from individual grids were also gridded in MapInfo. In this way the circles of one element could be overlayed on the gridded image of another element (Figs. 17 to 20). Inverse distance weighting was used to grid the data using a search radius of 800 m. MapInfo assigns the "coldest" colour - dark blue - to those response ratios that fall in the lowest 25% of response ratios's with increasingly warm colours in increments of 25% towards the top 25% of response ratios, so those response ratios that fall into the top 75 to 100% are coloured red. Folios showing this were also plotted on a 1:50 000 scale.

d) Oasis Montaj was also used to grid the data using linear minimum curvature but provided misleading images. The Mapinfo gridded images, whilst looking more grainy provided a truer reflection of the data.

Observations

1) Only two grids, grids C and D showed significant clustering of elevated response ratios.
2) Grid C did not show any support from elements other then Ni.
3) Grid D showed elevated response ratios when the response ratios were calculated using individual grids. This is because the background Ni values in grid D are low. The highest Ni value in grid D is lower than the highest Ni value in any other grid. This downgrades the potential of grid D (Refer to Table 12).
4) The Ni response ratios in all grids is fairly low with a maximum response ratios of 4 (Refer to Table 10).
5) The Ni histogram for the results from all grids shows they form a "normal population" with very few samples plotting outside of the mean (126 ppb) plus two standard deviations (208 ppb). Plots of the samples that returned values in excess of mean plus two standard deviations show no clustering of results with the more elevated values being distributed almost evenly throughout the grids. The bulk of the Ni values fall in the 120 to 140 ppb region. Histograms constructed for the individual grids do not show any significant number of samples with values outside of the normal population.
6) The histogram of all the Pd values shows the bulk of the values fall between 0.14 and 0.18 ppb and gradually "tail off" from there with no second population of higher Pd values (which could possibly have represented mineralised samples).
7) Histograms of the individual grids shows the Pd values for each grid can be split into two or possibly three populations clustered around 0,14 to 0,18; ~0,42 to 0,5 and 0,7 to 0,82 ppb. The bulk of the values fall in the first population with <10 samples per grid constituting the second population and only two to six per grid in the third category. Grids C, D, E and F show the largest second and third populations. The elevated Pd values in grid C are not coincident with the elevated Ni values from this grid. The elevated values in grids E and F are mostly single point samples that show no clustering. The most significant "third population" that is coincident with Ni and does show some clustering is that of grid D.
8) All the Co histograms merely reflect a decrease in values from about 15 ppb with no second population of elevated values.
9) All the histograms reflect that the range of sample values in each grid is fairly similar with no particular grid showing values that are particularly elevated relative to other grids. The Cu results showed no areas of significant, elevated response ratios.

Results

Results tabulated below (tables 11 to 14) and results are shown graphically in figures 17 to 19.

