# Nickel Sulphide Mineralization Associated with Archean Komatiites

**M Lane**

Dissertation submitted in partial fulfilment of the requirements for the degree of Master of Science (Exploration Geology) at Rhodes University, Grahamstown.

JANUARY 1992.

This dissertation was prepared in accordance with the specifications laid down by the University and was completed within a period of 8 weeks full-time study.

## ABSTRACT

The distribution of Archean Nickel sulphide deposits reflects tectonic controls operating during the evolution of the granitoid-greenstone terrains. Important deposits of komatiitic-affinity are concentrated within, and adjacent to, younger (~2.7 Ga), rift-related greenstone belts (e.g. Canada, Western Australia and Zimababwe).

Two important classes of Archean Nickel sulphide deposits exist, formerly known as "Dunitic" and "Peridotitic", these are now referred to as Group I and Group II deposits, based on their characteristic structure and composition.

Mineralization varies from massive and matrix to disseminated, and is nearly always concentrated at the base of the host unit. Primary ores have a relatively simple mineralogy, dominated by pyrrhotite-pentlandite-pyrite, and to a lesser degree millerite. Metamorphic grades tend to range from prehnite-pumpellyite facies through to lower and upper amphibolite facies.

Genesis of Group I and II deposits is explained by the eruption of komatiites into rift-phase greenstone belts, as channelized flows, which assimilated variable amounts of footwall rocks during emplacement. Sulphide saturation was dependent on the mode of emplacement and, the amount of sulphidic sediments that became assimilated prior to crystallization. This possibly accounts for variations in ore tenor.

The Six Mile Deposit (SMD) in Western Australia, is an adcumulate body of the Group IIB-type, exhibiting disseminated mineralization. The ore has been "upgraded" due to hydration and serpentinization. A profound weathering sequence exists, which was subsequently utilized during initial exploration.

Exploration techniques has been focused on Western Australia, as it is here that the most innovative ideas have emerged.

CONTENTS PAGE

PAGE

PAGE

List of Figures PAGE

PAGE

PAGE



**List of Tables**

PAGE



**List of Plates** **(Page 85)**

ACKNOWLEGEMENTS

I wish to express my thanks to the following people:

First, and foremost, to my parents Patrick and Diane Lane, without whom this year at Rhodes University, would not have been possible.

Mark Palmer at Dominion Mining Ltd., for the invaluable information and core sections, from the Six Mile Deposit, Western Australia.

Johann Stiefenhofer, for the proof reading of this dissertation.

R Cross, for equipement and guidance, associated with the microscope photography.

I also wish to extend my thanks to my fellow MSc students, who have made this an exceptional year: M Noppe, G Latorre, F Senzani, M Veselinovic, M Lynn and J Latorre.

## 1.0 INTRODUCTION

It is almost a rule for igneous rocks that the more iron-magnesium and less silicon-aluminium they contain, the higher the nickel content. A good chemical reason for the association of nickel with iron and magnesium, lies in the similar diameters of the divalent ions of all three elements. One can substitute for another, at least to a limited extent, without distorting the lattice structure of rock-forming crystals. An excellent example of this type of substitution is found in komatiites. One of the major constituents of komatiites is olivine,in which atoms of nickel may substitute for magnesium and iron.

In the context of komatiite-hosted nickel sulphide deposits, nickel is present in the sulphide form as pentlandite - $(Ni, Fe)_3 S_8$, and to a lesser extent as millerite (NiS), and heazlewoodite ($Ni_3S_2$). Pyrrhotite (an iron sulphide with a compositional range of FeS to $Fe_7S_8$ ), is an abundant mineral in nearly all sulphide nickel ores, and often contains up to 5% nickel.

Pentlandite is the most common sulphide ore mineral, and accounts for about three quarters of the nickel mined in the world.

The demand for nickel has changed very little in recent years, following the boom of 1987, for which the demand for stainless steel was undoubtedly the main cause. Stainless steel accounts for over 60% of total nickel demand (Fig. 1), and is of overwhelming importance in determining changes in the level of overall nickel consumption.

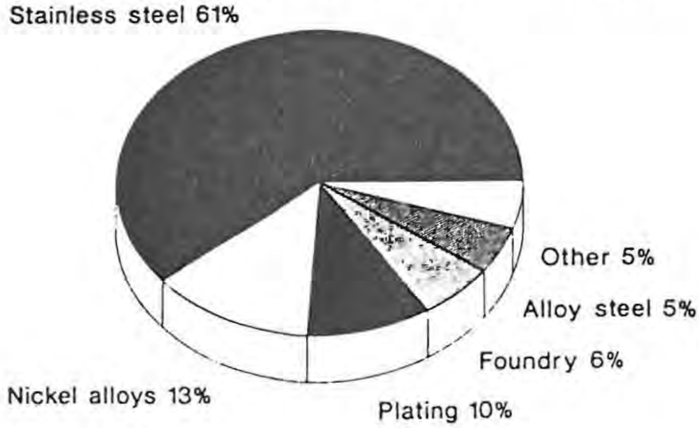



*Figure 1. Nickel consumption by first use, 1988 (source, Inco).*

It has been assumed (Lennon, 1990), that in the 1990's the trend growth in nickel consumption will be in the range of 2-4%/year, but that this would fall to an annual demand of 695,000-765,000 t by 1995.

Greenstone belts are tectonic-stratigraphic units of Archean shield areas which are characterised by structural domains and often contain broadly similar lithologies. They are a globally important source of metallic minerals, in particular nickel mineralization, associated with komatiites. Komatiites host, or are intimately associated with economic deposits of Ni, Cu, Sb and Au (Naldrett and Campbell, 1982).

Nickel sulphide deposits are known to occur in Archean greenstone belts in Canada (Abitibi Greenstone Belt), Western Australia (Norseman-Wiluna Greenstone Belt), and Zimbabwe. Most of these are associated with "younger" greenstone terrains (3.0 - 2.7 Ga). These deposits are the most important example of magmatic mineralization in volcanic rocks; containing about 25% of the world total identified nickel resources, in deposits with > 0.8% Ni; as well as significant amounts of the platinum group elements (PGE's) and copper.

This dissertation initially reviews selected Archean greenstone belt terrains; emphasis is placed on age and genesis, with particular reference to Western Australia, Zimbabwe and Canada. The following chapter on komatiites presents a brief review on classification, to together with the stratigraphical, mineralogical and genetical concepts condusive to nickel ore formation.

The Six Mile Deposit (SMD) in Western Australia, is cited as an "type" example, allowing some of the complexities associated with mineralogy, alteration and weathering to be dealt with in depth.

Exploration techniques have largely been focused on Western Australian deposits; and, it is in this context that the problems of laterization and thin residual soil, are dealt with in the final chapter.

## 2.0 ARCHEAN GREENSTONES TERRAINS

This chapter is concerned with the spatial distribution of Archean greenstone belts, their age and proposed genesis. Selected greenstone belts in Canada, Western Australia and Zimbabwe are highlighted, as these are deemed to represent important terrains for komattite-associated, Ni-sulphide deposits. These environments are subsequently discussed throughout this report in context with specific economic deposits.

The Archean basic/ultrabasic record stretches from approximately 3.8 to 2.5 Ga. Data by Sun (1982, 1984, 1987) suggests that as the Ti/P ratio (minor elements) is equal to 10, comparable with the ratio of modern basalts 10 ± 1, the Archean magmas erupted after core formation. Melt extraction from the mantle is believed to have occurred over a significant period of time prior to 3.8 Ga, leading to a depletion of the more incompatible elements in the asthenosphere, i.e a continuous process of depletion from before the eruption of the oldest preserved basic volcanics to the present day (Jacobsens, 1988). No samples of the Archean asthenosphere are available and therefore its composition cannot be directly measured; this can only be inferred from the composition of its partial melts - Archean basic and ultrabasic magmas.

There are 4 types of Archean terrain, each with a distinctive suite of metallogenic associations. Attention is focused on the granitoid-greenstone terrains because they provide a volcanic, sedimentary and tectonic record of the evolution of the early continental crust and are the most diversely mineralized. In the recent past, these terrains have been interpreted to represent either a single tectonic environment, amalgamated island arcs (Langford and Morin, 1976; Condie, 1986), collapsed continental rifts (Goodwin, 1981; Henderson, 1981), or back-arc basins (Tarney et al., 1976; Condie, 1986). A recent concensus (de Wit and Ashwal, 1986) suggests these terrains represent a variety of environments. It is unlikely that they represent oceanic crust, due to the presence of multiple horizons of interflow sediments, multiple cycles of ultramafic, mafic and felsic volcanism and clastic sedimentation; together with the absence of sheeted dykes.

Two main stages of evolution are suggested, an early platform-phase and a late rift-phase, producing spatially discrete greenstone sequences of contrasting type in individual terrains. Groves and Batt (1984) subdivided the greenstone belts in Western Australia on the basis of these two stages; here,the platform phase is represented by equi-spaced granitoid batholiths with intervening greenstone belts, characterised by komatiitic basalts and shallow water volcanoclastics. Oxide facies iron formations indicate where basement rocks and lower mafic/ultramafic volcanics provided insignificant detritus to the basin. Felsic centres are isolated and poorly represented in many terrains. The nature of the lower volcanic sequences suggest that they developed in an extensive shallow basin or platform with essentially zero or negative relief (c.f. Lowe, 1982)

There is no evidence for widespread fault control on basin development. The tectonic pattern of large equi-spaced granitoid batholiths is consistent with diapiric uprise of underlying granitoids through a greenstone slab of more-or-less constant thickness. The major phase of vertical tectonics, including granitoid diapirism, post-dated at least the early phase of major clastic sedimentation.

## 2.1 RIFT-PHASE GREENSTONES

Within some granitoid-greenstone terrains there are segments with more linear tectonic patterns, characterised by elongate greenstone belts and intervening granitoid domes. Major regional faults commonly cut the greenstone sequences into tectonic slices. These segments are characterised by a complex stratigraphy of mafic/ultramafic sequences, felsic volcanics and volcanoclastic sediments. Such sediments were deposited in both local terrestrial environments, related to volcanic vent construction and, faulting in large submarine fan systems. Argillaceous sediments were widespread and there was rapid facies changes across and along depositional basins.

Linear segments of the Abitibi Belt almost certainly represent rift -phase greenstones. However, the type example of such a terrain is taken here as the stratigraphically complex Norseman-Wiluna Belt of the Yilgarn Block, Western Australia. This is characterised by an elongate western segment in which thick extrusive komatiite sequences, intrusive komatiite dunites (refer to Section 3.2.2), and sulphidic shales and cherts are abundant. The presence of distal turbidites and thick, non-vesicular basalt sequences indicate deep water conditions in the central part of the elongate basin. The eastern segment of the belt is characterised by subaerial to shallow marine felsic centres and volcanoclastic sediment wedges. Banded Iron Formations (BIF) are abundant in these greenstones, formed on tectonically more active basins than the platform phase.

It is likely that the greenstones formed in an actively extensional fault bounded basin. The linear pattern of terrains is partly the result of imposed strike-slip faults. The gross linear tectonic pattern can be explained in terms of vertical tectonics with late diapiric uplift of granitoids, controlled by edge effects related to the fault boundary between greenstones and basement (Archibald and Battenay, 1977).

Available data from the Norseman-Wiluna Belt suggests that it may have evolved over a much shorter period of time (ca 0.2 Ga) than the platform-phase greenstone belts. Stratigraphic confirmation that the rifts were superimposed on earlier basins is provided by the distribution of BIF's; however, these only occur at the lowest stratigraphic level, at the southern end of the Norseman-Wiluna Belt (e.g Gemuts and Theron, 1981), suggesting that the bulk of the rift-related volcanism and sedimentation post dated BIF development.

Before 3.5 Ga, greenstones appear to have been confined to the Isua Sequence, Greenland. After 3.5 Ga, all other greenstones can be broadly subdidvided into two major temporal groups (Windley, 1977). Older greenstones ca 3.5 - 3.3 Ga, and the more widespread, younger greenstones (3.0 - 2.7 Ga); the latter forming much of the Yilgarn Block (Western Australia), Superior Province (Canada), and Zimbabwean Craton; and probably much of the Brazilian, Indian and Basaltic Shields. Older and younger greenstones refers to gross differences in age.

### 2.1.1 Rift-related, Older Greenstone Terrains

There are no significant komatiite-associated Ni-Cu deposits in these terrains. The absence of these reflects the relative lack of peridotitic komatiites (Group I-type; refer to Section 3.2.2), and the widespread, shallow water depositional environment characteristic of the early platform phase.

The relatively Fe-poor nature of these deposits suggests that at the volcanic stage this hydrosphere was above the level of available ferrous iron reservoirs, or was isolated from deeper basins in which such reservoirs were present. Rift-phase greenstones are poorly developed in older terrains.

### 2.1.2 Rift-related ,Younger Greenstone terrains

Greenstone belts associated with younger terrains contain the greatest concentration and diversity of important metallogenic associations. The great majority of greenstone-hosted, komatiite-associated Ni-Cu deposits are concentrated in such sequences. They are dominated, at low stratigraphic levels, by thick sequences of mafic and ultramafic volcanics that have been deposited in fault-bounded basins several hundreds of kilometres in length, and 200 km or more in width (the Norseman-Wiluna Belt). These features suggest major crustal extension.

Data from Ross and Travis (1981) suggest that at least 85% of global resources of such deposits occur in these zones (e.g parts of the Abitibi Belt), where komatiite-associated Ni-Cu deposits are generally small and/or low grade (Green and Naldrett, 1981).

In contrast, the Norseman-Wiluna Belt contains abundant high grade komatiite-associated, Ni-Cu deposits (Marston et al., 1981). Over 90% of pre-mining reserves of nickel in the Western Australian Shield are concentrated in this belt (Ross and Travis, 1981). These reserves occupy the central part of the belt and appear related to extensive eruption of thick sequences of komatiites in the more rapidly subsiding, deeper water axial zone of the rift,during the volcanic stage of the greenstone belt evolution (Groves, 1982). The presence of non-vesicular lavas and sulphidic shales or chert with a very low clastic component in these zones, is consistent with a deep water setting.

## 2.2 TECTONIC MODEL

An initial constraint on any model is the nature of the basement, if any, on which greenstones are formed. It has been argued that temporal differences in greenstones relate to changes in tectonic setting from ensimatic to ensialic (Lowe, 1982).

It is assumed that greenstone belts formed on ensialic crust. It was suggested by Hargreaves (1981), that the most appropriate model for their formation was one of early regional arching and fracturing of a relatively rigid, pre-existing sialic crust over divergent zones of mantle convection cells. The relationship of such zones to the platform-phase greenstones is uncertain; they may be related to superimposed rift-phase events. Basaltic volcanism and more restricted felsic volcanism produced volcanic sequences up to several kilometres thick. Peridotitic komatiites were generally poorly represented.

The end of the platform phase in both younger and older terrains was marked by widespread deposition of BIF's which may have been due to increased hydrothermal activity related to the initial stages of rifting, heralding the onset of a new phase of greenstone evolution.

The younger rift-phase greenstones appear to reflect greater extension and crustal thinning than the older terrains. This thinned crust and extensional faulting appears to have been important in promoting eruption of thick piles of komatiites with associated Ni-Cu mineralization in lower parts of the stratigraphic sequence.

Whether deformation was due to internal processes, or was imposed from the outside (by continental collision), does not effect conclusions relating to the relationship between metallogenic associations and recognised phases of greenstone evolution. A major enigma is that the older greenstones apparently developed under more stable conditions than the younger ones, contrary to theoretical considerations that tectonic activity would have been more vigorous in earlier times (e.g. Burke et al., 1976). The observed evolutionary trend may, however, relate more to changes in thickness, degree of differentiation and thermal state of the crust on which greenstones formed, than to changes in tectonic regime.

The following sections illustrate specific examples of Archean greenstone terrains associated with the Western Australian, Canadian and Zimbabwean shield provinces. These are subsequently mentioned throughout the context of this report.

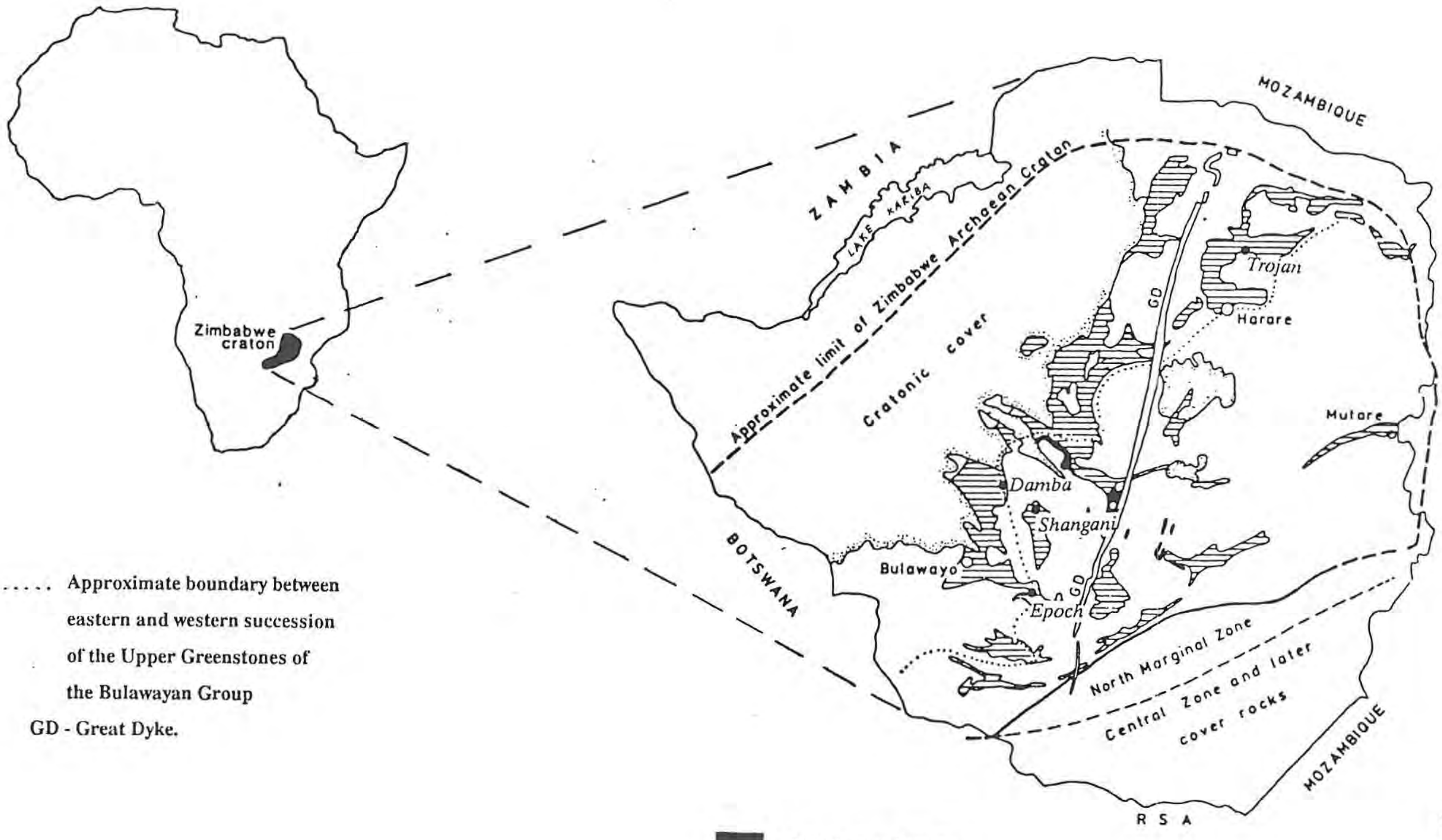
## 2.3 EXAMPLES OF ARCHEAN TERRAINS

### 2.3.1 Zimbabwe

The Zimbabwean Craton, a metamorphically low-grade, Archean granite-greenstone terrain, forms the geological foundation of the country (Fig. 2). It is part of the larger crystalline shield of southern Africa and extends into SW Botswana where it is mostly obscurred by younger cover rocks. Stabilization to form this "block" took place in late Archean times - achieved by ca 2.5 Ga ago. Since then, it has been fractured to varying degrees and intruded by various dykes and sills, but internally, has remained undeformed.

Archean continental crust growth, as interpreted by Moorbath (1984), occurred in a number of "accretionary super-events". In the Zimbabwean context, two such events seem recognisable (cf. Wilson, 1981). The first was at ca 3.5-3.3 Ga and resulted in the formation of the Sebakwian Group, occurring as tight, infolded sequences with tonalitic gneisses. The second "super-event", led to the accumulation of extensive greenstone terrains, whose deformed remains now constitute the Bulawayan and Shamvian Groups.

Within the Bulawayan Group, two ages of greenstone belt development can be recognised, allowing an upper and lower unit to be defined. Their correlation within Zimbabwe has been tentatively extended across the whole craton ( Foster and Wilson, 1984; Foster et al.,1986). The Lower Greenstones are believed to be approximately 2.9 Ga, consisting largely of the remains of cyclic units of felsic and ultramafic/mafic volcanics which were folded and eroded before the event of the Upper Greenstones, dated at 2.7 to 2.8 Ga. Ultramafic-hosted Ni deposits of komatiitic affinity are associated with volcanism and intrusion of the Upper (Bulawayan) Greenstones (cf. Wilson, 1979,1981). The western, upper part of this unit differs from the eastern, in that it consists of a bimodal unit of mafic-felsic volcanic cycles, overlain by an andesite-dominated calc-alkaline unit. The lower part of this unit is dominated by extensive "platform-type" basalts (cf. Groves and Batt, 1984).




........ Approximate boundary between eastern and western succession of the Upper Greenstones of the Bulawayan Group

GD - Great Dyke.

Sebakwian Group

Granites & gneisses of various ages.

Bulawayan & Shamvaian Groups

0 100 km

N

*Figure 2. Regional locality map of the Upper & Lower Bulawayan Greenstone Groups, Zimbabwe (adapted from Chimimba, 1982).*

The structural history of the craton is long and complex, and descriptions in terms of vertical movements are no longer adequate. Wilson (1981) believes that horizontal tectonics have played a major part in its formation. The present greenstone pattern, is explained as a progressive "main" deformation sequence involving SW movement of the Zimbabwe block relative to crustal masses to the north and south, as envisaged by Coward et al (1976). This is considered to have begun near the end of the upper greenstone volcanism, producing an early, cross-folded dome and basin pattern which was progressively deformed with time. Coward proposed the model of intrablock "billiard ball" tectonics (refer to section 3.6) to account for deformation,which involved the jostling of smaller blocks to produce major shear zones, and intense flattening and separation of once continuous structures. In the later stages of this deformation, the Upper Greenstones and Shamvian Group were deformed together.

Intrusion by the Sesombi Suite (pre-Upper Greenstone granites) followed. The last phase in cratonization was the intrusion of the Chilimanzi Suite of granites and its related Be-Li pegmatites.

### 2.3.2 Australia

The terrain of this craton has been disrupted by Proterozoic mobile belts of various ages that transect the shield, leaving large, equant relic Archean blocks, some of which are exposed and some buried. The most ancient tectonic units in the Western Australian Shield are the Archean Pilbara and Yilgarn Blocks, which are dominated by granitoid-greenstone terrains that range from ca 3.5 to ca 2.8 Ga in age, but are partly covered by Proteozoic sedimentary basins.

The granitoid-greenstone terrain of the Yilgarn Craton has been divided into the Eastern Goldfields, Southern Cross and Murchison provinces (Williams, 1974; Gee, 1979), mainly on the basis of differing structural trends and lithostratigraphic associations (Fig. 3). There is a major concentration of deposits of komatiitic affinity in the eastern part of this block. Of these, the most important are confined to the elongate N-S to NW-SE-striking Norseman-Wiluna Belt, with tectonic lineaments and fault systems dividing the belt into structural domains or "corridors". This belt contrasts in lithofacies and structural pattern with the other greenstone provinces, in that it

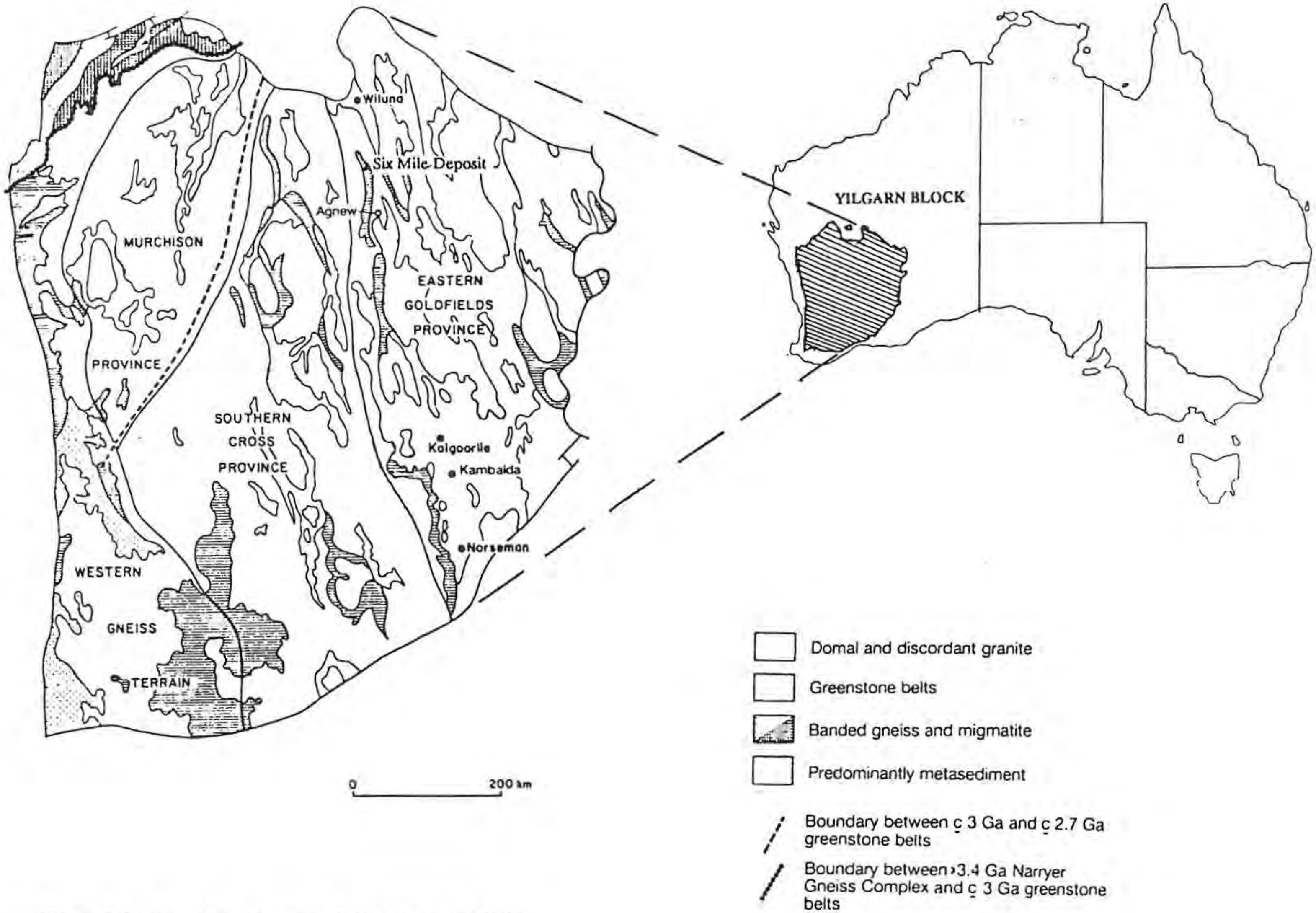



*Figure 3. Regional locality map of the greenstone belts of the Yilgarn Block, Western Australia (adapted from Barley and Groves, 1990).*

represents a distinctive segment of the Western Australian Shield and, significantly, is exceptionally well mineralized, containing most of the major nickel deposits. It appears to have been a fault-bounded graben or rift zone up to 200 km wide and at least 800 km long, bounded on both the east and the west by more stable basins characterised by BIF's. It has a complex stratigraphy, typified by abundant extrusive komatiites, numerous felsic volcanic centres, occasional BIF's, and sulphidic shales and cherts. Clastic sediments contain both mafic/ultramafic detritus, suggestive of fault reactivation of submarine mafic/ultramafic sequences. The gross structural and metamorphic pattern is markedly linear, with tectonic reactivation along major faults (with the same trend), having disrupted the zone into tectonic slices.

Groves and Lesher (1982), suggest that most of the deposits are localized in elongate depressions, developed around anticlinal structures, parallel to the dominant trend of the greenstone belts; and as a result, stratigraphically low mafic/ultramafic sequences have been exposed. The authors suggest that this provides further evidence that the present stratigraphical-structural pattern reflects original basin features.

Recent U-Pb dating of zircon in the Norseman-Wiluna Belt (Hill and Compston, 1987) indicates that the volcanosedimentary units, such as those at Norseman are > 2.9 Ga old, and are considerably older than komatiite volcanism at Kambalda, which has been dated at 2.69 Ga (Claoue-Long et al., 1988). An age of 2.66 Ga ± 6 Ma for a synkinematic granitoid at Kambalda (Claoue-Long et al.,1988) indicates that deformation commenced within 30 Ma of komatiite volcanism, and involved oblique compression. This resulted in recumbent folds and thrusts, upright folds and faults with a dominant oblique-or strike-slip component (Archibald, 1987). Vearncombe et al., in press) suggesting that both types of faulting were commonly linked and related to a single event.

Two main tectono-stratigraphic associations are noted. The eastern part of the belt contains calc-alkaline volcanics and associated I-type granitoids, and is interpreted to be associated with volcanic arc magmatism. To the west of this, separated by major faults, is an association containing tholeiites, komatiites and sulphidic shales overlain by silicic pyroclasts and associated sediments. This is interpreted as the remains of marine basin crust, which probably developed behind the volcanic arc. This possibly suggests a partly ensialic setting for those sequences preserved in the belt.

Komatiite-associated Ni-Cu deposits in the Norseman-Wiluna Belt are one of the world's most important resources (14.5% of identified resources) of nickel sulphide ores (Marston, 1984). These deposits are associated with komatiite lavas in the western half of the belt and their distribution directly reflects komatiite abundance.

A period of Yilgarn deformation, metamorphism and granitoid emplacement followed shortly (< 50 Ma) after ~ 2.7 Ga volcanism in the Norseman-Wiluna Belt. During this orogeny, deformation and metamorphism were also superimposed on older greenstones in the Murchison Province and Southern Cross Province, and a major suite of crustally derived granitoids were emplaced. Similar controls were operative in other Archean granitoid-greenstone terrains, e.g the Abitibi Belt in Canada.

### 2.3.3 Canada

The Canadian Shield includes two major Archean provinces; the large Superior Province (containing more than 30 greenstone belts), and the much smaller Slave Province.

The Superior Province is a remnant of a larger Archean continent, assembled in the late Archean, fragmented in the Early Proterozoic, and modified by collisional deformation during Proterozoic events. Mafic-ultramafic submarine lava plain sequences consisting of pillowed and massive tholeiitic flows with komatiites and mafic/ultramafic sills, form the lower, areally extensive parts of the greenstone belts, most of which are 2.75 - 2.7 Ga in age. They are chemically similar to oceanic volcanics (mid-oceanic ridge basalts, immature arc, oceanic island) and are comparable to oceanic submarine lava plain and Hawaiian-type shield volcanic accumulations. This province can be subdivided into a volcano-plutonic (granite-greenstone) subprovince, characterised by low-grade volcanosedimentary sequences, ranging in age from ca.3.0 Ga to 2.7 Ga; and metasedimentary, plutonic, and high-grade gneiss subprovinces. This division is based on lithology, structure, metamorphism, geophysical and metallogenetic characteristics and ages of rock units and tectonic events (Card and Ciesieski, 1986).

The existance of a ca. 2.8 Ga quartz-arenite-carbonate platform sequence suggests that some of the early-formed terrains were relatively stable and possibly extensive, although renewed magmatic activity in the Late Archean resulted in volcanism, plutonism and sedimentation throughout the Superior Province.

In the southern Superior Province, major volcanism ended about 2.7 Ga ago with the onset of polyphase deformation, again under general north-south major compression, with accompanying plutonism and low-pressure regional metamorphism. Deposition of the thick turbidite sequences of the metasedimentary belts also occurred at about this time.

Isotopic age determinations show that volcanic and plutonic rocks of the Superior province range from about 3.1 Ga to 2.6 Ga and that within this range there is evidence for several major magmatic episodes at about 3.0 and 2.7 Ga. During these episodes, tholeiitic, calc-alkalic, komatiitic and alkalic volcanics and, associated volcanogenic clastic and chemical sediments of the greenstone belts were deposited, as were the turbidites of the intervening metasedimentary subprovinces.

Much of the Superior Province represents new continental crust formed during several major mantle separation events in the Middle and Late Archean, probably in settings and by processes not unlike those existing today in parts of the Pacific.

The relatively voluminous nature of the Archean felsic volcanism (Thurston et al, 1985) and plutonism (Barker and Peterman, 1974) suggests development on continental, rather than oceanic crust. Evidence from isotopic (Gariepy et al, 1984; Compston et al., 1986) and geochemical (Ayres and Thurston, 1985; Arndt and Jenner, 1986) studies suggest the prior existence of sialic crust during development of Archean mafic to felsic cyclical volcanism.

The Superior Province is subdivided into a number of terranes (Ayres and Thurston, 1985), of which the Abitibi subprovince is significant, as it is dominated by the Abitibi Greenstone Belt (Fig. 4). This is the largest and most auriferous greenstone belt in the Superior Province, and has a similar tectonic history to the Norseman-Wiluna

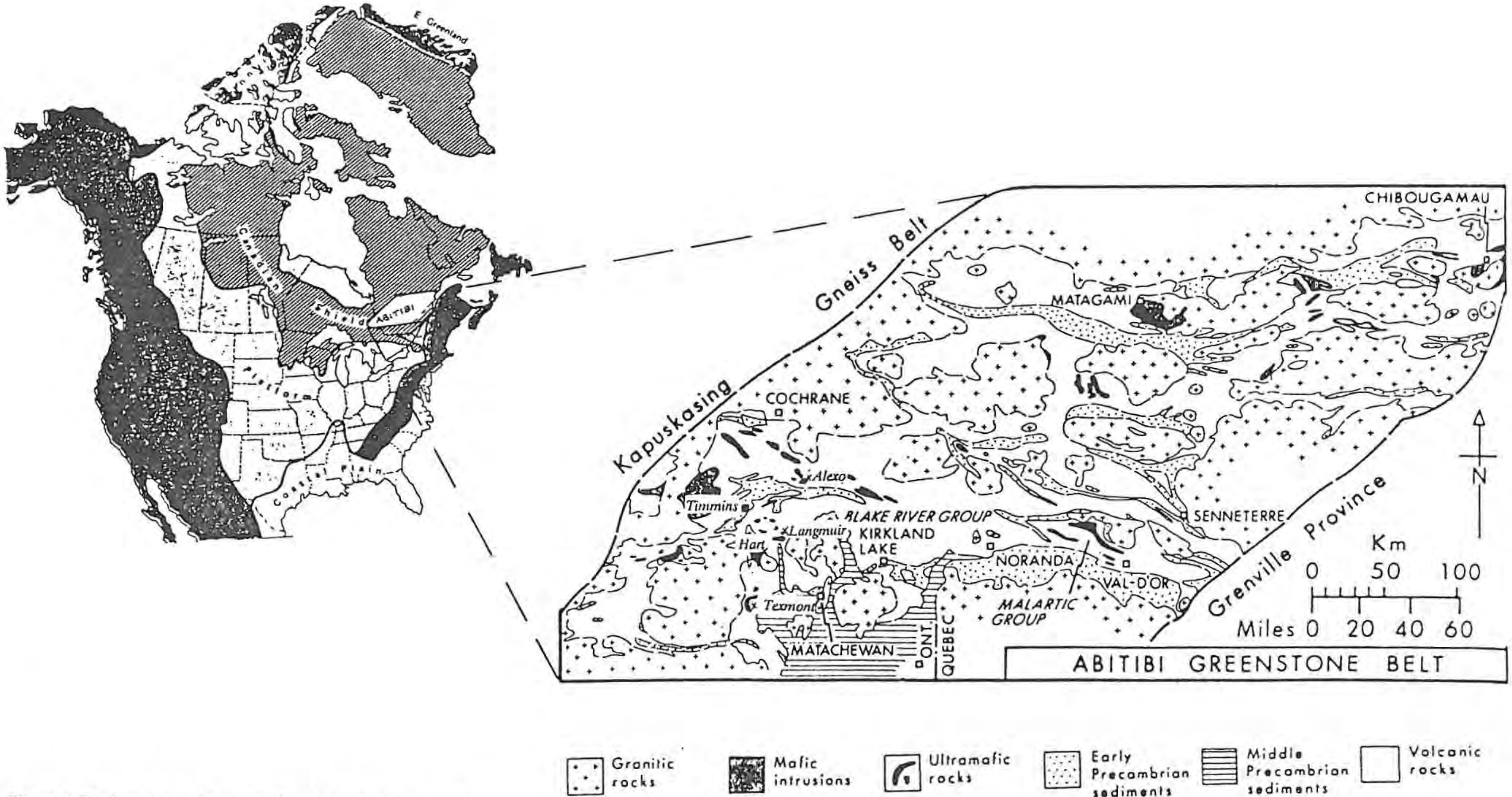



*Figure 4. Regional locality map of the Abitibi Greenstone Belt, Superior Province, Canada (adapted from Naldrett and Gasparrini, 1971).*

Belt (e.g. Ludden et al., 1986; Colvine et al.,1988). Deformation and metamorphism followed shortly after volcanism (Colvine et al., 1988), and this belt may also represent a late Archean convergent margin orogeny (Ludden et al., 1986).

Interpretation of the gravity field across part of the Abitibi greenstone belt and granitic batholiths indicates that this belt extends to depths of less than 5 km on average, with deeper keels down to 6-8 km.

