ECONOMIC GEOLOGY OF SULPHIDE NICKEL DEPOSITS

P.A. HARRISON

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CONTENTS

Page

1. CLASSIFICATION OF NICKEL DEPOSITS

It has been a long standing belief that many nickel sulphide ores are derivatives of magmatic processes in ultramafic and mafic rocks, and that they segregate from these magmas as immiscible sulphide droplets which are then concentrated into an orebody by gravitational settling either during intrusion or extrusion, or during the early stages of crystallization of the magma (Naldrett, 1981). Some geologists however, have suggested alternative mechanisms to explain the concentration of nickeliferous sulphides in the mafic and ultramafic hosts. These include hydrothermal replacement (Fleet, 1977), exhalative volcanic processes (Lusk, 1976), or major metamorphic upgrading of low grade, initially magmatic deposits (Barrett et al., 1977). It is not the purpose of this study to verify or disprove these hypotheses, but in so far as the initial concentration of sulphides in most deposits is concerned, these effects are relatively unimportant (Naldrett, 1981).

The nickel sulphide ores associated with these mafic and ultramafic host rocks, invariably consist of nickeliferous pyrrhotite as the dominant phase, together with lesser, but variable, amounts of magnetite, pentlandite, chalcopyrite, cubanite, and platinum group elements (Reynolds, 1982).

Nickel sulphide deposits are associated with many different classes of mafic and ultramafic rocks (Table 1).

Since nickel-copper sulphide deposits are intimately associated with ultramafic and mafic magmatism, and since this magmatism is dependent on specific tectonic settings, a number of classes of major nickel sulphide deposits can be delineated on the basis of their petro-tectonic setting (Naldrett et al., 1980b). The following four settings account for over 95% of the world's Ni-Cu reserves (Naldrett et al., 1980b; Naldret, 1981; Naldrett et al. 1980a; Naldrett, 1980; and Hopwood, 1981):