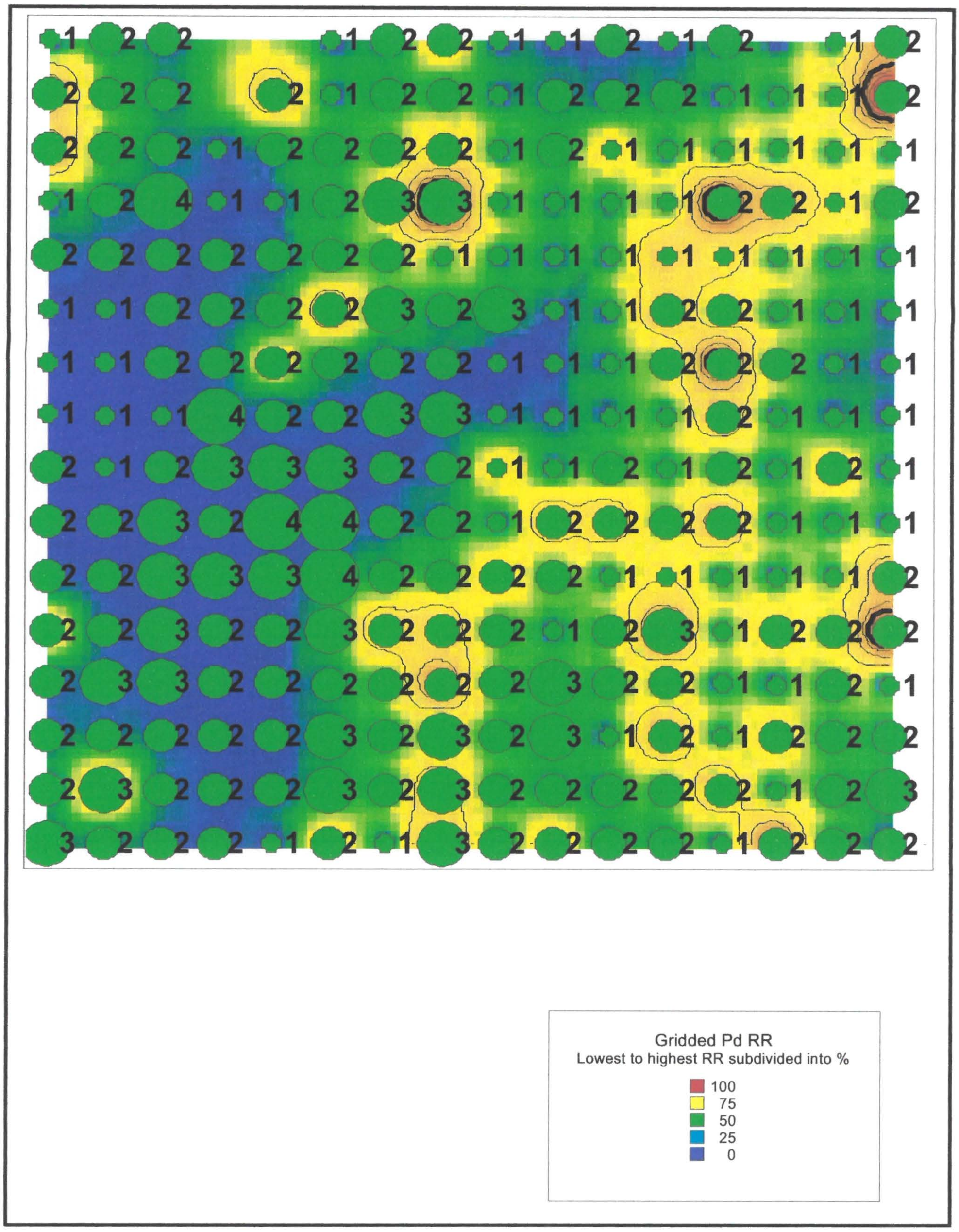


Fig 17. Grid C Normalised Ni response ratios (response ratios calculated from all grids) overlying gridded Pd response ratios (Inverse distance weighting used to grid Pd). The numbers are the Ni response ratios and they show that the elevated Ni response ratios do not coincide with elevated Pd values.

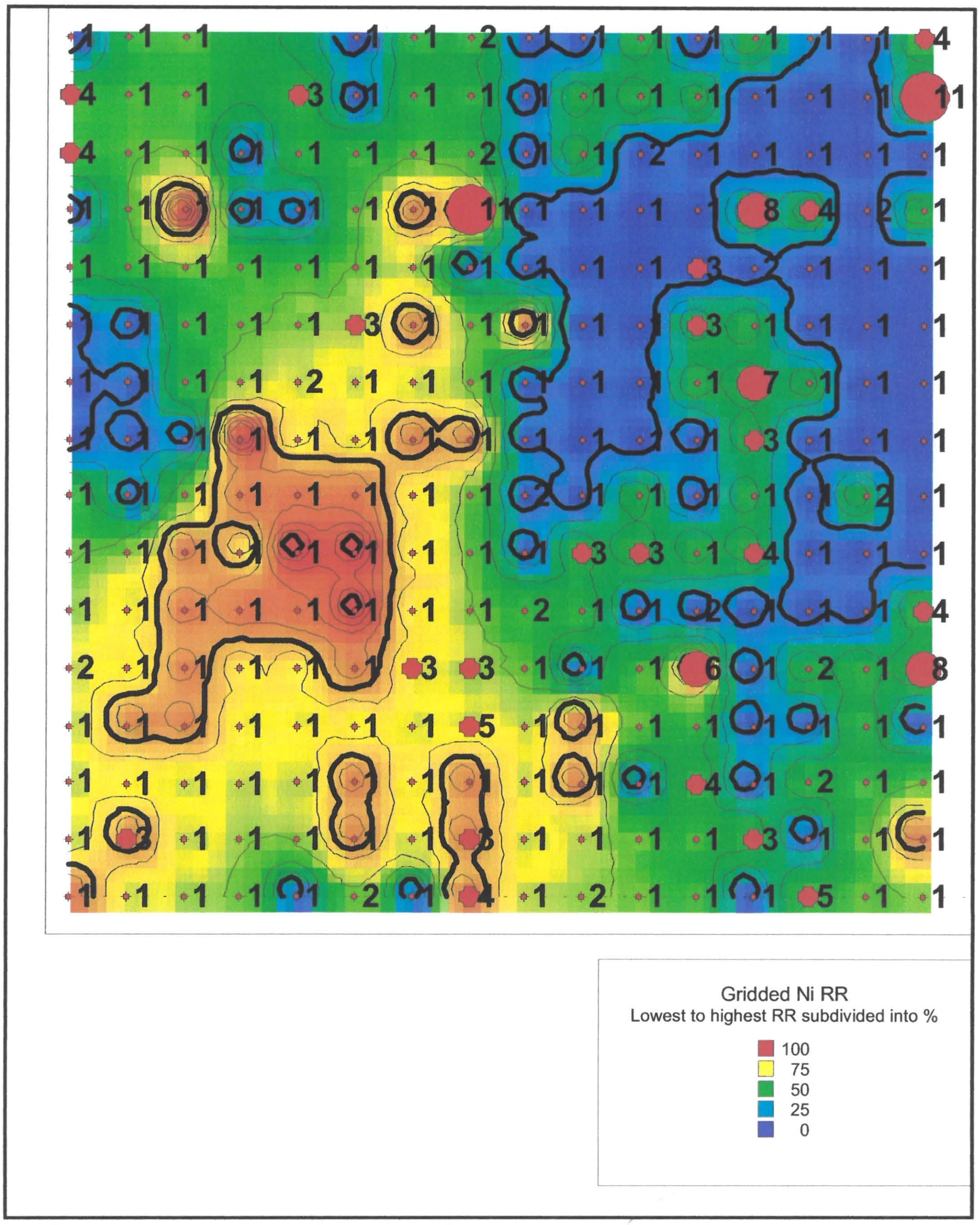


Fig. 18 Grid C, Pd normalized response ratios overlying gridded normalized Ni response ratios (Inverse Distance Weighting used to grid data). The numbers are the response ratios. This shows the same as the previous figure, i.e. lack of coincidence between elevated Ni and Pd.