The Abitibi greenstone belt comprises several major volcanic cycles. In a survey of cyclical volcanism, Thurston (1986) identified, in stratigraphic and petrologic terms, six types of cyclical volcanism; the komatiites and tholeiites are viewed as two separate magma clans. Ayres and Thurston (1985) consider that most Superior Province mafic to felsic volcanic systems are bimodal.

This belt is notable for its generally low grade of metamorphism; much of which is in lower greenschist facies, but there are also large areas in subgreenschist, prehnite-pumpellyite facies (Jolly, 1978; Fraser et al.,1978). Synkinematic regional metamorphism related to plutonism resulted in the formation of low-pressure greenschist and amphibolite facies assemblages. These sequences form the three major types of physiographic elements: submarine lava plain, submarine to subaerial central volcanic complexes, and subaerial to submarine rift basin fill. Submarine lava plains, comprised of both tholeiitic and komatiitic flow sequences and little else, are 5-7 km thick, exhibit broad lateral extent and low relief. Komatiitic pyroclastics present in the Val d'Or and Timmins areas suggest that not all komatiitic volcanism represents fissure eruptions.

Within the stratigraphy of the belt, komatiites form parts of thick sequences of ultramafic and mafic flows with minor felsic tuffs and chert. They decrease in abundance upwards (Ayres and Thurston, 1985), forming cycles ca. 1 km thick which extend over large areas. Interflow material consists of sulphidic shale (sulphide facies iron formation), with subsidary thin airfall tuffs. The association with ultramafic/mafic flows and the paucity of oxide-facies iron formation, vesicular lavas and hyalotuff, suggests accumulation in relatively deep water. Flow architecture and facies variation suggest eruption from mafic shield volcanoes (e.g. Ayres and Thurston, 1985).

None of the komatiites have been directly dated but they probably belong to two age groups, one older than 2.725 Ga and the other 2.715 ~ 2.7 Ga.

The model that best accounts for the features of this province involves subduction-driven accretion of Archean crustal elements, most of which range in age from 3.1 to 2.6 Ga. During Late Archean orogenesis, northward directed subduction led to successive accretion of alternating volcano-plutonic and metasedimentary terrains.

The last major orogenic event to affect the Superior Province, the Kenoran orogeny (Stockwell, 1982), occurred some 20 million years earlier in the north than in the south.

Models of global thermal evolution and the presence of komatiites indicate that the mantle was significantly hotter during Archean than at present.

## 3.0 KOMATIITES

In the following chapter komatiites, are explained in terms of their setting, mineralogical composition, the mineralogy of the deposits that they host, and their subsequent formation and genesis. Features discussed relate to deposits in Western Australia, Canada and Zimbabwe.

### 3.1 CLASSIFICATION

Following the recommendations of Arndt and Nisbet (1982), komatiites are defined here as ultramafic volcanic rocks with volatile-free Mg contents, ranging between 18 and 32% MgO. The limits of each category are defined precisely on the basis of MgO contents in $H_2O$-free analysis. Petrogenetically related basalts and olivine cumulate rocks are identified by the prefix "komatiitic", and show MgO ranges from 10-50%. The komatiite series contains lavas that exhibit unusual textures (spinifex; refer to 3.3.3.1), and volcanic structures (polyhedral jointing), related to both composition and cooling history of the lava. All members of the series have low $FeO^*/(FeO^* + MgO)$ ratios ($FeO^*$ = total iron), low $TiO_2$ and high MgO, NiO and $Cr_2O_3$

contents, and some, but not all have high $CaO/Al_2O_3$ ratios (Fig. 5).

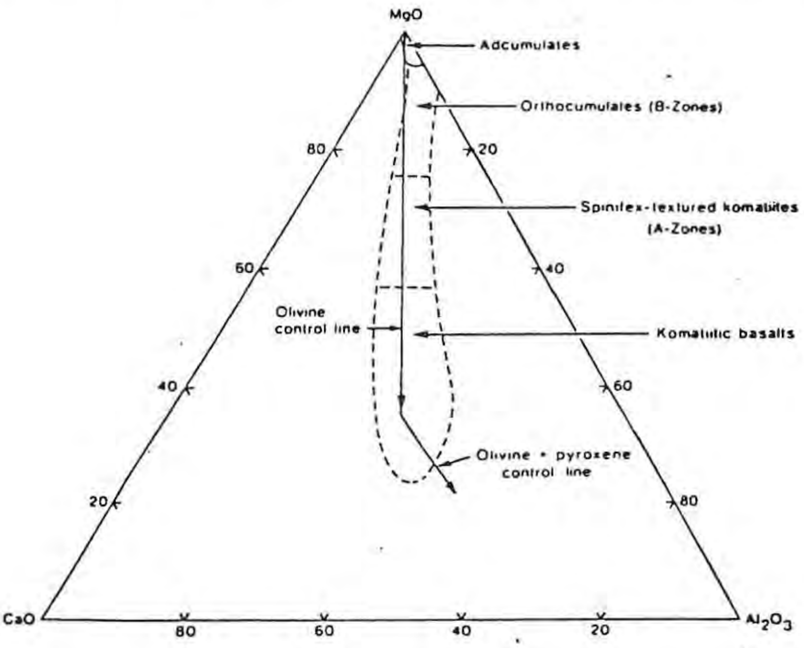



*Figure 5. $MgO$-$CaO$-$Al_2O_3$ diagram showing the range of composition for various komatiitic rocks and theoretical fractionation paths resulting from the removal of olivine and olivine + clinopyroxene (Hill et al., 1987).*

The most recent classification has been proposed by Lesher (1989), and is presented in Table 1. This scheme facilitates consideration of the deposit in terms of either host rock (Group I, II) or ore distribution (Type A, B) without implying any particular volcanic setting. Groups I and II are analogous to the "volcanic peridotite" and "intrusive dunite" associations of Marston et al (1981) and Ross and Travis (1981). Classes IA, IIA and IIB are analogous to the three groups defined by Naldrett (1981).

| | Lithological Group | TYPE | Ore Distribution | Size (tonnes) | Grade | Nature of mineralization | Examples |
|---|---|---|---|---|---|---|---|
| GROUP I | Komatiitic Peridotite-Hosted Deposits | A | Stratiform | Small (0.5-5x $10^6$) | high 2-4% Ni | msv/mtrx/diss, at base of peridotite. | Scotia, Nepean, Kambalda district |
| | | B | Stratabound | Med. (5-30x $10^6$) | low <1% Ni | diss/blebby. | Damba district |
| GROUP II | Komatiitic Dunitic-Hosted Deposits | A | Stratiform | Small/Med (1-40x $10^6$) | high 1.5-3.5% Ni | msv/mtrx/diss. | Forrestania district |
| | | B | Stratabound | large up to 300 x $10^6$) | low <1% | fine diss. | Six Mile, Betheno, Mt. Keith, Dumont |

(msv-massive; mtrx-matrix; diss-disseminated)

*Table 1. Classification of Komatiite-hosted, Ni-sulphide deposits after Lesher (1989).*

## 3.2 STRATIGRAPHIC SETTING

### 3.2.1 Generalized Stratigraphy of Komatiite Sequences

A typical stratigraphic sequence in an ore deposit consists of a basal layer of massive sulphides and olivine phenocrysts and other silicate minerals (e.g. clinopyroxene, chlorite), and an upper most layer lacking olivine phenocrysts.

Many mineralized komatiite sequences appear to grade systematically upwards from thick (sometimes laterally gradational) komatiitic dunites, peridotites and porphyritic komatiites, into basalts (Abitibi), rocks of mafic, intermediate and felsic composition (Abitibi belt),and flow top breccias, containing well-sorted, subangular to amoeboid fragments (Fig. 6).

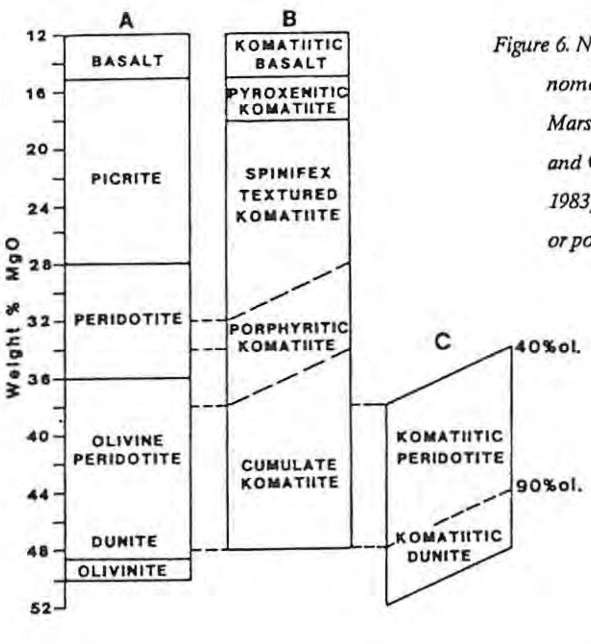



*Figure 6. Nomenclature of komatiitic ultramafic rocks.A. Previous nomenclature in Western Australia (Ross and Hopkins, 1975; Marston et al., 1981; Gresham and Loftus-Hills, 1981)* B *and* C *Nomenclature adopted here (modified after Lesher, 1983); distinction between* B *and* C *is based on skeletal* B *or poikilitic* C *mesostasis.*

The Dumont dunite is significantly different from other mineralized komatiitic dunites, in that it is overlain by Fe-rich tholeiitic basalts, not komatiites, and contains a thick upper zone of gabbroic differentiates (Duke , 1986).

It would appear that the thickness of the komatiite flows, period between eruptions, degree of olivine enrichment, and magnesium content of liquids decrease upwards. This probably reflects an evolutionary change from voluminous, episodic eruptions to smaller, more continuous eruptions.

At Kambalda, these stratigraphic variations define elongate prisms of rock parallel to, and overlying, linear ore shoots (Fig. 7) indicating a strong volcanic control on ore localization.

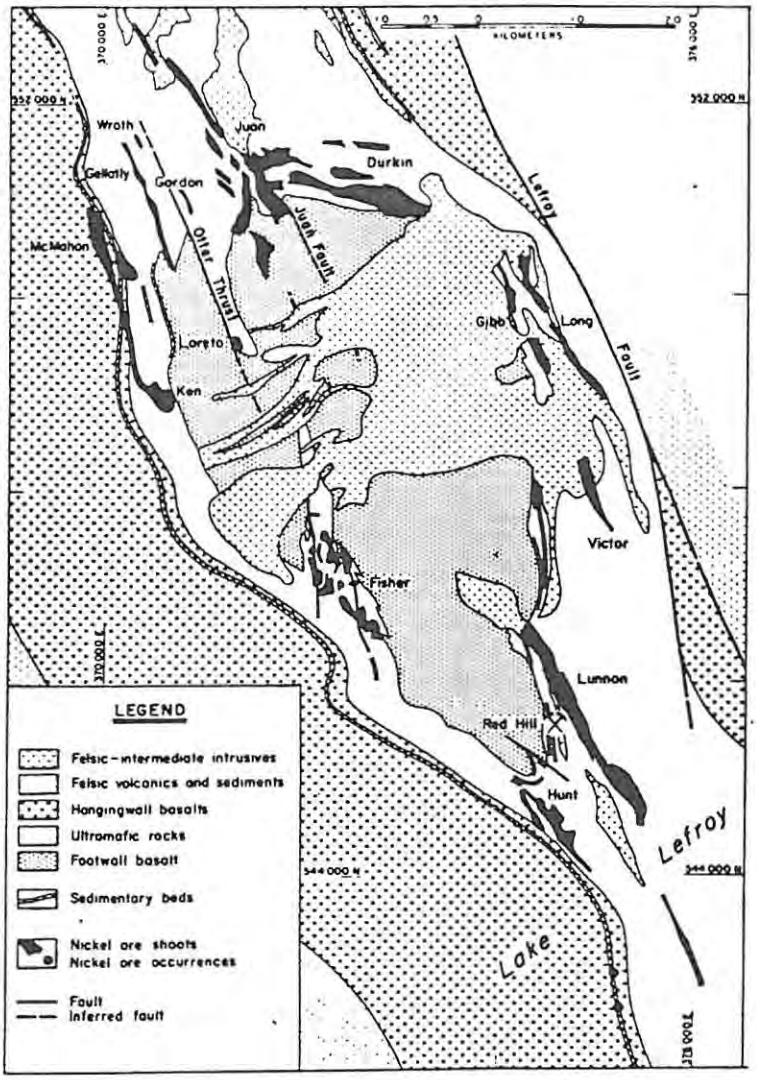



*Figure 7. Solid rock geology of the Kambalda dome, Western Australia, showing ore shoots in horizontal projection (after Gresham and Loftus-Hills, 1981).*

In contrast, barren komatiite sequences in Barberton, South Africa (Viljoen,1969;Viljoen et al., 1982), Belingwe, Zimbabwe (Nisbet et al., 1977, 1982), and Munro Township, Ontario (Arndt et al., 1977; Jensen and Pyke, 1982) contain few komatiitic peridotites or dunites, and are commonly comprised of interlayered komatiite and basaltic komatiite. They may represent less voluminous eruptions, or more distal portions of komatiite lava piles. Barren komatiites overlying ore zones may contain more cumulate flows and may be better differentiated than those further from mineralization.

There are also variations in the composition and texture of komatiite lavas across mineralised volcanic piles.The diverse shapes and sizes of olivine grains in the flow suggest that many olivine grains crystallized more or less *in situ*, rather than being extruded as phenocrysts.

### 3.2.2 Komatiitic "Peridotites" and "Dunites".

Group I deposits (Formerly Volcanic Peridotite), form the high-Mg components of komatiitic sequences, are of anomalous thickness, but are texturally and compositionally gradational with overlying and adjacent orthocumulate, porphyritic, and spinifex-textured komatiites. (Table 2).

| | Komatiitic peridotite | Komatiitic dunite |
|---|---|---|
| **Internal Structure** | | |
| Form | both: lenticular cross section, highly elongate | |
| Thickness | thick, generally 30–100 m | very thick, commonly 300–1000 m |
| Layering | both: fine-scale cryptic-rhythmic (olivine texture, olivine composition, sulfide content) | |
| Texture | orthocumulate to mesocumulate, some crescumulate | mesocumulate to adcumulate |
| Margin(s) | spinifex-textured or aphyric | poikilitic or recrystallized |
| Grain size | fine-medium, generally 0.5–5 mm | medium-coarse, generally 1–10 mm |
| **Composition** | | |
| Whole rock | 38–45% MgO* | 45–50% MgO* |
| Modal olivine | 50–75% | 75–95%, normally >90% |
| Olivine | both: 90–95 mole% forsterite | |
| Parent | both: 28–32% MgO* | |
| Chilled margins | 16–26% MgO* | 20% MgO* |

*Table 2. General characteristics of komatiitic peridotite (Group I) and komatiitic dunite (Group II) hosts to nickel sulphide mineralization in Archean greenstone belts. * Volatile-free. Compositional data for chilled margins are limited (from Lesher, 1989).*

Some are highly elongate, and largely confined within the footwall embayments (Fig. 8). Others appear to be more sheet-like in form (Fig. 9), correlating with single or multiple flow units along strike.

These have been interpreted as phenocryst-enriched lava flows (e.g.Gresham and Loftus-Hills, 1981; Gresham, 1986), overflowing lava ponds (Naldrett, 1973) and, ponded lava flows (e.g.Stolz and Nesbitt, 1981; Naldrett and Campbell, 1982) but, petrographic and geochemical constraints indicate that they are probably dynamic lava channels (Lesher et al., 1984; Lesher and Groves, 1986; Barnes and Naldrett, 1987; Cowden, 1988).

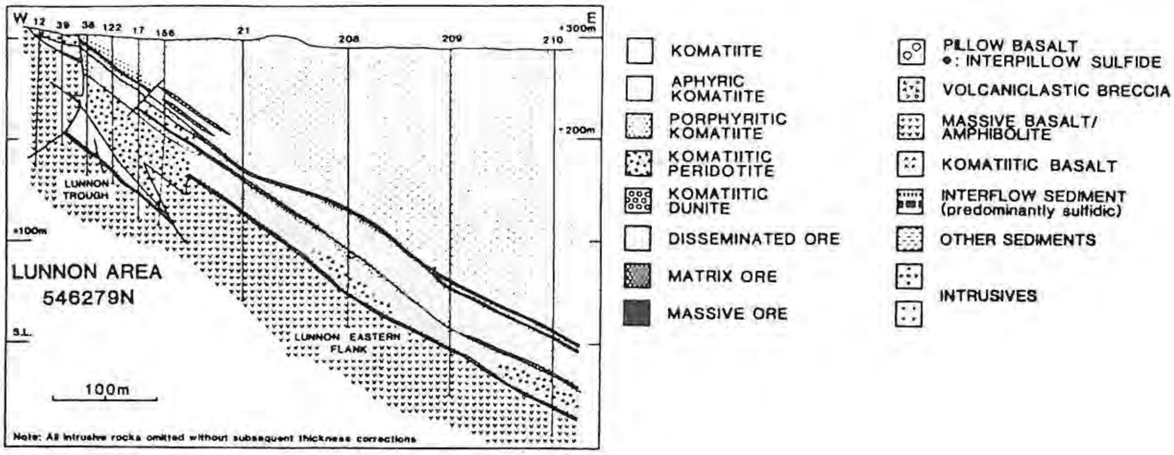



*Figure 8. Cross section of Lunnon shoot, Kambalda (modified from Western Mining Corporation, inpubl. data)*

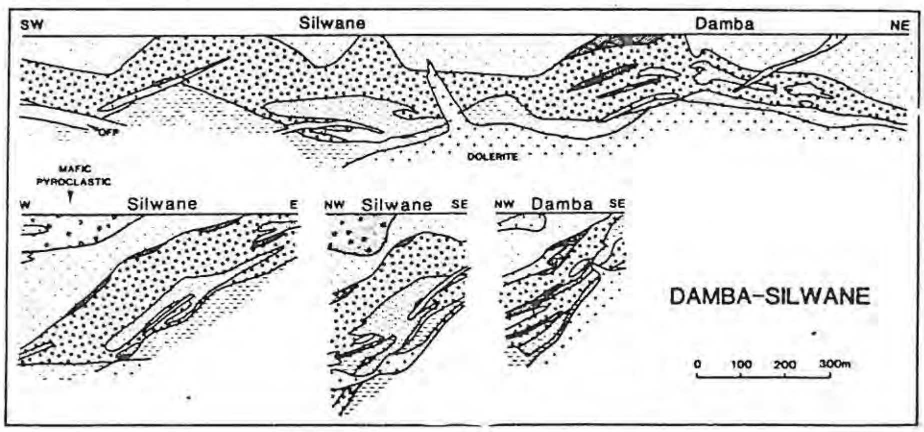



*Figure 9. Cross section of the Damba-Silwane deposits, Zimbabwe (after Williams, 1979). Ornamentation as for Fig. 8.*

As with Canada and Western Australia the Archean komatiite sequences in Zimbabwe are associated with peridotitic bodies that occur as shallow intrusions or lava flows. The mineralization is commonly controlled by syndepositional structures.

Group II deposits (Formerly Intrusive Dunite Associated) have previously been classed as "Dunite-Hosted". But it has now been established that the host olivine adcumulates are extrusive in origin, and that typical examples (e.g the Agnew deposit, Fig. 10), previously considered to fall into the "Intrusive -Dunite Associated" class, are hosted by komatiite flows genetically equivalent to those at Kambalda. Group II deposits occur as large, layered bodies of olivine cumulates, showing mineralogical, textural and compositional layering as well as cyclic variation in olivine composition.

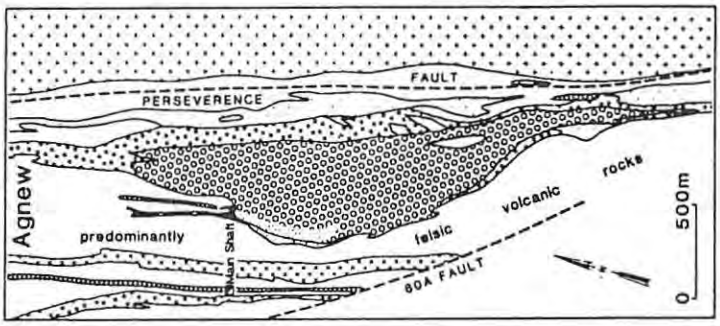



*Figure 10. Solid rock geology of the Agnew mine area, Western Australia (after Barnes et al., 1988). Ornamentation as for Fig. 8.*

Host rocks range from olivine-sulphide orthocumulates to olivine sulphide adcumulates.

Mineralized group II deposits in Western Australia are lenticular in cross section, thicker and more magnesian in central parts, and thinner and less magnesian at the margins (Fig. 11). They occupy the thickened zones at, or very near the base, of komatiitic sequences, grade along strike into komatiitic peridotites and komatiites, and are conformable with overlying komatiites, komatiitic basalts and tholeiitic basalts. The lenses exhibit gradational contacts with laterally equivalent spinifex-textured flows.

They have previously been interpreted as dykes (Binns et al., 1977) or subvolcanic sills (Naldrett and Turner, 1977). However, the above stratigraphic relationships and the virtually identical compositions of their mineral phases to those of komatiite flows, suggest that many are also dynamic lava channels (Donaldson et al., 1986; Hill et al., 1987; Barnes et al., 1988). These are believed to have crystallized in deep channels (100-150 m) akin to lunar sinuous rilles, that formed during the continuous eruption of turbulently flowing superheated lavas. The differences in shape and extent between the types of adcumulate bodies reflects the nature of the floor over which the lavas flowed (Fig. 12).

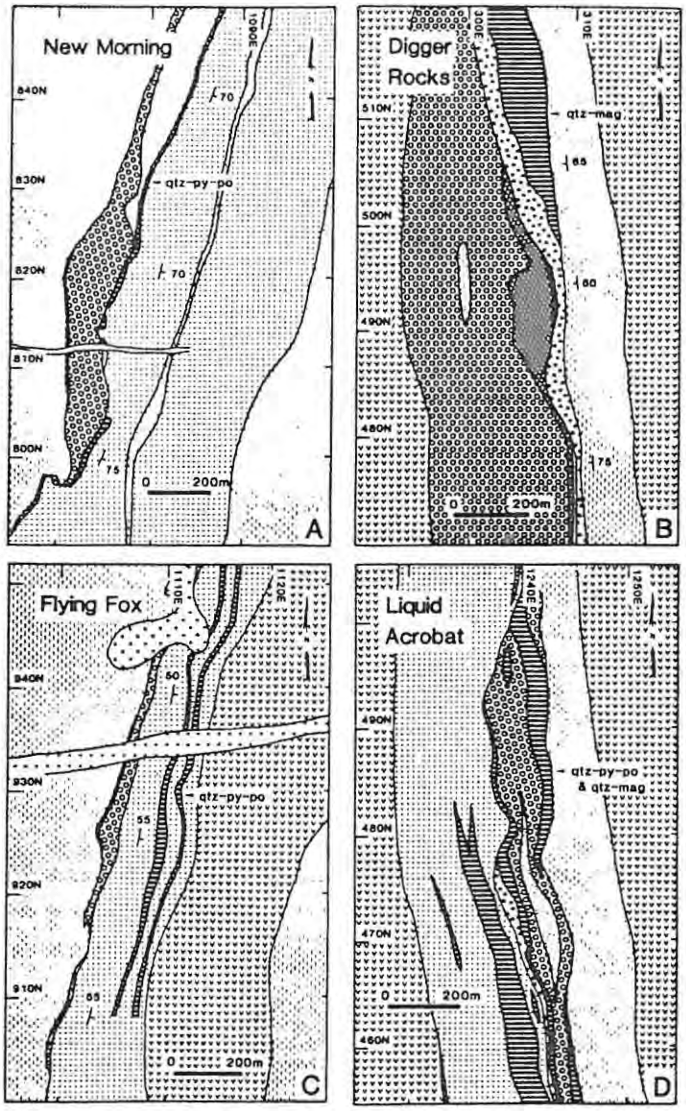



*Figure 11. Solid rock geology of New Morning (**A**), Digger Rocks (**B**), Flying Fox (**C**) and Liquid Acrobat (**D**) deposits, Forrestania district, Western Australia (after Porter and McKay, 1981). Ornamentation as for Fig. 8.*

Trace element contents of relict olivine in both komatiite flows and komatiitic dunites, particularly the relatively high Ni, Ca and Cr contents are also indicative of crystallization from similar Mg-rich, high-temperature magmas. However, the contrasting textural features of Groups I and II indicate very different cooling regimes.

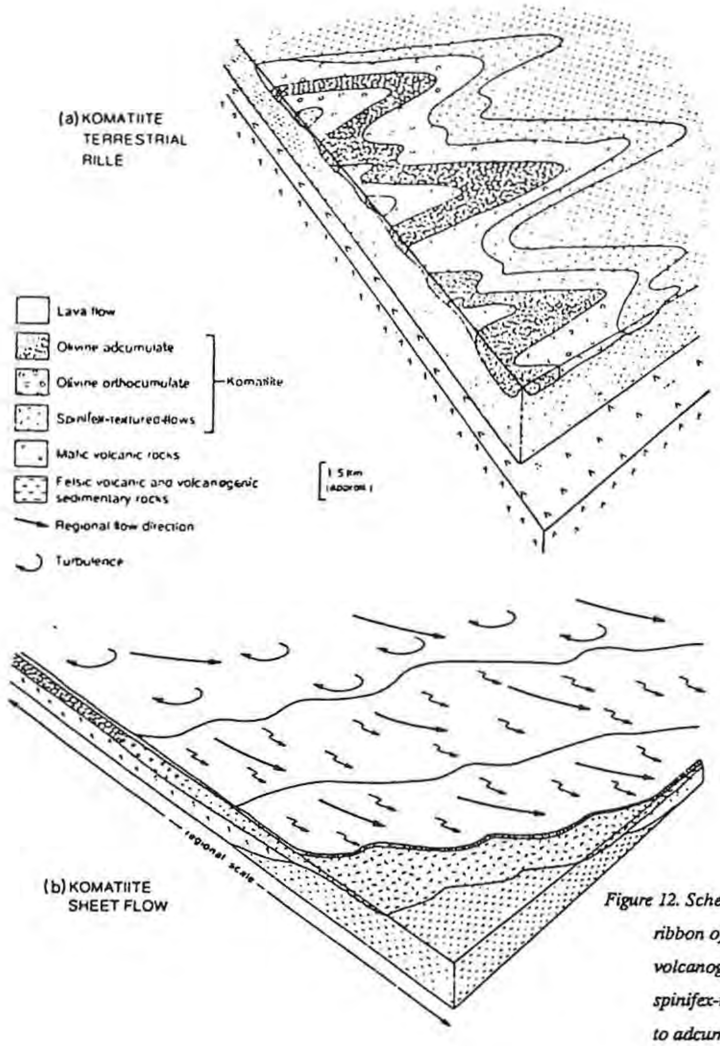



*Figure 12. Schematic illustrations of* **a)** *long, regional-scale sinuous ribbon of olivine adcumulate filling rille in felsic volcanogenic sediments. Olivine orthocumulates and spinifex-textured flows flank adcumulate. Model may apply to adcumulates of Agnew-Wiluna greenstone belt.*
**b)** *Massive, unrestricted, regional-scale komatiite sheet flow over mafic volcanic floor rocks, crystallizing olivine adcumulate, olivine orthocumulate, and spinifex-textured flows, progressively away from magma vent. Distal flows are illustrated forming on a felsic volcanic complex (from Hill and Gole, 1989).*

### 3.2.3 Footwall Rocks

The principle footwall lithologies vary from district to district, emphasizing the different tectonic settings, stages and environment in the evolution of greenstone belts,that these deposits may have formed in. Footwall rocks include (Lesher, 1989): tholeiitic basalt (Kambalda-Widgiemooltha), mafic-felsic volcanoclastic (Mt.Keith-Agnew), oxide facies iron-formation (Forrestania), andesitic volcanic rock (Timmins), and quartzo-feldspathic sediments (Damba-Shangani).

### 3.2.4 Interflow Sediments

Ore-sediment relationships vary considerably, even between deposits in the same district. Ore may grade laterally into sediments (Lunnon shoot, Kambalda), directly overlie or overlap onto sediments which may be altered, thinned or discontinuous beneath the ore zone (Langmuir, Canada) or, occur along strike from sediments, separated by a zone of barren contact (most Kambalda shoots).

Most class IA and IIA deposits overlie, or are stratigraphically correlative with, sulphidic sediments. Class IB and IIB deposits also occur in sequences that contain sulphidic sediments, but stratigraphic relationships are more obscure. The nature and composition of the sediments varies from siliaceous and carbonaceous, sulphidic shales (Norseman-Wiluna belt), to sulphidic cherts (Forrestania and Trojan districts).

### 3.2.5 Footwall Embayments

Most models of lava emplacement require pre-existing topographic depressions (troughs) to localize flow and to explain the apparent thickening of the ore-bearing flow in the immediate ore environment.

Komatiite-associated nickel deposits are generally localized in or over embayments in the footwall (refer to section 3.5.7). The geometry varies considerably from deposit to deposit and includes broad, shallow depressions (Damba, Fig. 9; Alexo), discontinuous re-entrant troughs (most Kambalda shoots) and deep trenches that are transgressive to the footwall stratigraphy (Agnew, Fig. 10). Some embayments are highly elongate, parallel to the length of the ore shoots (Kambalda), others are more irregular (Langmuir), and some are elliptical. The only exceptions appear to be extremely deformed deposits (Trojan) and intrusive bodies (Dumont).

However, at Durkin mine (Kambalda), Cowden (1988) has shown that deep (>5 m) depressions do not necessarily account for the observed stratigraphic relations.These relations, together with the absence of sediments at the base of the ore-bearing flows in troughs has led to speculation that :

1) Fe-Ni sulphides and sulphidic sediments are different facies of a volcanic exhalative event (Lusk, 1976).

2) Sulphide-bearing flows are restricted to deep troughs, while flanking flows and sediments are later events (Ross and Hopkins, 1975).

3) Komatiite flows melted and assimilated the ground, incorporating

both basalt and sediments to produce deep, sediment-free troughs (Huppert et al., 1984).

4) Lava channels were located in pre-existing topographic depressions (troughs) in the underlying basalt, and sediments were assimilated (Lesher et al., 1984).

The embayments at Kambalda have been interpreted previously as syn-volcanic grabens (Ross and Hopkins,1975; Gresham and Loftus-Hills, 1981; Gresham, 1986), but it is more likely that they formed by a combination of structural deformation (Cowden and Archibald,1987; Cowden, 1988), thermal erosion (Huppert et al., 1984; Evans et al., 1988) and volcanic topography (Green and Naldrett, 1981; Lesher et al, 1984).

## 3.3 HOST UNITS

### 3.3.1 Internal Structure and Composition

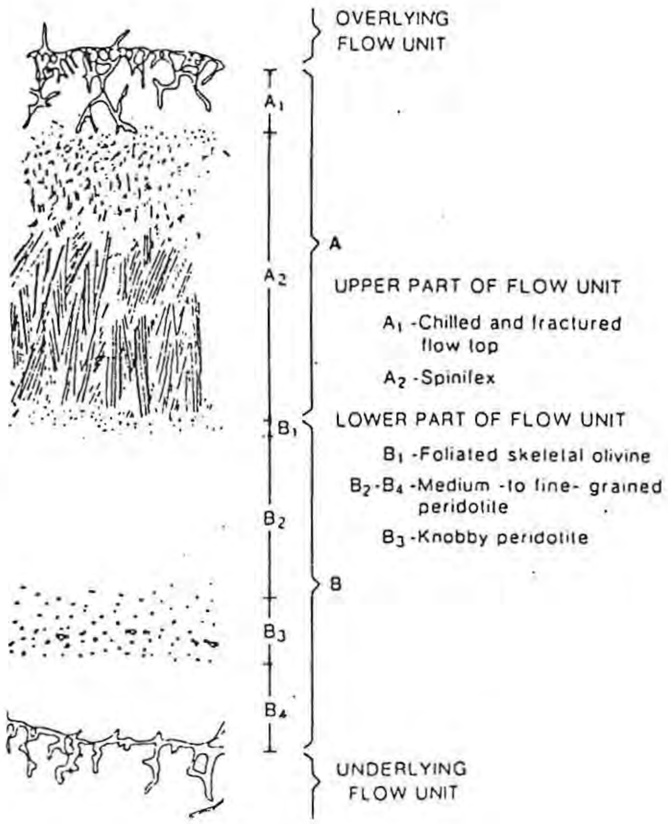
Both types of host units are texturally and compositionally gradational with overlying komatiite flows, and are interpreted to be integral parts of the extrusive lava sequence. Most exhibit systematic variations in olivine texture, olivine composition, and/or whole rock composition with stratigraphic height (e.g. Ross and Hopkins, 1975). A enigmatic feature of komatiite lava flows is their layering. Flows differentiate into an upper spinifex layer and lower layer called the cumulate or "B" layer, which is composed largely of closely packed, equant olivine grains.

The thick komatiitic dunite bodies (Group II) were initially considered to be largely homogenous (monomineralic olivine, or its serpentinized equivalent), or to consist of dunite cores with peridotitic to pyroxenitic margins. However, detailed petrography and microprobe studies of relict olivine in unmineralized (Mount Clifford), and mineralized (Six Mile) bodies have identified various types of igneous layering on a centimetre to multi-metre scale. The layering is largely defined by accessory minerals (chromite), with abrupt transitions to barren dunite (Hill, 1982).

Peridotitic flows are characterised by a thick spinifex-textured zone, containing a few solid, equant olivine phenocrysts, or more commonly, fine-grained, randomly orientated, equant skeletal or thin bladed olivine crystals, set in a matrix of glass, now altered to chlorite and serpentine. The olivine phenocrysts tend to increase in size downward from the spinifex-textured portion of the flow.

At the base of the flow the olivine blades are arranged parallel to one another in books or sheaths that are orientated subperpendicular to the plane of flow (Fig. 13).

Pyke et al. (1973) refer to the upper polyhedrally-jointed cap-rock as the $A_1$ zone and the underlying, coarser-grained spinifex-textured material as the $A_2$ zone. The $A_2$ zone is in sharp contact with the underlying $B_1$ zone, which consists of tabular olivine grains of a more skeletal habit than those of the $A_2$ zone, orientated parallel to the plane of flow.




A. Schematic crossection showing internal structure of a typical komatiite flow unit (after Arndt *et al.* 1977)

B Upper portion of thin komatiite flow containing chilled flow top and portion of $A_2$ spinifex zone (altered).

*Figure 13. Schematic representation of textural patterns exhibited by typical thin spinifex-textured flows (Hill et al., 1987).*

The elongate skeletal, hollow needles of the $B_1$ zone give way downwards to solid, more equant grains of the $B_2$ zone. The equant grains are similar to cumulus olivine crystals in peridotites from many environments, but are set in a matrix of skeletal, subcalcic clinopyroxene, chromite and a hydrous alteration product after glass.

### 3.3.2 Mineralogy

Table 3 summarises the variety in compositions of Group I and II deposits.

| | Spinifex-textured komatiite (MgO 25-34%) GROUP I | Olivine orthocumulate (MgO 34-45%) GROUP I | Olivine mesocumulate to adcumulate (45-52%) GROUP II |
|---|---|---|---|
| VERY LOW GRADE<br>Prehnite - Pumpelleyite Facies | Lizardite + chlorite + magnetite replacing spinifex olivine blades. Groundmass : clay minerals + chlorite ± albite ± relict dendritic pyroxenes, relict skeletal chromite. | Lizardite + chlorite + magnetite after olivine cumulus grains. Chlorite + clays ± albite ± relict pyroxene in groundmass. | Lizardite - brucite serpentinite, usually retaining ghost igneous texture. Magnetite veinlets. Minor chlorite. Possible relict igneous olivine, relict euhedral or lobate chromite. |
| LOW-MEDIUM GRADE<br>Greenschist Facies | Chlorite + antigorite + magnetite after spinifex olivines. Chlorite + tremolite/actinolite ± relict pyroxene, spinel in groundmass. | Antigorite + chlorite + magnetite after olivine, chlorite + tremolite/actinolite groundmass, possible relict pyroxene altering to fibrous amphibole. | Antigorite + brucite serpentinite. Magnetite veining. Minor chlorite + tremolite, relict chromite. |
| MEDIUM-HIGH GRADE<br>Amphibolite facies | Tremolite - chlorite intergrowth with sheaves and blades of cummingtonite, ± talc. Possible relict spinifex texture defined by trains of fine magnetic grains. Recrystallized ferrochromite. | Tremolite + chlorite, + porphyroblasts of colourless metamorphic olivine, ± talc. Anthophyllite or enstatite at higher grades or in $CO_2$ - metasomatized environments. | Metamorphic olivine (clear, granular), ± relict igneous olivine recognizable by red-brown colouration. Relict chromite. Minor chlorite + tremolite ± talc, anthophyllite or enstatite. |

*Table 3. Summary of mineral assemblages found in Group I & II komatiites (Hill et al., 1987).*

Studies have shown that the only minerals to form phenocryst or cumulus (relict) phases were olivine (which tends to be completely serpentinized), chromite and, to a minor degree, clinopyroxene. The first two are important petrogenetic indicators and are potentially useful exploration tools (Groves et al., 1977; Duke and Naldrett, 1978; Lesher and Groves, 1984). Therefore, any post-eruption, fractional crystallization is only likely to involve these minerals.

3.3.2.1 *Chromite* is an ubiquitous cumulus-intercumulus accessory phase in komatiites and komatiitic dunites (Donaldson, 1983). Most grains exhibit Cr-bearing magnetite rims that increase in width with increasing metamorphic grade (Plate. 6). The Zn content in the chromite of mineralized sequences tends to be high, but a difference is noted between mineralized Group I and II deposits. This may reflect early sulphide saturation in the former and late sulphide saturation in the latter (Lesher and Groves, 1984). The higher zinc in komatiitic peridotites may also result from assimilation of a proportionally larger amount of zinc-rich sediments during emplacement.