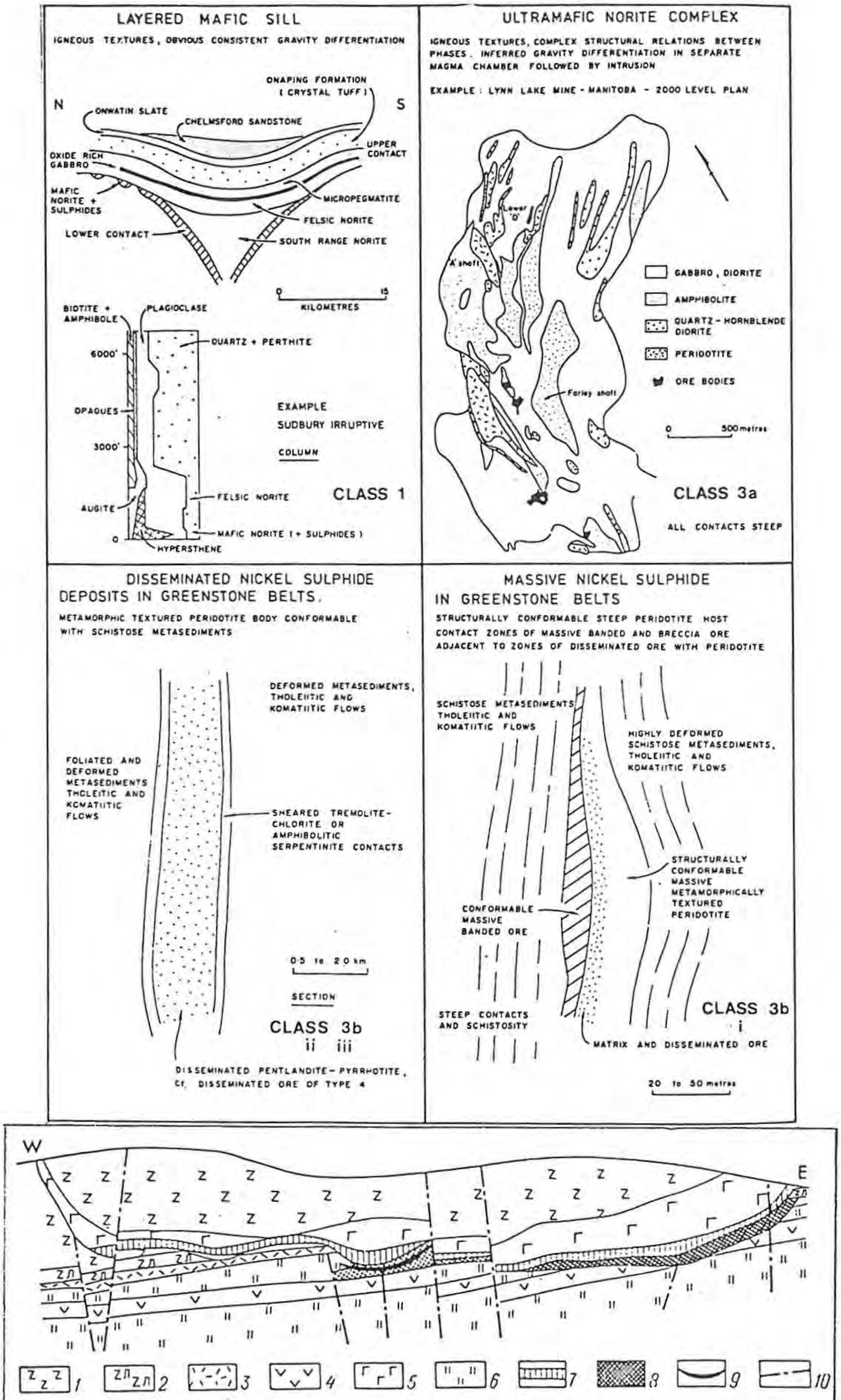
Setting I: includes deposits associated with noritic rocks in a large layered complex associated with an astrobleme (a scar resulting from a meteorite impact)(Fig.1.1). The sole example of this type of deposit is the Sudbury mining camp. The overall composition of the rocks is mafic rather than ultramafic. Disseminated as well as massive breccia-type ores occur at the base of the relatively undeformed and weakly metamorphosed intrusion.

TABLE 1. Classification of mafic and ultramafic rocks and their associated nickel-copper-PGE mineralization (modified after Naldrett, 1981; Naldrett and Cabri, 1976; Besson et al., 1979; Lambert and Groves, 1981; and Naldrett et al., 1980a).