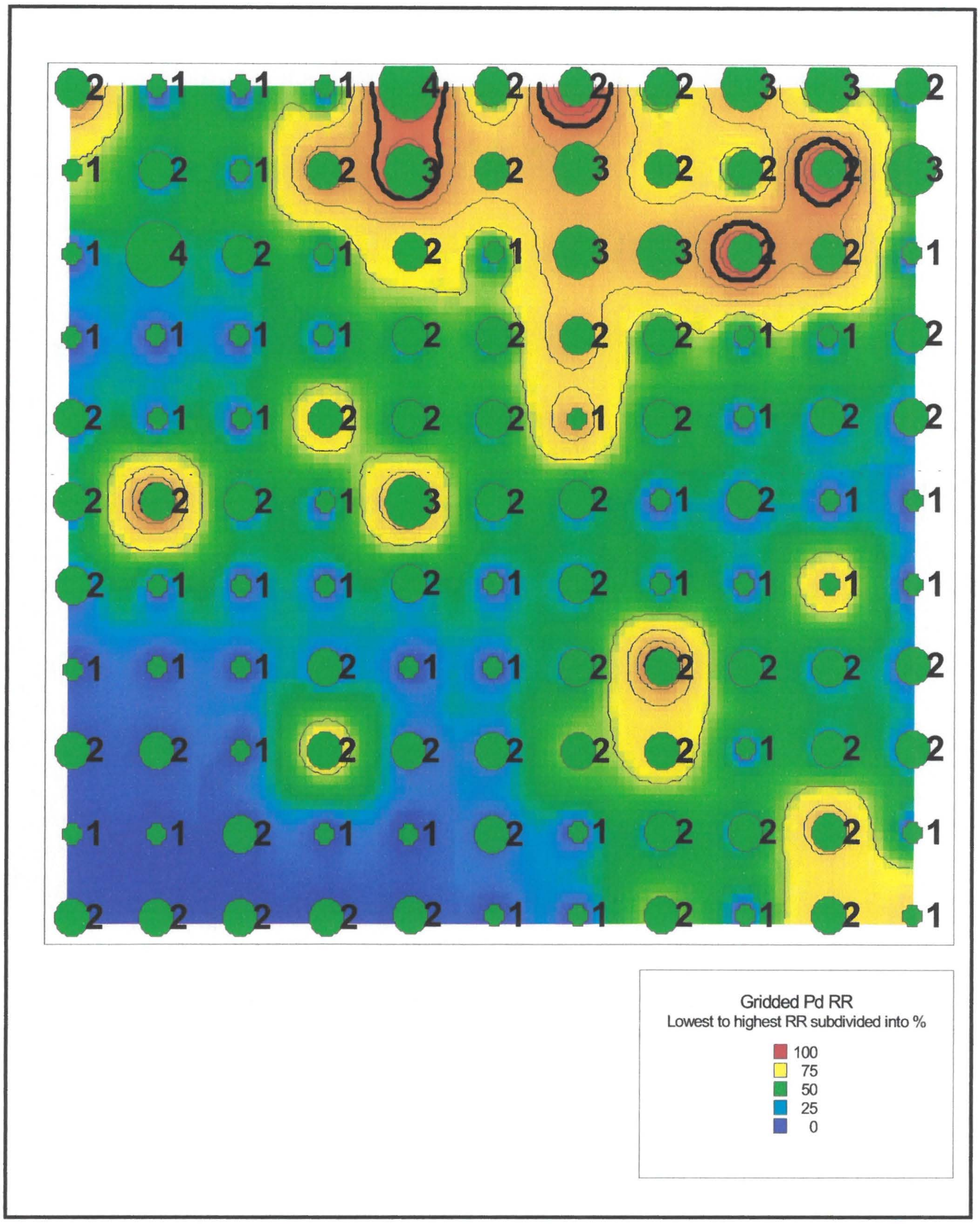


Fig. 19 Grid D normalized Ni response ratio overlying gridded Pd response ratio (inverse distance weighting used to grid data). Note there are some coincident elevated values in the northern part of the grid.