### 3.3.3 Whole Rock Geochemistry

Regional metamorphism, including serpentinization and commonly talc-carbonate alteration, has chemically modified most komatiites. Alkalic (Cs, Rb, K,Na) and calc-alkalic elements (Ba, Sr, Ca, $Eu^{2+}$) were most mobile, especially in cumulate rocks where there are few metamorphic phases capable of housing those elements. Si, Al, Mg, trivalent transition metals (Sc, Ti, V, Cr), some divalent transition metals (Fe, Co, Ni) and most rare earth elements (REE) and high field strength elements (Y, Zr, Nb) remained relatively immobile. Donaldson et al. (1986) carried out a series of whole rock geochemical analyse on samples taken from Mt Clifford and Marshall Pool, in the Yilgarn Block. Table 4 summarises their results for komatiitic-dunite (Group II), and komatiite flow-associated (Group I) deposits.

| Group I | Group II |
|---|---|
| In cumulate komatiite flows:<br>MgO - 34-48% (average 44%)<br>$TiO_2$ - 0.1%<br>$Al_2O_3$ - 2.0%<br>Olivine incompatable elements - Ti, Al and Ca - high levels.<br>Na, K and P slightly less than Group II deposits, reflecting a lower modal olivine content.<br>In spinifex-textured komatiites:<br>MgO - 18-32% | MgO - 44-51% (depending on fosterite content of former olivine);<br>Total Fe (as FeO) 6-14%<br>$SiO_2$ - 40%<br>Olivine incompatable elements<br>Low $TiO_2$ - < 0.02%<br>$Al_2O_3$ - < 0.5%<br>CaO - < 0.02% (not strictly incompatable)<br>Cr and Ni varies with former fosterite content. |

*Table 4. Whole-rock geochemical analyses for Group I & II deposits, Marshall Pool and Mt. Clifford (adapted from Donaldson et al., 1986).*

#### 3.3.3.1 *Aphyric and Spinifex-textured Rocks*

Chill-margins and spinifex-textured zones are usually accepted as the initial liquid composition. Unfortunately, chill zones are not always available, and not all spinifex-textured komatiites represent initial liquids (Smith et al., 1980; Barnes et al., 1983). Petrographic data indicates that olivine and sulphides are the predominant liquidus phases. Extreme *in situ* differentiation of komatiites has caused various textures to predominate. Pyroxenitic komatiites at Lunnon shoot (Kambalda), are characterised by skeletal crystal forms (Fig. 14).

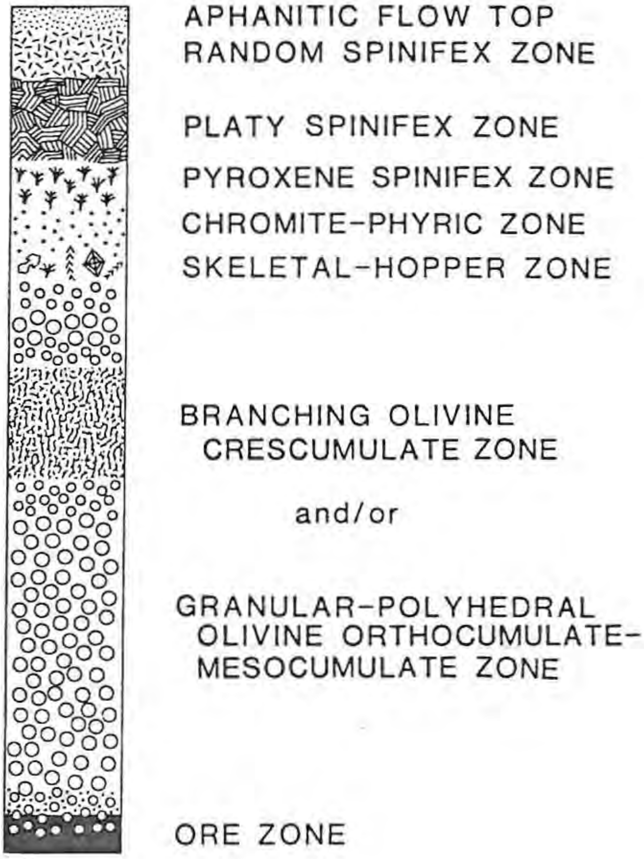



*Figure 14. Schematic structural subdivisions of typical Kambalda basal cumulate komatiite host unit; relative thicknesses of zones very variable and spinifex divisions may be very much thinner. From Lesher, 1983.*

In contrast, differentiation in a komatiitic dunite body (Mt Clifford) produced a coarse-grained clinopyroxene adcumulate.

Spinifex-textured divisions, skeletal and hopper olivine grains do not form part of coarse-grained adcumulate dunite units, except in rare marginal zones, although they are common in komatiite flows which overlie many thick komatiite dunites (Group II deposits).

Major element geochemical variations within aphyric and spinifex-textured komatiites at Kambalda (and most other deposits), both within the komatiite sequence and individual basal host units, are consistent with fractional crystallization of olivine. The composition of intial liquids may be deduced from the composition of random spinifex-textured zones of the host units, or calculated from the composition of cumulus olivine, using experimentally determined partial coefficients, or inferred.

3.3.3.2 *Cumulates*

Textures are subdivided on the basis of the ratio of cumulus crystals to the crystallization products of magma trapped between cumulus crystals, giving rise to ortho - ,meso - , and adcumulate textures (refer to section 4.4.2). Geochemical variations within the cumulate rocks are controlled primarily by accumulation of olivine and minor chromite into komatiitic liquids. In thin section, olivine and chromite are found to be the only cumulus minerals, with clinopyroxene, orthopyroxene and plagioclase as postcumulus phases.

Within mineralized komatiite sequences, host rocks are typically more magnesian than stratigraphically equivalent units flanking the ore zone (Gresham and Loftus-Hills, 1981; Hill et al., 1987).At Kambalda, for example, the basal host units are significantly enriched in Mg and Ni, and are depleted in Ti, Al, Cr, Fe and Zn relative to adjacent barren flanking units. These variations were studied by Lesher and Groves (1984), who analysed chilled margins, cumulate rocks, and relict olivine, and then modelled the geochemical variations in the cumulate rocks. They concluded that the basal units crystallized from more magnesian liquids (28-31% MgO) and more forsteritic olivine ($Fo_{94-91}$) than the adjacent units (< 26% MgO and $Fo_{91-89}$). These variations preclude models involving accumulation of intratelluric olivine.

Clinopyroxene is generally the least altered silicate in the ultramafic rocks, but does show some replacement by light green amphibole where alteration has been extensive. The flows in the Munro Township occur within a sequence of pillowed basalts and cherty sediments indicative of extrusion underwater.

Another important rock type is olivine harrisite. Characterised by coarse, dendritic branching olivine crystals (crescumulate), denoting the transition from orthocumulate towards spinifex-texture (refer to section 3.3.3.1).

#### 3.3.3.3 *Lower/Lateral Chilled Margins*

Some host units exhibit lower chilled margins, preserved beneath ore zones (Alexo) or along lateral margins of embayments (most Kambalda shoots). Analogous contact zones occur along the margins of some komatiitic dunites (Mt. Clifford). Those at Kambalda are typically less magnesian than the upper margins, but are compositionally distinct from metasomatic reactions produced during metamorphism, suggesting that they are hybridized komatiites rather than metasomatic reaction zones (Lesher, 1985).

## 3.4 MINERALIZATION

Mineralization in komatiite-associated nickel sulphide deposits varies from stratiform, massive/matrix/disseminated sulphides in class IA and IIA, through stratabound to fine disseminated sulphides in class IIB.

A typical contact ore profile comprises a thin, discontinuous layer of massive sulphides (< 20% gangue), directly overlying footwall rock and overlain successively by a thick, more continuous layer of matrix (net-textured) sulphides (20-60% gangue), disseminated sulphides (60-90% gangue), and barren host rocks. The proportion of massive ore appears to increase with shoot size (Marston et al., 1981), and thicknesses are influenced to a very large degree by deformation. Although some host units contain very thick zones of low-grade disseminated mineralization overlying the contact ores (e.g. Lunnon shoot: Ross and Hopkins, 1975), most contain negligible mineralization outside of the ore zones.

Class IA ore shoots vary considerably in size and grade, both within and between major districts. They are generally less than $5 \times 10^6$ tonnes, and contain between 2 and 4% Ni. The shoots are typically ribbon-like, and vary from 100m to 2.5 km in length and 50 to 250 m in width. Class IB deposits appear to be subeconomic unless associated with stratiform mineralization (Keele and Nickel, 1974).

Class IIA ores are, in general, fairly high grade (1.5-3.5% Ni), but only moderate tonnage (< 5 x $10^6$ tonnes), compared to class IIB ores which are typically low grade(< 1% Ni), with large tonnage (up to 250 x $10^6$ tonnes). Disseminated zones in the Agnew-Wiluna belt are 100-300 m wide and 1-2 km long.

### 3.4.1 Ore Mineralogy

Primary stratiform ores (Group IA, IB) have a relatively simple mineralogy, dominated by pyrrhotite-pentlandite-pyrite-millerite (and minor chalcopyrite) assemblages. Magnetite is more abundant in matrix and disseminated ores, apparent as coarse grained bands comprising up to 70% by volume of ore in places. Whereas pyrite is more abundant in massive ores (Cowden and Woolrich, 1987). The relative proportions of these minerals vary as a function of sulphide abundance.

At Langmuir the bottom half of the lower most flow contains all the ore-grade mineralization, which grades upwards from massive ore through net-textured ore to disseminated sulphides. Where best developed, massive ore is overlain by interstitial ore, disseminated sulphides in cumulate olivine peridotite, barren cumulate olivine peridotite, spinifex-textured peridotite, and a brecciated flow top. In some intersections, the massive ore zone is split in two by a layer of olivine peridotite. In these cases the top of the massive ore zone is now a sheared, tectonic contact.

Three gradational ore mineral assemblages occur at Langmuir: relatively unaltered pyrrhotite-rich ore (preferentially developed in serpentinized rocks), texturally altered pyrite-rich ore and highly oxidized millerite-pyrite-magnetite ore (preferentially developed in talc-carbonate rocks). The high pyrite, millerite and magnetite contents of much of Langmuir 1 are not compatable with crystallization from a magmatic sulphide liquid, rather with the alteration of original, more pyrrhotite-rich, oxide-poor ores. The formation of these may be explained by the control of alteration reactions in ultramafic rocks over nickeliferous opaque mineral assemblages (Eckstrand, 1975; Groves et al., 1974).

Two main mineral assemblages have been identified at the Damba deposits (Hendricks, 1970; Williams, 1979; Viljoen and Bernasconi, 1979). A millerite-rich assemblage with significant amounts of magnetite and minor amounts of pyrrhotite, pentlandite and chalcopyrite, and a pentlandite-rich type, containing major pyrite and pyrrhotite and minor millerite, chalcopyrite and magnetite.

At the Agnew deposit the Ni and PGE contents are lower than at other komatiite-associated deposits in the Yilgarn Block. These are interpreted to be the result of higher degrees of pre-emplacement differentiation involving extensive equilibrium crystallization of olivine and separation of significant proportions of sulphide liquid (Barnes et al., 1988).

Ferrochromites are normally concentrated at the margins of massive ore layers, and are normally coarse-grained (0.5-2.0 mm), euhedral, and most exhibit narrow Cr-bearing magnetite rims. Compositionally, they are Al-poor, Fe-chromites (Fig. 15), and are thought to have crystallized at the magmatic stage, at interfaces between layers of different sulphide content in response to $f_{O2}$ gradients (Marston and Kay, 1980; Woolrich et al., 1981).

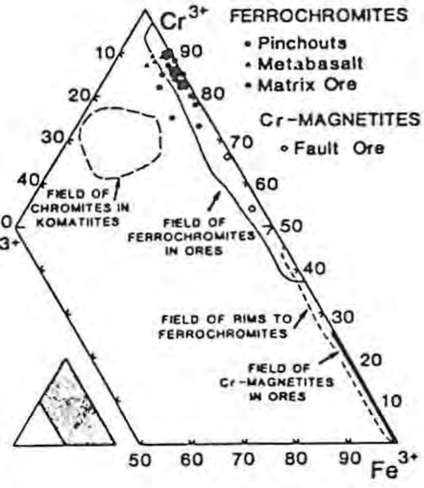



*Figure 15. $Al^{3+}$-$Cr^{3+}$-$Fe^{3+}$ plot of ferrochromites and Cr-magnetites in ore at Kambalda (after Lesher, 1983;compositional fields from Groves et al., 1981).*

Finely disseminated stratabound sulphides (Groups IIA, IIB) are mineralogically more variable and generally more Ni-rich, as a result of reactions with host rocks during metamorphism (Eckstrand, 1975; Groves et al, 1974; Groves and Keays, 1979; Donaldson, 1981). Typical sulphide assemblages for progressively altered dunites are shown in

Table 5. Chromite and chalcopyrite are ubiquitous accessory phases. Additional phases include godlevskite, vaesite, awaruite, bravoite, cobaltite, nickeliferous linnaeite, and cubanite.

| *pentlandite (dunite)* | *(partially serpentinised dunite)* | *(black lizardite serpentinite)* | *(green antigorite serpentinite)* | *(talc-carbonate rock)* |
|---|---|---|---|---|
| *pentlandite*<br>*heazlewoodite*<br>*magnetite* | *pyrrhotite*<br>*pentlandite*<br>*pyrite* | *pyrrhotite*<br>*pentlandite or*<br>*pentlandite*<br>*millerite* | *pyrrhotite*<br>*pyrite-*<br>*pentlandite* | *pyrite*<br>*millerite*<br>*polydymite* |

*Table 5. Typical sulphide assemblages for progressively altered "dunites" (Group II). From Lesher (1989).*

Magnetite occurs in 3 forms (Williams, 1979): as rims to primary chromite, as an intrinsic part of the sulphide assemblage, and as veins and fine disseminations of secondary origin generated during serpentinization.

### 3.4.2 Deformation

Owing to the greater ductility of sulphides, massive ore layers have been a locus for penetrative deformation resulting in mobilization along fault planes and emplacement in response to differential wall rock movement, accompanied by stress induced diffusion of Cu and PGE's (Barrett et al., 1977; Keays et al, 1981). Massive ores are commonly thickened in fold hinges, and tectonically displaced into wall rocks (Barrett et al., 1977; Marston and Kay, 1980; Maiden et al., 1986).

Contacts between massive ores and more disseminated ores are generally tectonic boundaries. Evidence of remobilization of sulphides in the disseminated ores occurs in the form of sulphide blebs, elongated parallel to, and situated along foliation planes in sheared serpentinite and, as the "spiky" or lamellar intergrowths between the sulphides and metamorphic silicate assemblages in the serpentine. At Alexo, folding induced the physical remobilization of primary massive sulphides into the fold noses and along shear zones sub-parallel to axial planes.

Repeated deformation of the ores is indicated by cross-cutting relationships with late-metamorphic, largely post-tectonic dykes and hydrothermal quartz-carbonate veins. As a consequence, footwall rocks are often mineralized to varying degrees; footwall stringers rich in chalcopyrite and PGE are present beneath many shoots at Kambalda (Ross and Keays, 1979).

3.4.3 Metamorphism

Since komatiites probably formed on the seafloor (Beatty and Taylor, 1982) it is important to recognise the effects of alteration such as seawater interaction and regional metamorphism. Binns et al. (1977) noted a correlation between metamorphic grade and the nature of sulphide mineralization in Group II deposits. In low-grade environments, the lenses are generally barren in sulphides, whilst disseminated sulphides prevail in intermediate-grade and low-strain environments. In areas of high-grade metamorphism (high-strain), the lenses contain massive, matrix and disseminated sulphides that accumulated in the high-strain zones (refer to section 4.0, Yakabindie: Naldrett and Turner, 1977). Characteristic alteration products of the ultramafic rocks include serpentine (antigorite with subordinate chrysotile and lizardite), talc, magnesite and phlogopite. The lizardite was formed at relatively low temperatures and was replaced by antigorite during metamorphism. At a later stage, talc-carbonate alteration partially replaced the serpentinized rocks (Table 3).

As a consequence of deformation and metamorphism, most massive ores exhibit layering of metamorphic phases and tectonic fabrics. Ore fabrics at Kambalda mimic tectonite fabrics in adjacent silicate assemblages and preserve the total sequence of deformation (Cowden and Woolrich, 1987), indicating that the ores predate metamorphism and the earliest recognisable deformation. In higher grade, more complexly deformed areas, ore fabrics record only annealing events at lower metamorphic temperatures following the unmixing of Fe-Ni-Cu sulphides from MSS (Monosulphide Solid Solution), (Barrett et al., 1977). Philpotts (1961) and Dillion-Leitch et al. (1986) describe the generation of "reverse net-textured sulphides", i.e. almost complete pseudomorphous replacement of serpentinized olivine by sulphides. Studies indicate that the ore reserves reverted to mixtures of Fe -

and/or Ni-rich MSS, Cu-Fe intermediate solid solution (ISS), pentlandite and/or pyrite, and relict spinels during the metamorphism.

In disseminated ores, oxidation, sulphidation, and carbonation reactions between sulphides, igneous silicates, and metamorphic fluids have substantially modified original sulphide compositions (refer to section 4.4.5; Groves et al., 1974; Eckstrand, 1975; Groves and Keays, 1979; Donaldson, 1981). All ore metals, except possibly Ir, are potentially mobile during metamorphism. At Kambalda, Fe, Ni, Cu, Co, Cr, Zn and especially Pd and Au have been locally mobilized into post-tectonic hydrothermal quartz-sulphide ± carbonate veins in the footwall (Lesher and Keays, 1984).

Metamorphic grades range from prehnite-pumpellyite facies at Alexo and Dundonald (Barnes, 1985) through lower amphibolite facies at Kambalda (Cowden and Archibald, 1987) to upper amphibolite facies at Nepean and Forrestania (Barrett et al., 1977). Economic and marginally economic volcanic type nickel ores of Western Australia have all been metamorphosed under amphibolite facies conditions, where metamorphic pressures and temperatures exceed 500°C and 2 kbar. Many occur in dynamic environments where deformation is dominant; even those ore shoots that occur in static-style metamorphic environments have been deformed.

Metamorphic grades vary along the Agnew-Wiluna belt, from prehnite-pumpellyite to amphibolite facies. Rocks around the Agnew mine have been subjected to peak metamorphic temperatures of about 500°C and pressures up to 3 kb (Gole et al., 1987) and komatiites have mostly been reconstituted to olivine-chlorite-tremolite-cummingtonite assemblages, with olivine-prograde antigorite in the more magnesian rocks. Carbonate-rich assemblages are irregularly distributed within the ultramafic body near its western margin

The peak metamorphic grades at Trojan are of lower amphibolite facies. The assemblage of green hornblende and plagioclase ($An_{35}$ - $An_{55}$) in the mafic lavas suggest a temperature of at least 500°C. The olivine crystals have been extensively altered to antigorite by retrogressive metamorphism and only the cores of phenocrysts remain unaltered.

The use of molecular proportion ratio (MPR) diagrams have recently been advocated by Barnes (1985). From the distribution of the whole-rock composition on these plots, one can distinguish compositional trends that are consistent with primary magmatic processes from those that are the vestiges of secondary alteration or metamorphism.

The molecular proportions of the $SiO_2$ and FM (FM = $FeO^*$ + MgO), normalized to an oxide incompatible with olivine ($TiO_2$) are plotted against each other (whole rock composition). The data lie along two distinct trends (Fig. 16). One group lies along a trend having a slope of 1:2; the ratio of the two normalized oxides ($SiO_2$ and $FeO^*$ + MgO) in olivine. A second group lies along a trend having a 2:1 slope, the ratios of these oxides in clinopyroxene. The disposition of the samples along these two trends implies that the observed compositional variation in the two groups is consistent with a primary magmatic process such as fractionation or melting of clinopyroxene and olivine. It is therefore apparent that the subsequent secondary processes such as metamorphism and seawater interaction have not notably altered the original $SiO_2$, $FeO^*$, MgO and $TiO_2$ contents of these rocks.

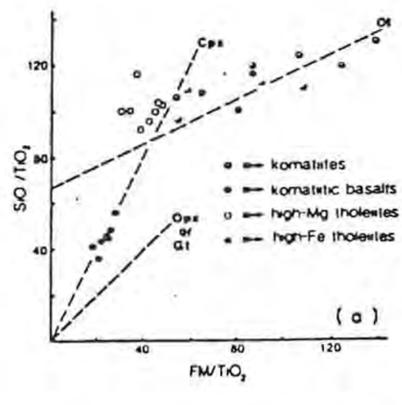



*Figure 16. Molecular proportion ratio (MPR) plot for major and trace elements, using $TiO_2$ as a normalizing oxide. a) dshed lines are clinopyroxene (Cpx), olivne (Ol), and garnet or orthopyroxene (Opx or Gt) control lines having slopes of 2:1, 1:2 and 1:1 respectively. Note scatter of samples along lines of olivine and clinopyroxene control (Barnes, 1985).*

Deviations (scattering)of compositions along the olivine control line when normalised to CaO (Fig. 17), suggest that some chemical alteration with respect to CaO has occurred due to secondary processes. No scattering along the clinopyroxene trend when normalised to CaO, indicates that there has been no significant alteration of their initial CaO content.

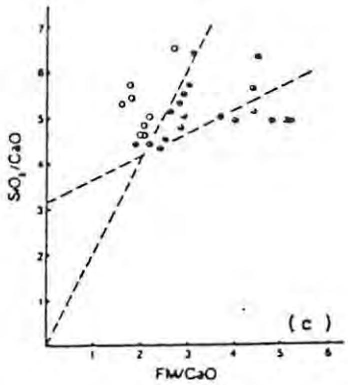



*Figure 17. Molecular proportion ratio plot, using CaO as a normalizing oxide. Note scatter of samples off the igneous trends (Barnes, 1985).*

Barrett et al. (1977) proposed, from studies in Western Australia, that the net-textured ore may be upgraded by volume changes accompanying metamorphism and that sulphides can be selectively mobilized from sulphide-silicate aggregates during deformation (due to their ability to deform plastically at moderate temperatures in response to stress), resulting in the formation of discordant massive sulphide veins from disseminated sulphides. Willett et al. (1978) concluded that postmagmatic alteration processes especially talc-carbonate alteration were of major importance in upgrading some Ni mineralization in Western Australia.

### 3.4.4 Ore Chemistry

Komatiite-associated nickel sulphide deposits are characterised by high Ni/Cu and low Pd/Ir ratios that distinguish them from most other magmatic sulphide ores (Naldrett, 1981; Barnes et al., 1988), and from hydrothermal and volcanic-exhalative nickel sulphides (Keays et al., 1981). Sulphides hosted by high-Mg komatiites (e.g Langmuir, Kambalda, Trojan, Dundonald) contain, near-chondritic abundances of PGE's and exhibit slightly fractionated chondrite-normalized PGE distribution patterns (Pd/Ir = ca. 10), whereas those associated with low-Mg komatiites (Alexo, possibly Shangani), exhibit more fractionated PGE patterns (Pd/Ir = ca. 30: Barnes and Naldrett, 1987). High-Mg and low-Mg komatiites exhibit complimentary patterns at 0.001 - 0.01 x chondritic abundances, consistent with high degree partial melting of a mantle source.

Most chalcophile elements (Ni, Cu, Co, Pt, Pd, Os, Ir, Rh, and Ru) correlate negatively with Fe, and vary systematically with Ni content (Ross and Keays, 1979; Keays et al., 1981; Cowden et al., 1986; Cowden and Woolrich, 1987). Metal ratios are relatively constant within single ore horizons, but vary considerably between deposits, among different ore shoots within a single deposit, and across individual ore profiles. The latter have been attributed to metamorphic mobilization and/or magmatic fractionation (cf. Keays and Davison, 1976; Keays et al., 1981; Cowden et al., 1986). Compositional variations between deposits are interpreted to represent original magmatic variations (Ross and Keays, 1979; Woolrich et al., 1981; Barnes and Naldrett, 1987;Cowden and Woolrich, 1987).

### 3.4.5 Chalcophile Element Depletion

Lesher et al. (1981) noted that all komatiitic rocks associated with sulphide deposits are depleted in chalcophile elements, compared with the komatiites in areas without associated nickel sulphides. This feature was taken as proof of the magmatic origin of sulphides and of the saturation of a silicate melt with sulphides early in its evolution.

Chalcophile elements such as Ni, Co, Cu and the PGE's partition preferentially into the sulphide phase relative to olivine or silicate magma. Thus, the abundance of the elements in the derivative silicate liquids should be strongly influenced by the proportions of fractionated olivine and sulphide that equilibrate in a magma (Duke and Naldrett, 1978; Duke, 1979; Campbell and Barnes, 1984), and should be a sensitive test of magmas that have equilibrated with sulphides (Lesher et al., 1981; Naldrett et al., 1984).

Spinifex-textured komatiites from barren sequences (Barberton), barren sequences that correlate with mineralized sequences (Belingwe, Munro), barren flows overlying class IIB deposits (Yakabindie), or flows that are associated with only weakly disseminated mineralization (Mt Clifford), plot along a trend that correlates closely with that of a sulphide unsaturated model (Fig. 18a,b).

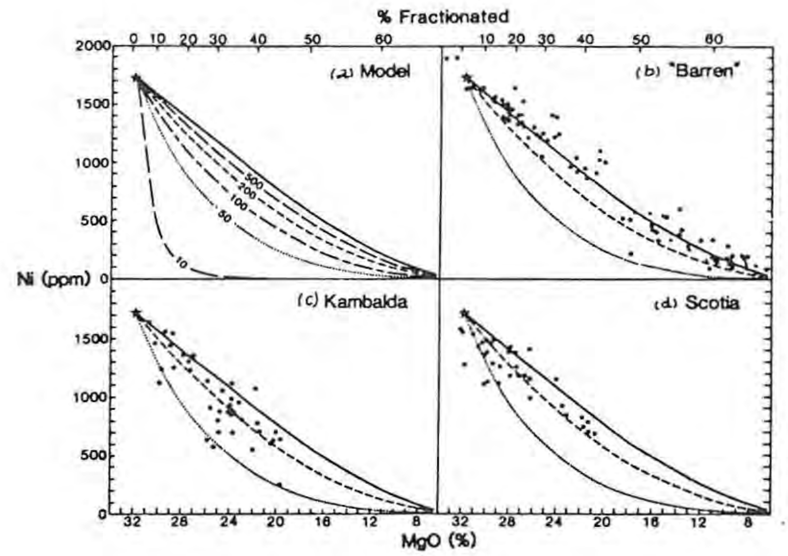



*Figure 18. Fractional crystallization model of Ni-MgO relationships in aphyric and spinifex-textured komatiites (after Naldrett et al., 1984)* **A:** *Reference diagram showing different magma:sulphide ratios.* **B:** *"Barren" komatiites from Barberton (diamonds), Belingwe (circles), Yakabindie (triangles), and Munro (squares).* **C** *and* **D:** *Mineralized komatiites from Kambalda and Scotia. Data from Herrmann et al., (1976), Nisbet et al., (1977), Naldrett and Turner (1977), J.M.Duke (unpubl. data), Lesher et al., (1981), and Stolz (1981).*

In contrast, spinifex-textured komatiites from mineralized sequences at Kambalda (Fig. 18c), and Scotia (Fig. 18d), are slightly, but significantly, depleted in Ni and Co, relative to barren komatiites and to sulphide-undersaturated examples.

Spinifex-textured rocks from thin flow units above Lunnon are similarily depleted. Lesher et al.(1981) found that there were no systematic variations between the degree of Ni depletion and the type of alteration, proximity to sulphide mineralization, or stratigraphic position, and attributed the depletion at Kambalda to scavenging of chalcophile elements by sulphides at the magmatic stage, prior to eruption. They noted, however, that dispersion in the data required more than one petrographic process. Coarse, platy spinifex-textured rocks at Lunnon shoot are not as depleted in Ni and Co, which may be attributed to crystallization from replenished liquids that did not equilibrate with sulphides.

3.4.6 Sulphur Isotopes and S/Se ratios

The problem in the generation of magmatic sulphide deposits is not the origin of the metals, but the origin of sulphur and suitable conditions for the reaction of magmatic chalcophile metals with external sulphur to form sulphide-rich liquid (refer to section 3.6.2).

Naldrett (1973) suggested that ore-bearing komatiite magmas may have been derived from zones within the mantle particularly rich in sulphides. The magmas were either saturated before ascending to the surface, or became saturated during ascent (sulphide assimilation model; where nickel deposits form by the upgrading of the sulphide content of a ultramafic or mafic magma, as the result of the incorporation of sulphide rich country rock). Eckstrand (1988, pers. comm.) used the S/Se ratios of Ni-Cu deposits to discriminate between a crustal and mantle origin of sulphur (refer to section 3.6.2).

Detailed sulphur isotopic data for ores and sulphidic country rocks in class IA deposits are available only from Alexo, Kambalda, Langmuir #2, and Windara (Fig. 19; Lesher, 1989).

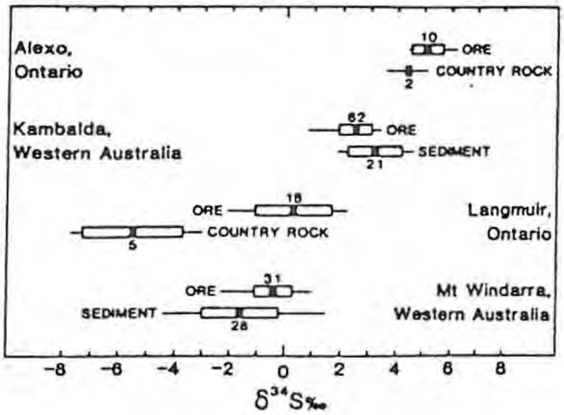



*Figure 19. Sulphur isotopic variations in ores and sulphidic sediments at Alexo, Kambalda, Langmuir and Mt. Windarra (after Lesher and Groves, 1986). Data from Naldrett (1966), Seccombe et al., (1981), and Green and Naldrett (1981).*

Reconnaissance data indicates that sulphur isotopic ratios of sulphides in ores and country rocks within an individual district are generally very similar, but systematically different from other districts.

At Kambalda, sulphur isotopic compositions of pyrrhotite from massive and matrix ores are identical and there is no apparent variation in isotopic composition with stratigraphic height through an ore profile (Seccombe et al., 1981). Reconnaissance sulphur isotopic values for Group II deposits in the northern part of the Norseman-Wiluna belt (Donelly et al., 1978) are more negative (- 2.2 at Agnew; -2.3 at Mt. Keith), probably reflecting metamorphic modification during alteration of host rocks.

Langmuir is the exception in that the sulphur isotopic ratios of the ores are slightly lower than those for most other nickel deposits.

S/Se ratios - selenium species are not so readily dispersed as sulphur species during low-temperature geochemical processes, especially under oxidising conditions. Thus, broadly speaking, magmatic sulphides have S/Se ratios between 3,000 and 10,000, volcanic exhalative sulphides have ratios of 3,000 to 20,000 and sedimentary sulphides have variable, but often much higher ratios (Standton, 1972). The Langmuir ores contain an average of 10.5 ppm Se, corresponding to 20 ppm in 100% sulphides. Most other nickel sulphide deposits for which S/Se ratios have been determined have a ratios of less than 12,000. Therefore, it is suggested that the source of sulphur at Langmuir may not be entirely juvenile magma.

However, it is unlikely that the high S/Se ratios of the original Langmuir ore were imposed on ore with an original magmatic S/Se ratio of <10,000 during serpentinization or talc-carbonate alteration, since similar alteration does not appear to have caused significant fractionation of S from Se in the Western Australian nickel deposits. Thus, the high S/Se ratios have been attributed to the assimilation of sulphide-rich cherty iron formations, which have a high S/Se ratio, and are abundant stratigraphically below the Langmuir deposits.

At Kambalda, the S/Se ratios of hydrothermal ($2\text{-}9\times10^3$) and metamorphically mobilized ($6\text{-}12\times10^3$) sulphides are slightly, but significantly lower than normal sulphide ores ($10\text{-}20 \times 10^3$: Lesher and Keays, 1984), suggesting that S and Se have decoupled slightly during deformation and metamorphism.

## 3.5 PHYSICAL VOLCANOLOGY OF HOST KOMATIITES

Experimental and theoretical studies suggest that komatiite lavas have very low viscosities, high densities, high liquidus temperatures, a large liquidus-solidus interval, and high heat content.

### 3.5.1 Magma Generation

Requirements for magma generation include a heat source and circulating aqueous fluids, a supply of reduced sulphur, a "plumbing connection" (fumerolic vents, fractures), and a source rock for nickel, copper and other metals.

High magnesium contents, low abundance of incompatible elements, and near chondritic ratios for many incompatable elements indicate that komatiites were derived by partial melting of the mantle. The degree of partial melting influences the volume and rate of magma produced, its discharge rate, the sulphur content and hence, the likelihood of it being sulphide saturated. Experimental studies of komatiite generation (Bickle et al., 1977) and thermal constraints (McKenzie, 1984) indicate depths of 200 km or greater. If the Archean mantle was broadly similar to that of today, komatiitic liquids would need to be generated by one or more model. A number have been proposed, including:

i) high degree partial melting (Nesbitt et al., 1979),

ii) multi-stage melting (Arndt, 1977),

iii) low degree partial melting at high pressure (Takahashi and Scarfe, 1985),

iv) polybaric assimilation (Bickel et al., 1977),

v) two-stage melting-mixing (Smith and Erlank, 1982), and

iv) derivation from a laterally extensive mantle melt layer (Nisbet and Walker, 1982).

None individually accounts for the geochemical variations between suites (Belingwe vs. Abitibi vs. Norseman-Wiluna), therefore some degree of mantle heterogeneity has been inferred (Beswick, 1982; Ludden and Glinas, 1982; Smith and Erlank, 1982).

Studies by Campbell and Jarvis (1984) suggest instead that komatiites formed by hot parcels of mantle rising from the core-mantle boundary. The parcels formed as a consequence of the early convective history of the mantle. At about 450 km the diapir began to melt and at about 300 km the melt separated from the restite. This model offers no direct explanation for the depleted nature of the komatiites. However, one of the most important observations noted during their studies was the change of the liquidus phase from olivine through majorite to Mg-perovskite with increasing pressure. Results of ultra-high pressure melting of the primitive mantle indicate that majorite fractionation is the key process in determining the geochemical nature of magmas generated in the deep upper mantle and the transition zone.

3.5.2 Ascent and Eruption

It is believed that fluid magmas rise through the lithosphere via filled cracks (Shaw, 1980), onto submarine basins with relatively shallow slopes. Huppert and Sparks (1985) modelled the vertical ascent of komatiite magma and concluded that high temperature, low viscosity komatiites should ascend turbulently, and form very extensive flows, consistent with their broad regional extent. High MgO contents, LREE-depletion (Light Rare Earth Elements), low abundances of incompitable elements indicate that the degree of crustal contamination of komatiites is very small.

Preserved primary textures indicate that the Damba sulphide deposits are hosted by komatiite lavas extruded at the beginning of a new volcanic cycle into a subaqueous environment. The relatively persistent and thick nature of the flows, and lack of flow breccias, indicate that the lavas were extruded on to a regionally, slightly inclined palaeosurface, with moderate topography (Arndt et al., 1979) maintained by synvolcanic faulting throughout the period of komatiite volcanism. The lavas probably ponded, whilst still turbulent, in depressions after eruption. The rate of eruption must have been fast in order to produce the thick compound lava flows suggested by compositional trends (MacDonald, 1972). In addition, the fast eruption rate explains the minimal amount of interflow material present.

Nisbet and Walker (1982) suggest that whether a melt will erupt at surface is dependent on its composition and depth of formation. For melts of komatiitic composition, at pressures greater than about 30 kbar, the magmas are denser than the restite and they sink down into the mantle to form " large laterally linked Archean magma anomalies" (LLLAMA). Komatiites are thought to erupt when there is an addition of heat from below which causes the komatiite melt in the LLLAMA, to digest the overlying refractory cap and break through the surface.

This model has been applied to the Abitibi komatiites, where it is believed that mafic melts were removed from the outer layer of the mantle at an unspecified time and a refractory cap developed. In the vicinity of the Abitibi Belt there was a LLLAMA at about 2.7 Ga which experienced an influx of heat; the komatiite melt then digested the overlying refractory mantle and erupted. The digestion of the refractory mantle could result in LREE, Zr and Hf depleted melts and possibly positive $\epsilon_{Nd}$ (epsilon neodymium) values (2.4 ± 0.5, at Alexo). The Nd model age calculated from the more depleted samples is 3.1 Ga. The mantle source, therefore, was LREE-depleted and probably differentiated from a chondritic resevoir 400 Ma before eruption of the komatiites.

### 3.5.3 Fractional Crystallization

The MgO contents of olivines at Angew (Hill et al., 1987; Barnes et al., 1988), and Dumont increase upwards through the host units. This has been attributed to decreasing amounts of olivine fractionation prior to emplacement, but may also reflect higher discharge rates in the upper parts, resulting in less fractionation during fractional accumulation, and/or more contamination in the lower parts.

It has been suggested (Naldrett and Mason, 1968) that the magma responsible for the formation of the lenses at Dundonald, ascended into the upper layers of the crust, carrying equant olivine crystals in suspension that had crystallized slowly at depth. During intrusion, these crystals were swept away from the margin and the residual silicate liquid was displaced towards the margins. As the intrusion rose up into the sequence of volcanic rocks, the rate of cooling increased and eventually the marginal liquid became supersaturated and skeletal olivine and chromium-spinel started to form. As long as the intrusion continued to move, crystals were swept away from the the walls. This could account for the continuous gradation in the olivine content of the rocks overlying the lenses.

The above model may explain the apparent "gap" in lava compositions between 16 and 20% MgO reported in many areas as a frequency minimum between:

i) the limited range of lava compositions produced by surface fractional crystallization of high-Mg parents and,

ii) the wider range of lava compositions produced by variable degrees of partial melting, crustal assimilation, and fractional crystallization prior to eruption.