CLASS OF BODY	DESCRIPTION	ORE DEPOSITS
A. SYNVOLCANIC BODIES (apart from those related to intracratonic volcanism).		
1. KOMATIITIC SUITES		
(a) Lava flows. Munro-MacDonald Townships, Ontario. Eastern Goldfields, W. Australia.	Members of the komatiitic Suite range from dunite (40% MgO), through peridotitic komatiite (20%-40% MgO), basaltic komatiite (12%-20% MgO), magnesian basalt (10%-12% MgO), to basalt (< 10% MgO). Both extrusive and intrusive variants of komatiite are present with the former predominating. Thus, range from simple flows, spinifex-capped flows, and differentiated sills. Composition of the flows ranges from peridotite to basalt and that of the sills from dunite to anorthositic gabbro.	W.Australia: Kambalda, Windarra, Scotia, Nepean, Wannaway, Redross, Mt. Edwards, Spargoville. Zimbabwe: Damba, Epoch, Shangani, Trojan, Hunters Road, Matopos, Selukwe, Lower Gwelo. Canada: Langmuir, Texmont, McWatters, Sothman, Hart, Dundonald, Marbridge, Alex
(b) Layered Sills Kaapmuiden type complexes, Barberton Greenstone Belt.		No known deposits.
(c) Intrusive dunite-peridotite lenses. Dumont, Quebec. Eastern goldfields, W. Australia.		W. Australia: Perserverance, Forrestania, Yakabindie, Mt. Keith, Black Swan. Canada: Dumont, Manitoba nickel belt.
(d) Uncertain type in reworked terrains. Manitoba, Canada.		Thompson Mine, Manitoba nickel belt.
2. THOLEIITIC SUITES		
(a) Pictritic synvolcanic layered intrusions. Dundonald sill, Centre Lake Complex, and Kakagi Lake, Ontario.	Ultramafic rocks occur as basal accumulations to gravity differentiated flows or sills. They also occur as zones of hyaloclastic (13%-15% MgO = olivine tholeiite/picrite), fine-grained pyroxenite capping the flows, or as vent breccias related to the sills.	Lynn Lake, Manitoba. Dumbarton and Dundonald sill, Abitibi bel Carr Boyd, W. Australia. Pechenga, USSR.
(b) Anorthositic bodies. Dorē Lake Complex and Bell River Complex, Quebec. Kamiscotia Complex, Ontario.	Conformable to discordant bodies consisting of anorthosite, gabbroic anorthosite, anorthositic gabbro, and layers rich in titaniferous magnetite. Ultramafic rocks are rare and are restricted to layers rich in cumulus pyroxenite.	No known mineralization.
3. DEPOSITS FOR WHICH KOMATIITIC OR THOLEIITIC PARENTAGE UNCERTAIN		
(a) Stratiform intrusions. Mountcalm gabbro, Ontario		Mountcalm Ni-Cu deposit, Ontario. Mt. Sholl, W. Australia. Empress and Perserverance (?), Zimbabwe.
(b) Deposits in tectonically reworked terranes.		Botswana: Pikwe, Selibe, Phoenix, Selkirk
(c) Deposits in iron formation.		Sherlock Bay, Pilbara Block, W.Australia.

TABLE 1. Continued/...

CLASS OF BODY	DESCRIPTION	ORE DEPOSITS
B. INTRUSIONS IN CRATONIC AREAS		
1. INTRUSIONS RELATED TO FLOOD BASALTS:		
Noril'sk-Talnakh, U.S.S.R. Duluth Complex, Minnesotta. Insizwa-Ingeli Complex, Transkei. Dufec, Antarctica.	Tholeiitic flood basalts and their compositionally similar subvolcanic intrusive equivalents. Intrusions tend to be very large, e.g. Dufek is 6-7 km thick and has an area of 8000 sq.km.	Duluth Complex ores Noril'sk-Talnakh field Insizwa-Ingeli waterfall gorge, Transkei.
2. LARGE LAYERED COMPLEXES WITH NO RELATION TO FLOOD BASALT		
(a) Sheetlike		
(i) With repetitive layering Bushveld Complex, S.Africa. Stillwater Complex, Montana. Muskox Complex, Canada.	Subhorizontal stratiform gravity layered mafic sheets/sills/funnel shaped intrusions. Overall composition tends to be mafic rather than ultramafic. Composition of differentiates ranges from pyroxenite, norite and gabbro, through anorthosite, to diorite and granophyre. Ultramafic zones may be present at the base.	Bushveld Complex: bronzitite pipes, UG2, Merensky Reef. Ores associated with the Stillwater Complex and Muskox Complex.
(ii) Without repetitive layering. Sudbury Complex, Canada.	Differs from the above in that it contains no ultramafics at the base and lacks repetitive layering.	Sudbury nickel deposits.
(b) Dikelike		
Great dyke, Zimbabwe. Jimberlana dyke, W. Australia.		
3. OTHER MEDIUM AND SMALL INTRUSIONS		
Skaergaard. Rhum.		Losberg, South Africa.
4. ALKALIC ULTRAMAFIC ROCKS	Carbonatites and kimberlites.	No known examples.
C. BODIES EMPLACED DURING OROGENESIS		
1. SYNOROGENIC INTRUSIONS		
Aberdeenshire gabbros, Scotland. Seiland Province and Rhonå, Norway. La Perousse, Alaska.	These mafic intrusions are common in the Appalachian and Caledonian orogenic belts. Exhibit evidence of a synorogenic emplacement (tectonite fabrics, irregular distribution of a wide variety of igneous rock types), assimilation of country rocks and partial metamorphism during the late stages of deformation.	Rhonå, Norway. La Perousse, Alaska. Hitura and Kotalahti, Finland.
2. TECTONICALLY EMPLACED BODIES (ALPINE-TYPE)		
(a) Ophiolite Complexes New Caledonia. Bay of Islands, Newfoundland.	Portions of oceanic crust and upper mantle obducted onto the continents. Characterized by a basal zone of metamorphic-textured periodotite overlain by a sequence of cumulates ranging from dunite through peridotite to gabbro, a sequence of pillow lavas and associated feeder dykes, and a capping of deep sea sediments including radiolarian chert.	No significant examples.
(b) Possible mantle diapirs. Mt. Albert, Quebec.	High temperature diapiric intrusions of solid mantle emplaced during orogenesis.	No significant examples.
3. ALASKAN-TYPE COMPLEXES		
Duke Island, Alaska. Union Bay, Alaska. Urals. Venezuela. South-Central British Columbia.	Some of the larger complexes show a rough concentric zoning with a dunitic core, surrounded by successive shells of olivine clinopyroxenite, magnetite-rich clinopyroxenite and hornblendite. As a group, they are distinguished from the alpine-type ultramafics or stratiform intrusions in having highly calcic clinopyroxene, no orthopyroxene or plagioclase and abundant hornblende. They contain abundant iron rich chromitite and magnetite.	Salt Chuck, Alaska.