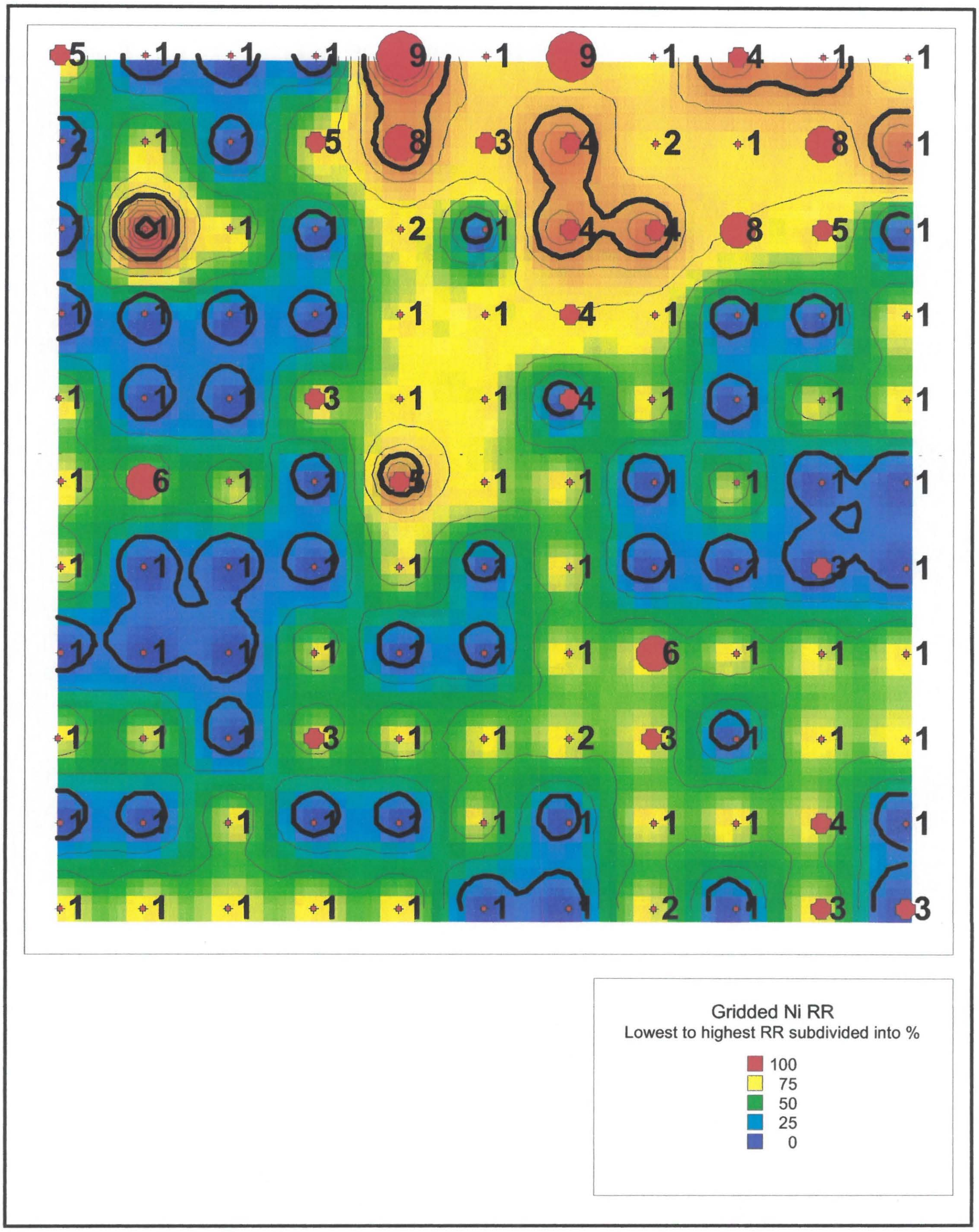


Fig. 20 showing the reverse of the previous fig with normalised Pd response ratios overlying gridded,normalized Ni response ratios.

Table 10 – Maximum RR's for Each Grid Using the 3 methods of Calculation

	Grid A RR calc from Indiv. Grids	Grid A RR calc from all Grids	Grid A RR calc from 2001 Helicopter Sampling + 2002 Grids	Grid C RR calc from Indiv Grids	Grid C RR calc from all Grids	Grid C RR calc from 2001 Helicopter Sampling + 2002 Grids	Grid D RR calc from Indiv Grids	Grid D RR calc from all Grids	Grid D RR calc from 2001 Helicopter Sampling + 2002 Grids	Grid E RR calc from Indiv Grids	Grid E RR calc from all Grids	Grid E RR calc from 2001 Helicopter Sampling + 2002 Grids	Grid F RR calc from Indiv Grids	Grid FRR calc from all Grids	Grid F RR calc from 2001 Helicopter Sampling + 2002 Grids	Grid H RR calc from Indiv Grids	Grid H RR calc from all Grids	Grid H RR calc from 2001 Helicopter Sampling + 2002 Grids	Grid I RR calc from Indiv Grids	Grid I RR calc from all Grids	Grid I RR calc from 2001 Helicopter Sampling + 2002 Grids
Max Ni RR	3	3	3	4	4	3	4	2	2	4	4	4	3	5	5	4	3	3	4	4	4
Max Pd RR	7	7	3	11	11	11	9	9	8	11	11	11	17	17	17	10	10	10	14	14	14
Max Co RR	9	7	7	26	25	25	19	19	19	9	10	10	17	16	16	15	14	14	28	28	28