3.5.4 Lava Emplacement

A fundamental feature of turbulent flows is that heat transfer is much greater than in laminar flows, where heat is lost entirely by conduction. In turbulent flows, mixing maintains a uniform temperature throughout the span of the flow and greatly increases heat flow to the surroundings. Thus, the ground surface would be quickly heated up to temperatures of 1,600-1,700°C. Huppert et al., (1984), speculated that, because of their low viscosity, komatiite liquids would display turbulent flow rather than the laminar flow typical of low-temperatures being maintained at the base of the flows, so that the komatiite liquids would be capable of thermally eroding the underlying rocks. Consequently, the komatiite flows might create their own channels and, as a result, assimilation of underlying material could take place.

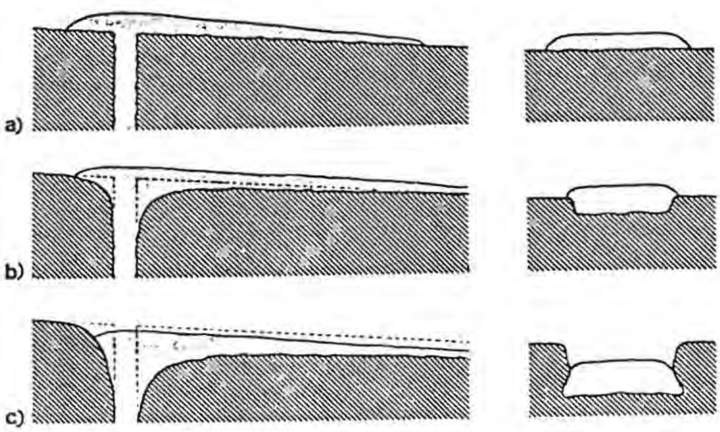



*Figure 20. Longitudinal and cross-sectional sketches of the fissure and lava flow showing the melting of the ground and the formation of an erosional channel with time. The original ground surface and fissure width is indicated by dashed lines in* b) *and* c) *(from Herbert et al., 1984).*

A geometric sketch is presented in figure 20, related to a proposal by Hulme (1973, 1982), that the sinuous rilles on the Moon were caused by thermal erosion of lava channels by turbulent lunar flows.

Groves et al., (1986), now suggest that the thermal-erosion model only works if a pool of sulphide liquid already exists - the sulphide providing the high thermal conductivity medium necessary to initiate melting in the underlying rock. Their evidence comes from the hanging-wall ore bodies at Kambalda, which are unusual in that they are found between flows higher in the section rather than at the base of the first flow. In light of the conflicting views by Huppert et al., (1984) and Groves et al., (1986), Nesbitt (1986) has proposed a model whereby thermal erosion took place within the crust. Studies of zircon ages in the Kambalda area indicate the influence of crustal contamination. Therefore, sulphide contamination of komatiites may have occurred en route rather than at the surface.

Because of the high heat content and large interval between the liquidus and solidus, komatiite lava should solidify relatively slowly, resulting in very extensive flows. Efficient heat transport to the top of the flow prevents a crust thicker than a few centimetres from forming (Huppert et al., 1984).

Fluctuations in discharge rate may cause lava channels to overflow, producing compound flanking units. If komatiites erupted into crustal rift zones, as inferred above, then emplacement of lava piles may have been controlled by topographic gradients within the rift zones (e.g. Lesher et al., 1981). Such piles would comprise multiple overlapping lava channels, separated by massive sheet flows and rare lava ponds, grading down into compound lava flows.

At Kambalda, field, geochemical and Pb-isotopic studies indicate that komatiite lava channels have thermally eroded:

i) tops of underlying komatiite flows, producing spinifex-textured ores and domes of silicate liquid (Fig. 21),

ii) sulphidic sediments, producing rare ocellar komatiites (xenomelts) that accumulated along levees adjacent to lava channels, and

iii) footwall basalt, enhancing the re-entrant geometry of the embayments.

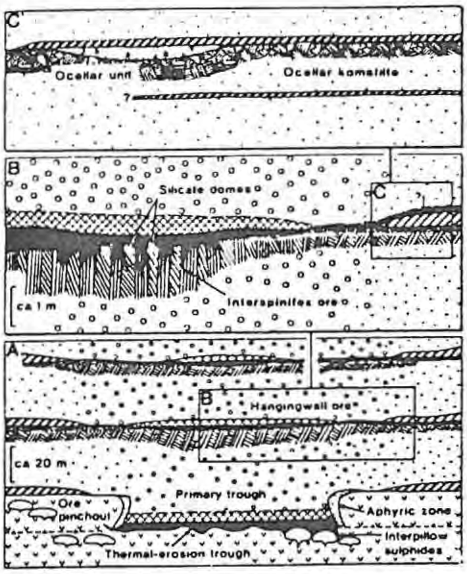



*Figure 21. Sketches summarizing stratigraphic relationships at Kambalda: contact ores (A: modified after Lesher et al., 1981), stratiform hanging wall "interspinifex" ores (B: after Groves et al., 1986) and ocellar komatiites (C:after McNaughton et al., 1988). Ornamentation as for Fig. 8.*

The relative lack of massive ore in the sulphide deposits of Damba suggests that the lava was emplaced as a homogenous immiscible suspension of sulphide and silicate liquids and intratelluric olivine phenocrysts; and, that a large proportion of phenocrysts had accumulated prior to solidification of the sulphides (Usselman et al., 1979). Despite the lack of massive ore, palaeotopography was important in localizing the mineralization and significant ponding and settling of sulphides must have occurred.

### 3.5.5 Crystallization

Post-eruptional differences in the geochemistry of the komatiites at each locality developed because of differences in the crystallization history.

Because of their high temperature and viscosity, komatiites should convect vigorously and cool relatively rapidly ( Huppert et al., 1984). The abundance of porphyritic and cumulate olivine textures (Dundonald, Texmont),reflects the large temperature interval over which olivine is the only crystallizing phase (Arndt, 1976). It is believed that textural variations were produced by variations in the degree of supercooling and rates of nucleation and crystallization within the lava flow profile (e.g. Turner et al., 1986; Fig. 22).

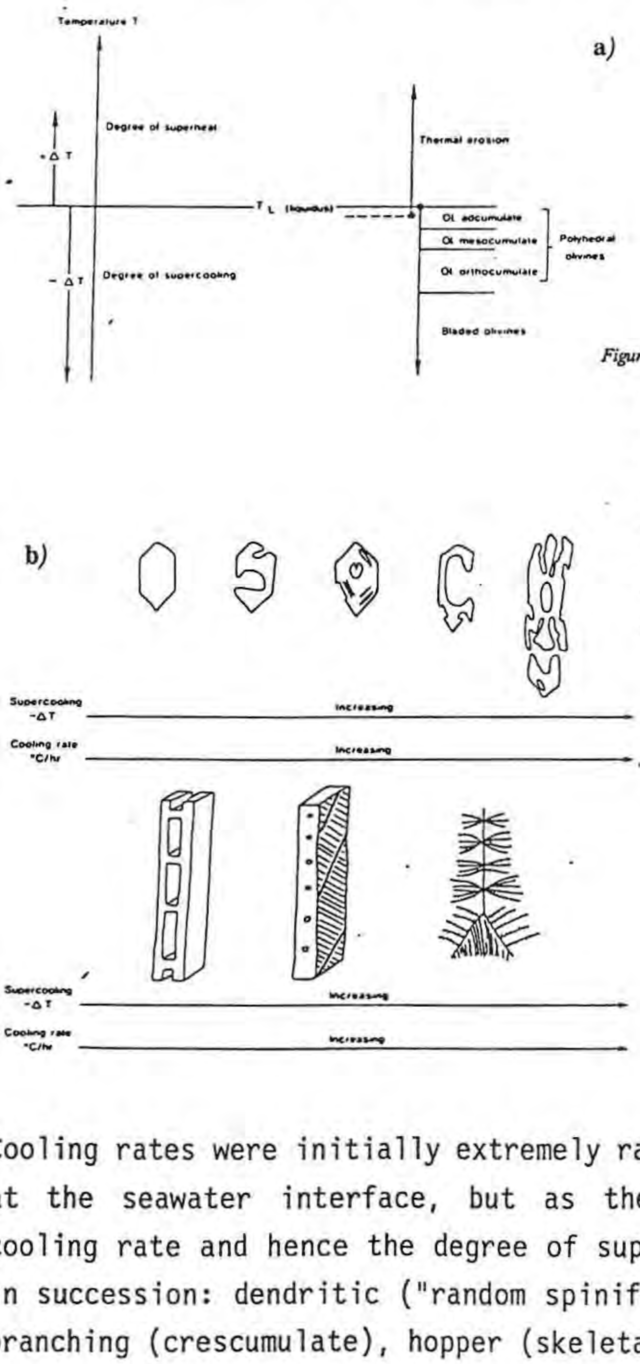



*Figure 22. a) Diagram illustrating the relationship between degree of supercooling (−ΔT) and the development of olivine adcumulate, mesocumulate, orthocumulate and bladed textures. The relationship between degree of superheat and the ability of komatiites to thermally erode their floor rocks is shown. b) Variations in shapes of olivine crystals grown from mafic melts as a function of cooling rate and degree of supercooling at the time of olivine crystallization (adapted from Hill et al., 1987).*

Cooling rates were initially extremely rapid, producing glassy margins at the seawater interface, but as the lava crust thickened, the cooling rate and hence the degree of supercooling declined producing, in succession: dendritic ("random spinifex"), platy (platy spinifex), branching (crescumulate), hopper (skeletal or embayed), and polyhedral (orthocumulate) olivine textures.

Nucleation of the crystals on the roof resulted in the development of spinifex texture. Spinifex olivines grew downwards from the roof into convecting liquid in the lower part of the flow (Fig. 23).

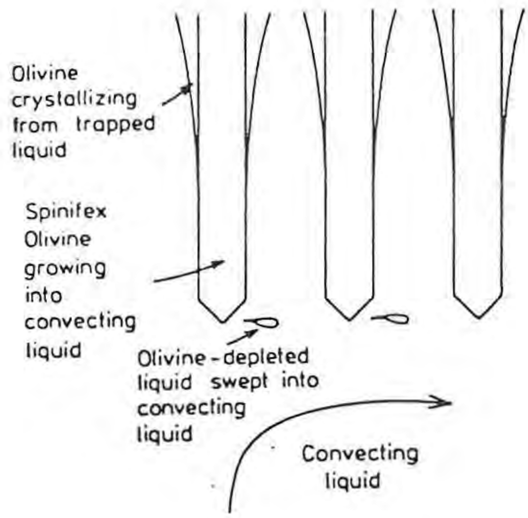



*Figure 23. Diagram illustrating growth of spinifex olivine downwards into convecting liquid in the lower part of a komatiite flow, showing how this process might result in the incorporation of a small proportion of cumulus olivine in spinifex lavas (from Arndt, 1986).*

As they grew, the olivine depleted residual liquid was swept away from the crystals and mixed into the convecting liquid. In this way, the spinifex rocks aquired an olivine content higher than that of the liquid from which they grew (Barnes et al., 1983; Kinzler and Grove 1985). However, olivine accumulation in spinifex lavas could not account for all the olivine that fractionated in the flow. The bulk of fractionating olivine therefore crystallized in the lower part of the flow, where it remained as phenocrysts suspended in the convecting liquid. As the spinifex portion of the flow continued to thicken and olivine continued to crystallize, the olivine phenocrysts became concentrated in an ever decreasing volume of liquid in the lower part of the flow. When the proportion of phenocrysts exceeded 50%, the viscosity of the lava became high enough to inhibit convection, or mobility of the flow. The final product was a differentiated flow with an upper spinifex layer and a lower, olivine-enriched layer.

Assimilation of the footwall rocks beneath lava channels may have depressed the liquidus, resulting in sustained crystallization of polyhedral or crescumulate olivine.

Huppert et al (1984) suggested that during flow, high cooling rates caused either pre-existing phenocrysts to grow, or high nucleation rates. Granular, equant olivine would remain suspended during turbulent flow and initially on emplacement, when thermal convection might occur. As convective stirring diminshed in vigour, the olivine would settle out to form a cumulate layer. The authors believed that olivine crystals nucleated on the roof and at first grew as dendrites in many orientations. However, compositional convection caused a pool of differentiated melt to form between crystals beneath the roof. As the pool developed, the tips of the olivine crystals grew preferentially at the margins, and grew increasingly perpendicular to the roof.

During the formation of the random spinifex part of the flow, at Alexo, the liquid evolved and phenocrysts accumulated in the lower part. However, the chevron spinifex lavas grew from a new pulse of lava which entered the flow at this stage. The liquid had a higher MgO content than the more evolved liquid that was present in the flow, and also a slightly different trace element composition. The high MgO contents of the chevron spinifex lavas is explained partly by the more magnesian liquid and partly by the higher proportion of cumulus olivine that they contain.

Away from the channel, at the terminal flow front, or in associated thinner flows, lavas would cool more rapidly, fractionate more, and crystallize as porphyritic and aphyric flows. The preservation of glassy mesostases in many cumulate rocks indicates that they crystallized rapidly once flow had ceased, prior to reaching their clinopyroxene-plagioclase cotectic.

Huppert and Sparks (1985) suggest that olivine will not settle out of a komatiite magma while it is flowing. The komatiite lava flow will advance whilst the rate of magma supply is sufficient to overcome the drag effect of increased viscosity at the cooling lava front; when the rate of the magma supply falls below some threshold value the lava advance stops. During the static phase crystallized olivines can settle out and form the B-zone. A new influx of magma will displace the earlier, now fractionated magma down the tube. When the new magma flux wanes and flow advance ceases, a new batch of olivines can be added to the B-zone. The earlier fractionated magma, now at the distal end of the flow might be sufficiently fractionated to crystallize pyroxene and form a clinopyroxene spinifex-textured flow (Fig. 24).

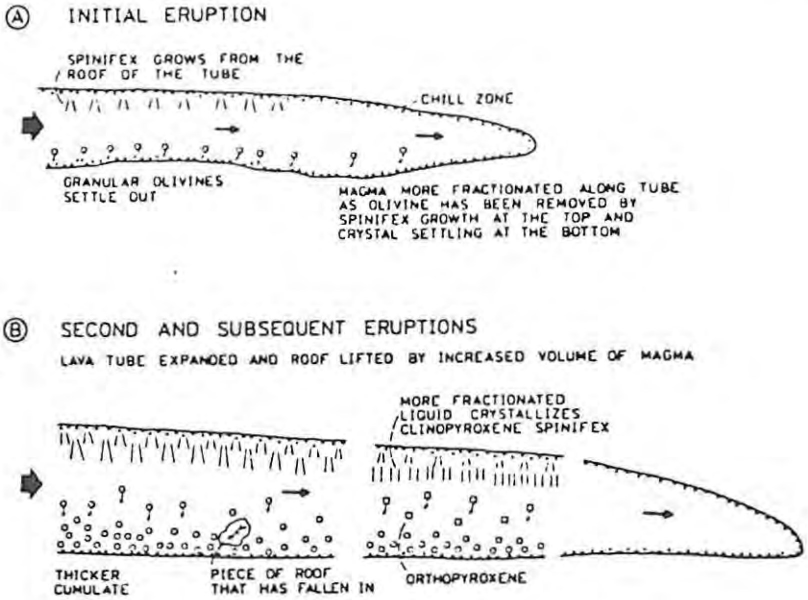



*Figure 24. Model for the formation of komatiite flows (Huppert and Sparks, 1985).*

Mass balance calculations indicate that , at Dundonald and Texmont, more than twice as much liquid, than observed in the A-zone, is necessary to form the volume of olivine in the B-zone. The excess B-zone olivine cannot be intertelluric, since the chill margins contain, at maximum 5% olivine as phenocrysts. This problem may be resolved if it is assumed that flows are dynamic and in fact reflect lava tubes or rivers through which the magma passed whilst crystallizing olivine and sulphides. The poor exposure at Alexo makes a mass balance calculation, such as carried out at Dundonald and Texmont, impossible.

Until recently the B-layer was believed to have formed by gravitational settling of olivine grains, but as noted by Bickle (1982), and shown quantitatively by Turner et al. (1986), convective velocities in cooling komatiite flows probably greatly exceed olivine settling velocities. The olivine grains should have remained suspended in the convecting liquid until it came to rest, and could not have settled to form the lower layer. This model has much in common with the ideas expressed by Turner et al. (1986). However, these authors assign an important role to compositional convection which they believe led to the upward migration and accumulation of an olivine depleted liquid. In the model described above, the differentiation is achieved solely by redistribution of the olivine phenocrysts. From figure 25, it can be seen that the composition of the liquid in the flow changes markedly as olivine fractionates and accumulates in the lower part of the flow.

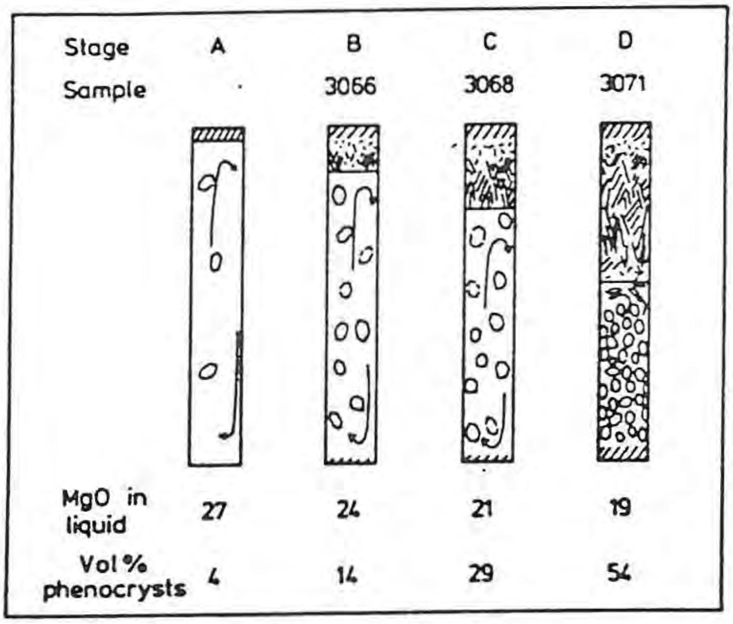



*Figure 25. Diagram illustrating four stages in the solidification of a komatiite flow from Munro Township, Ontario. Mineralogical compositions and analytical data fron Arndt et al., (1977) and A.J.Naldrett (unpubl.data).*

When the lowest spinifex-textured sample crystallized, olivine phenocrysts were present in the lower part of the flow, enough to inhibit convection. It is assumed that the flow crystallized as a closed system.

### 3.5.6 Olivine Enrichment

Observed facies variations, reflect variable degrees of olivine enrichment and internal differentiation, probably resulting from variation in effusion rate, degree of channelization and rate of cooling and crystallization (Fig. 26).

Pyroclastic komatiites are rare, probably because of rapid exsolution of volatiles (if any) from low viscosity lava and the low $SiO_2$ content.

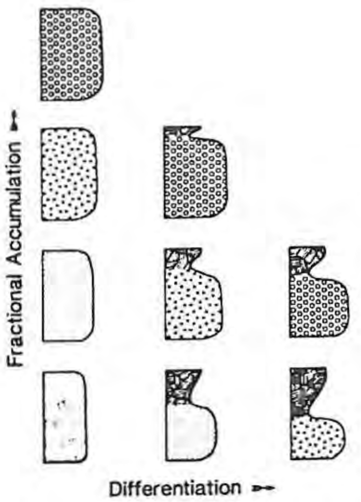



*Figure 26. Facies variations in komatiitic lavas as a function of olivine enrichment (fractional accumulation) and in situ differentiation (fractional crystallization) (modified from Lesher et al., 1984). Aphyric lava is unornamented, other ornamentation as in Fig. 8. Width of profiles is proportional to MgO content.*

The best interpretation of these units is that they represent dynamic lava channels (Lesher et al., 1984; Lesher and Groves, 1986; Barnes and Naldrett, 1987; Cowden, 1988). Textural and compositional variations reflect varying flow conditions. Continuous or periodic lava flow within the channel would replenish crystallizing olivine components without producing excessive fractionation of the silicate liquid. The degree of olivine enrichment in the host units at Kambalda (35 - 65%, calculated by mass balance) could be produced by negligible fractionation of the lava (1-2%) by only 5-10 times the volume of the host unit. The degree of olivine enrichment of the dunitic host units would require proportionally larger volumes of lava.

Proximal parts of lava channels process more lava than distal parts, so lava facies should grade from komatiitic dunite through komatiitic peridotite to komatiite, and possibly komatiitic basalt, along the length of the flow.

The study of pseudomorphs at Kambalda, indicate that olivine occurs in the following habits :

1) large skeletal grains > 2 cm
2) small crystals with hollow or skeletal cores
3) long platy crystals, developed parallel or near parallel to one another,
4) large elongated olivine crystals, showing little skeletal development.

Drever and Johnston (1957) found that skeletal olivine is particularly common in the chilled margins of intrusive bodies, and postulated that direct growth rather than resorption is responsible for skeletal development, and that this development is promoted by crystallization at low temperatures from a supersaturated host. They concluded that there is ample evidence to show that large skeletal olivine phenocrysts can form *in situ* from a rapidly cooling magma and that such phenocrysts have not necessarily been derived from elsewhere.

Mesocumulate-adcumulate textures in komatiitic dunites, textural and compositional variations of olivine with stratigraphic location within komatiitic peridotites and komatiitic dunites, the absence of phenocrysts in the upper chilled margins of the komatiitic peridotites, the presence of crescumulate olivine within, and at the base of some komatiitic peridotites, and geochemical models of komatiitic peridotites and dunites indicate that most olivines crystallized *in situ*.

### 3.5.7 Footwall Embayments

Sulphide ores are normally localized in or over embayments in the footwall (refer to section 3.2.5). Four models presently exist:

1) synvolcanic faulting (Ross and Hopkins, 1975; Gresham, 1986),

2) post-volcanic structural deformation (Cowden and Archibald, 1987; Cowden, 1988),

3) thermal erosion (Huppert et al., 1984; Huppert and Sparks, 1985; Barnes et al., 1988; Evans et al., 1988), and

4) volcanic topography (Green and Naldrett, 1981; Lesher et al., 1984).

It is possible that all have influenced the present geometry of the embayments to some degree.

#### 3.5.7.1 *Synvolcanic faulting*

This model is based on the Lunnon shoot. The Lunnon fault system comprises a series of faults producing net displacement on marker horizons in the komatiite sequence. Cowden (1988) contended that the embayment at Lunnon was generated from a roughly planar contact by strike-slip faults cutting dipping contacts, but this cannot explain the volcanological and stratigraphic relationships. It is unlikely that many of the embayments have been generated by syn-volcanic faulting.

### 3.5.7.2 *Post-volcanic deformation*

Most embayments at Kambalda have been modified to some degree by superimposed polyphase deformation. Cowden (1988) suggested that most have been generated entirely by deformation of near planar contact (Fig. 27). Although Lesher et al. (1984) have maintained the presence of 2-30 m deep pre-tectonic embayments, detailed underground mapping of stratigraphy in the footwall basalt in other areas in Kambalda, supports the presence of pre-tectonic embayments. In many cases, embayment contacts correlate with cooling unit boundaries in the basalt.

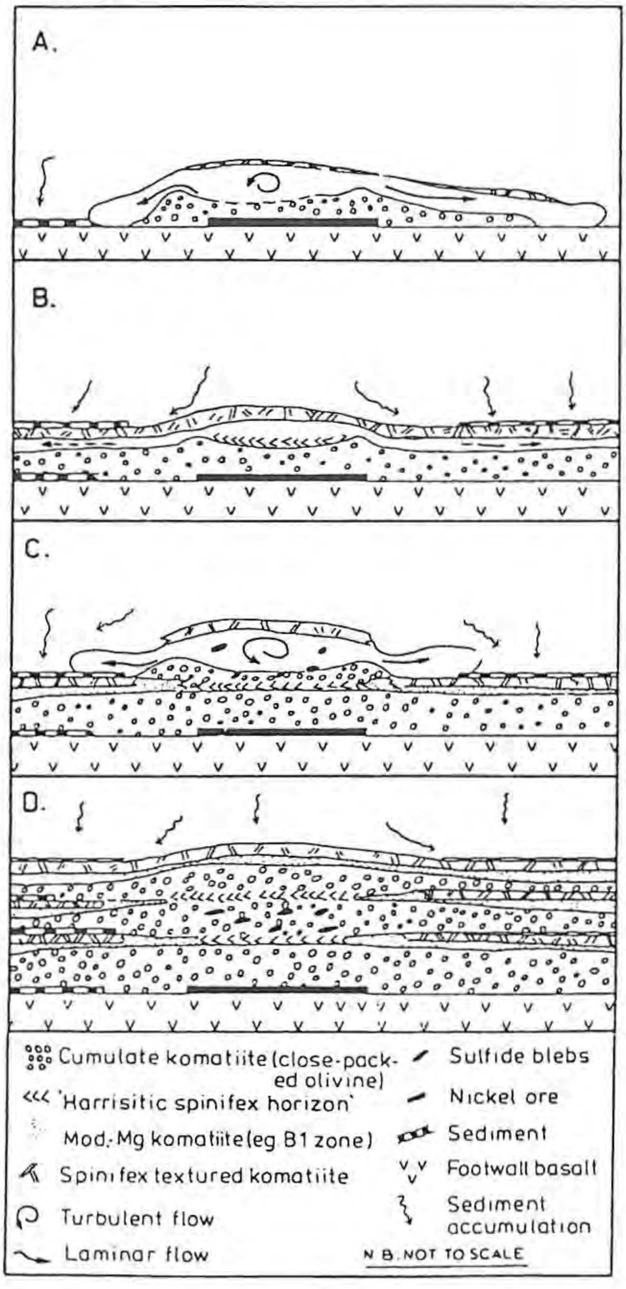



*Figure 27. Diagrammatic rendering of the development of the komatiite lava complex, stage by stage. A. Single lava flow with turbulent flow and bottom crystallization-accumulation of olivine in the main channel and a lateral, laminar flow of derivative liquid. B. Cessation of flow-through in the main channel, cooling and crystallization of flanking flows, accumulation of sediments, and growth of harrisite in the stagnant lava tube. C. A new pulse of sulphide-bearing magma inflates the stagnant lava tube an spills laterally to give more differentiated flanking flows. D. The final lava complex with a continuous spinifex cap to the whole feature, and the lateral equivalence of multiple lava channel and flanking flows (Cowden, 1988).*

3.5.7.3 *Thermal erosion*

Thermal erosion explains the general correlation between depths of embayments and ore-sediment relationships of class IA deposits. Huppert et al. (1984) and Huppert and Sparks (1985) suggest that the embayments at Kambalda may have been generated by thermal erosion beneath linear lava channels; the highly deformed central part of the Foster shoot shows clear evidence of this.

There are other field relationships, however, which suggest some embayments may not have been generated entirely by thermal erosion. The bases of most embayments at Kambalda are parallel to the stratigraphy in the footwall, many correlate with cooling unit boundaries in the adjacent basalts, and therefore appear to be stratigraphically conformable within the footwall sequence. Some embayments at Kambalda are elliptical and are not likely to have formed by thermal erosion.

3.5.7.4 *Volcanic topography*

Lesher et al. (1984) proposed that embayments represented kipukas, (inliers between non-overlapping basalt flows), which have been variably modified by thermal erosion and superimposed structural deformation. Volcanic topography would also explain the general correlation between the depth of embayment and nature of the substrate that is evident in class IA deposits. Embayments in the southern part of the Norseman-Wiluna belt and the Timmins areas of the Abitibi belt, for example, overlie volcanic rocks that are more pronounced than those in the Windarra district or Zimbabwe province that overlie sedimentary rocks.

It seems almost certain that there were original topographic variations in volcanic terrains and that these would focus and channelize lava flows.

3.5.8 Volcanic Setting

The stratigraphy of most komatiite host sequences (refer to section 3.2.1), suggests emplacement within a relatively deep subaqueous environment (Fig. 28).

Proximity to eruptive sites may be inferred from proximity to volcanic feeders, physical volcanology of lavas, and stratigraphic relationships with associated volcanic and sedimentary rocks. The Dumont dunite appears to be derived from a komatiite parental magma, but it is significantly different from other class IIB deposits:

1) it is intrusive into a sequence of tholeiitic basalts and

2) it contains a thicker upper zone of gabbroic differentiates. Thus, it is intruded into petrogenetically unrelated rocks and evolved by fractional crystallization without significant magma replenishment.

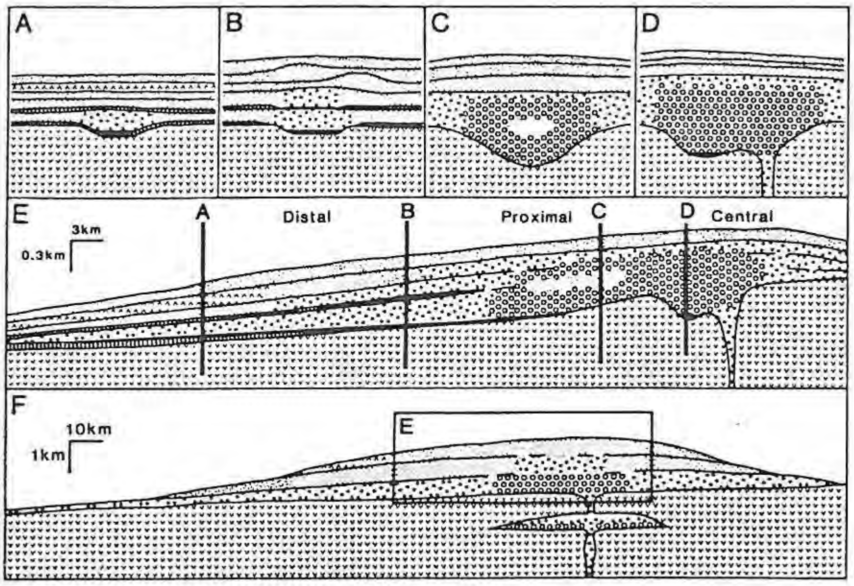



*Figure 28. Schematic cross section through an Archean komatiite volcano showing possible volcanic settings (A-D) and regional-scale stratigraphic relationships (E-F) of komatiite-associated nickel sulphide deposits (modified after Lesher and Groves, 1986) Ornamentation as in Fig. 8.*

The Shangani and Epoch deposits in Zimbabwe are associated with barren differentiated komatiitic sills (Williams, 1979).

The Shangani deposit appears to occur directly within a volcanic vent, and is associated with a thick differentiated komatiitic intrusive complex. Part of the mineralization at the stratigraphically equivalent Silwane deposit also occurs within a possible footwall feeder. These appear to be the only examples of deposits in central volcanic settings.

The Damba and Langmuir #2 deposits (Green and Naldrett, 1981) occur near possible feeder zones. Both deposits have been interpreted to occur in proximal volcanic settings (Williams, 1979; Green and Naldrett, 1981).

The majority of these deposits, including all of those in the southern and northern parts of the Norseman-Wiluna belt,do not occur near volcanic feeders and are not associated with pyroclastic rocks or intrusives. They are therefore interpreted to occur in distal volcanic settings (Lesher et al., 1984; Donaldson et al., 1986; Lesher and Groves, 1986; Hill et al., 1987). The concentration of class IA deposits in the southern part of the belt and class IIB in the northern part may simply reflect different eruption rates in the two areas, komatiitic dunites (Group II) may have been ponded to a greater degree, or komatiitic peridotites (Group I), may represent a distal facies of komatiitic dunites.

## 3.6 ORE GENESIS

A variety of evidence supports ore genesis associated with a magmatic origin:

1) The sulphide ore is associated exclusively with the most magnesian, lowermost units in the komatiite sequence. A strong volcanic control is observed in Class IA deposits, which are spatially related to variations in the internal structure, physical volcanology, and stratigraphy of the overlying komatiite sequence.

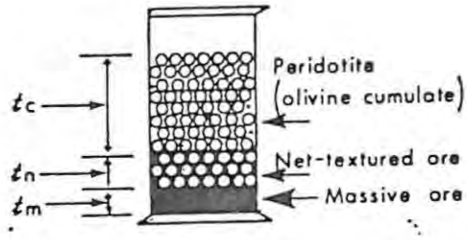
2) Stratabound disseminated sulphides and stratiform massive sulphides predate deformation, metamorphism and alteration of host rocks.

3) Stratiform sulphides exhibit a massive/disseminated matrix ore segregation profile, indicative of gravitational settling. They also contain distinctive chalcophile ferrochromites, similar to those crystallized experimentally from sulphide-oxide liquids.

4) The high Ni and PGE contents, high Ni/Cu and Pd/Ir ratios, and low Zn contents of the ores are consistent with well known and inferred metal partitioning behaviour in ultramafic-mafic magmatic systems. Olivine-silicate and silicate-sulphide data are internally consistent and support a magmatic origin for the sulphides.

A variety of different models have been proposed for the genesis of komatiite-associated nickel sulphide deposits, most involving segregation of immiscible sulphide-oxide liquids from komatiitic magmas.

The fully developed sequence of ore types fits the magmatic "billiard ball" analogy (Fig. 29; Naldrett, 1973), in which the sequence within an ore deposit is compared to billiard balls that have settled through water and become partially immersed in a basal layer of mercury (refer to section 2.3.1).




$\rho s$ = density of sulfide liquid

$\rho o$ = density of olivine

$\rho l$ = density of silicate liquid

if porosity of net ore is 50% and of olivine cumulate is 40%

then $t_n \times 0.5 \times (\rho s - \rho o) = t_c \times 0.6 \times (\rho o - \rho l)$

but $\rho s - \rho o \simeq 0.7$ and $\rho o - \rho l \simeq 0.35$

thus $t_c \simeq 1.7 \times t_n$

*Figure 29. The billiard-ball model (Naldrett, 1973).*

Usselman et al. (1979) have used a finite element thermal modelling approach to check the "billiard ball" analogy. They concluded that the massive sulphide would have crystallized by heat loss to the underlying country rock prior to the accumulation of substantial amounts of olivine, provided that the phenocryst content of the flow at the time of emplacement was less than 10-20%. At Langmuir there is no such evidence and it is quite possible the magma carried less phenocrysts than this.

However, the introduction of the "channel concept" for lava emplacement (refer to section 3.5.4), has proved a further explanation for the occurrence of Ni-Fe-Cu sulphides at the base of the komatiite flows. If sulphide-bearing sediments were assimilated, they would immediately form an immiscible sulphide liquid, because sulphur has low solubility in silicate melts (Nesbitt, 1986). The liquid would then scavenge Ni and Cu out of the komatiite melt and the resultant Ni-Fe-Cu sulphide liquid would settle into topographical lows at the base of the komatiite flow, which itself was still molten. Although the sulphide-silicate immiscibilty model is not new one, this scheme provides an explanation for the origin of the sulphur and for the channel or trough-like structures, which are a prominant feature of almost all komatiitic nickel sulphide deposits.

### 3.6.1 Timing of Sulphide Separation

Sulphide separation is time dependent, and only occurs in a silicate melt when it becomes saturated in $S^{-2}$. Naldrett (1979) noted that a number of factors affected sulphur solubility:

i) decreasing temperature,

ii) decreasing $a_{FeO}$ or increasing $a_{SiO2}$,

iii) decreasing $f_{S2}$ or increasing $f_{O2}$ and/or

iv) increasing pressure.

#### 3.6.1.1 *Strata-bound Deposits*

The disseminated nature of the strata-bound sulphide ores, their concentration in central parts of host units, and the presence of multiple ore horizons in some deposits, indicates that sulphide saturation occurred relatively late in their crystallization history.

The proportions of olivine and sulphide (60:1) at Dumont, for example, are roughly consistent with crystallization along the intersection of the olivine liquidus and the sulphide-silicate liquid solvus in a komatiite magma (Duke, 1986). However, there is no simple relationship between degree of accumulation and degree of mineralization. Duke (1986) suggested that sulphide saturation occurred when fractionated, sulphur-enriched intercumulus liquid was expelled upward by filter pressing of partially molten underlying cumulates, and mixed with less evolved liquid at the temporary floor of the magma chamber. In this model the proportions of olivine and sulphide which separate from the melt are constrained by the thermodynamic properties of the melt and there is a limit on the amount of sulphides that may precipitate (Duke, 1986). This is consistent with the restricted range of grades for deposits of this type (< 0.8% Ni).

3.6.1.2 *Stratiform Deposits*

In contrast, the segregation of stratiform ores at the base of the host unit indicates that sulphide saturation occurred relatively early in their crystallization history. The question has been whether sulphides -

i) where transported directly from the mantle,

ii) separated in a sub-volcanic magma chamber,

iii) separated during ascent, or

iv) separated during eruption and emplacement.

3.6.2 Sulphur Source

Groves et al. (1979) suggested that the near-zero value of isotopic ratios for Archean sulphides in ultramafic and metasedimentary rocks indicate that sulphur is exclusively of magmatic origin and that there was limited fractionation in the sedimentary environment (refer to section 3.4.6). They further point out that a marked variation in the $\delta^{34}S$ could not be expected from the sulphides derived directly from the mantle and the sulphides derived from crustal contamination.

To further test the origin of sulphur in the ores, the sulphur isotope ratios of ore and footwall samples were determined (Green and Naldrett, 1981). Ore samples from Langmuir have $\delta^{34}S$ values ranging from -2.2 per mil to +2.2 per mil (Fig. 19). However, the near-zero values of these samples were not considered to be diagnostic of a particular origin for the ores. Therefore the sulphur isotopic data was not regarded as permissive of different origins and not diagnostic of a source of the sulphur in the Langmuir deposits.

Muir and Comba (1979) proposed a magmatic flow origin for Dundonald. Studies at Alexo, Hart and Texmont deposits confirm their overall similarities to Langmuir.

A magmatic origin is likely for them all. However, the degree of contamination by crustal sulphides may well have been different among the deposits. In a study of the Pipe deposit (Manitoba) Naldrett et al. (1979), concluded that the metal values there, were best explained by postulating that a large amount of sulphide had reacted with a large amount of magma, possibly as a result of the assimilation of country rock sulphide. Considering the small size of most of the deposits in the Abitibi belt, this process may be an important one.