* RR = Response Ratio

Table 11 – Maximum Reported Values for Each Grid

	Grid A	**Grid C**	**Grid D**	**Grid E**	**Grid F**	**Grid H**	**Grid I**
Max Ni (ppb)	239	282	195	314	400	262	314
Max Pd (ppb)	0.33	0.54	0.45	0.56	0.83	0.5	0.71
Max Co (ppb)	28	98	74	39	61	53	108

Table 12 – Highest Average Calculated Response Ratio for each Grid and "Build-Up" of RR

	Grid A	**Grid A "Build-up" of RR**	**Grid C**	**Grid C "Build-up" of RR**	**Grid D**	**Grid D "Build-up" of RR**	**Grid E**	**Grid E "Build-up" of RR**	**Grid F**	**Grid F "Build-up of RR**	**Grid H**	**Grid H "Build-up of RR**	**Grid I**	**Grid I "Build-up of RR**
Ave of Highest Ni RR (from table 1)	3	Not for Ni	4	Yes for Ni	3	Yes for Ni	4	Not for Ni	4	Weak "Build-up"	3	Not for Ni	4	Not for Ni
Ave of	6	Not for	11	Not for	10	Yes for	11	Not for	17	Weak	10	Not for	14	Not for

	Grid A	**Grid A "Build-up" of RR**	**Grid C**	**Grid C "Build-up" of RR**	**Grid D**	**Grid D "Build-up" of RR**	**Grid E**	**Grid E "Build-up" of RR**	**Grid F**	**Grid F "Build-up of RR**	**Grid H**	**Grid H "Build-up of RR**	**Grid I**	**Grid I "Build-up of RR**
Highest Pd RR (from table 1)		Pd		Pd		Pd		Pd		"Build-up"		Pd		Pd
Ave of highest Co RR (from table 1)	8	Not for Co	25	Not for Co	19	Not for Co	10	Not for Co	16	Not for Co	16	Not for Co	28	Not for Co

10)RR = Response Ratio

11)

Table 13 – Coincident Elevated RR for different Elements

Grid	**Coincident Elevated Elements**
A	No significant coincidence
C	No significant coincidence
D	Ni, Pd and Co
E	No significant coincidence
F	Ni, Pd, and Co
H	No significant coincidence
I	Ni, Pd and Co

Conclusions

1) The current sampling interval of 200 x 200 m is thought to be adequate to detect mineralisation.
2) Sudbury style mineralisation would have produced a large footprint expected to be at least 2 000 x 2 000 m. Based on a conservative 1 000 x 1 000 m footprint there should be at least 25 adjacent samples showing elevated response ratios's.
3) The current samples show some encouragement in grids C and D but there are no targets that show enough sufficiently elevated, adjacent and coincident response ratios.
4) The histograms of the raw data do not show any significant, anomalous populations. (Histograms of the response ratios were not useful in interpreting the data as the bulk of the response ratios had values of 1 or 2).
5) The detailed soil sampling has not resulted in the identification of any targets that justify follow-up under the current circumstances.

4.3.6.3c Analytical Work Conducted on Borehole M 3

Objectives and samples taken

Borehole M3 had been sampled by Business Venture Investments 33 down to 470 m. The remainder of the hole has subsequently been sampled by Falconbridge (30 samples). These samples have been submitted to Lakefield Research (South Africa) for analyses by XRF for majors and traces (including Ni, Cu and Co) and twenty nine samples were submitted to Microsearch for petrographic descriptions.

Six samples have been submitted to Genalysis in Australia for analyses by NiS collection followed by ICP-MS for six PGM's plus Au. Five samples have been submitted for detection of rare earth elements.

Eleven samples were selected for XRF for majors and traces from the upper part of borehole M3 in order to calibrate the results from the samples Falconbridge Ventures submitted (from the lower half of the borehole) with results from sampling previously done by Business Venture Investments 33 (of the upper part of the borehole).

The geochemistry of the hole and its bearing on the potential for the Morokweng Impact Structure to host a Ni-PGM massive sulphide deposit was evaluated by Maier (2002).

In addition eight samples were taken over an area containing disseminated sulphides to determine the grade of this horizon.

Observations

1) Between 350 and 365 m in borehole M3 there is a band of clast-rich norite. The clasts consist of hornfels, mafic and ultramafic material. Minor, disseminated, fine-grained sulphides are associated with the latter. The sulphides are millerite and pentlandite. Nickel rich oxides including trevorite and nickel-ilmenite are also present. Nickel rich silicates are also common. It is within this region (355,27 to 358,83 m, 3,56 m intersection) that samples were taken to detect extensions of the mineralisation previously recorded by Business Venture Investments 33.
2) Assays of M 3 borehole core samples from 355,27 to 358,83 m (3,56 m intersection) did not show any extensions of mineralisation previously identified by Business Venture Investments 33. They had previously sampled an interval of 0,70 m from 356,7 to 357,4 m that returned 0,59% Ni and 0,78 g/t Pt, Pd plus Au. Samples on either side of this interval returned values ranging from 0,2 to 0,18 g/t for combined Pt, Pd and Au and from 0,08 to 0,12% Ni with Cu values below detection.

To aid in the geochemical interpretation thin-sections were taken from throughout the hole. These showed the following:

Major Constituent Minerals

Plagioclase	40-50%
Orthopyroxene	~30%
Quartz	6-7%
Cpx	5-8%

Typical Classification
Partly altered (limonitised, chloritised) quartz bearing norite.

Notes

Contains quartz throughout.
Contains up to 3% opaque minerals throughout.
Described (intermittently) as granophyric down to 604 m.

The quartz norite hosts occasional, generally widely spaced, xenoliths (generally ~5 cm diameter) which are mostly mafic or ultramafic and less commonly are felsic (the felsic inclusions occur at the base of the melt sheet). The mafic and ultramafic xenoliths may be derived from the Linopen greenstone rocks. There are a small number of sulphide blebs of predominantly millerite and pentlandite, which tend to be associated with the more primitive clasts.

Table 15 – Petrographic and Geochemical Variarions down borehole M3

Petrographic Description	**Depth (m)**	**% Clinopyroxene**	**Depths (m) marking variations in geochemical trends (MgO, Cr, Ni)**
Quartz Norite	0 – 493,35	5	0-300
Quartz Norite/Gabbronorite	493,35 - 703,52	5-7	300-400/500
Gabbronorite	703,52 – 870,71	7-8 but occasionally 20%	400/500-870

Based on this data it is concluded that the M3 borehole has the following stratigraphic subdivisions:

Table 16 – Morokweng Impact Structure Stratigraphic Subdivisions

Morokweng Depths (m) in borehole M3	**Morokweng Stratigraphy**	**Equivalent Sudbury Stratigraphy**	**Sudbury depths through North Range (m)**
	Eroded	Granophyre and quartz gabbro	0-918
0-300	Quartz Norite	Felsic Norite	918 – 1 887
300-400	Transitional Zone	Felsic/Mafic Norite	
400-600	Gabbronorite	Mafic Norite	1 887 – 2 346
600-870	Clast rich Gabbronorite	Sublayer	2 346 – 2 496
870-1 076	Pyroxenite Gneiss Footwall	Brecciated Basement	2 496 - 2 596

Sudbury stratigraphy and depths taken from McCormick et. al. (2002)

(The Petrographic descriptions do not correlate directly with the geochemical trends).

Maier (2002) observed the following with regard to the melt sheet of the Morokweng Impact Structure:

Mass balance calculations show that the concentration of most elements can be accounted for if the sheet consists of about 5% impact material (assuming C1 chondrite) and 95% upper crust.
Ratios of incompatible trace elements remain fairly consistent throughout the melt sheet indicating that the sheet represents a well mixed and homogenised crustal melt.
Fractionation of the PGE's did not occur, probably because of the fast cooling of the melt sheet.

Conclusions

1) There is no increase in metal tenor towards the basal contact as is seen in the lower 150 m of melt sheet at Sudbury. Maier (2002) argues that this could be because M3 is not overlying a sulphide-rich portion of the melt sheet (which may be located elsewhere in the Morokweng Impact Structure, perhaps in a trough for instance). Maier argues further that it is unlikely that there would be other more sulphide rich parts of the melt sheet. This he explains, is because of the metal rich sulphides high in the sequence in M3. If sulphides coalesced at the base of the melt sheet to form sulphide rich portions than it would be unlikely to see sulphides higher in the sequence.
2) Maier (2002) concludes that the silicates did not equilibrate with sulphides and that the there is a low potential for Sudbury style mineralisation although the possibility of metal depleted portions of the melt sheet existing elsewhere in the structure remains.

4.3.6.4 Dicussion

The norite sheet at Morokweng formed as a melt sheet in a large impact Structure was potentially a large impact structure as indicated by the degree of erosion and studies conducted on shocked dolostone (Skala et al., unpublished) which show that the original diameter may have been as much as 250 km (similar to Sudbury with a diameter of 200 km). Some models for the mineralizing process at Sudbury show that sulphides are upgraded as a result of convective cells – the diameter of these cells is constrained by the thickness of the melt sheet. Borehole M3 shows that Morokweng has a minimum thickness of ~870 m at its current erosion level. If the Morokweng Impact Structure has experienced about 1 000 m of erosion, and if Skala et. al.'s interpretations are correct, then the melt sheet could have been much thicker at its time of emplacement. Emperical observations of mineralisation at Sudbury show that a thickness of about 2 000 m is required for a medium sized ore body to form. It is conceivable that prior to erosion the Morokweng Impact Structure was ~2 000 m thick.