3.6.2.1 *Mantle Sulphur*

A number of authors have proposed a model by which sulphur is of mantle derivation (e.g Malyuk, 1984). However, Lesher and Groves (1986)have noted that there are a number of constraints that would adversely affect the eruption of sulphide-saturated komatiites.

a) Petrogenetic constraints - the degree of sulphide-saturation of a magma is very much dependent on the amount of sulphur in the source and the degree of partial melting. Depending on the mechanism of magma generation, there are several possible scenarios:

i) Komatiites derived from a laterally extensive mantle melt layer (Nisbet and Walker, 1982), should not be saturated in sulphides, because of the large volume of melt;

ii) Komatiite melts generated by multistage melting or mixing processes (Bickel et al., 1977; Smith and Erlank, 1982),are unlikely to be saturated in sulphide. Sulphur would partition into early melts and/or be physically lost as dense sulphide during melt segregation, and residual melts would be driven off the sulphur saturation surface by continued partial melting/mixing;

iii) Komatiitic melts generated by single-stage partial melting (Takahashi and Scarfe, 1985), may or may not be sulphur saturated.

Shima and Naldrett (1975) suggested that in order to achieve concentrations of 0.16-0.27% S at 50-70% partial melting, a source would be required that contained 800-1900 ppm S; whereas at 10-30% melting, only 160-810 ppm S would be required. Current estimates of S abundance in the Archean mantle (Sun, 1982) suggest a S range of 350-100 ppm, but assume that the mantle melts are not saturated in sulphide and that 50% partial melting is required to produce a komatiitic magma.

b) Thermodynamic constraints - experimental studies by Helz (1977), Huang and Williams (1980), and Wentlandt (1982) have shown there is a strong negative pressure dependence on sulphur solubility in basaltic melts and, sulphur saturation isopleths are parallel to anhydrous silicate liquidi. If sulphur saturated at depth, magmas which ascend along liquidus paths should be sulphur saturated during ascent (Fig. 30), and may therefore exsolve an immiscible sulphide liquid during and after eruption.

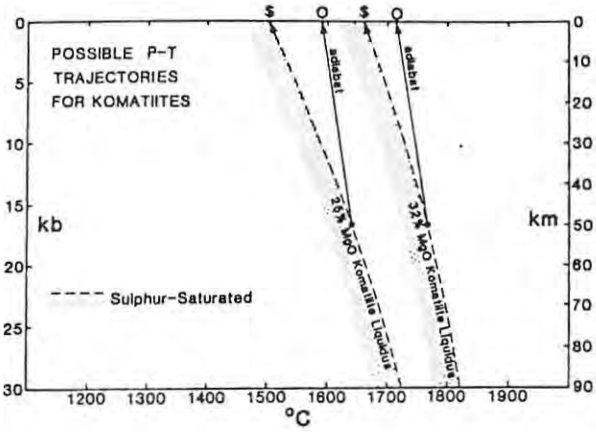



*Figure 30. Sulphide saturation model showing possible P-T trajectories of komatiites (after Lesher and Groves, 1986). Dashed curves are liquidus ascent paths (Arndt, 1976; Bickle et al., 1977; Bickle, 1978); solid curves are adiabetic ascent paths (dT/dP = 3½C/kb). $ = sulphide saturated lava, O = sulpdie-undersaturated lava.*

However,there is no evidence of significant intratelluric phenocryst contents in komatiites, and magmas of such low viscosity should ascend rapidly and lose little heat. Komatiites should ascend along steeper P-T trajectories, nearer to an adiabatic gradient and should arrive at the surface superheated and sulphur-undersaturated.

c) Geochemical constraints - nickel depletion in spinifex-textured komatiites and Zn enrichment of chromites throughout mineralized komatiite sequence in Western Australia have been used to infer that the precusor magmas were sulphur-saturated prior to eruption (Lesher et al., 1981; Lesher and Groves, 1984; Naldrett et al., 1984). It is quite possible that the barren upper parts of a mineralized sequence in one area of the volcanic belt may be the facies equivalent of mineralized parts of a sequence in another area of the belt. Thus, chalcophile element depletion and Zn enrichment may be attributed to assimilation of Zn-rich sulphidic sediments and precipitation of sulphides during emplacement.

The sulphur isotopic differences between districts and significant deviations from chondritic values are not consistent with derivation from a homogenous mantle source. It is unlikely that there is any oxidized sulphur in the mantle, and at such high temperatures significant fractionation of sulphur isotopes between oxidised and reduced species would be unlikely anyway (Ohmoto, 1986).

d) Geological constraints - the present distribution of sulphide is not necessarily representative of their abundance in the original magma, because the host units are laterally more extensive than the ores. Possibly the strongest argument that the komatiites were not sulphide-bearing during eruptionis the virtual absence of mineralization outside of the ore zones. If sulphide-bearing magmas were erupted, then the entire host unit should contain ubiquitous disseminated mineralization, for example, sulphides should have been trapped in the chill margins of the host units, they should have continued to exsolve throughout host units as the lavas cooled, oxidised, and crystallized after emplacement. Fractional accumulation of the sulphur-saturated komatiitic lavas should have resulted in significant enrichment of sulphides as well as olivine.

3.6.2.1 *Crustal Sulphur*

Sedimentary sulphur sources were proposed by Prider (1970), Hudson (1972), Lusk (1976), and Hopwood (1981). More recently, assimilation of crustal sulphur has been proposed to explain the anomalous S/Se and sulphur isotopic variations between deposits (refer to 3.4.6). Lesher and Groves (1986) have proposed assimilation of sulphur from sediments during lava emplacement, related to the "channelization" process. However, sedimentary xenoliths are rarely preserved due to the dynamics of these lava channels (Bavington 1981). Pb-Pb isotope studies of iron sulphides from nickel ores and adjacent sulphidic sediments suggest mixing of mantle and older crust lead (Parker, 1984). Biotite-rich zones in the Six Mile dunite are also interpreted to represent partially digested sediments (Naldrett and Turner, 1977).

The restriction of sulphide ores to embayments in the footwall, in areas where sulphidic sediments are thinned or locally absent, suggests that they were thermally eroded beneath active lava conduits (refer to section 3.5.4), melting sulphide, which scavenged chalcophile elements from the komatiite lava to form Fe-Ni-Cu sulphide ores. The absence of sediments and mineralization in areas adjacent to ore zones may indicate assimilation of sulphide into sulphide undersaturated lava, or physical mobilization in the central part of the channel.

The sulphur isotope variations in these deposits are best attributed to fractionation of sulphur isotopes in a hydrothermal-exhalative-sedimentary environment with subsequent incorporation in, and mixing with, magmatic sulphur in komatiitic magmas. Windarra and Langmuir occur in volcanic sequences that contain oxide facies iron-formations, indicating a more oxidizing environment than the sulphidic sediments at Kambalda and Trojan, which is consistent with their higher S/Se ratios.

The mixing of crustal and magmatic sulphur would explain the minor, but systematic differences between sulphur isotopic compositions of ores and associated sulphidic country rocks.

### 3.6.3 Ore Tenor Variations

Bulk ore compositions vary between deposits, particularly at Kambalda, where they appear to define belts; yet, they occur within the same metamorphic and tectonic setting, and are hosted by similar lithologies. These variations have been attributed to a number of factors:

#### 3.6.3.1 *Magma Composition*

Rjaamini and Naldrett (1978) demonstrated that the composition of the silicate melt strongly influences the partioning behaviour of chalcophile elements between immiscible sulphide liquid and silicate magma. The equilibrium crystallization model, however, requires over 50% fractionation to produce a basaltic derivative liquid in order to produce the range of Kambalda ore compositions. Models by Duke and Naldrett (1978) indicate that the range of Kambalda ore compositions could be accounted for by 40% fractionation of olivine and sulphide in a ratio of 100:1 from a 32% MgO parental komatiite, to produce 22% MgO derivative liquid (Fig. 31).

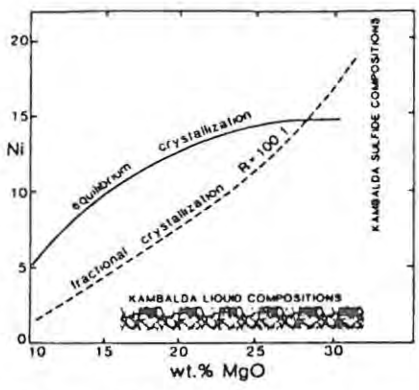



*Figure 31. Equilibrium and fractional crystallization models of Ni-MgO relationships between sulphide ores and komatiite magmas (modified after Cowden and Woolrich, 1987).*

Lesher and Groves (1986) and Cowden and Woolrich (1987) argued that the limited 28-32% MgO range of the initial liquid compositions of the host units indicates that the ore tenor variations between different ore shoots could not be attributed entirely to variations in the compositions of the komatiitic magma. However, this interpretation is valid only if komatiites were erupted carrying immiscible sulphide droplets. Although the absence of a chilled margin of komatiite beneath the ore zones at most Kambalda shoots has been used previously to infer that sulphides were emplaced early, chilled margins were probably thermally eroded (Huppert and Sparks, 1985). If sulphide separation and equilibration occurred after formation of the chilled margin, the sulphides may have equilibrated with more fractionated/hybridized lavas. Thus, variable degrees of fractionation and hybridization during emplacement in a dynamic lava conduit could account for the range of ore compositions within the different ore shoots at Kambalda.

Barnes and Naldrett (1986) noted that the ore composition at Alexo is consistent with equilibration of a low-Mg liquid, not the high-Mg represented by the chilled margins, and proposed that sulphides separated after the flow had begun to crystallize and fractionate.

3.6.3.2 *Variations in $f_{O2}$ (oxygen fugacity)*

The oxidation of a silicate magma will result in a reduction in the number of octahedral sites available to metals (Cowden and Woolrich, 1987) As the octahedral site preference energy (OSPE) for Ni is greater than that for Fe, they theorise that Ni/Fe in sulphide should increase with increasing $f_{O2}$ and calculate that the entire range of Ni abundances in Kambalda ores could be accounted for by by increasing $F_{O2}$ by only one log unit. They suggest that high tenor ores reflect equilibration during emplacement, whereas low and medium tenor ores reflect disequilibrium compositions inherited from equilibrium at depth. In contrast, Doyle and Naldrett (1987) suggest that the Ni-Fe distribution constant between sulphide and olivine decreases with increasing O/O + S in the magma, suggesting that Ni/Fe in sulphide should decrease with increasing $F_{O2}$ in the magma. The Cowden and Woolrich (1987) model requires sulphides to be erupted from depth and requires different ore shoots to be emplaced separately as different eruptive episodes. This is inconsistent with the above evidence against early sulphide separation, and with observed stratigraphic relationships. Low viscosity komatiites should form sheet-like flows. The different ore shoots (channels) were probably emplaced at or near the same time.

Woolrich et al. (1981) suggested that variable oxidation also could have occurred in the cooling lava. Small volumes of sulphides (high tenor shoots) may have oxidized more rapidly than large volumes of sulphides (low tenor shoots).

### 3.6.3.3 *Magma:Sulphide Ratio*

Campbell and Naldrett (1979) noted that the partitioning behaviour of metals between sulphide and silicate liquids should be strongly influenced by the mass ratio (R) of the two phases.

Magmas that equilibrate with large amounts of sulphide should be rapidly depleted in chalcophile elements (refer to section 3.4.5), resulting in lower tenor ores, whereas magmas that equilibrate with small amounts of sulphides should retain normal abundances of chalcophile elements, resulting in high tenor ores. Lesher and Groves (1986) suggested that the lower tenor of the thicker ore shoots at Kambalda confirms a relationship between ore tenor and the amount of sulphide.

# 4.0 THE SIX MILE NICKEL DEPOSIT, EASTERN GOLDFIELDS, WESTERN AUSTRALIA

## 4.1 INTRODUCTION

The Six Mile Deposit (SMD) on the Yakabindie homestead is 100 % owned by Dominion Mining Ltd. This deposit is a large, disseminated Ni-sulphide occurrence, with a grade of about 0.55 % Ni with minor cobalt. The nature of the deposits' mineralogy enables a unique nickel product to be produced, for primary ore, grading at about 20% Ni, 0.5% Co, 30 % Fe and 27% S.

At the planned milling rate of 6.0 mt/y of ore, this deposit will produce over 20,000t/y of Ni in concentrate for 12 - 13 years, by this stage, the planned pit will be 350 m deep.

## 4.2 REGIONAL SETTING

The Six Mile nickel deposit occurs within Archean rocks of the Yilgarn Block of Western Australia (Fig. 3). The characteristic occurrence and form of numerous greenstone sequences allows the Yilgarn to be subdivided into three regions: the Western Gneiss Terrain, the central region (Murchison and Southern Cross Provinces), and the Eastern Goldfields Province.

The Western Block is characterised by banded quartz-feldspar-biotite gneisses. The remaining two regions are characterized by greenstone belts and comprise, the Central area subdivided into the Murchison and Southern Cross Provinces and, the eastern division known as the Eastern Goldfields Province, the largest area of Archean rocks in Australia.

It is generally believed that greenstone accumulation occurred in a gneissic basement over a sustained period about 2.0 Ga ago, contemporaneous with rifting along crustal sutures. Continued rifting in the waning stages of greenstone development, resulted in a late phase of conglomeratic sediments.

It is within the Eastern Goldfields Province that the Six Mile nickel deposit lies, nestled within the 650 km long, 330 km wide Norseman-Wiluna Belt. The area consists of metamorphosed and sedimentary sequences with an age range of 2.8-2.65 Ga. Stratigraphic correlations throughout the area are tenuous, although detailed stratigraphic columns have been erected for specific fault-bounded areas (Groves and Batt., 1984). Such sections comprise a thick, lowermost tholeiitic basalt sequence, overlain by komatiites and Mg-rich (or komatiitic) basalts, and an upper felsic-volcanic and clastic sedimentary sequence. The Norseman-Wiluna greenstone belt is NNW-trending, anastomosing belt intruded by syn- and post tectonic granitoids and characterised by one or more generation of NNW-trending upright folds, which deform earlier recumbent folds or thrusts (e.g Archibald et al., 1981). Regional deformation was largely synchronous with late deformation. Low-strain domains of very low to moderate metamorphic grade, in which relict textures are well preserved, contrast with more localized domains of high strain and moderate to high metamorphic grade (Binns et al., 1977).

Although komatiite bodies are widely distributed, mineralized bodies are restricted to two main areas of the Yilgarn Block. Most are in the northern part where discontinuous lenses occur over a 150 km long linear zone between Agnew and Wiluna. Komatiite dunites (Group II) have an almost antipathetic relationship with well-mineralized komatiites.

### 4.2.1 The Agnew - Wiluna Greenstone Belt

This belt forms the northern third of the Norseman-Wiluna Greenstone Belt (Fig. 32). Northwards, the belt thins considerably, and is characterised by tectonic lineaments or strike faults, traceable over hundreds of kilometres. Faulting in the belt produced elongate slices, which has allowed relatively easy lithological correlation.

Naldrett and Turner (1977) proposed a subdivision, for the lithologies between Agnew and Mt Keith, based on substantial diamond drilling in the Yakabindie area. These divisions are the Upper and Lower Greenstones sequences.

The Lower greenstones, exposed in the Agnew-Lawlers area, include sequences of layered gabbros, mafic volcanics and komatiites overlain by siltstones, pebbly sandstones and conglomerates, collectively known as the Lawlers Conglomerate.

The remaining lithologies between Agnew and Wiluna are assigned to the Upper Greenstones, above the Lawlers Conglomerate.

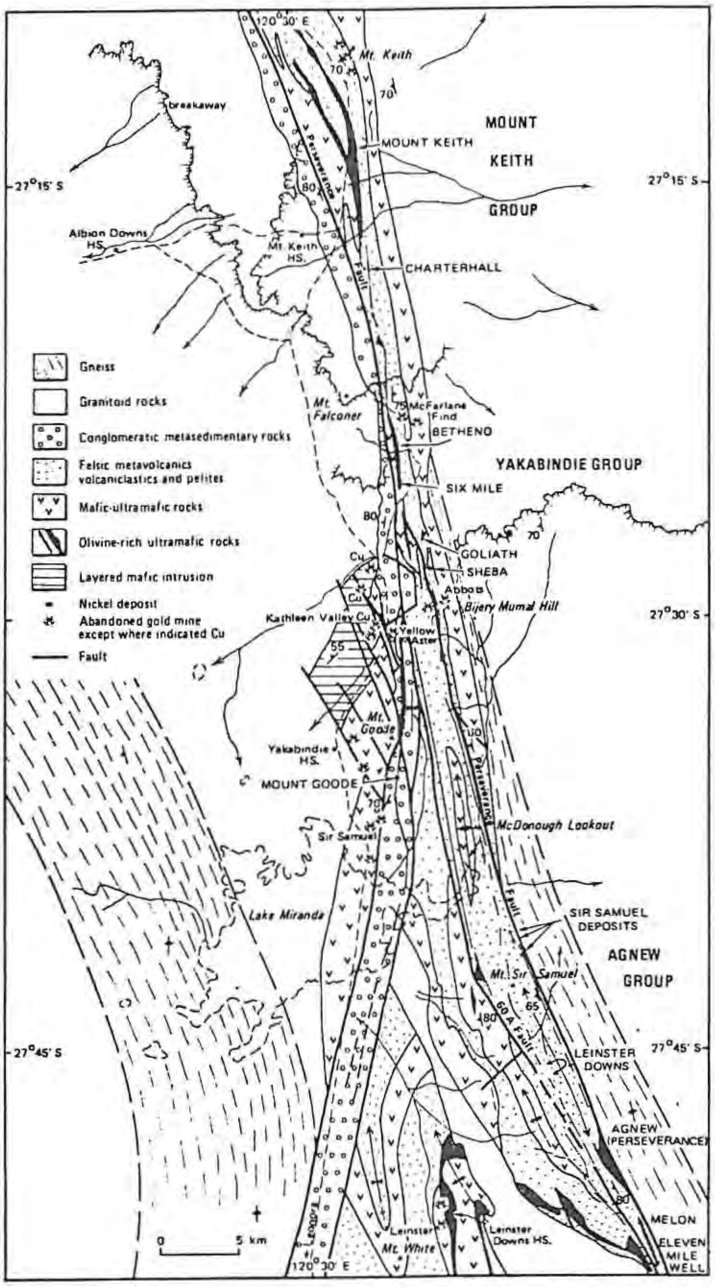



*Figure 32. Geologic map showing the setting of the Agnew, Mt. Keith and Yakabindie groups of nickel deposits (Marston et al.,1981).*

The most notable characteristics of the deposits in this area are the spatial association with large lenticular bodies of dunite, discordant on a local scale. The observed differences between the host rocks of these deposits, led to the classification of Dunite and Peridotite-associated deposits (Naldrett, 1973). (Refer to section 3.1).

## 4.3 LOCAL SETTING - THE YAKABINDIE/SIX MILE WELL SECTION

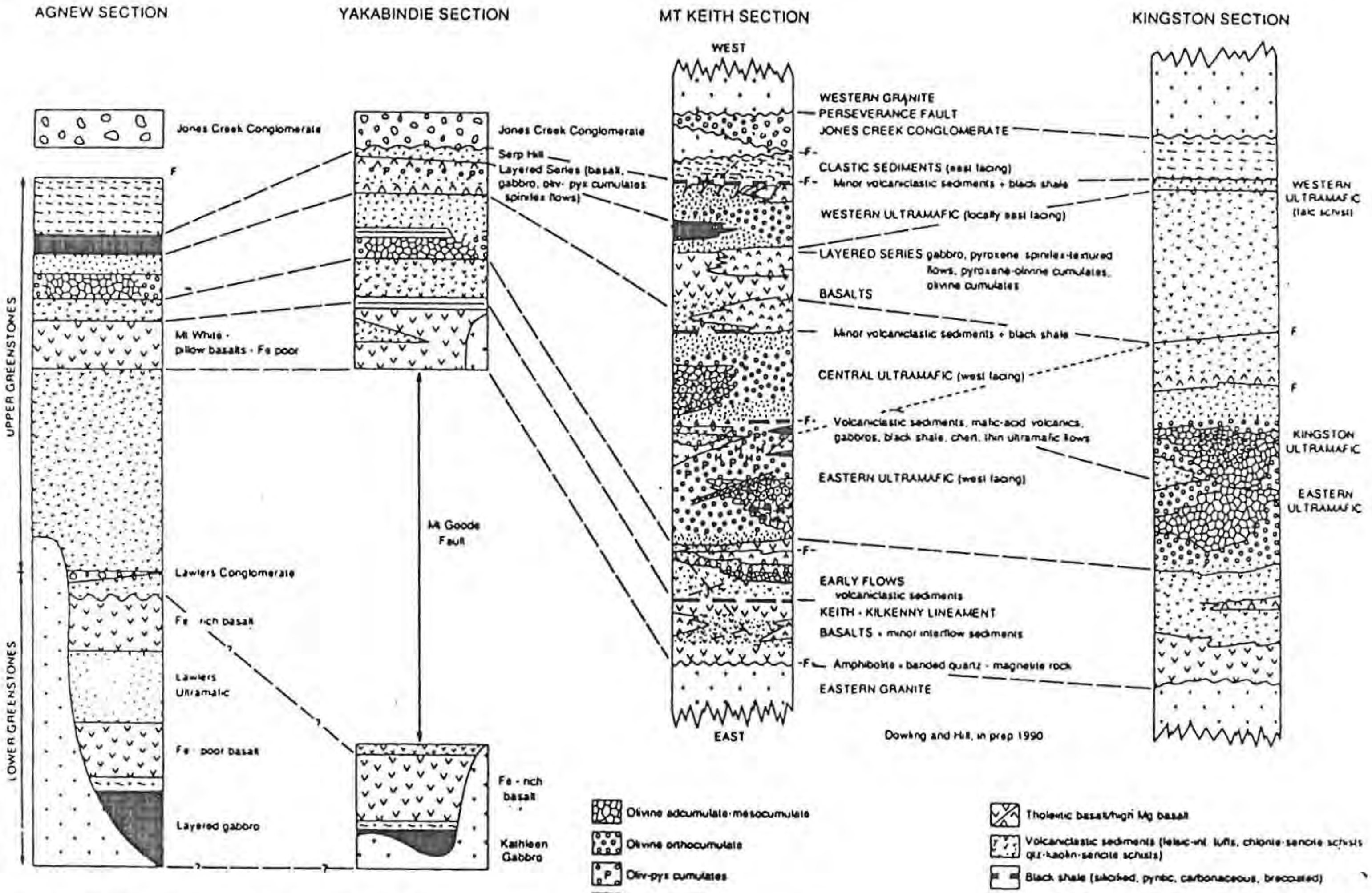
The structure of the Yakabindie section is dominated by two major NNW - striking faults; the "Mt Goode Rift" and the "Perserverance Fault", which are responsible for dividing the area into three separate blocks. The Yakabindie section is defined as the area between Mt Sir Samuel and the Six Mile deposit itself.

Despite complex structural disruption and areas of poor outcrop, the Upper Greenstone lithologies, of Naldrett and Turner (1971) are well exposed in the Yakabindie area, and are of particular importance in housing the Six Mile Deposit. A characteristic stratigraphy was developed (Fig. 33), consisting of a lower basalt unit overlain by a thin chert (including minor high-Mg variants), hosting a series of dunitic-peridotitic lenses, a thick sequence of felsic to mafic volcanoclastics with minor pelitic sediments and black shales, surmounted by a zone dominated by extensive komatiitic volcanic flows and, a upper series characterised by thin komatiite flows (interspersed mainly with layered gabbroic units), high-Mg and tholeiitic basalts, and subordinate felsic volcanic units. The fine to medium-grained clastic sedimentary units and the Jones Creek Conglomerate constitute the youngest sequences exposed, interpreted as having formed in a linear basin or graben structure.

In the northern part of the area near Six Mile Well, the Mt Keith fault transects the stratigraphy westwards, and a complex series of strike slip and oblique faults has removed some of the lower lithologies. The stratigraphy above the komatiite units is exposed in a shallow, northward plunging syncline, referred to as the "Serp Hill" syncline.

### 4.3.1 Ultramafic Rocks

The Upper Greenstone Sequence is continuous for at least 100 km of



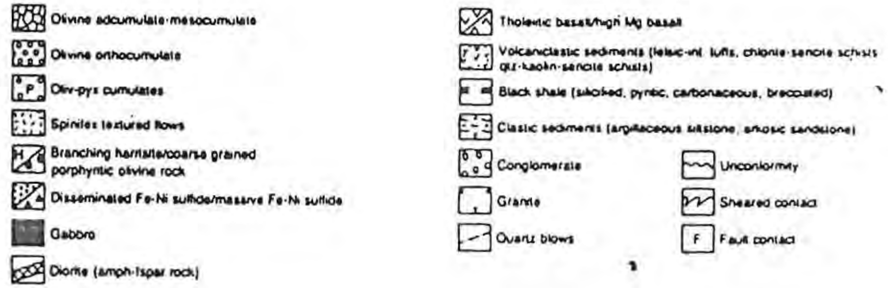



*Figure 33. Schematic stratigraphic columns through the Agnew-Wiluna Greenstone Belt, showing tentative correlations between successions in the Agnew, Yakabindie (Naldrett and Turner, 1977), Mt. Keith and Kingston areas (Dowling and Hill, unpubl ms., 1990).*

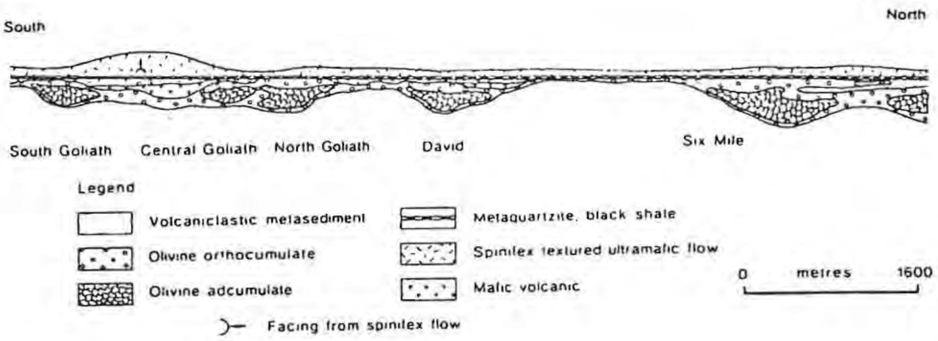
strike length, however, the ultramafic rocks are confined to a particular interval within the stratigraphy, attaining thicknesses of up to 1.5km. With the aid of relict igneous textures, in surface exposures and drill cores, a reconstruction of the spatial association of various igneous lithologies has been made. This constitutes the laterally persistent ultramafic zone from the Agnew Mine area, down to the Honeymoon Well in the south, which is located in the northern extremity of the Greenstone Belt.

The komatiites form between one and five horizons of variable thickness, intercalated in places with felsic to intermediate volcanic sediments. It is significant that throughout the length of the greenstone belt, the ultramafic rocks are underlain by felsic-intermediate volcanoclastic sediments and, always overlain by a hangingwall sequence containing variable proportions of high-Mg basalt, layered gabbroic units, minor thin komatiite flows and tholeiites.

The stratigraphy of the komatiite lenses are dominated by units of spinifex-textured flows and olivine orthocumulates; within which there is the lateral restriction of large, irregularly disposed elliptical zones of thickening, occupied by concordant lenses of coarse-grained olivine adcumulate and mesocumulate (refer to section 4.4.2). Seven such bodies have been located in association with the Six Mile area, including Betheno, Goliath North - Central - and South, David and the Six Mile Deposit itself (Fig. 34).

The bodies are all at the same stratigraphic level and are exposed as small hills capped by dense, brown ferruginous jasperoidal and scoriaceous laterite,which pseudomorphs the primary igneous olivine adcumulate texture. The flow units lateral to the adcumulate bodies are, in places, separated by felsic tuffaceous metasediments which thin and pinch out abruptly against the adcumulate pile.

The bodies are enclosed in the marginal zones of olivine orthocumulate and exhibit gradational lateral contacts with thinner orthocumulate and spinifex-textured horizons. Careful reconstruction of the stratigraphic relationships prior to folding and faulting, has illustrated that the five lenses were originally linked by these horizons and suggests a consanguineous relationship. Naldrett and Turner (1977) concluded that the adcumulate bodies were an intrusive a)




b)

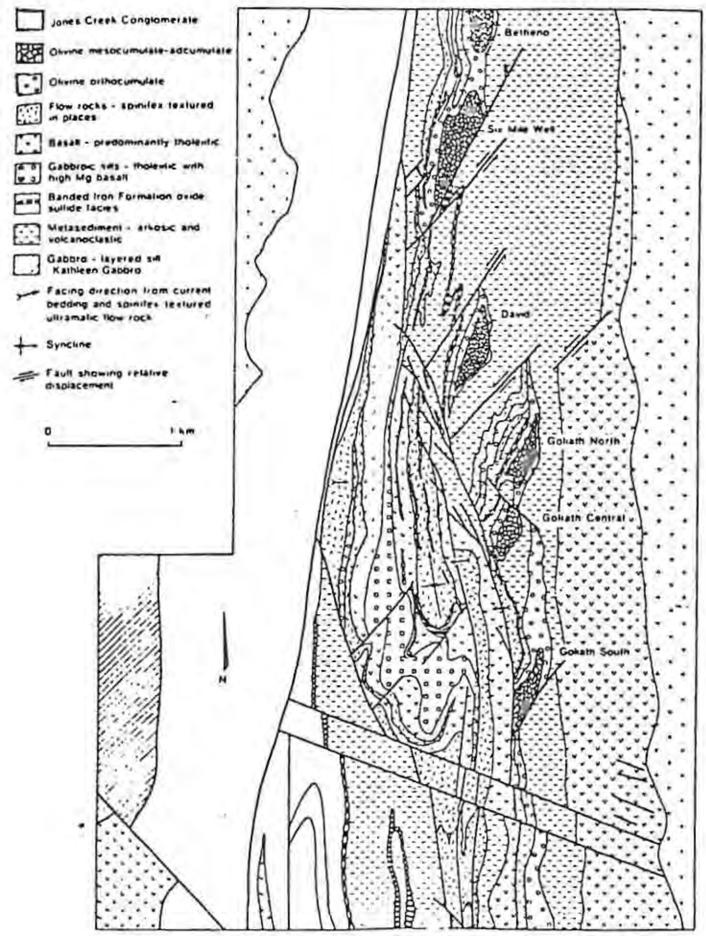



*Figure 34.* **a**) *Reconstruction of the Six Mile Well, David and Goliiath adcumulate lenses before major folding and faulting (after Naldrett and Turner, 1977);* **b**) *geological interpretation of the surface geology of the Six Mile Well after Naldrett and Turner (1977).*

phase of komatiite magmatism, and as such represented linked feeder zones to the overlying rocks. The above authors believed that these "zones" hosted crystal-charged magma comprising 90% olivine grains and 10% silicate liquid, which were surrounded by a lubricating sheath richer in liquid, represented by the olivine orthocumulates.

Some of the lenses exhibit mineralogical, textural and compositional layering on a centimetre to metre scale, as defined by olivine and chromite (refer to section 3.3.1). Others show a gradational change from adcumulate to orthocumulate at their margins. Hill (1982) noted that most other Group II-type deposits only showed subtle variations compared to the Six Mile Deposit.

Olivine adcumulate and orthocumulate lithologies host vast tonnage of low-grade disseminated nickel sulphide. Rare, higher grade nickel reserves such as those at Agnew and Mt. Keith, are present as zones of massive sulphide and olivine sulphide cumulate, associated with komatiite flows. At Agnew, high grade mineralization is associated with thinner flows which lie stratigraphical below the olivine adcumulate lens.

On a local scale there is a peak metamorphic grade from prehnite-pumpellyite facies in the Wiluna area, to lower amphibolite facies at Perserverance. The metamorphic grade a the Six Mile Deposit is mid- to upper greenschist facies.

## 4.4 GEOLOGY OF THE SIX MILE DEPOSIT (SMD)

The Six Mile Well was discovered in close association with the highly dismembered northern part of the Yakabindie Region by Anaconda Australia Inc., during an extensive nickel exploration programme in the late 1960's and early 1970's.

The complex is 1500 m long, 400 m thick and concordant with the NS - striking and west facing lithologies. Its sheared, western margin dips steeply westward, whilst the eastern margin is a fault that strikes NNE and dips to the SE. To the north, the dunite body exhibits gradational contact with a zone of olivine orthocumulate (Fig. 35).

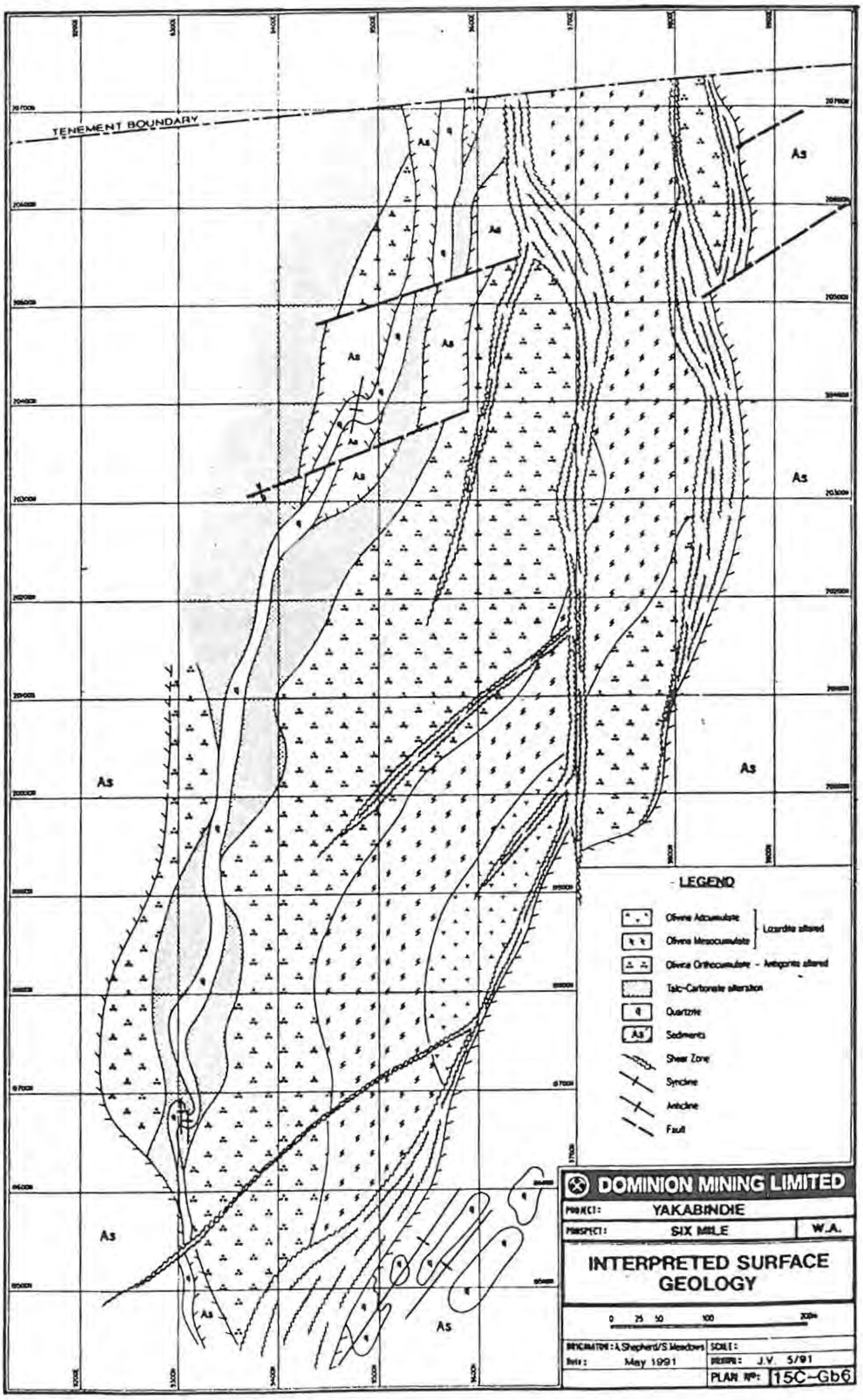



*Figure 35. Interpreted surface geology of the Yakabindie area (unpubl.ms., Dominion Mining Ltd., 1990).*

### 4.4.1 Stratigraphy and Structural Setting

The Western, hanging-wall contact is strongly sheared but appears to be stratigraphically intact, exhibiting an interlayered series of mafic colcaniclastic sediments and thin ultramafic flows (completely altered to talc-carbonate rock). The mineralogy of the mafic sediments reflects the degree of metamorphism in the form of a complex assemblage of quartz, tremolite, biotite with accessory garnet, pyrite and pyrrhotite. Fine-scale mineralogical banding and recognisable volcanoclastic textures are diagnostic of a sedimentary origin.

The contact with the late stage Jones Creek Conglomerates (approximately 300m to the west), is represented by granitic and mafic boulders (up to 1m across), in a matrix of similar composition. The contact is a major shear zone which is interpreted as being the northern extension of the Perserverance structure.

On the eastern footwall side, the contact of the ultramafic rocks, is marked by a major NNE-striking, steeply dipping fault, which has removed a large proportion of the igneous stratigraphy, forming the southern truncation of the deposit. The footwall structure is one of a number of faults, which have dislocated the stratigraphy in the area.

In the southern part of the complex, the footwall structure is steeply dipping near surface, but flattens to a shallow easterly dip at depth, and consists of fine to medium grained mafic to intermediate volcanoclastic units with pervasive silicification. The units are strongly folded and deformed as a result of movement along the footwall structure. Tight, north-plunging cylindrical faults in cherts are exposed in the Jones Creek at the southern end of the Six Mile deposit. Associated with the cherts are bodies of massive pyrrhotite/pyrite mineralization.

To the north, the complex exhibits a gradational contact with a thick unit of olivine orthocumulate with only minor occurrences of mesocumulates. Despite a strong alteration overprint, there is a suggestion of complete igneous stratigraphy, i.e. with a preserved igneous footwall, in the area.

The surface expression of the body is subdued and varies from rubbly, friable, goethitic silica capping over the olivine adcumulate, to fresh outcrops of serpentinized olivine orthocumulate on the western margin. The complex has been metamorphosed, with a grade peaking at lower amphibolite facies. Present mineral assemblages include serpentine (lizardite, antigorite), brucite, magnetite, pyroaurite, magnesite, dolomite, talc, chlorite and tremolite. Igneous textures have largely been preserved.

Naldrett and Turner (1977) have described igneous layering or cyclicity in the orthocumulate envelope on the western margin of the complex; this is reflected in regular variations of MgO, CaO and $Al_2O_3$.

4.4.2 Textures

A range of textures exist, from orthocumulate through mesocumulate to adcumulate, particularly in the cumulate or "B" zone; These textures have great genetic significance. Irvine (1982), has revised cumulate terminology to remove the genetic connotation of crystal settling; it is this terminology that is employed throughout the text.

A **cumulate** is defined as an igneous rock containing a framework of touching crystals, which were concentrated by fractional crystallization.

Cumulate textures are subdivided on the basis of the ratio of cumulus crystals to the crystallization products of the magma trapped between cumulus crystals.

**Orthocumulates** are rocks that exhibit a high proportion of trapped intercumulus liquid and the cumulus crystals are euhedral to subhedral in form (e.g. Plate 1).

**Mesocumulates** are rocks in which the cumulus crystals exhibit extensive mutual boundary contact, but in which there is some recognisable primary igneous porosity (e.g Plate 2).

**Adcumulates** are rocks containing little or no intercumulus material and are characterised by anhedral crystals exhibiting a very high degree of mutual boundary contact and triple-point junctions. The SMD is an olivine adcumulate body with minor cumulus chromite (Plate 3, 6).

A gradational evolution in igneous textures exits, from olivine adcumulate to olivine orthocumulate, westward and upward across the igneous stratigraphy, together with a consistent, correlatable primary igneous lamination. In the case of the SMD, Hill et al. (1982) invoked a mechanism of lava flow over a bed of growing crystals.

Detailed studies of core, drilled by Anaconda in section 19520N (an area under the flat dipping section of the footwall structure), led Hill to subdivide the SMD from west to east, into four units/zones. Boundaries between these are somewhat diffuse (Fig. 36)

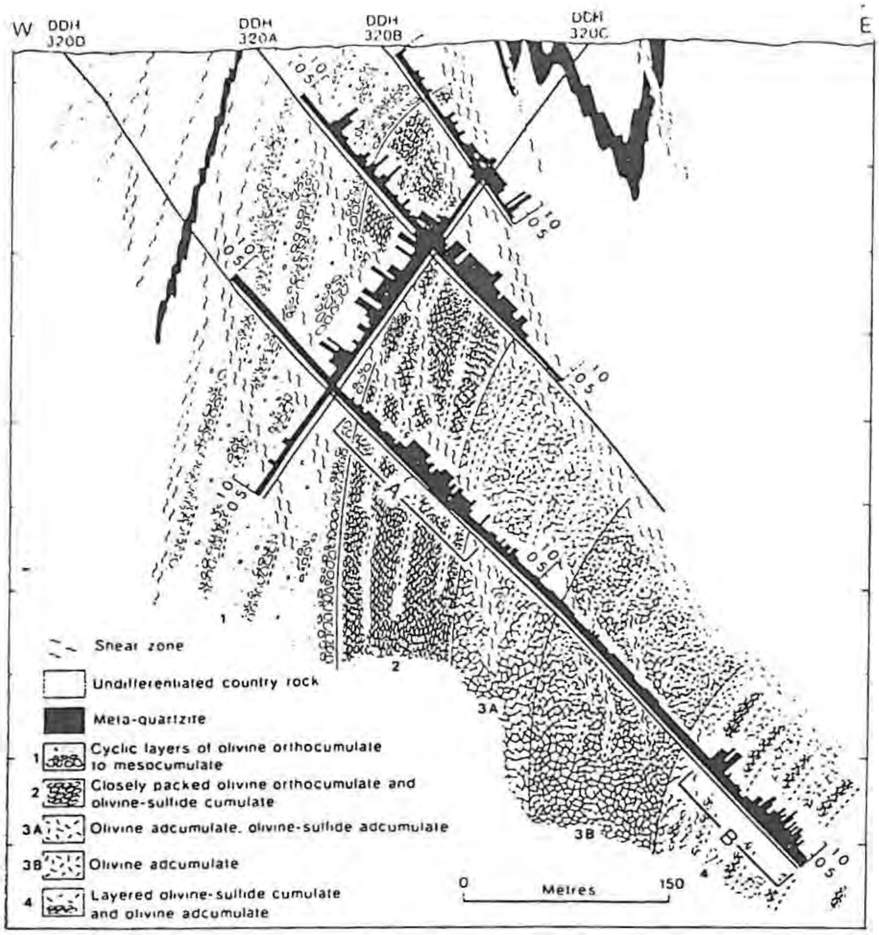



*Figure 36. Geological cross section on line - 19520N, showing the four types of textural zones (from Hill et al., 1987).*

### 4.4.2.1 *Zone 1*

The western margin, orthocumulate zone is characterised by textures which exhibit cyclicity from medium-grained olivine mesocumulate-adcumulate to olivine orthocumulate on a scale of several metres. The bulk of the sulphide mineralization occurs in the mesocumulate parts of the mesocumulate-adcumulate. Some of the more evolved orthocumulates contain serpentinized pyroxene oikocrysts. Others contain relics of primary unaltered intercumulus aluminous, amphibole and apatite.

In the orthocumulates, olivine is commonly bimodal in size, ranging from 300 μm to 3 mm. The present mineralogy of the rocks of this unit include antigorite pseudomorphs after olivine (Plate 1), rarer lizardite, chlorite, talc, ferroan magnesite dolomite, very rare brucite, and ubiquitous minor fine-grained spinel. The bulk of rocks in this zone are barren of sulphides.

#### 4.4.2.2 *Zone 2*

This is characterised by an abrupt textural and grain-size layering and is dominated by closely packed olivine orthocumulates and olivine sulphide orthocumulates. Cumulus sulphide is generally confined to finer-grained layers which contain higher proportions of intercumulus liquid. Some layers are coarse-grained and exhibit adcumulate textures. Contacts between mineralized and unmineralized lithologies are generally sharp. Serpentine pseudomorphs after olivine vary from antigorite-carbonate assemblages to lizardite-brucite. Primary intercumulus silicates have been altered to chlorite, talc and carbonate. Rare cumulus-textured, subhedral spinel is ubiquitous.

Relict primary olivine was only found in three samples; the olivines are unzoned and have compositions $Fo_{89}$, $Fo_{91.2}$. (Fo* = mole % fosterite).

#### 4.4.2.3 *Zone 3*

Zone 3 is an essentially sulphide-free, coarse-grained mosaic textured olivine adcumulates (Plate 3). A large proportion of this zone contains relict olivine and in places the rock is essentially unaltered. Olivine compositions range from $Fo_{93.7}$ to $Fo_{94.7}$ and are relatively uniform through out the zone. Chromite is very rare in this adcumulate, but in contrast to other units it is characteristically anhedral.

#### 4.4.2.4 *Zone 4*

This is the lowermost unit that was intersected by drilling, and is the second significant sulphide bearing zone. Medium to coarse-grained olivine adcumulates are the dominant lithology. However, the zone is also characterised by the presence of grain size, textural and phase layering. Abrupt changes from fine to medium-grained olivine sulphide mesocumulates to coarse-grained barren olivine adcumulates are common. Rare, relict olivine is present in the upper levels of the unit, with compositions in the range $Fo_{92.6}$ to $Fo_{93.8}$.

The hanging wall orthocumulate is largely as described by Hill (1982), for Zone 1. The broad scale fractionation is seen as a change from east to west, from olivine orthocumulates to olivine orthocumulates with pyroxene, to pyroxene-plagioclase cumulates. Within particular drill-holes the subdivision of the orthocumulates into fractionated subunits is possible, largely on the basis of very coarse grained oikocrystic pyroxenes marking the top of the fractionated sub-unit.

Rare, thin bands of coarse "hopper" olivines are seen. These have been logged as harrisites, the texture is considered to be a result of rapid cooling during a hiatus in lava flow (harrisitic texture - olivine crystals which are at right-angles to the cumulate layering of the rock). See Plate 4.

### 4.4.3 Chemical Considerations

Various plots of whole rock compositions and the compositions of contained rare relict olivines, characterise each of the major units (Naldrett and Turner, 1977). There is a gradual change from olivine adcumulates to orthocumulates with higher initial igneous porosities and a concommitant fractionation towards more evolved compositions upwards across the complex from Zone 3 to the western margin, as suggested by plots of $MgO-FeO-SiO_2$ and $MgO-FeO-Al_2O_3$ for representative samples from each zone. Significant MgO variation in the orthocumulate is suggestive of a series of magmatic cyclical units. (Zone 1: Naldrett and Turner; 1977). The olivine adcumulates from Zone 4 are consistently more Fe-rich than those from the overlying Zone 3.

Chromite associated with Ni-sulphide mineralization is not normally as rich in Zn as chromite in komatiite flows (Group I; Groves et al.,1982). It crystallizes from a silicate melt when the Cr content of that melt reaches a critical threshold value, called the Cr-solubility, which is strongly dependent on temperature and oxygen

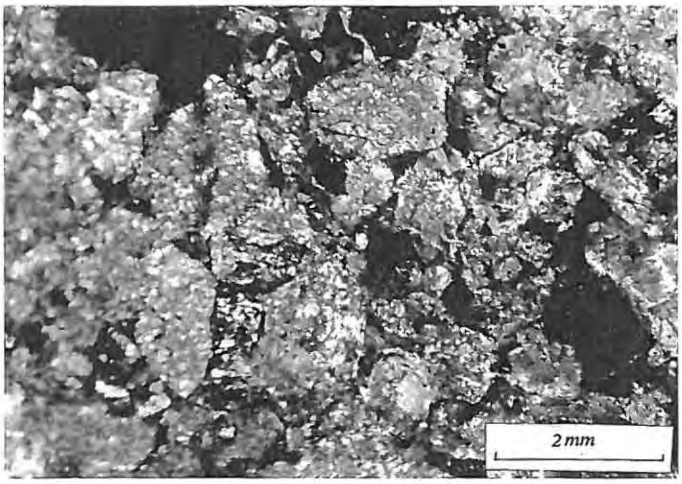



*PLATE 1. Orthocumulate. Barren. Euhedral to subhedral olivine crystals.Antigorite pseudomorphs after olivine. (Transmitted light. XPL).*

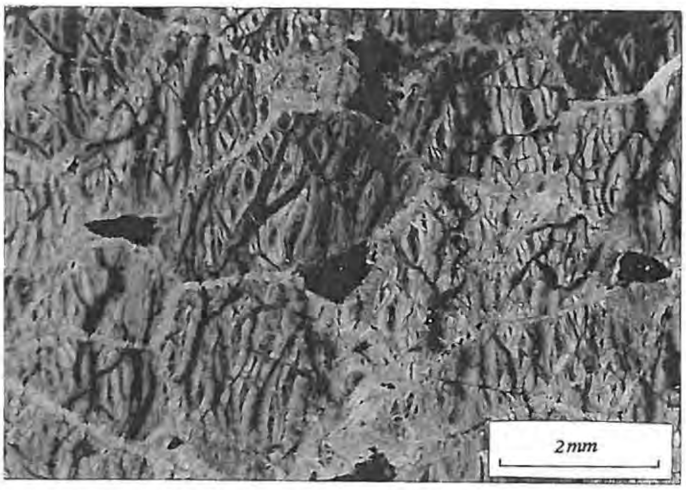



*PLATE 2. Mesocumulate. Mineralized. Mesh-textured olivine, with brucite intergrowths. Carbonate localized along grain boundaries (vein-netting). Lizardite altered. Sulphides interstitial to olivine grains (refer to plate 5). (Transmitted light. PPL).*

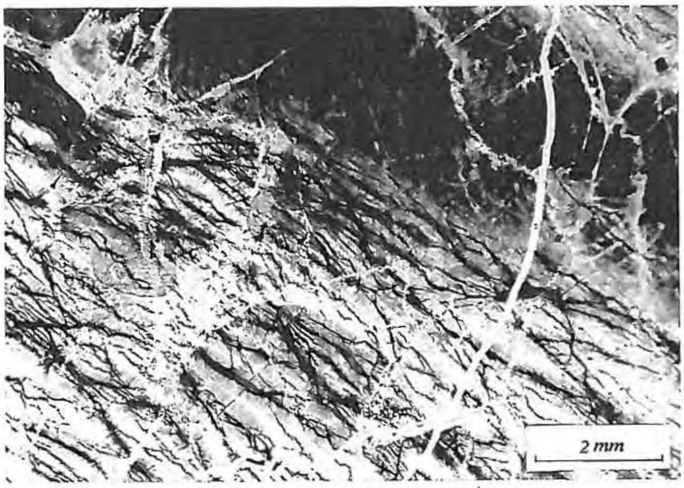



*PLATE 3. Adcumulate. Minor sulphides.Polygonal/mosaic olivine grains, with brown relict igneous cores, and clear recrystallized, partly granulated margins. Grains exhibit mesh-texture.Presence of fine magnetite leds to characteristic dusky, black appearance. (Transmitted light. XPL).*

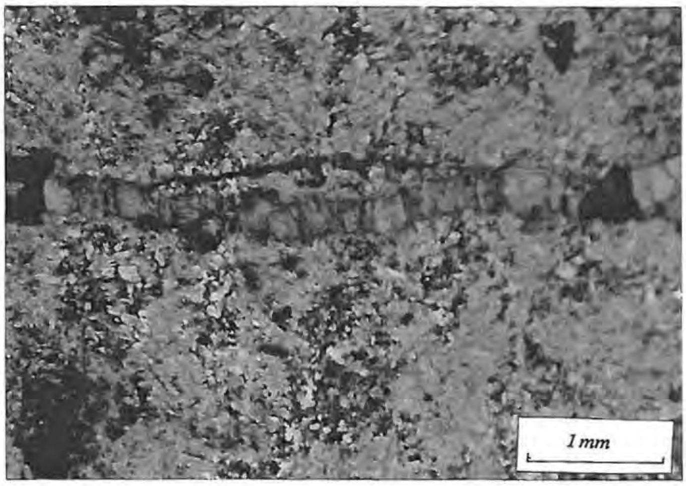



*PLATE 4. Talc-altered harrisitic unit.Talc alteration picks out dendritic olivines. Late-stage, cross-cutting carbonate veinlet. Minor intercumulus chromite (black). Refer to plate 6. (Transmitted light. XPL).*

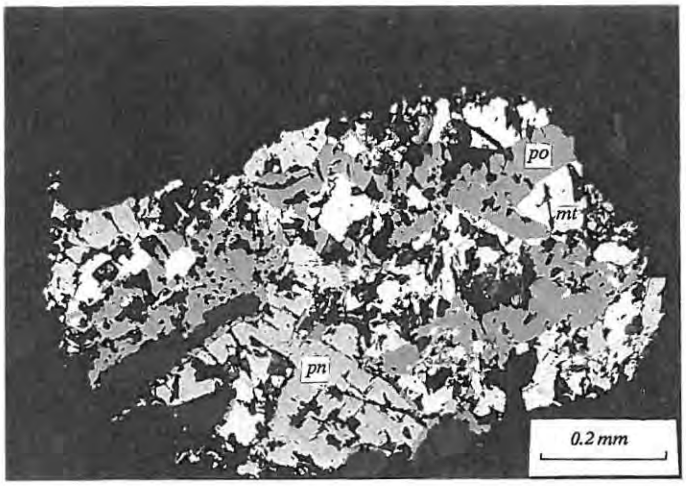



*PLATE 5. Mineralized, lizardite altered mesocumulate (refer to plate 2). Sulphide blebs interstitial to former olivine grains. Assemblage = pyrrhotite (po), pentlandite (pn), intergrown; and minor magnetite (mt). (Reflected light).*

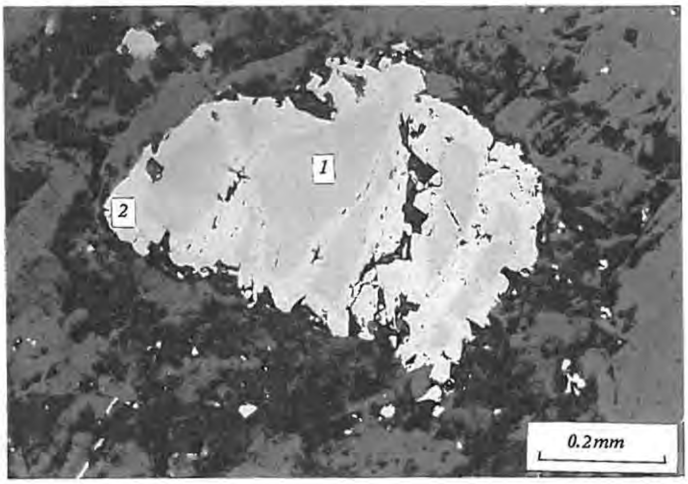



*PLATE 6. Talc-altered harrisitic unit (refer to pate 4). Equant, subhedral-anhedral, intercumulus chromite (1) grains. Margins consist of magnetite-rich chromium spinel (2). (Reflected light).*

fugacity (Murck and Campbell, 1986). Chromite occurs as coarse-grained lobate intercumulus grains and fine-grained cumulus euhedra (Plate 6). Lobate grains occur in dunites with olivine compositions of $Fo_{92}$ to $Fo_{95}$. The shape and presence of the Cr grains is a useful field guide to the composition of olivine in adcumulates. Higher temperatures favour lobate Cr, whilst lower temperatures favour euhedral Cr, trapped in olivine.

Chromite compositions have commonly been modified even in areas of only moderate metamorphic grade, with cores from the lowest grade areas presumably resembling magmatic compositions.

### 4.4.4 Sulphide Mineralization

The Six Mile Deposit is a typical example of low-grade disseminated-type Ni mineralization. A critical assumption in the evaluation of the resource is that the sulphide mineralization is of primary magmatic origin. The mode of sulphide occurrence strongly favours a magmatic origin, most of the sulphides occur as fine blebs interstitial to olivine. They are assumed to have formed by the cotectic accumulation of olivine and sulphide-oxide liquid from a sulphide-saturated komatiite liquid. On cooling, the mineralogy of the sulphides blebs would have been similar to that of most sulphide nickel deposits, ie, a pyrrhotite-pentlandite-pyrite ± chalcopyrite assemblage. However, subsequent alteration has had the effect of upgrading the nickel content of the sulphides as well as changing their mineralogy.

Sulphides are common throughout the Six Mile complex. However, the broad zones of nickeliferous sulphides are restricted to within, or near to, the mesocumulate-adcumulate unit. Within the orthocumulates irregular zones of high-grade Ni mineralization occur close to, or on the mesocumulate-orthocumulate boundary. Further west in the orthocumulates, irregular zones of nickel-poor sulphides are intersected, particularly around 20080 N. These are interpreted as being late-stage sulphide zones from an already nickel depleted magma.

In the sulphide-bearing zones, there appears to be a direct relationship between the size of the sulphide grains and the olivine grains, presumably because the olivine grain size determines the size of the intercumulus space. Sulphides also normally form lobate intercumulus patches up to about 2 mm across, moulded around relict or former olivine. In some of the coarser grains, mesocumulate sulphide blebs can be up to 1 cm across, interstitial to the former olivine grains (Plate 5). Grain boundaries are curvilinear and meet in approximately 120° triple-point junctions. Poikilitic textures are developed where the modal olivine content falls below 95%, as in some marginal zones.

The relative proportions of the sulphide minerals vary as a function of sulphide abundance. Pentlandite and pyrite tend to prevail where the modal sulphide is low i.e < 5 modal %.

There is an apparent relationship between cumulate texture and sulphide tenor. The close packed olivine adcumulates tend to have very low sulphide contents, whereas the mesocumulates and orthocumulates can have sulphide contents of up to 10%.

In places, subsequent alteration and/or shearing has had the effect of modifying the sulphide shape and size, resulting in a reduction of sulphide grain size. Zoned assemblages of alteration products reflect the compositional variations in $CO_2/H_2O$ metamorphic fluids. The alteration has also generated a secondary phase of ultra-fine sulphide blebs within the olivine grains. These fine grains account for a small percentage of the sulphide content but, are generally too fine to be recovered metallurgically.

#### 4.4.4.1 *Sulphide Mineralogy and Form*

The mineralogy of the disseminated sulphides at Six Mile have been progressively altered as a result of sub-solidus, re-equilibrium with nickel in the olivines and in response to the chemical conditions induced by alteration of the volumetrically predominant silicates.

As disseminated sulphides constitute a relatively low proportion of the total rock volume, distribution of elements (particularly Ni), from olivine during metamorphism and alteration has had a pronounced effect on sulphide composition (and mineralogy).

During initial cooling, Ni was preferentially partitioned into the sulphides resulting in a Ni-rich sulphide assemblage. The relict igneous zone is characterised by a simple sulphide mineralogy of pentlandite, where a pyrrhotite rich assemblage would be expected. The enrichment is likely to be proportional to the volume of sulphides available. The indications are that the nickel content of the serpentinized olivines in the ore zone of the Six Mile deposit is as low as 400 - 800 ppm Ni. The re-equilibration of silicate and sulphide nickel would have continued during metamorphism.

A number of authors have investigated the effects on sulphide mineralogy of serpentinization and carbonatization (e.g Donaldson, 1981). The expectations are a pentlandite-heazlewoodite-magnetite assemblage in the partially serpentinized core, pyrrhotite-pentlandite-magnetite in lizardite (Plate 5), pyrrhotite-pentlandite-pyrite in antigorite and pyrrhotite-pentlandite-pyrite ± millerite ± gersdorffite ± chalcopyrite in talc-carbonate.

### 4.4.5 Silicate Alteration

Due to their ultramafic composition, komatiites are very susceptible to both hydration and carbonatization at low temperature, as well as low $H_2O$ and $CO_2$ activity levels. The alteration processes affecting the SMD can be divided into serpentinization, prograde metamorphism and retrograde metamorphism (carbonatization). In practice, the 3 events are more likely to be a single on-going process.

#### 4.4.5.1 *Serpentinization*

Upon cooling, the first alteration process to affect the SMD would have been low temperature hydration, due to burial and dewatering of the enclosing sedimentary sequence. The following equation summarizes the serpentinization reaction:

$$30(Mg_{0.9}Fe_{0.1})_2SiO_4 + 41H_2O = 15Mg_3Si_{0.2}O_5(OH)_4 + 9Mg(OH)_2 + Fe_3O_4 + 2H_2$$

*Olivine* *Water* *Serpentine* *Brucite* *Magnetite* *Hydrogen*

Serpentinization resulted in the oxidation of iron in sulphides to form magnetite, with the Ni in the magnetite preferentially partitioned into the remaining sulphide, thereby continuing the enrichment process. During serpentinization, there appears to have been a local redistribution of sulphur which has combined with the nickel from the olivines to form the very fine sulphide blebs within the olivine grains.

The serpentine mineral formed is usually one of three, lizardite, antigorite or chrysotile (Fig. 37).

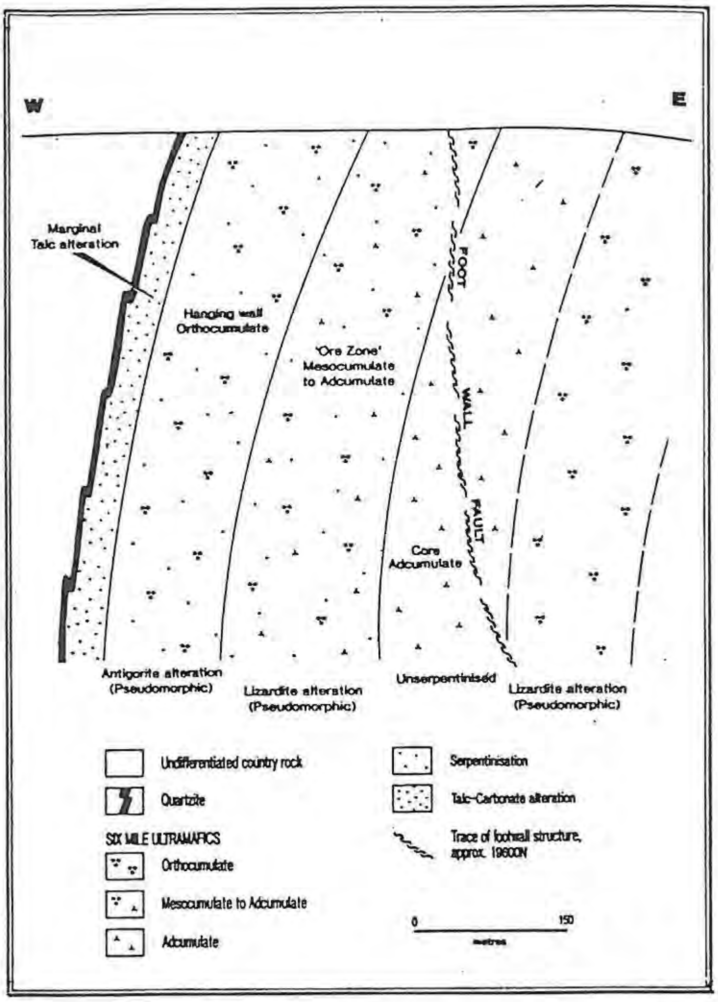



*Figure 37. Pattern of serpentinization at the Six Mile deposit (unpubl.ms. Dominion Mining Ltd., 1990).*

Chemically, the three are identical but there are significant differences in their crystallography, determined by particular combinations of temperature, pressure and stress. The factors determining serpentine mineral generation are listed below:

i) antigorite will not nucleate at low temperature, pressure and $CO_2$ activity,

ii) pseudomorphic replacement by lizardite is common, due to its crystal structure being very similar to that of olivine,

iii) antigorite is the most stable in the presence of $CO_2$, both lizardite and chrysotile are metastable with respect to talc in the presence of $CO_2$ bearing fluids,

iv) the presence of Al and/or Ca in a rock may catalyse the nucleation of antigorite,

v) chrysotile does not replace the parent olivines.

All 3 serpentine minerals have a low preference for iron in their structure which gives rise to the formation of magnetite, and substitution of iron in the brucite lattice. Serpentinization to lizardite results in the exsolution of clouds of fine magnetite giving the rock a characteristic dusky black colour (Plate 3).

Due to the low porosity of the cumulate lens, the SMD would have serpentinized from the outside towards the centre, with a local metamorphic grade of mid-upper greenschist facies. The central portion of the deposit is essentially unaltered (Hill, zone 3). To the west and east of this core is a zone of dominantly lizardite/brucite-altered olivine mesocumulate-adcumulate (Hill, zone 2). The lizardite alteration of olivines characteristically developed as a mesh-textured intergrowth with brucite (Plate 2). The interstitial areas are altered to a chlorite, talc and carbonate assemblage. Chromite occurs as equant, subhedral to anhedral grains mantled and veined by a lighter grey spinel. The margins of these grains now consist of magnetite and magnetite-rich chromium spinel (Plate 6).

Despite total serpentinization, textural features are commonly well preserved, and there is normally no doubt these rocks formed from ultramafics containing over 95 modal % olivine.

#### 4.4.5.2 *Prograde Metamorphism*

The second alteration to affect the ultramafic complex was a regional prograde metamorphic event associated with burial and granite diapirism. Increasing temperature and pressure led to dehydration of the serpentine mineralogy and placed the complex into the stability field of antigorite. The unserpentinized core was largely unaffected.

Donaldson and Bromley (1982) have noted that variations in S/Ni essentially reflect the pyrrhotite and pentlandite ratios. A value of 1.8 has been recorded for the Six Mile serpentinites, in contrast to the Agnew deposit (0.4) which occurs in the highest metamorphic grade and contains the most massive and mobilized ore in the Agnew-Wiluna belt.

Heating of felsic igneous olivines resulted in the exsolution of Ca, Al and Cr as inclusions and lamellae of tremolite, chlorite and chromite. In the lizardite-altered zone, recrystallization of antigorite was common, with predominant laths forming from the crackle texture on the olivine grain boundary, together with minor parallel blades. Associated with the antigorite generation, there was irregular alteration of early carbonate veins to pyroaurite and/or brucite.

To the west the hangingwall olivine orthocumulates have been psuedomorphously replaced by fine antigorite/carbonate. (The diagnostic characteristics of pseudomorphic antigorite, in hand specimens are patches of high reflectance, a pale green colour and fine scale replication of original igneous texture).

Associated with the lizardite alteration was a weak, 'early' phase of carbonate alteration which preferentially occurred within interstitial sites and along olivine grain boundaries. The alteration developed a characteristic crackle (mesh) texture (Plate 3), which picked out the original igneous texture. At its most extreme, this alteration gave rise to rims of carbonate around the sulphide grains. Weak carbonate alteration also induced the alteration of brucite to pyroaurite and partial alteration of chromite to stitchite.

4.4.5.3 *Retrograde Metamorphism/Carbonatization*

The final alteration event to affect the Six Mile complex was due to low temperature, high $CO_2$ activity fluids at the retrograde phase of metamorphism. The main effect of this alteration would have been to increase the size of the talc carbonate marginal zone. The margin of the SMD is marked by a zone approximately 50 m wide of intense talc-carbonate alteration and shearing. In hand specimen talc carbonate is characteristically white and very soft; deformation resulted in igneous textures rarely being preserved.

The carbonate alteration reaction is summarized as:

$$\underset{\text{Serpentine}}{18Mg_3Si_2O_5(OH)_4} + \underset{\text{Magnetite}}{Fe_3O_4} + \underset{\text{Carbonate}}{30CO_2} =$$

$$\underset{\text{Talc}}{9Mg_3Si_4O_{10}(OH)_2} + \underset{\text{Magnesite}}{30(Mg_{0.9}Fe_{0.1})CO_3} + \underset{\text{Water}}{27H_2 + \tfrac{1}{2}O_2}$$

During carbonatization there is a tendency for magnetite to be altered to magnesite and in doing so, an oxidising environment is produced. This is seen at its most extreme in the talc carbonate rocks where pyrite-pentlandite-pyrrhotite assemblages occur. Ni, Cu and As may undergo metasomatic migration in talc carbonate shear zones which can lead to depletion or enrichment of one or all of these elements. Enrichment tends to produce unusual mineral assemblages associated with millerite, gersdorffite and chalcopyrite.

Most of the serpentinized dunite contains fine veins of carbonate, commonly localized along grain boundaries, giving rise to the characteristic "vein-netting". Carbonate veinlets cross-cut original olivine grains, splitting them into smaller areas. Recrystallization of lizardite to antigorite proceeded outwards from the carbonate veinlets, giving the false impression that the smaller areas represent original olivine grains.

Any regional stress was likely to have been taken up by ductile deformation of the marginal, low strength talc carbonate, which would have acted as a protective sheath around the SMD. Hence the widespread preservation of fine primary igneous textures within the ultramafic body, in a major, regional deformation zone.

At the SMD, routine microscope examination of the sulphide mineralogies has been largely directed at determining assemblages due to weathering, rather than attempting to characterise primary mineralogical assemblages. However, the work has been sufficiently detailed to allow the following observations to be made.

In the lizardite ore zones the usual primary opaque mineral assemblage is pentlandite-pyrrhotite-magnetite. Occasionally, fine, ragged inclusions of pyrrhotite can be seen in pentlandite. These are interpreted as being relic pyrrhotite after the upgrading of pyrrhotite to pentlandite. Textures are generally coarse to fine-grained intergrowths of the two sulphides (Plate 5). Magnetite occurs as coarse laths between pentlandite and pyrrhotite grains, usually along pentlandite cleavage orientations and as coarse, irregular rims to the sulphide minerals. Minor millerite, heazlewoodite and chalcopyrite have been noted.

The 'early' carbonatization alteration event (refer to section

4.4.5.3),is seen in the lizardite zone as carbonate rims to sulphide grains. The carbonate seems to have replaced the sulphides, or an intermediate phase. Within the carbonate rim the sulphide assemblage is generally Ni-rich and magnetite-poor compared to the unrimmed parts of the lizardite zone. Textures may be complex with antigorite laths forming an interpenetrant texture within the sulphides. It is suggested that the carbonate rim favours the formation of antigorite on a very local scale within the lizardite zone, and can be seen as "lacy", diffuse intercumulus sulphide blebs. The alteration appears most widespread in the southern and northern parts of the deposit.

Within the antigorite alteration zones, pentlandite-pyrrhotite is the dominant assemblage with magnetite being less common than in the lizardite zone. The lack of magnetite, Ni enrichment and interpenetrant antigorite may reflect the high carbonate content. As with the lizardite zone, millerite, heazlewoodite and chalcopyrite have been noted as rare to minor phases.

In the talc carbonate altered zones, the dominant sulphide assemblage is pentlandite-pyrrhotite-chalcopyrite. Hypogene pyrite and millerite have been noted as minor phases. The lack of magnetite with sulphides is characteristic. Deformation of the talc carbonate zone has led to physical remobilization of sulphides along foliation planes where they occur as trains of fine fragments. Metasomatic introduction of Cu and S has been invoked to account for the copper rich mineralogy. The very low nickel grades in the footwall structure are considered to be evidence of metasomatic depletion of Ni.

### 4.4.6 Weathering

Weathering-induced alterations to sulphide mineralogy can have a profound effect on metallurgical response. Using divisions proposed by Butt and Nickel (1981), the SMD was subdivided into 5 weathering zones (Fig. 38).

#### 4.4.6.1 *The Primary Zone*

The primary zone is unweathered. The upper boundary is marked by the development of incipient alteration of pentlandite to violarite. The top of the Primary Zone at SMD varies from 360 m RL to 440 mRL.

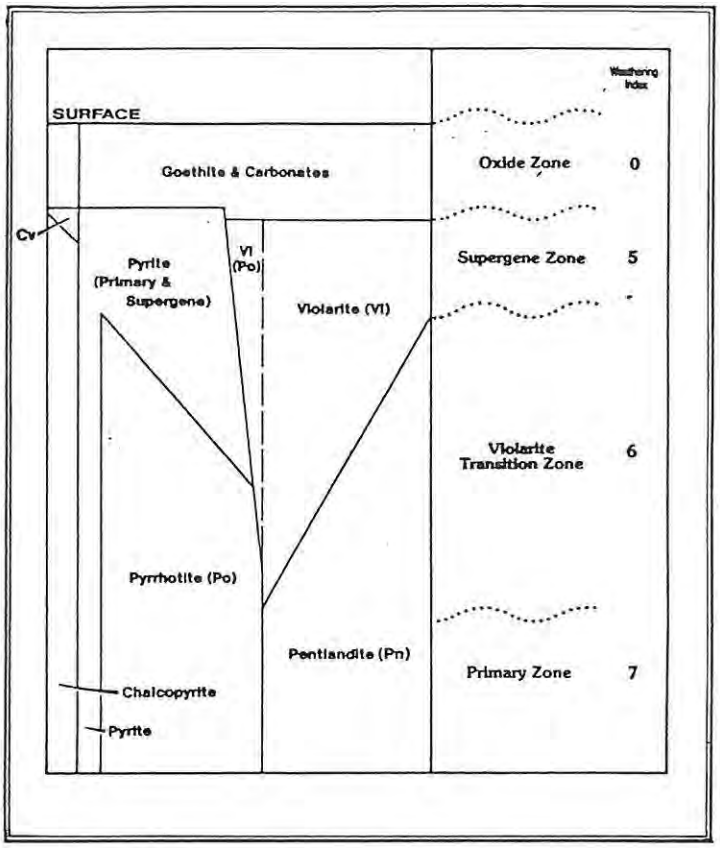



*Figure 38. Mineralogy of the sulphides as a result of weathering, at the Six Mile deposit (unpubl. ms. Dominion Mining Ltd. 1990).*

4.4.6.2 *The Violarite Transition Zone*

Weathering effects within this zone are restricted to the sulphide minerals. The weathering process is one of alteration of sulphide minerals, to sulphides with higher oxidation states, and occurs in response to changes in the local Eh caused by downward percolation of oxygen dissolved in groundwater.

The first effects noted at SMD are incipient, alteration of pentlandite to violarite, taking the form of fine blebs and veinlets of purple violarite. Concomittant with this is the production of ultra-fine magnetite laths along the cleavage cracks.

In the transition zone pyrrhotite alters to pyrite. This usually occurs at the pyrrhotite grain boundaries and is characterised by a very ragged alteration front and the development of very fine, irregular crystals of magnetite within the pyrite. The top of this zone is taken to be where both pentlandite and pyrrhotite are completely altered to supergene assemblages being around 440 m RL. Both the upper and lower boundaries of this zone are very irregular.

Attempts have been made "in-house" (Dominion Mining Ltd.), to determine the controls on the depth and degree of sulphide weathering. It is suggested that there are a combination of two, rather than one primary controls, these being sulphide abundance and silicate alteration type. There is a marked increase in the thickness of the violarite transition zone in the centre of the ore blocks where the sulphide abundance is greatest, but this is partly offset by an amouring of sulphide grains by 'early' carbonate alteration rims.

4.4.6.3 *Supergene Zone*

The Supergene Zone is chemically complex with a number of reactions occuring as a result of rapid changes in Eh and pH with depth. This zone marks the first noticeable weathering of silicate minerals. Going upwards the serpentines become progressively more bleached and rapidly becomes porous and friable. The increased porosity is thought to be one of the reasons for the accelerated weathering seen in the zone. At the top of the zone, the serpentines are bleached to the extent that the distinction of serpentine types in hand specimens becomes very difficult.

The base of the supergene zone is defined by the complete alteration of primary sulphides to supergene assemblages, while the top is defined by the complete oxidation of sulphides. Form the base upwards the zone is characterised by the gradual decomposition of violarite, black to blue-black in colour. Towards the top of this zone, a goethite rim developes around the violarite.