The presence of sulphides in borehole M3 (355,22 to 358,83 m) shows that the process of sulphide segregation has taken place. What is negative is that these sulphides are trapped high in the sequence, which indicates that the system may have cooled too quickly for segregation and coalescence of sulphides in the basal breccia overlying the footwall. Borehole M3 does not overlie mineralisation so it has been postulated that the geochemistry of M3 will not give any signs of mineralisation such as Ni depletion. This is indeed what Maier (2002) concludes in his statement that the Morokweng Impact Structure did not equilibrate with sulphides. He does, however, suggest that other metal depleted portions of the melt could be present elsewhere in the Morokweng Impact Structure. Boreholes 500 to 1 000 m away from the deposits at Whistle Mine and Victor Main in Sudbury do, however, show a distinctive increase in Ni and Cu values above the dark Norite breccia (which hosts the mineralisation along strike at the aforementioned deposits). This peak in metal values is not seen in M3 which indicates that either there is no mineralisation at Morokweng Impact Structure or it is greater than 1 000 m away from the borehole. Results in table 2 show that the quartz norite at Morokweng is not depleted in Ni as the felsic norite at Sudbury is (whether or not it overlies mineralisation, i.e. the entire felsic norite section of the Sudbury melt sheet is depleted in Ni).

A positive indication for mineralisation, from a genetic point of view, is that the incompatible trace elements and incompatible trace element spider diagrams remain broadly consistent throughout the melt sheet suggesting the magma is well mixed. A well homogenised melt is analogous to Sudbury where the extreme heat generated during the impact would have caused extensive convective overturn. It is this same heat that causes devolatilising and movement of metals through thick covers of melt rock. For this reason mineralisation can be detected at Sudbury from rock samples 2 km above the ore deposits (such as Fraser Strathcona and Craig).

The MMI survey did not detect any signs of significant mineralisation as would be expected if the samples were taken over deposits such as those found in Sudbury. Indeed there are not even encouraging indications of minor sulphide deposits. Based on the MMI results the conclusion is that either there is no mineralisation or the MMI technique has failed. It is evident at Sudbury that mineralisation can be detected through a thick cover of felsic norite. This leaves the question of whether MMI would detect mobile metal ions above the Kalahari cover. Studies elsewhere have shown that partial extraction techniques are successful in detecting mineralisation below transported overburden. An example is Nepean which is a 15 m thick Ni deposit hosted in Archaean ultramafic rocks and covered by 180 m of fresh Archaean rock and 120 m of deeply weathered Cainozoic sediments, and was found using MMI (R. Fripp, e-mail correspondence). Field experiments done using trenches filled with barren (zero MMI signal) sand over base metal deposits indicated that a year was sufficient to give a detectable signal (R. Fripp, e-mail correspondence).

Implementing ground EM at Morokweng Impact Structure is problematic because of the saline ground waters and Falconbridge Ventures has had extensive experience in the Kalahari where EM has resulted in drill testing spurious targets. One possibility of seeing through the conductive overburden is to conduct moving loop EM with a small loop of 100 to 200 m using a low frequency of about 2,5 Hz. One problem with this technique is that the depth of penetration is constrained by the size of the loop (a 200 m loop will penetrate to 200 m). This technique could possibly be applied around the margins of the melt sheet.

4.3.6.5 Conclusion

The lack of significant indications of mineralisation generated from the MMI work has lead Falconbridge Ventures and Impala Platinum Holdings to abandon the project as it is not thought to hold any reasonable potential to host a Ni-Cu-PGE target. The M3 borehole geochemistry does not provide any indications of mineralisation either.

Chapter 5 - Conclusion

This chapter would endeavor to demonstrate how the various components discussed in the previous chapters forms part of an exploration strategy and execution programme. In this case they are aimed at discovering new nickel sulphide deposits. Initially several world class deposits namely Voisey's Bay, Noril'sk, Uitkomst, the Sudbury Igneous Complex, Kabanga and Jinchuan were discussed as an example of the desk top study required during the pre-target generation phase. An overview was given of their geology, mineralisation, ore genesis and key aspects of each deposit relevant to mineralisation. The objective was to describe features of world class deposits in order to be able to derive characteristics common to these that could be used to discover new deposits. These common features were discussed in chapter 2 which gave recommendations for Ni-Cu-Co-PGM exploration. A description of all large deposits is beyond the scope of this treatise, but most of the key deposits have been covered (excluding komatiites and laterites). This is followed by the actual target generation phase where the identified criteria are applied to new regions (providing these regions have appropriate fiscal and political policies as outlined at the end of chapter two).

The following chapters then introduced some of the geophysical and geochemical techniques that can be used in exploration once an area has been identified that warrants further work.

Two case studies were then given which gave examples of how the criteria in the initial chapters can be used to define targets. The one example was Insizwa which was seen to be analogous to Noril'sk and displayed many of the features described at the end of chapter 2. The second was Morokweng which was identified as having Ni-sulphide potential because of its similarities to the Sudbury Igneous Complex. Morokweng provides an example of how regional geophysical surveys could be followed by geochemical techniques such as MMI that could potentially detect blind mineralisation for confirmation by drilling.

The objective of this treatise is to demonstrate how complex information needs to be gathered and interpreted by critically assessing those criteria that would discriminate between a mineral showing and a deposit.

Geological exploration can be broken down into two broad categories namely target generation and project evaluation. The former entails identifying areas of interest based on their geological merit whilst the latter involves the work conducted on the ground to evaluate the targets that have been generated. The objective of this treatise was to address both these aspects (as stated in section 1.1) by answering the question:

"which are the diagnostic features of hypabyssally formed Ni-sulphide deposits that may be used in an exploration programme aimed at new discoveries; and how can these be used, together with exploration techniques, to implement a Ni-sulphide exploration programme?"