Supergene alteration commences at the base of the transition zone with the development of minute, dispersed flecks of violarite which eventually replace pentlandite. Shrinkage cracks in violarite suggest a decrease in volume during replacement giving a distinct "blocky" appearance. A generalized equation for violarite replacement of pentlandite, indicates that both Fe and Ni are released from pentlandite during oxidation. Fe is fixed in the supergene environment as siderite. Deposits low in carbonate have Fe fixed in magnetite.

High Ni contents of secondary pyrite and development of rare Ni minerals are attributed to Ni-rich solutions (groundwater) that are derived from the overlying oxide zone.

Statistical analysis of assay data indicates a nickel enrichment within the supergene zone. This is due to the alteration of pentlandite to violarite, the generation of secondary millerite and a contribution from mobile nickel occuring as carbonates and sulphates.

Accessory pyrauorite and brucite are converted to magnesite towards the top of the zone. A further characteristic of this zone is the development of fine clear, botroidal quartz veinlets filling open joints (solution cavities) at the base of the zone.

4.4.6.4 *Quartz-Carbonate Zone*

The quartz-carbonate and ferruginous zones are subdivisions of the oxide profile, the base of the quartz-carbonate zone being defined by the complete oxidation of sulphide minerals. The sulphur content is the best chemical discriminator for determining the base of oxidation, sulphur assays show an order of magnitude decrease across the base of the quartz-carbonate zone.

The quartz-carbonate zone contains a considerable enrichment of both secondary minerals. Carbonate (dolomite) tends to be concentrated towards the top of this zone. Further up the profile the secondary carbonate leaches out forming irregular pits. The carbonate is derived from the decomposition of serpentine minerals and re-precipitation of Mg with soluble carbonate. Associated with the carbonate precipitation is the generation of silicic acid, which in turns leds to silicification. Sulphide textures are not preserved; however, the magnetite associated with the sulphides is psuedomorphously replaced by hematite. Towards the top of this zone the serpentine minerals become increasingly soft and friable and replacement by clay minerals commences.

The silicate carbonate zone reports considerable enrichment of nickel, with assays (total Ni) of up to 2% Ni.

4.4.6.5 *Ferruginous Zone*

This zone is characterised by a high iron content and complete conversion of serpentine minerals to clays. Local hardening and silicification result in the development of coarse, ferruginous nodules within this zone.

As with the quartz-carbonate zone, the ferruginous zone contains a considerable enrichment of nickel compared to the underlying ore zones. No lateral dispersion of Ni is evident.

## 5.0 EXPLORATION METHODS

Although class IIB deposits represent a very large nickel resource, most are presently subeconomic, due to their low grade and the difficulty of extracting these fine-grained sulphides from their host rocks. The best exploration targets are clusters of group IA deposits.

The discussion in this chapter is biased towards deposits in Western Australia, since it is in this area, that most new developments have been introduced.

A guideline for regional exploration is postulated, based on the characteristic features of nickel sulphide deposits, as highlighted in the previous chapters (2 & 3). A summary of these features is presented in Table 6.

**Metallogenic Province Selection**

1) Younger Archean (2.7–3.0 Ga) greenstone belts or lower Proterozoic fold belts
2) Rift-phase greenstones (elongate granitoid domes; linear tectonic patterns; complex volcanic stratigraphy; abundant komatiites, including komatiitic peridotites and komatiitic dunites; sulfidic shales and cherts)

**Intra-Province Area Selection**

1) Komatiite sequences with komatiitic peridotites or komatiitic dunites in lower part, typically not interlayered with komatiitic basalts
2) Komatiites containing Zn-rich ferrochromites
3) Komatiites exhibiting chalcophile element depletion
4) Structural highs

**Selection of Local Ore Environments**

1) Thickened areas of komatiite sequences
2) More "disordered" stratigraphic sequence (sporadic komatiitic peridotites in upper parts, poor lateral continuity of flow units)
3) Locally better textural and compositional differentiation in overlying komatiites
4) Locally absent sulfidic sediments
5) Anomalously thick, highly magnesian basal host units (depleted in Ti, Al, Cr, and Zn relative to flanking units; more magnesian olivine than flanking units; more magnesian chilled margins)
6) Footwall embayments

*Table 6.Exploration guidelines for komatiite-associated nickel sulphide deposits (adapted from Lesher et al., 1982; Gresham and Loftus-Hills, 1981; Lesher and Groves, 1984).*

Local exploration utilizes the chemical and physical properties of these deposits. Subsequently, these are discussed in terms of geochemical, geophysical and remote sensing applications.

Most of the deposits of Western Australia resulted from the correct identification of gossans, representing the surface expression of a weathering profile that comprises a oxide, supergene and transition zones and primary ore (refer to section 4.4.6).

## 5.1 GEOCHEMICAL APPLICATIONS

Ultramafic rocks which host Ni sulphide deposits are a typical example of a high background source rock and are enriched in Cr, Ni, Co and Mg.

Geochemical expressions of Ni-Cu sulphide deposits are highly variable. Thus, specific programmes must be designed in areas of residual soil, where the Cu and Ni anomalies appear to accurately define the location of mineralization. In areas of intense lateritic weathering, orientation studies are required in order to discern the nature of the soil profiles over various lithologies, and the dispersion of Ni and Cu within these profiles.

The chemical environment surrounding an oxidizing Fe-Ni-Cu sulphide ore body is highly anomalous. (e.g Thornber, 1975). Metal cations, notably Fe and Cu, are liberated into the groundwater together with sulphate, which results from the breakdown of sulphides. Adsorption of Ni and Cu onto the soil minerals surrounding the ore zone, together with mechanical surface dispersion of gossan fragments, establishes a potentially favourable situation for surface geochemical exploration. Soil and weathered rock geochemistry have been of particular use in Western Australia as a follow-up to initial gossan discoveries.

The Yilgarn Block is a product of many factors that have been operative during a weathering history of more than 100 million years.

Approximately 85% (Brodie-Hall, 1975) of the Yilgarn Block, with potential for Ni sulphide mineralization, is covered by strongly leached (laterized) or transported materials. Several problems with sampling have arisen here: there is extensive remobilization of elements due to mid-Tertiary laterization (Six Mile Deposit), commonly truncated and overlain by a variety of aeolian and waterlain sediments. Areas of outcropping rock are relatively rare, and residual soils are only poorly developed.

### 5.1.1 Gossans

Because of the limited applicability of conventional prospecting methods in deeply weathered terrains, e.g. the Eastern Goldfields Province, the use of gossan evaluation has proven invaluable; because the gross structure of the massive sulphide ores is commonly preserved in such environments.

Most sulphide gossans and other ironstones are variably silicified, chemically stable and refractory, and commonly form linear ridges or spines of positive, topographical expression. Many gossan outcrops, for example those at Empress Nickel mine (Zimbabwe), reflect fairly accurately the style and configuration of the underlying sulphide body as projected at surface.

Initial selection of areas for the detailed search of gossans is directed by geological, geophysical and geochemical data. To distinguish between gossans of mineralized and unmineralized types, the study of textural features or boxworks has been applied (Reynolds, 1982). This can provide considerable information on the nature of the ore at depth, with respect to the minerals present, their mutual relationships, relative proportions, grain size and gangue mineralogy. Based on field observations, Blanchard (1968) noted an exaggeration in the width of the sulphide bodies, as expressed by the surface gossans. Blanchard and his co-workers showed how the leached derivatives of the principal base metal sulphide minerals and associated gangue minerals from numerous deposits, commonly exhibit characteristic cellular boxwork textures on a macroscopic scale.

Unfortunately, good replication of the original textures of sulphides are not always encountered, and in general, only 10% of gossan samples will yield diagnostic features (Reynolds, 1982). This is particularly true in the case of silicified and jasporoidal gossans, where Ni is readily removed, and therefore there is little distinction left between mineralized and unmineralized rock, based on either absolute or relative Ni and Cu values. The cellular boxwork criteria, documented by Blanchard finds little application in this situation.

The mineralogy of gossans is dominated by limonite and silica in mutually antipathetic abundance. Identification of accessory residual minerals in gossans by optical microscopy, may assist in the interpretation of primary sulphide mineralogy and lithological associations.

Retention of many elements within this environment is enhanced by the presence of Fe and Mn oxides. Goethite-hematite gossans (iron-oxide gossans), after pyrite mineralization, tend to indicate a more mature gossan, with hematitic boxwork structures occasionally prevailing, replaced by secondary silicified jasperite. Pseudomorphous replacement of supergene sulphide textures, preserved ultimately by goethite-hematite silica, are readily identifiable on polished mineragraphic surfaces.

The morphology of these boxworks is genetically related to the crystallographic symmetry of their precursory sulphide minerals. Block octohedral (111) cleavages of pentlandite, expressed as symmetrically triangular patterns, are commonly preserved through progressive alteration and retained in the gossan. An indirect indication of pentlandite is the pseudomorph of a "feathery" margin of secondary violarite, that replace adjacent pyrrhotite during supergene alteration.

In the alteration sequence,two distinct types of violarite are formed. The recognition of residual textures in these forms provides an indication of the ore grade in the underlying sulphide body.

Diagnostic features of Ni-Cu gossans include:

1. High Ni-Cu,
2. High Pd-Pt
3. Variable Co-As and,
4. Low Cr-Mn-Zn-Pb.

Gossans, capping non-nickeliferous sulphides and ironstones, and representing laterized sulphides, can generally be distinguished by:

1. Low Cu-Ni/high Zn and
3. high Ni-Cr-Mn and low Cu respectively.

Even siliceous nickel gossans generally retain some characteristics or geochemical "signatures" of their diluted metal contents.

### 5.1.2 Soil Sampling

Because of their inherently high content of Ni, Mg and Cu, poorly exposed ultramafic bodies can be mapped quite accurately from soil sampling results. Well-defined Ni and Cu anomalies occur over known outcropping sulphides and there is a limited dispersion away from the ore zone in areas of residual soil. Where these soils persist (15-60 cm deep), Ni values (for -80 mesh fraction) accurately reflect Ni distribution, but more detailed sampling is required to precisely define the ore shoots.

Cu is regarded as a sulphide indicator, and the drilling of soil anomalies with coincident high Cu and moderately/high Ni values has met with considerable success. Cr and Co are important pathfinders, Cox (1975), highlighted the importance of these in soil surveys carried out around the Pioneer Dome (Western Australia). The Shangani deposit was discovered during a regional soil sampling programme.

The highest Ni values occur in the coarser fractions of the soil (except when "diluted" with clastic quartz), largely in fragments of chrysoprase; there is an association of Ni with secondary iron oxide in the -80 mesh fraction. Ni and Cu show a strong relationship with the distribution of secondary Fe and Mn oxides. The excess Fe over Mn in ultramafic rocks, particularly in greenstone belts, renders Fe of more importance. However, geochemical applications may be complicated by the erratic behaviour, or scavenging effect of Mn and Fe, which can give false anomalies for Ni and Cu, effectively causing apparent enrichment irrespective of the presence of mineralization.

Mazzucchelli (1972), carried out detailed examinations of Ni and Cu distributions at Kambalda, in terms of soil horizons, soil mineralogy, size fraction and bedrock. He noted that Ni mineralization gives rise to well defined Ni and Cu anomalies, in the -80 mesh fraction of near surface soils (Fig. 39).

A sharp peak in the Ni anomaly was believed to relate to leaching of Ni from the -80 mesh fraction immediately adjacent to the ore. The Ni in the fine fractions, appeared to be more closely related to Fe (scavenging effect).

Cox (1975) carried out similar experiments at Pioneer and showed that well-defined Ni, Cu, Co and Ni/Cr anomalies in the residual soils and calcrete coincided with the gossans now exposed. Cox recommended soil sampling at 10-20 cm depth, to minimise aeolian contamination.

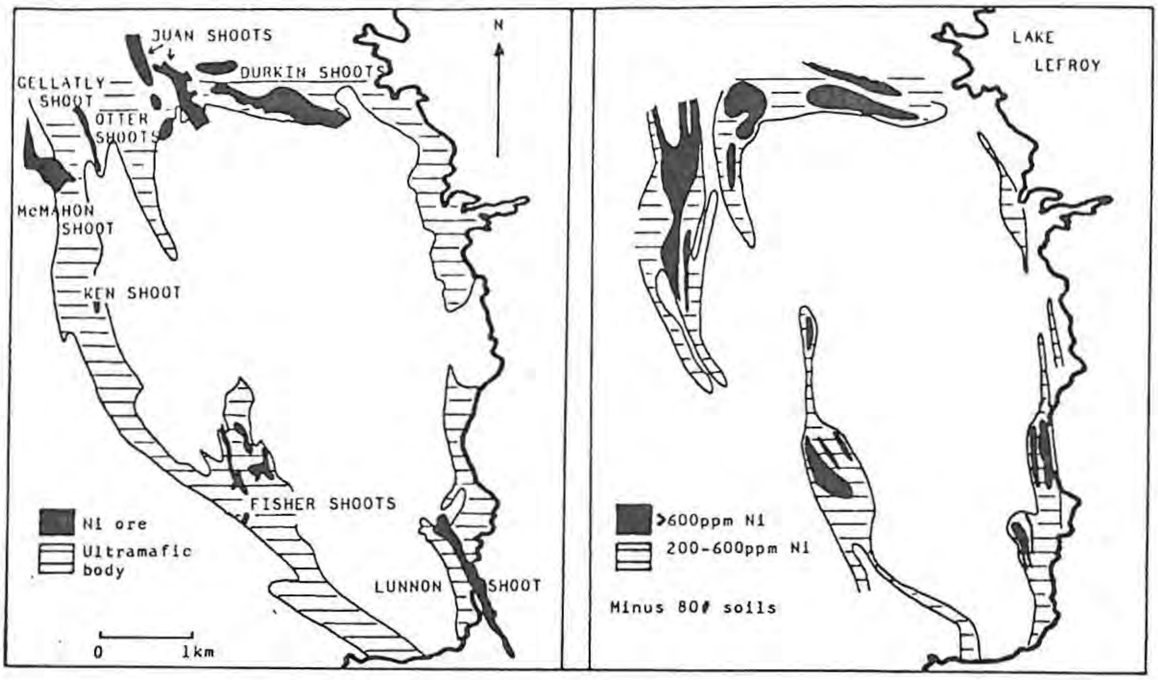



*Figure 39. Maps showing the near surface distribution of ore shoots and ultramafic rock near Kambalda, Western Australia, in comparison with the Ni content of -80# soil samples (adapted from Mazzucchelli, 1972).*

In areas of extensive, deep lateritic weathering (SMD, Mt Keith), and where there is extensive cover of transported overburden, surface sampling of soils is generally unrewarding. Where carried out, it reveals that the coarser fractions in the soil contain the highest concentration of Ni. This is possibly due to re-cementation of secondary minerals during ferruginization and silification. Smith (1977), suggested that the saprolite zone, usually overlying oxidized bedrock, represents the most useful indicator of bedrock samples in a laterized terrain. In general, it is cheaper to sample this zone; and the secondary halo tends to be enlarged due to dispersion by fine clays. However, if the saprolite layer is silicified, the metal values may be considerably reduced.

The only method of obtaining geochemical samples for analysis in this environment, appears to be by rotary drilling. Orientation studies over areas of known mineralization (mainly 0.6% Ni), reveal that thresholds of 4000 ppm Ni and 300 ppm Cu in weathered zones are indicative of disseminated mineralization, although local silicification may dilute anomalies in some cases. However, similar anomalies overlie essentially barren areas and appear to be the result of concentration due to laterization.

### 5.1.3 Biochemical Exploration

In recent years, some of the most important work in geobotanical methods has been concerned with Ni sulphide exploration. Brooks et al. (1977) and Brooks and Wither (1977) analysed a variety of plant species in order to identify plant accumulators of nickel that might be indicative of nickeliferous ultramafic rocks.

In Western Australia, the use of the widespread shrub, *Melaleuca sheathiaria*, has been applied. This plant tends to exhibit anomalously high values of Ni and Cu over areas of mineralization concentrated in its leaves. However, this is limited to areas with residual soil.

The use of biochemical applications may provide a simple, rapid and inexpensive method of locating potentially mineralized ultramafic body in heavily vegetated areas.

## 5.2 GEOPHYSICAL APPLICATIONS

Geophysical methods are based on the study of natural and artificial fields, which are influenced by the distribution of rocks characterised by certain physical properties such as density, magnetic susceptibility, electric conductivity and radioactivity.

### 5.2.1 Gravity Methods

In areas covered by alluvium, or where the overburden is shallow and of uniform thickness, gravity methods can be used to detect the lateral changes in sub-surface density. This method highlights the difference between the more dense mafic and ultramafic rocks, and the less dense sediments; which in turn can be related to the presence of an orebody.

However, although massive pentlandite-pyrrhotite ore contrasts dramatically from the host rock, the relatively small size and deep oxidation of the deposits often reduces the size of the anomaly.

Therefore, it would appear that gravity methods are best applied on a regional basis, where they can be used to locate major structural trends of metallogenic significance e.g. the boundary between the Churchill and Superior Provinces in Canada, was marked by a gravity low. The limitations of this method should, however, be noted.

1. It tends to be slow, expensive, requires high level precision and is sensitive to variations in the overburden thickness and topography (Furnell, 1981),

2. As the density of sulphide minerals decreases with weathering, this method is of limited use in heavily weathered or deeply buried deposits.

3. Most sulphide bodies constitute residual high frequency anomalies, therefore, regional "noise" may suppress responses. In such cases regional, low frequency anomalies are removed by mathematical modelling.

5.2.2 Magnetic Methods

This method is extremely useful as a cheap reconnaissance tool, and in some cases for the detection of the high MgO units, that host Ni mineralization, as these portions tend to be the most magnetic. The amount of magnetite present is, however, dependent on the degree of serpentinization and talc-carbonate alteration (increasing alteration results in a decrease in MgO). Although pyrrhotite is abundant in Ni-sulphide deposits, it has a low magnetic susceptibility,

In the Yilgarn Block, there is generally a marked regional distinction between greenstone belts and granitoids on the basis of aeromagnetic data. This has proved most useful in first order definition of prospective areas, where it was used to delineate the position and geometry of the Windarra South deposit under 30m of alluvial cover.

The use of magnetics, to directly define the ore zone, is less rewarding. The effectiveness of this method is often severely reduced by the presence of irregularly distributed patches of iron oxides, originally present as pisoliths in the ferruginous and mottled zones of the laterite profile.The surrounding ultramafic rocks and/or pyrrhotite-rich metasediments may also modify the magnetic response.

This "noise" does not obscure the anomaly, but it makes interpretation unreliable. This can be overcome using airborne magnetics - although the amplitudes of the anomalies may be smaller, they cease to be affected by surficial material.

Airborne electromagnetics (AEM), have proved to be one of the cheapest and most effective means in the delineation of potentially mineralized areas. This is especially true in poorly exposed areas.

AEM data indicates that despite the limited thickness of greenstone units, they can be traced almost continuously around domal structures (Pioneer Dome, Norseman; Cox and Tyrwhitt, 1975). This is due to the enhanced magnetic susceptibilities, characteristic of mafic and ultramafic rocks.

On this regional scale, there is a common association between many Ni deposits and major fault zones. The Manitoba nickel belt, as mentioned in Section 2.3.3, is related to a rift zone, and although not very apparent on the ground, it is easily detected by AEM. Accurate calculation of shapes, dips and depths of magnetic sources can be made from magnetic profiles.

In addition, localized tectonic thickening of these units eg. drag folds,are in themselves, favourable indicators of sulphide deposition, and will generally increase the apparent magnetism of the unit resulting in an amplitude enhanced response. This method requires a high contrast in density between host rock and ore.

### 5.2.3 Electromagnetic Methods

Electromagnetic methods rely on the electrical continuity between conducting minerals. Ideally this requires the presence of pyrrhotite or massive sulphides. Those sulphides that are disseminated in nature effectively interupt the current.

As magnetite and pyrrhotite are common constituents of Ni sulphide ores, the orebodies may, themselves, be detectable. However, good EM responses are only found over deposits with massive mineralization (massive/matrix-associated Group I, and high grade Group II deposits). Disseminated deposits (SMD, Dumont) are poor targets for electromagnetic (EM) targeting.

Problems in the application of this technique have arisen in Western Australia, due to the development of highly saline, weathered zones. These are zones of low resistivity, that inhibit penetration by most EM methods.

Water filled faults, shears and conductive overburdens all produce spurious EM anomalies.

The advent of transient electromagnetic techniques (TEM), have shown considerable promise in deeply weathered terrains, but still remain largely untested.

5.2.4 Electrical Methods

The resistivity of the Ni sulphides is quite variable depending on the amount of sulphides present and their degree of connection. The most successful geophysical tool has been induced polarization (IP).

5.2.4.1 *Induced Polarization (IP)*

The induced polarization resistivity method was primarily designed to detect disseminated sulphide mineralization, the effectiveness of which is now firmly established (Furnell, 1981). An important advantage of IP, stems from its ability to distinguish between metallic and ionic conductors (Furnell, 1981). Magnetite, in particular, can produce a significant IP response. Depth penetration is greater with IP (than with EM methods), and was of particular use in the Yilgarn Block, where the depth of the conductive overburden preluded EM methods. The SMD was discovered on the basis of IP methods, whereby diamond drilling followed geologic targeting of noteworthy IP anomalies (Turner & Ranford, 1975).

However, the detection of sulphide mineralization is often "masked" by weathered zones, exhibiting low resistivity. The presence of overburden reduces the coupling between the geophysical sensing system and the target, both geometrically and electrically. For both IP and EM methods, the effects of overburden is to reduce the sensitivity and resolution of each technique.

This can only be overcome by careful study of the weathering profile and choice of a suitable electrode array. False anomalies may be generated by pyritic tuffs, graphitic shales and volcanoclastic sediments. IP methods fail to distinguish between graphitic shales and massive sulphide layers, due to their similarity in resistivity.

Strongly-sheared serpentinites may also give rise to high IP anomalies that are difficult to distinguish from sulphide-rich zones. In this situation, polarization is apparently similar to membrane polarization displayed by certain lithologies containing clay minerals. Only those samples displaying IP transient decay curves with very short time constants may be positively distinguished as non-metallic polarizers.

The net result is that only a small percentage of IP anomalies actually represent significant nickel mineralization.It would appear that the IP method is best used when constrained by geological and geochemical data.

5.2.4.2 *Self Potential (SP)*

SP anomalies will develope over any conducting medium with an oxidizing environment at the top, and a reducing environment at the base. Negative self-potential anomalies develope over Fe-Ni-Cu deposits that intersect the water table, due to upper electron flow during the oxidation of pyrrhotite and pentlandite.

Although sulphidic and graphitic sediments in the ore environment will provide significant negative anomalies, SP methods are only effective over small bodies that are present at shallow depths (Ward, 1966). If the overburden is deeper than 35m, this method becomes redundant. Spurious SP anomalies may be caused by rapid changes in topography.

## 5.3 REMOTE SENSING

Black and white photography continues to have its application. However, colour, infrared and multiband images can provide more specific data where the metallic mineralization is known to cause geological and/or botanical anomalies that are detectable with specified film/filter combinations.

The use of Multispectral Surveys (MSS) as a Landsat application, has been successfully employed where heavy mineral concentrations produce stress conditions in plants, creating a depressed chlorophyll concentration. Metal stress retards the normal development of the plant pigment system (Chang and Collins, 1983).

The use of MSS has also been applied to differentiate between different types of iron oxides e.g. hematite and goethite, using the relationships between surficial mineralogy and visable and near infrared reflectance spectra, based on supergene weathering of host rocks. Ferric-bearing iron gossans have a unique electronic spectral absorption feature between 850 and 950 μm, which may be used to highlight areas of interest. Colour composite images produced from Landsat MSS band ratio data, have been used to differentiate between ferric iron-bearing rocks in semi-arid and arid environments.

Follow up evaluation

This generally involves a pattern of surface diamond drilling, with space intervals dictated by the dimensions of the ore shoot - as determined by surface exploration. An appreciation of the regional and local structure is important in providing maximum efficiency at this stage.

## 6.0 CONCLUSION

Important conclusions are that major metallogenic associations are preferentially developed within the rift-phase of greenstone basin evolution. The initiation of major extension and crustal thinning, with the development of rapidly subsiding, volcanically active, deep water rift zones at ca 2.8 Ga, was the major control on the marked peak in Archean greenstone belt metallogenesis. Cited examples of greenstone belts, in Canada, Zimbabwe and Western Australia, confirm the importance of age and tectonic association, on the development of economic nickeliferous deposits.

It can be concluded, that the genetic model that best explains these deposits, involves voluminous eruption of komatiites into rift-phase greenstone belts forming large (Group I) and very large (Group II) channelized flows, that assimilated various amounts of footwall rocks during emplacement. The distribution of the mineralization was influenced by

i) the volcanic setting and mode of emplacement of the host unit,

ii) the composition of the substrate and degree of assimilation,

iii) the volume of lava and its capacity to dissolve sulphur/silica; and

iv) the timing of sulphide saturation and the opportunity for sulphide segregation. Flows that assimilated proportionately larger amounts of footwall rocks, especially sulphidic sediments, achieved sulphide saturation early in their crystallization history. Sulphides segregated rapidly, settled to the base of the flow, and formed stratiform massive/matrix/disseminated ores (type A). Flows that assimilated proportionately smaller amounts of material achieved sulphide saturation later in their crystallization history and formed stratabound disseminated sulphide ores (type B).

Although the greatest degree of thermal erosion and assimilation would occur beneath the lava channel, minor amounts may occur beneath flanking parts of the flow, especially near the channel. This is consistent with the well defined margins of ore shoots, but absence of sediments along flanking contacts and minor mineralization in flanking areas of Kambalda. The presence of thermally, highly conductive sulphides at the base of the flow, may have enhanced thermal erosion but accumulation of sulphides in areas with the greatest degree of thermal erosion is attributed, primarily, to these being topographic lows.

All ores would have been above their liquidus at temperatures above the komatiite solidus, so low viscosity sulphides may have been mobilized subsequent to segregation. As a consequence, distal parts of flows may have been more mineralized than proximal parts. The intensity of mineralization at any location would have been influenced by the topography of the footwall rocks which would trap dense sulphides and pond komatiite flows.

The observed massive/matrix/disseminated ore profile in class IA deposits can probably be attributed to a combination of dynamic flow segregation and static buoyancy ("billiard ball model").The interpretation that ferrochromites preferentially crystallized at the margins of individual ore layers, obviates models involving multiple stage emplacement. Variations in the mode of emplacement of the host unit influenced the degree of assimilation and probably accounted for variations in ore tenor, intensity of mineralization, and stratigraphic relationships with sediments that were observed in different deposits.

This model explains the absence of deposits in areas that contain sulphidic sediments, but have no lava channels, or lava channels but no sulphur source. Of major consequence is that mineralization is localized in specific parts of the volcanic pile i.e. lava channels. Barren cumulate sheet flows in one part of the area may be lateral facies equivalents of cumulate lava channels in another part.

The Six Mile Deposit was used to exemplify the characteristics of a Group IIB deposit, aquainting the reader with the complexities of mineralogy, alteration and weathering - topics which could not be covered in detail in the previous "komatiite" chapter.

It would appear, when considering exploration techniques for Ni (and Cu) deposits, specific programmes must be designed to account for the highly variable expressions of these deposits, both geophysically and geochemically. In arid environments (Yilgarn Block), the effects of laterization must be noted, as there is often extensive remobilization of elements.

Remote sensing remains, essentially a regional tool. Both gravity and magnetic methods appear to be most useful in highlighting differences between host rocks and ore bodies, rather than in the direct detection of ore shoots. Electromagnetic methods have proven the most successful in actual orebody delineation. Though this technique has proved of limited use in highly weathered areas the introduction of TEM, has shown promising results in Western Australia.

## 70 REFERENCES


ARCHIBALD A L (1987) Metamorphic patterns in the Greenstone Belts of the Southern Cross Province, Western Australia. *Geol. Surv. Western. Aust., Prof. Pap.*, 1984., pp 1-21.

ARCHIBALD N J & BETTENAY I F (1977) Indirect evidense for tectonic reactivation of a pre-greenstone sialic basement in Western Australia. *Earth Planetary Sci. Letters. Vol 33.*, pp 370-378.

ARCHIBALD N J, BETTENAY L F, BICKLE M J & GROVES D I (1981) Evolution of Archean crust in the Eastern Goldfields Province of the Yilgarn Block. In: Glover J E & Groves D I (Eds.), Archean Geology: 2nd International Synopsium. *Geol. Soc. Aust., Spec. Publ., No. 7.* pp 491-504.

ARNDT N T (1976) Melting relations of ultramafic lavas (komatiites) at 1 atm and high pressure: Carnegie Institute of Washington Yearbook. Vol 75. pp 555-562.

ARNDT N T (1977) Thick, layered peridotite-gabbro lava flows in Munro Township. *Can. J. Earth Sci., Vol 22.* pp 2620-2637.

ARNDT N T (1986) Differentiation of komatiite flows. *J. Petrol., Vol 27, pt 2.* pp 279-301.

ARTH J G, ARNDT N T & NALDRETT A J (1977) Genesis of Archean komatiites from Munro Township, Ontario: Trace element evidence. *Geology., Vol 5.* pp 590-594.

ARNDT N T, FRANCIS D & HYNES A J (1979) The field characteristics and petrology of Archean and Proterozoic komatiites. *Can. Miner., Vol 17.* pp 147-163

ARNDT N T & JENNER G A (1986) Crustally contaminated komatiites and basalts from Kambalda, Western Australia. *Chem. Geol., Vol 56.* pp 229-255.

ARNDT N T, NALDRETT A J & PYKE D R (1977) Komatiitic and iron-rich tholeiitic lavas of Munro Township, Northeast Ontario. *J. Petrol., Vol 18.*, pp 319-369.

ARNDT & E G NESBIT .Eds. (1982) Komatiites. Allen, London, pp 518

AYRES L D & THURSTON P C (1985) Archean supracrustal sequences in the Canadian Shield: An Overview. In. Ayres L D, Thurston P C, Card & Weber W (Eds.), Evolution of Archean Supracrustal Sequences. *Geol. Assoc. Can. Spec. Pap., 28.* pp 343-380.

BARKER F & PETERMAN Z E (1974) Bimodal tholeiitic-dacitic magmatism and the Early Precambrian Crust. *Precambr. Res., Vol 1.* pp 1-12.

BARLEY M E & GROVES D I (1990) Deciphering the tectonic evolution of Archean greenstone belts: Importance of contrasting histories to the distribution of mineralization in the Yilgarn Craton, Western Australia. *Precamb. Res., Vol 46.* pp 3-20.

BARNES S-J (1985) The petrology and geochemistry of komatiite flows from the Abitibi greenstone belt, Canada, and a model for their formation. *Lithos. Vol 18.* pp 241-270.

BARNES S-J, GORTON M P & NALDRETT A J (1983) A comparative study of olivine and clinopyroxene spinifex flows from Alexo, Abitibi Greenstone Belt, northern Ontario, Canada. PhD thesis, University of Toronto, Toronto, Ontario. (unpubld.).

BARNES S-J & NALDRETT A J (1986) Variations in platinum group element concentrations in the Alexo mine komatiite, Abitibi Greenstone Belt, northern Ontario. *Econ. Geol., Vol 82.* pp 165-183.

BARNES S-J & NALDRETT A J (1987) Fractionation of platinum group elements and gold in some komatiites of the Abitibi Greenstone Belt, northern Ontario. *Econ. Geol., Vol 82.* pp 165-183.

BARNES SJ, GOLE M J & HILL R E T (1988) The Agnew nickel sulphide deposit, Western Australia: Part I. Structure and stratigraphy: *Econ. Geol., Vol 83.*, pp 524-537.

BARNES SJ, GOLE M J & HILL R E T (1988) The Agnew Nickel Deposit, Western Australia: Part II. Sulphide geochemistry, with emphasis on the platinum-group elements: *Econ. Geol., Vol 83.*, pp 537-550.

BARNES S J, GOLE M J & HILL R E T (1988) The Perseverence ultramafic complex, Western Australia: The product of a komatiite lava river *J. Petrol., Vol 29.*, pp 305-331.

BARRETT F M, BINNS R A, GROVES D I, MARSTON R J & MCQUEEN K G (1977) Structural history and metamorphic modification of Archean volcanic-type nickel deposits, Yilgarn Block, Western Australia. *Econ. Geol., Vol 72.* pp 1195-1223.

BAVINGTON O A (1981) The nature of sulphidic sediments at Kambalda and their broad relationships with associated ultramafic rocks and nickel ores. *Econ. Geol., Vol 76.* pp 1606-1628.

BEATTY D W & TAYLOR H P (1982) The oxygen isotope geochemistry of komatiites - evidence for water-rock interaction. In: Arndt N T & Nesbit E G (Eds.) Komatiites, Allen, London. pp 267-280.

BESWICK A E (1982) Some geochemical aspects of alteration and genetic relations in komatiite suites. In: Arndt N T & Nisbet E G (Eds.), Komatiites. George Allen and Unwin, London. pp 283-307.

BICKLE M J (1978) Melting experiments on peridotitic komatiites: Progress in experimental petrology, Natural Environmental Research Council, 4th Progress Rep., series D, No 11. pp 187-195.

BICKLE M J (1982) The magnesium contents of komatiitic liquids. In: Arndt N T & Nisbet E G (Eds.), Komatiites, George Allen and Unwin, London. pp 479-493.

BICKLE M J, FORD C E & NISBET E G (1977) The petrogenesis of peridotitic komatiites: Evidence from high-pressure melting experiments. *Earth and Planetary Science Letters. Vol 370.* pp 97-106.

BINNS R A, GROVES D I & GUNTHORPE R J (1977) Nickel sulphides in Archean ultramafic rocks of Western Australia. In: Sidorenko A V (Ed) Correlation of the Precambrian, Vol 2: Nauka, Moscow. pp 349-380.

BLANCHARD R (1968) Interpretation of leached outcrops. Nevada State Bur. Mines. Bull., No. 66.

BOLDT J R. jnr (1967) The winning of nickel. Methuen & Co. Ltd., London. pp 453.

BRODIE-HALL Sir Laurence, Chairman (1975) Understanding the near-surface environment of the Kalgoorlie region to aid mineral exploration and water management. C.S.I.R.O., Perth. pp 24.

BROOKS R R, LEE J, REEVES R D & JAFFRE T (1977) Detection of nickelliferous rocks by analysis of herbarium specimens of indicator plants. *J. Geochem. Expl., Vol 7.* pp 49-58.

BROOKS R R & WITHER E D (1977) Nickel accumulation by Rinorea bengalensis (wall). *J. Geochem. Expl., Vol 12.* pp 67-78.

BUCHANAN D L & JONES M J, Eds. (1982) Sulphide deposits in mafic and ultramafic rocks. Proceedings of IGCP Projects 161 and 91, 3rd Nickel Sulphide Field Conference, Perth, Western Australia. *Inst. Min. Metall.*, pp 155.

BURKE K, DEWEY J F & KIDD W S F (1976) Dominance of horizontal movement, arc and microcontinental collisions during the later per mobile regime. In: Windley B F (Ed.), The Early History of the Earth. J Wiley & Sons, New York, NY. pp 113-130.

BUTT C R M & NICKEL E H (1981) Mineralogy and geochemistry of the weathering of the disseminated nickel sulphide deposit at Mt. Keith, Western Australia. *Econ. Geol., Vol 76*. pp 1736-1751.

CAMPBELL I H & BARNES S J (1984) A model for the geochemistry of the platinum-group elements in magmatic sulphide deposits. *Can. Miner., Vol 22*. pp 151-160.

CAMPBELL I H & JARVIS (1984) Mantle convection and early crustal evolution. *Precambr. Res., Vol 26*. pp 15-56.

CAMPBELL I H & NALDRETT A J (1979) The influence of silicate: sulphide ratios on the geochemistry of magmatic sulphides. *Econ. Geol., Vol 74*. pp 1503-1505.

CANIL D (1986) The geochemistry of komatiites and basalts from the Deadman Hill area, Munro Township, Ontario, Canada. *Can. J. Earth Sci., Vol 24*. pp 998-1008.

CARD K D (1990) A review of the Superior Province of the Canadian Shield, A product of Archean accretion. *Precamb. Res., Vol 48*. pp 99-156.

CARD K D & CIESIELSKI C (1986) DNAG No. 1. Subdivision of the Superior Province of the Canadian Shield. *Geosci. Can., Vol 13*., pp 5-13.

CATELL A, KROGH T E & ARNDT N T (1984) Conflicting Sm-Nd whole rock and U-Pb zircon ages for Archean lavas from Newton Township, Abitibi Belt, Ontario. *Earth Planet. Sci. Lett., Vol 70*. pp 280-290.

CHANG S H & COLLINS W (1983) Confirmation of the airborne biogeophysical mineral exploration technique using laboratory methods. *Econ. Geol., Vol 78*. pp 723-736.

CHIMIMBA L R (1982) Geology and mineralization at the Trojan nickel mine, Zimbabwe. BSC. thesis. In: Buchanan D L & Jones M J, (Eds.), Sulphide deposits in mafic and ultramafic rocks. Proceedings of IGCP Projects 161 and 91, 3rd Nickel Sulphide Field Conference, Perth, Western Australia. *Inst.Min. Metall.*, pp 147-155.

CHIMIMBA L R & NCUBE S M N (1986) Nickel sulphide mineralization at Trojan mine, Zimbabwe. In: Anhaeusser C R & Maske S (Eds.),Mineral Deposits of Southern Africa, Vol I & II. *Geol. Soc. S. Afr.*, pp 249-253.

CLAOUE-LONG J C, COMPSTON W & COWDEN A (1988) The age of the Kambalda Greenstones resolved by ion microprobe: Implications for Archean dating methods. *Earth Planet. Sci. Lett., Vol 89*. pp 239-259.

CLAOUE-LONG J C & NESBITT R W (1985) Contaminated komatiites. *Nature, Vol. 313*., pp 247.

CLUTTEN J M, FOSTER R P & MARTIN A (1981) Nickel mineralization in Zimbabwe. *Episodes. Vol 1981, No. 2*. pp 10-15.