The answer to the first part of this question was addressed in section 2.4, i.e. what the diagnostic features of a Ni-sulphide deposit are. The second part of the question asks how these can be used together with exploration techniques to implement a Ni-sulphide exploration programme. This has been illustrated in the two case studies reviewed in chapter four which illustrate the following:

1) Airborne EM systems are considered by Ni-sulphide exploration companies to be particularly useful in detecting ore bodies as massive sulphides are highly conductive. The case studies show that this system cannot always be applied as

local conditions (such as the conductive overburden at Morokweng) may prevent this. The Dighem survey flown at Insizwa located fifteen anomalies but many were related to conductive scree on the margins of the talus slopes around the complex (the talus and steep slopes also caused poor coupling). The Dighem system also had limited application as it only penetrated to a depth of about 60 m and was difficult to fly at Insizwa due to the steep topography and strong winds (refer to section 1.1.2 in Appendix 1).

2) Airborne conductors are often further delineated using ground EM techniques such as UTEM. UTEM is considered to be one of the best techniques available to discriminate between massive sulphides and conductive sediments. Nonetheless several UTEM conductors drill tested at Insizwa were attributed to conductive graphitic shale. The UTEM survey could not be implemented at Morokweng because of the conductive overburden (refer to section 4.3.6.1).
3) It is useful to use geophysical and geochemical survey results together to help distinguish spurious anomalies generated by either survey type. Unmineralised geophysical anomalies could result from conductive sediments (refer to table 4 of section 3.3.2). Barren geochemical anomalies are sometimes attributable to silicates (as opposed to sulphides) – this is why points 5 and 6 of section 3.2.1.1 are important. It is not always possible to implement both types of surveys. The UTEM anomalies at Insizwa were largely covered by shale and not amenable to geochemical detection. Likewise the MMI anomalies generated at Morokweng could not be verified with geophysical surveys.
4) The helicopter borne sampling technique at Morokweng was found to be a quick and efficient means of sampling a large area.
5) The MMI sample results at Morokweng did reflect the underlying geology and could be used to identify anomalies (refer to conclusions to section 4.3.6.3.a). The anomalies were, however, very subtle and quality control was difficult to implement with this technique.
6) Stream sediment surveys are also useful during the initial stages of target evaluation. The lack of topography at Morokweng prevented the use of this technique. Geophysical techniques were favoured at Insizwa and stream sediment surveys were limited to an orientation sampling programme (Appendix 1, section 2.4).
7) Lithogeochemistry is another tool that can be used in nickel sulphide exploration. Whole rock analyses show if the prospective (ultramafic) rock types are actually present in the project area. Lithogeochemistry was used at Insizwa to determine if intrusives around the Insizwa Lobe were potential “feeder dykes” or simply normal Karoo intrusives (refer to “Off-Lobe Areas” in section 4.2.6). Lithogeochemistry was used at Morokweng to compare the melt sheet with that of the Sudbury Igneous Complex (refer to section 4.3.6.3.c).
8) Once anomalies have been identified, their size needs to be assessed in terms of the size of the targeted deposit. At Morokweng MMI anomalies were detected, but were not thought to be large enough to meet the size requirements of an economically viable target (refer to conclusions of section 4.3.6.3.c).
9) At Morokweng and Insizwa the survey results were continuously integrated with geological models in order to focus future surveys and to evaluate the projects viability (refer to sections 4.2.7 and 4.3.6.3). At Insizwa the focus changed from looking for an extension (along or down-dip) from Waterfall Gorge to looking for “feeders” to the lobes. Shifts in focus need to be well motivated and open to critical review.
10) It is important to always determine what value an additional survey will add to one’s current understanding of the area and when conducting further work is likely to just increase costs with little likelihood of a discovery i.e. it is important to make an informed decision as to whether or not to “walk away”. The conclusions to the case studies (sections 4.2.7 for Insizwa and sections 4.3.6.4 and 4.3.6.5 for Morokweng) outline the reasons for discontinuing these projects.

11) Generating targets is inexpensive and should be done thoroughly. Evaluating targets is more costly and should be conducted in the most efficient manner possible. The economic potential of the Morokweng project was quickly established by implementing two surveys (excluding the evaluation of existing geophysical data) - steps a and b outlined below. Variations of steps a to c were implemented a number of times, in different areas, at Insizwa. The Insizwa project covered a large area with many showings, but the five years taken to evaluate its potential was probably too long. It is recommended that project evaluation follows these three phases (which can normally be completed in one to two years):
    a. The first should be a regional survey consisting of airborne EM and/or (depending on local conditions) regional geochemistry (stream or soil surveys).
    b. The second entails follow-up of the best anomalies generated in phase one using ground EM and/or a detailed soil survey. (Stopping the project after phase one is usually premature even if anomalies appear weak). (Geological mapping and sampling can also be conducted during this phase).
    c. The final phase is to drill test the best anomalies generated from the detailed follow-up phase (if warranted). If drill results are favourable additional surveys can be implemented, if not the project can be dropped.

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