COLVINE A C, FYON J A, HEATHER K B, MARMONT S, SMITH P M & TROOP D G (1988) Archean lode gold deposits of Ontario. *Ontario Geol. Surv., Misc. Pap., 139*. pp 136.

COMPSTON W, WILLIAMS I S, CAMPBELL I H & GRESHAM J J (1986) Zircon xenocrysts from the Kambalda volcanics: Age constraints and direct evidense for older continental crust below the Kambalda-Norseman greenstones. *Earth Planet. Sci. Lett., 76*. pp 299-311.

CONDIE K D (1986) Geochemistry and tectonic setting of Early Proterozoic supracrustal rocks in the southwestern United States. *J. Geol. Vol 94*., pp 845-864.

COWARD M P, JAMER P R & WRIGHT L (1976) Northern margin of the Limpopo Mobile Belt, Southern Africa. *Bull. Geol. Soc. Am. Vol 87*. pp 601-611.

COWDEN A (1988) Emplacement of komatiite lava flows and associated nickel sulphides at Kambalda, Western Australia. *Econ. Geol., Vol 83*. pp 436-442.

COWDEN A & ARCHIBALD N T (1987)Massive-sulphide fabrics at Kambalda and their relevance to the infered stability of mono-sulphide solid-solution. *Can. Miner., Vol 25*. pp 37-50.

COWDEN A, DONALDSON M J, NALDRETT A J & CAMPBELL I H (1986) Platinum-group elements and gold in komatiite-hosted Fe-Ni-Cu sulphide deposits in Kambalda, Western Australia. *Econ. Geol., Vol 81*. pp 1226-1235.

COWDEN M P & WOOLRICH P (1987) Geochemistry of the Kambalda iron-nickel sulphides: Implications for models of sulphide-silicate partitioning. *Can. Miner., Vol 25*. pp 21-36.

COX R (1975) Geochemical soil surveys in the exploration for nickel copper sulphides at Pioneer, near Norseman, Western Australia. In: Elliot I & Fletcher W K (Eds.), Geochemical Exploration. pp 437-460.

COX R & TYRWHITT D S (1975) Pioneer nickel prospects, near Norseman. In: Knight C L (Ed), Economin Geology of Australia and Papua New Guinea. *Aust. Inst. Min. Metall., Mono 5*. pp 79-81.

DE WIT M J & ASHWAL L (1986) Workshop on tectonic evolution of greenstone belts. *Lunar Planet. Inst. Tech. Rep., 86-10*, Lunar & Planetary Institute, Houston., pp 227.

DILLION-LEITCH H C H, WATKINSON D H & COATS C J A (1986) Distribution of platinum-group elements in the Donaldson West deposit, Cape Smith Belt, Quebec. *Econ. Geol., Vol 81*. pp 1147-1158.

DONALDSON M J (1981) Redistribution of ore elements during serpentinization and talc-carbonate alteration of some Archean dunites, Western Australia. *Econ. Geol., Vol 76*. pp 1698-1713.

DONALDSON M J (1983) Progressive alteration of barren and weakly mineralized Archean dunites: A petrological, mineralogical and geochemical study of some intrusive dunites from Western Australia: Unpublished Ph. D thesis, University of Western Australia, Perth. pp 345.

DONALDSON M J & BROMLEY G J (1982) The Honeymoon Well nickel sulphide deposits, Western Australia. *Econ. Geol., Vol 76*. pp 1550-1564.

DONALDSON M J, LESHER C M, GROVES D I & GRESHAM J J (1986) Comparison of Archean dunites and komatiites associated with nickel mineralization in Western Australia: Implications for dunite genesis. *Mineralium Deposita. Vol 21*. pp 296-305.

DONNELLY T H, LAMBERT I B, OEHLER D Z, HALLBERG J A, HUDSON D R, SMITH J W, BAVINGTON O A & GOLDING L Y (1978) A reconnaissance study of stable isotope ratios in Archean rocks from the Yilgarn Block, Western Australia. *J. Geol. Soc. Aust., Vol 24*. pp 409-420.

DOYLE C D & NALDRETT A J (1987) The oxygen content of "sulphide" magma and its efeect on the partitioning of nickel between coexisting olivine and molten ores. *Econ. Geol., Vol 82*. pp 208-211.

DREVER H I & JOHNSTON R (1957) Crystal growth of forsteritic olivine in magmas and melts. *Trans. Roy. Soc. Edinburgh. Vol 63, pt 2, No. 13*. pp 289-317.

DUKE J M (1979) Computer simulation of the fractionation of olivine and sulphide from mafic and ultramafic magmas. *Can. Miner., Vol 76*. pp 507-514.

DUKE J M (1986) The Dumont nickel deposit: A genetic model for disseminated magmatic sulphide deposits of komatiitic affinity. In: Gallagher M J, Ixer R A, Neary C R & Prichard H M (Eds.), Metallogeny of Basic and Ultrabasic Rocks. *Inst. Min. Metall.*, London. pp 151-160.

DUKE J M (1986) Petrology and economic geology of the Dumont Sill: An Archean intrusion of komatiitic affinity in northwestern Quebec. *Econ. Geol. Rep. 35: Geol. Surv Can.*, Ottawa. pp 56.

DUKE J M & NALDRETT A J (1978) A numerical model of the fractionation of olivine and molten sulphide from komatiite magma. *Earth and and Planetary Science Letters. Vol 39.* pp 255-266.

DUPRES B, CHAUVEL G & ARNDT N T (1984) Pb and Nd isotopic study of two Archean komatiite flows from Alexo, Ontario. *Geochem. Cosmochim. Acta., Vol 48.* pp 1965-1972.

ECKSTRAND O (1975) The Dumont serpentine: A model for control of nickeliferous opaque mineral assemblages by alteration reactions in ultramafic rocks. *Econ. Geol., Vol 70.* pp 183-201.

EVANS D M, COWDEN A & BARRATT R M (1988) Deformation and thermal erosion at the Foster nickel deposit, Kambalda-St.Ives, Western Australia. In: Proceedings of the 5th Magmatic Sulphide Conference, Harare, Zimbabwe. IMM, London.

FOSTER R P, MANN A G, STOWE C W & WILSON J F (1986) Archean gold mineralization in Zimbabwe. In. Anhaeusser C R & Maske S (Eds.) Mineral Deposits of South Africa. *Geol. Soc. S. Afr., Vol 5.*, pp 25-38.

FOSTER R P & WILSON J F (1984) Geological setting of Archean gold deposits in Zimbabwe. In. Foster R P (ed.) GOLD '82: The Geology, Geochemistry and Genesis of Gold Deposits. A A Balkema, Rotterdam. pp 521-551.

FRASER J A, HEYWOOD W W & MAZURSKI M A (1978) Metamorphic map of the Canadian Shield. Geol. Surv. Ca. Map 1475A, scale 1: 3,5000,000.

FURNELL R G (1981) A review of the use of geophysics in base- and precious- metal exploration. Unpubl. MSc. diss., Rhodes Univ., pp 131.

GARIEPY C, ALLEGRE C J & LAJOIE J (1984) U-Pb Systematics in single zircons from the Pontiac Sediments, Abitibi Greenstone Belt. *Can. J. Earth Sci., 21.* pp 1296-1304.

GEE R D (1979) Structure and tectonic Style of the Western Australia Shield. *Tectonophysics. Vol 58.* pp 327-369.

GEMUTS I & THERON A C (1981) The Archean between Coolgardie and Norseman - Stratigraphy and Mineralization. In. Knight C L (ed), Econ. Geol. Aust & PNG, I. Metals, Mono. 5: *Aust. Inst. Min. Metall.*, Prkville. pp 66-74.

GOLE M J, BARNES S J & HILL R E T (1987) The role of fluids in the metamorphism of komatiites, Agnew nickel deposit, Western Australia. *Contr. Miner. Petrol., Vol 96.* pp 151-162.

GOLE M J, BARNES S J & HILL R E T (1989) The geology of the Agnew nickel deposit, Western Australia. *C.I.M., Bull., Vol 82, No. 929.*, pp 46-56.

GOODWIN A M (1981) Archean Plates and Greenstone Belts. In. Kroner A (Ed.) Precambrian Plate Tectonics, Elsevier, Amsterdam., pp 105-135.

GREEN A H & NALDRETT A J (1981) The Langmuir volcanic peridotite-associated nickel sulphide deposits: Canadian equivalents of the Western Australian occurrences. *Econ. Geol. Vol 76.*, pp 1503-1523.

GRESHAM J J (1986) Depositional environments of volcanic peridotite-associated nickel sulphide deposits with special reference to the Kambalda Dome. In: Friedrich G H, Genkin A, Naldrett A J, Ridge J D, Sillitoe R H & Vokes F M (Eds.) Geology and Metallogeny of Copper Deposits, Proceedings of the 27th International Geological Congress, Moscow. Springer-Verlag, Berlin. pp 63-90.

GRESHAM J J & LOFTUS-HILLS G D (1981) The geology of the Kambalda nickel field, Western Australia. *Econ. Geol., Vol 76.* pp 1373-1416.

GROVES D I (1982) The Archean and earliest Proterozoic evolution and metallogeny of Australia. In. Proceedings of the Int. synop. on Archean and Early Proterozoic Geologic Evolution and metallogenesis. *Revista Brasileira de Geociencias*(in press).

GROVES D I & BATT W D (1984) Spatial and temporal variations of Archean metallogenesis associated in terms of evolution of granite-greenstone terrains with particular emphasis on the Western Australian Shield. In. Kroner A, Hanson G N & Goodwin A M (Eds.), Archean Geochemistry, Springer-Verlag, Berlin., pp 73-93.

GROVES D I, BARRETT F M, BINNS R A & MCQUEEN K G (1977) Spinel phases associated with metamorphosed volcanic-type iron-nickel sulphide ores from Western Australia. *Econ. Geol., Vol 72.* pp 1224-1244.

GROVES D I, BARRETT F M & BROTHERTON R H (1981) Exploration significance of chrome-spinels in mineralized ultramafic rocks and Ni-Cu ores. In: de Villiers J R R & Cawthorn G A (Eds.), ICAM 81-Proceedings of the 1st International Conference on Applied Mineralogy. *Geol. Soc. S. Afr., Spec. publ. No 7.*, Johannesburg, South Africa. pp 21-30.

GROVES D I, BARRETT F M & MCQUEEN K G (1979) The relative roles of magmatic segregation, volcanic exhalation and regional metamorphism in the generation of volcanic-associated nickel sulphide ores of Western Australia. Can. Miner., Vol 17. pp 319-336.

GROVES DI, HUDSON D R & HACK T B C (1974) Modifications of iron-nickel sulphides during serpentinization and talc-carbonate alteration at Black Swan, Western Australia. *Econ. Geol., Vol 69.* pp 1265-1281.

GROVES D I & KEAYS R R (1979) Mobilization of ore-forming elements during alteration of dunites, Mt. Keith-Betheno, Western Australia. *Can. Miner., Vol 17.* pp 373-389.

GROVES D I, KORKIAKOSKI E A, MCNAUGHTON N J, LESHER CM & COWDEN A (1986) Thermal erosion by komatiites at Kambalda and genesis of nickel ores. *Nature, Vol 319.*, pp 136-139.

GROVES D I & LESHER C M, Eds. (1982) Regional geology and nickel deposits of the Norseman-Wiluna Belt, Western Australia. Univ. West. Aust. geol. Dep. Extension Service Publ. no. 7. pp 234.

GROVES D I, LESHER C M & GEE R D (1982) Tectonic setting of the sulphide nickel deposits of the Western Australian Shield. In. Buchanan D L & Jones M J (Eds.) Sulphide Deposits in Mafic and Ultrmafic Rocks. Proc. ICGP. proj. 161 & 91, 3rd Ni. Sulph. Field. Conf. Perth, West. Aust. IMM: pp 1-13.

HARGREAVES R B (1981) Precambrian tectonic style: a liberal uniformitarian interpretation. In. Kroner A (ed) Precambrian Plate Tectonics. Elsevier, Amsterdam., pp 21-56.

HARRISON P A (1983) Economic geology of sulphide nickel deposits. MSc thesis. Rhodes University. pp 253.

HELZ R T (1977) Determination of the P-T dependence of the first appearance of FeS-rich liquid in natural basalts to 20 kb. EOS., Vol 58. pp 523.

HENDERSON J B (1981) Archean basin evolution in the Slave Province, Canada. In. Kroner A (ed.) Precambrian Plate Tectonics, Elsivier, Amsterdam. pp 213-236.

HENDRIKS L P (1970) Mineralogical examination of mineralized drill cores from Damba and Shangani prospects, Rhodesia. Unpubl. Rep. Miner. Processing Res. Lab., Johannesburg Consolidated Investment Co. Ltd., pp 6.

HERBERT E, HUPPERT H E & SPARKS S J (1985) Komatiites I: Eruption and flow. *J. Petrol., Vol 26*. pp 694-725.

HERRMANN A G, BLANCHARD D P, HASKIN L A, JACOBS J W, KNAKE D, KOROTEV R L & BRANNON J C (1976) Major, minor, and trace element compositions of peridotitic and basaltic komatiites from Precambrian crust of Southern Africa. *Contr. Min. Petrol., Vol 59*. pp 1-12.

HILL R E T (1982) The six mile well nickel deposit. In: Groves D I & Lesher C M (Eds.) Regional geology and nickel deposits of the Norseman-Wiluna Greenstone Belt, Western Australia. Publ. 7: University of Western Australia Department of Geology and Extension Service, Perth, part C., pp 101-109.

HILL R E T, GOLE M J & BARNES S J (1987) Physical volcanolgy of komatiites, A field guide to the komatiites between Kalgoorlie and Wiluna, Eastern Goldfields Province, Yilgarn Block, Western Australia, Excursion Guide Book No. 1. *Geol. Soc. Aust.*, Western Australian Division, Perth. 74 pp.

HILL R I & COMPSTON W (1987) Age of granite emplacement, southeastern Yilgarn Block, Western Australia. Aust. National Univ., *Res. School Earth Sci., Ann. Rept., 1986*. pp 70-71.

HILL R I & GOLE M (1989) The volcanology of komatiites and implications for the classification of magmatic nickel deposits. *Expl. Res. News*. pp 3-5.

HOOD P J, Ed. (1979) Geophysics and geochemistry in the search for metallic ores. Proceedings of Exploration 77, Canada. Geol. Surv. *Can. Econ. Geol. Rep 31. pp 809.*

HOPWOOD T (1981) The significance of pyritic black shales in the genesis of Archean nickel sulphide deposits. In: Wolf K H (Ed), Handbook of Strata-bound and Stratiform Ore Deposits. Vol 9. Elsevier, Amsterdam. pp 412-467.

HUANG W-L & WILLIAMS R J (1980) Melting relations of the system Fe-S-Si-O to 32 kb with implications as to the nature of the mantle-core boundary. Lunar Planetary Science Conference XI, Lunar and Planetary Science Institute, Houston. pp 486-488.

HUDSON D R (1972) Evaluation of genetic models for Australian nickel

HULME G (1973) *Modern Geol., Vol 4*. pp 107-117.

HULME G (1982) *Geophys. Surv., Vol 5*. pp 245-279.

HUPPERT H E, SPARKS R S J, TURNER J S & ARNDT N T (1984) Emplacement and cooling of komatiite lavas. *Nature. Vol 309*. pp 19-22.

HUPPERT H H & SPARKS S J (1985) Cooling and comtamination of mafic and ultrmafic magmas during ascent through continental crust. Earth and Planetary Science Letters. Vol 74. pp 371-386.

HUPPERT H E & SPARKS s J (1985) Komatiites I: Eruption and flow. *J. Petrol., Vol 26, pt 3*. pp 694-725.

IRVINE T N (1982) Terminology for layered intrusions. *J. Petrol., Vol 23*. pp 127-162.

JENSEN L S & PYKE D R (1982) Komatiites in the Ontario portion of the Abitibi Belt. In: Arndt N T & Nisbet E G (Eds.) Komatiites: George Allen and Unwin, London. pp 147-156.

JOLLY W T (1978) Metamorphic history of the Archean Abitibi Belt. In. Fraser J A & Heywood W W (Eds.), Metamorphism in the Canadian Shield. *Geol. Surv. Can. Pap., 78-10*. pp 63-78.

JOYCE A S (984) Geochemical exploration. *Aust. Min. Fdn. Inc.*, pp 179.

KEAYS R R & DAVISON R M (1976) Palladium, iridium and gold in the ores and host rocks of nickel sulphide deposits in Western Australia. *Econ. Geol., Vol 71*. pp 1214-1228.

KEAYS R R, ROSS J R & WOOLRICH P (1981) Precious metals in volcanic peridotite-associated nickel sulphide deposits in Western Australia, II: Distribution within ores and host rocks at Kambalda. *Econ. Geol., Vol 76*. pp 1645-1674.

KEEL R A & NICKEL E H (1974) The geology of a primary millerite-bearing sulphide assemblage and supergene alteration at the Otter shoot, Kambalda, Western Australia. *Econ. Geol., Vol 76*. pp 1102-1117.

KILLICK A M (1986) The Damba sulphide nickel deposits, Zimbabwe. In: Anhaeusser C R & Maske S (Eds.), Mineral Deposits of Southern Africa, Vol I & II. *Geol. Soc. S. Afr.*, pp 263-273.

KINZLER R J & GROVE T L (1985) Crystallization and differentiation of Archean komatiitic lavas from northeast Ontario: phase equilibrium and kinetic studies. *Am. Miner., Vol 70*. pp 40-51.

LANGFORD F F & MORIN J A (1976) The development of the Superior Province of northwestern Ontario by merging island arcs. *Am. J. Sci.276.*, pp 1023-1034.

LENNON J (1990) The prospects for nickel - what price new capacity ?. *Bull. Inst. Min. Metall., No 94*. pp 23-26.

LESHER C M (1983) Localization and genesis of komatiite-hosted Fe-Ni-Cu sulphide mineralization at Kambalda, Western Australia. Unpubl. Ph.D. diss., Univ. Western Australia, Perth. pp 318.

LESHER C M (1985) Evidence for thermal erosion of basalt and hybridization of komatiite. *Geol. Soc. Am.* Annual Meeting, Program with Abstracts. *Vol 17, no 7*. pp 642.

LESHER C M (1989) Komatiites-associated nickel sulphide deposits. In. A J Whitney & A J Naldrett (Eds.) Ore Deposition Associated with Magmas. *Reviews in Econ. Geol. Vol 4*. pp 45-96.

LESHER C M, ARNDT N T & GROVES D I (1984) Genesis of komatiite-associated nickel sulphide deposits at Kambalda, Western Australia: A distal volcanic model: In. Buchanan D L & Jones M J (Eds.) Sulphide deposits in mafic and ultramafic rocks, Proceedings of International Geological Correlation Projects 161 and 91, 3rd

LESHER C M, DONALDSON M J & GROVES D I (1982) Nickel deposits and their host rocks in the Norseman-Wiluna belt. In: Groves D I & Lesher C M (Eds.), Regional geology and nickel deposits of the Norseman-Wiluna Greenstone Belt, Western Australia, Publ 7. Univ. Western Australia Dept. Geology and Extensional Service, Perth, part B. pp 1-63.

LESHER C M & GROVES D I (1984) Geochemical and mineralogical criteria for the identification of mineralized komatiites in Archean greenstone belts of Australia. In: Petrology: Igneous and Metamorphic Rocks, Proceedings of the 27th International Geological

Congress, Moscow. Vol 9: VNU Science Press, Utrecht. pp 283-302. Nickel Sulphide Field Conference, Perth, Western Austrlia: *Inst. Min. metall.*, London., pp 70-80.

LESHER C M & GROVES D I (1986) Controls on the formation of komatiite-associated nickel-copper sulphide deposits: In, Friedrich G H, Genkin A, Naldrett A J, Ridge J D , Sillitoe R H & Vokes F M (Eds.) Geology and Metallogeny of Copper Deposits, Proceedings of the 27[th] International Geological Congress, Moscow, Springer-Verlag, Berlin. pp 43-62.

LESHER C M, LEE R F, GROVES D I, BICKLE M J and DONALDSON M J (1981) Geochemistry of komatiites at Kambalda: I. Chalcophile element depletion - a consequence of sulphide liquid separation from komatiite magmas. *Econ. Geol., Vol 76*. pp 1714-1728.

LESHER C M & KEAYS R R (1984) Metamorphically and hydrothermally -mobilized Fe-Ni-Cu sulphides at Kambalda, Western Australia. In: Buchanan D L & Jones M J (Eds.) Sulphide deposits in mafic and ultramafic rocks, Proceedings of International Geological Correlation Program Projects 161 and 91, 3[rd] Nickel Sulphide Field Conference, Perth, Western Australia. IMM, London. pp 70-80.

LOWE D R (1982) Comparative sedimentology of the principle volcanic sequences of Archean greenstone belts in S. Africa, Western Australia and Canada: Implications for Crustal Evolution. *Precamb. Res. Vol 17*. pp 1-29

LUDDEN J N & GELINAS L (1982) Trace element characteristics of komatiites and komatiitic basalts from the Abitibi metavolcanic belt of Quebec. In: Arndt N T & Nisbet E G (Eds.), Komatiites, George Allen and Unwin, London. pp 331-345.

LUDDEN J, HUBERT C & GARIEPY C (1986) The Tectonic evolution of the

LUSK J (1976) A possible volcanic-exhalative origin for lenticular nickel sulphide deposits of volcanic association with special reference to those in Western Australia. *Can. J. Earth. Sci., Vol 13*. pp 451-458.

MAIDEN K J, CHIMIMBA L R & SMALLEY T J (1986) Cuspate ore-wall rock interfaces, piercement structures, and the localization of some sulphide ores in deformed sulphide deposits. *Econ. Geol., Vol 81*. pp 1464-1472.

MACDONALD G A (1972) Volcanoes. M.I.T. Press, Cambridge, Massachusetts. pp 177.

MACKENZIE D P (1984) The generation and compaction of partially molten rock. *J Petrol., Vol 25*. pp 713-765.

MACNAUGHTON N J, FROST K M & GROVES D I (1988) Ground melting and ocellar komatiites: A lead isotope study at Kambalda, Western Australia. *Geol. Mag., Vol 125*. pp 285-295.

MACRAE N D (1969) Ultramafic intrusions of the Abitibi area, Ontario. *Can. J. Earth Sci., Vol 6*. pp 281-303.

MALYUK B I (1984) A juvenile-magmatic model of the formation of stratiform nickel-sulphide ore deposits in komatiite host rocks. *Geologiya i Geofizika. Vol 25*. pp 84-91.

MARSTON R J (1984) Nickel mineralization in Western Australia. *Surv. West Aust., Mineral Resour. Bull., 14*. 271 pp.

MARSTON R J, GROVES D I, HUDSON D R & ROSS J R (1981) Nickel Sulphide deposits in Western Australia. *Rev. Econ. Geol. Vol 76*. pp 1330-1363.

MARSTON R J & KAY B D (1980) The distribution, petrology and genesis of nickel ores at the Juan Complex, Kambalda, Western Australia: *Econ. Geol., Vol 75*., pp 546-565.

MAZZUCCHELLI R H (1972) Secondary geochemical dispersion patterns associated with the nickel sulphide deposits at Kambalda, Western Australia. *J. Geochem. Expl., Vol 1*. pp 103-116.

MOORBATH S M (1984) Patterns and geological significance of age determinations in continental blocks. In. Holland H D & Trendall A F (Eds.) Patterns of Change in Earth Evolution. Dahlem Konferenzen, Springer-Verlag, Berlin., pp 207-220.

MUIR J E & COMBA C D A (1979) The Dundonald deposit: an example of volcanic-type nickel-sulphide mineralization. *Can. Miner., Vol 17*. pp 351-359.

MURCK B W & CAMPBELL I H (1986) The efeects of temperature, oxygen fugacity and melt composition on the behaviour of chromium in basic and ultrabasic melts. *Geochim. Cosmochim. Acta., Vol 50. pp 1871-1888.*

NALDRETT A J (1966) The role of sulphurization in the genesis of iron-nickel sulphide deposits of the Porcupine District, Ontario. *Can. Inst. Min. Metall. Trans., Vol 69*. pp 147-155.

NALDRETT A J (1973) Nickel sulphide deposits - their classification and genesis with special emphasis on deposits of volcanic association: *CIMM.,Bull. Vol 66*., pp 45-63.

NALDRETT A J (1979) Partitioning of Fe, Co, Ni and Cu between sulphide liquid and basaltic melts and the composition of Ni-Cu sulphide deposits: a reply and further discussins. *Econ. Geol., Vol 74*. pp 1520-1528.

NALDRETT A J (1981) Nickel sulphide deposits: Classification, composition and genesis. In: Skinner B J (Ed) 75[th] Anniv. Vol., *Econ. Geol*. Publishing Co., El Paso., pp 628-685.

NALDRETT A J (1989) Magmatic sulphide deposits. Oxford University Press, New York. pp 157.

NALDRETT A J & CAMPBELL I H (1982) Physical and Chemical Constraints on genetic models for komatiite-related nickel-sulphide deposits. In: Arndt N T & Nisbet E G (Eds.) Komatiites, George Allen and Unwin, London. pp 423-434.

NALDRETT A J, DUKE J M, LIGHTFOOT P C & THOMPSON J F H (1984) Quantative modelling of the segregation of magmatic sulphides: An exploration guide. *Can. Inst, Min. Metall. Bull., Vol 71*. pp 46-56.

NALDRETT A J & GASPARRINI E L (1971) Archean nickel sulphide deposits in Canada: their classification, geological setting and genesis with some suggestions as to exploration. *Geol. Soc. Australia. Spec. Pub., Vol 3*. pp 201-226.

NALDRETT AJ, HOFFMAN E L, GREEN A H, CHOU C L, NALDRETT S R & ALCOCK R A (1979) The composition of Ni-sulphide ores with particular reference to their content of PGE and Au. *Can. Miner., Vol 17*. pp 403-415.

NALDRETT A J & MASON G D (1968) Contrasting Archean ultramafic igneous bodies in Dundonald and Clergue townships, Ontraio. *Can. J. Earth Sci., Vol 5*. pp 111-143.

NALDRETT A J & TURNER A R (1977) The geology and petrogenesis of a greenstone belt and related nickel sulphide mineralization at

Yakabindie, Western Australia. *Precambr. Res., Vol 5.* pp 43-103.

NISBET E G (1984) The continental and oceanic crust and lithosphere in the Archean: isostatic, thermal and tectonic midels. *Can. J. Earth Sci., Vol 21.* pp 1426-1441.

NESBITT R W (1986) Are komatiite lavas voracious?: *Nature.Vol 319.*, pp 97-98.

NISBET E G, BICKLE M J & MARTIN A (1977) The mafic and ultramafic lavas of the Belingwe Greenstone Belt, Rhodesia. *J. Petrol., Vol 18.*, pp 521-566.

NESBITT R W , SUN S-S & PURVIS A C (1979) Komatiites: Geochemistry and genesis. Springer-Verlag, Berlin,.Vol 17, pp 165-186.

NISBET E G & WALKER D (1982) Komatiites and the structure of the Archean Mantle. *Earth and Planetary Science Letters. Vol 60.*, pp 105-113.

OHMOTO H (1986) Stable isotope geochemistry of ore deposits. In: Valley J W, Taylor H P.jr & O'Neil J R (Eds.), Stable Isotopes in High Temperature Geological Processes, *Reviews in Mineralogy. Vol 16. Min. Soc. Am.*, Washington, D.C., pp 491-559.

OHTANI E (1990) Majorite fractionation and genesis of komatiites in the deep mantle. *Precambr. Res., Vol 48.* pp 195-202.

PALMER H (1991) Six mile nickel deposit: Geological review II. Unpubl. Rep. Dominion Mining Ltd., pp 30.

PARKER P (1984) The role of contamination in the formation of the nickel sulphide ores at Wannaway and Mt. Edwards, Western Australia. Unpublished BSc Honours thesis, University of Western Australia, Perth. pp 144.

PHILPOTTS A R (1961) Textures of the Ungava nickel ores. *Can. Miner., Vol 6.* pp 681-688.

PORTER D J & MCKAY K G (1981) The nickel sulphide mineralization and metamorphic setting of the Forrestania area, Western Australia. *Econ. Geol., Vol 76.* pp 1524-1549.

PRIDER R T (1970) Nickel in Western Australia. *Nature. Vol 226.* pp 691-693.

PYKE D R, NALDRETT A J & ECKSTRAND A R (1973) Archean ultramafic flows in Munro Township, Ontario. *Bull. Geol. Soc. Am., Vol 84.* pp 955-978.

RAJAMANI V & NALDRETT A J (1978) Partitioning of Fe, Co, Ni and Cu between sulphide liquid and basaltic melts and the composition of Ni-Cu sulphide deposits. *Econ. Geol., Vol 73.* pp 82-93.

REYNOLDS I M (1982) Weathering of ore minerals and textural evaluation of gossans. Unpubl. Short Course notes, Rhodes Univ., pp 58-88.

ROSS J R & HOPKINS G M F (1975) Kambalda nickel sulphide deposits. In: Knight C L (Ed) Economic Geology of Australia and Papua-New Guinea, Vol I. *Inst. Min. Metall., Mono. 5.* Parkville., pp 100-121.

ROSS J R & KEAYS R R (1979) Precious metals in volcanic-type nickel sulphide deposits in Western Australia. I. Relationships with the composition of the ores and host rocks. *Can. Miner., Vol 17.* pp 417-436.

ROSS J R & TRAVIS G A (1981) The nickel sulphide deposits of Western Australia in global perspective. *Econ. Geol. Vol 76.*, pp 1291-1329.

SECCOMBE P K, GROVES D I, MARSTON R J & BARRETT F M (1981) Sulphide paragenesis and sulphur isotopic evidence. *Econ. Geol., Vol 76.* pp 1675-1685.

SHAW H H (1980) The fracture mechanisms of magma transport from the mantle to the surface. In: Hargreaves R B (Ed.), Physics of Magmatic Processes. Princeton University Press. pp 201-264

SHIMA H & NALDRETT A J (1975) Solubility of sulphur in an ultramafic melt and the relevance of the system Fe-S-O. *Econ. Geol., Vol 70.* pp 960-967.

SMITH B H (1977) Some aspects of the use of geochemistry in the search of nickel sulphides in lateritic terrains in Western Australia. *J. Geochem. Expl., Vol 8.* pp 259-281.

SMITH H S & ERLANK A R (1982) Geochemistry and petrogenesis of komatiites from the Barberton greenstone belt, South Africa. In. Arndt N T & Nisbet E G (Eds.), Komatiites: George Allen and Unwin, London. pp 348-393.

SMITH H S, ERLANK A R & DUCAN A R (1980) Geochemistry of some ultramafic komatiite lava flows from the Barberton Mountain Land, South Africa. *Precamb. Res., Vol 11.* pp 399-415.

STANTON R L (1972) Ore petrology. New York. McGraw-Hill. 713 pp.

STOLZ G W (1981) A petrographic and geochemical investigation of tha Archean volcanic succession in the vicinity of the Scotia nickel deposit. Unpubl. Ph. D thesis. Univ. Adelaide. pp 234.

STOLZ G W & NESBITT R W (1981) The komatiite nickel sulphide association at Scotia: a petrochemical investigation of the ore environment. *Econ. Geol., Vol 76.* pp 1480-1502.

STOCKWELL C H (1982) Proposals for time classification and correlation of Precambrian rocks and events in Canada and adjacent areas of the Canadian Shield, Part I: A time classification of Precambrian rocks and events. *Geol. Surv. Can. Pap., 80-19.* 135 pp.

SUN S-S (1982) Chemical composition and origin of the earth's primitive mantle. *Geochim. Cosmochim. Acta Vol 46.*, pp 179-192.

SUN S-S (1984) Geochemical characteristics of Archean ultramafic and mafic volcanic rocks: Implications for mantle composition and evolution. In. Kroner A, Hansen G N & Goodwin A M (eds.) Archean Geochemistry, Springer-Verlag, Berlin., pp 25-46.

SUN S-S (1984) Some geochemical constraints on mantle evolution models. Proc. 27th Int. Geol. Congr. vol 9, VNU Sci. Press., pp 475-508.

SUN S-S (1987) Chemical composition of Archean komatiites: Implications for the early history of the earth and mantle evolution. *J. Volc. Geotherm. Res., Vol 32.* pp 67-82

TAKAHASHI E & SCARFE C M (1985) Melting of peridotite to 14 GPa and the genesis of komatiite. *Nature., Vol 315.* pp 566-568.

TARNEY J, DALZIEL I W D, & DEWIT M J (1976) Marginal basin "Rocas Verdes" complex from Southern Chile: A model for Archean greenstone belt formation. In. Windley B F (ed.) The Early History of the Earth. Wiley-Interscience, London., pp 131-136.

THOMPSON J F H, BARNES S J & DUKE J M (1984) The distribution of nickel and iron between olivine and magmatic sulphides in some natural assemblages. *Can. Miner., Vol 22.* pp 55-66.

THORNBER M R (1975) Supergene alteration of sulphides. I. A chemical model based on massive nickel sulphide deposits at Kambalda, Western Australia. *Chem. Geol., Vol 15.* pp 1-14.

THURSTON P C (1986) Volcanic cyclicity in mineral exploration: The caldera cycle and zoned magma chambers. In. Wood J & Wallace H

(Eds.). Volcanology and Mineral Deposits. *Ontario Geol. Surv. Misc. Pap., 129*. pp 104-123.

THURSTON P C, AYRES L D, EDWARDS G R, GELINAS L, LUDDEN J N & VERPAELST P (1985) Archean bimodal volcanism. In. Ayers L D, Thurston K D, Card & Weber W (Eds.), Evolution of Archean Supracrustal Sequences. *Geol. Assoc. Can., Spec.Pap., 28*. pp 7-22.

THURSTON P C & CHIVERS K M (1990) Secular variation in greenstone sequence development emphasizing Superior Province, Canada. *Precamb. Res. Vol 46*. pp 21-58.

TURNER J S, HUPPERT H H & SPARKS R S J (1986) Komatiites II: Experimental and theoretical investigations of post-emplacement cooling and crystallization. *J. Petrol., Vol 27*. pp 397-437.

TURNER A R & RANFORN L C (1975) Six Mile nickel prospect. In: Knight C L (Ed), Economic Geology of Australia and Papua New Guinea. *Aust. Inst. Min. Metall., Mono. 5*. pp 156-158

USSELMAN T M, Hodge D S, Naldrett A J & Campbell I H (1979) Physical constraints on the characteristics of nickel-sulphide ore in ultramafic lavas. *Can. Miner., Vol 17*. pp 361-372.

VEARNCOMBE J R, BARLEY M E, EISENLOHR B N, GROVES D I, HOUSTON S M, SKWARNECKI M S, GRIGSON M W & PARTINGTON G A ., in press. Structural controls on mesothermal gold mineralisation: Examples from the Archean terrains of Southern Africa and Western Australia. *Econ. Geol*. Monograph, Proceedings of Gold'88.

VILJOEN M J & VILJOEN R P (1969) The Geology and geochemistry of the lower ultramafic unit of the Onverwacht Group and a proposed class of igneous rocks. *Geol. Soc. S. Afr., Spec. Publ. 2*. pp 55-85.

VILJOEN M J & BERNASCONI A (1979) The geochemistry, regional setting and genesis of the Shangani-Damba nickel deposits, Rhodesia. *Spec. Publ. geol. Soc. S. Afr., Vol 5*. pp 67-98.

VILJOEN M J, VILJOEN R P & PEARTON T N (1982) The nature and distribution of Archean komatiite volcanics in South Africa. In: Arndt N T & Nisbet E G (Eds.) Komatiites: George Allen and Unwin, London. pp 53-78.

WATSON J (1976) Mineralisation of Archean provinces. In. Windley B F (ed) The Early History of the Earth. Wiley & Sons, London. pp 443-454.

WENTLANDT R F (1982) Sulphide saturation of basalt and andesite melts at high pressures and temperatures. *Am. Miner., Vol 67*. pp 877-885.

WHITNEY J A & NALDRETT A J, Eds. (1989) Ore deposits associated with magmas. *Rev. Econ. Geol., Vol 4*. pp 250.

WILLET G, ESHUYS E & GUY B (1978) Ultramfic rocks of the Widgiemooltha-Norseman area, Western Australia. Petrological diversity, geochemistry and mineralization. *Precambr. Res., Vol 6*. pp 135-156.

WILLIAMS I R (1974) Structural subdivision of the Eastern Goldfields Province, Yilgarn Block. *Geol. Surv. Western Aust., Annu. Rep., 1973.*, pp 53-59.

WILLIAMS D A C (1979) The association of some nickel sulphide deposits with komatiite volcanism in Rhodesia. *Can. Miner., Vol 17*. pp 337-349.

WILSON J F (1979) A preliminary re-appraisal of the Rhodesian basement complex. *Spec. Publ. Geol. Soc. S. Afr., Vol 5.*, pp 1-23.

WILSON J F (1981) The granitic-gneiss greenstone shelld, Zimbabwe. In. Hunter D R (ed.) Precambrian of the Southern Hemisphere. Elsevier, Amsterdam., pp 454-488.

WILSON J F, BICKLE M J, HAWKESWORTH C J, MARTIN A, NISBET E G & ORPEN J L (1978) Granite-greenstone terrains of the Rhodesian Archean craton. *Nature. Vol 271*. pp 3-7.

WILSON J F & NUTT T H C (1990) The nature and occurrence of mineralisation in the Early Precambrian crust of Zimbabwe. In. Naqvi S M (ed.) Precambrian Continental Crust and its Economic Resources. *Developments in Precambrian Geology, 8*. Elsevier, Amsterdam. pp 555-592.

WINDLEY B F (1977) The Evolving Continents. John Wiley & Sons. London. pp 385.

WOOLRICH P, COWDEN A & GIORGETTA N E (1981) The chemical and mineralogical variations in the nickel mineralization associated with the Kambalda dome. *Econ. Geol., Vol 76*. pp 1629-1644.