CLASS 2

Geological section through Noril'sk I deposit

1) undifferentiated eruptives; 2) labradorite basalts; 3) titan-augite basalts; 4) sills of titanaugite dolerites; 5) Noril'sk I gabbro-dolerite intrusion; 6) sedimentary rocks of the Tungusska Series; 7) segregated ores in intrusion; 8) segregated ores in rocks of the exocontact; 9) vein ores; 10) tectonic disturbances

Fig. 1.1. Host environments for the major nickel sulphide deposits (modified after Hopwood, 1981, and Smirnov, 1977).

Setting II: embraces deposits found within the intrusive equivalents of tholeiitic basalts in areas of intracontinental rifting. Important examples of this type of mineralization include the Noril'sk camp and the unexploited sulphides at the western edge of the Duluth Complex (Fig 1.1).

Setting III: contains deposits associated with magmatic activity accompanying the formation of Precambrian and Proterozoic greenstone belts. The ore deposits are found in two petrologically distinct hosts within these terrains, namely: tholeiitic intrusions and komatiitic volcanics.

IIIA: Tholeittic intrusions host nickel-copper sulphide ores in intrusive plug-like ultramafic-norite complexes (Fig. 1.1). Some complexes range in composition from peridotite to gabbro, while others consist entirely of mafic rocks. The irregular shaped intrusions are composed of a series of igneous phases arranged in an unsystematic manner, are structurally complex, and are generally only partially layered. Gravity differentiation is thought to have taken place in a separate magma chamber followed by multiple intrusion of each of the phases. The intrusions are generally found in metamorphosed greenstone belts. Concentrations of both disseminated and massive sulphides occur in steep ore lenses associated with the more silica-rich amphibolitic rock types. Examples of this type of mineralization include the ores of the Pechenga nickel camp in the Kola Peninsula, USSR; Lynn Lake in Manitoba; and the Carr Boyd deposit in Western Australia.

IIIB: The deposit associated with komatiitic volcanism can be divided into three sub-types.

Group I: Small (1 to 5 million tonnes) high grade (1,5% to 3,5% Ni) ore bodies occurring at the base of highly magnesian (>35%) ultramafic (peridotitic komatiite) flows in thick sequences of progressively thinner and less magnesian peridotitic komatiite, basaltic komatiite, and tholeiitic flows (Fig. 1.1). Mineralization is of a more massive type at the base, which then passes upward into disseminated mineralization. Examples of this type of deposit include those developed around the Kambalda and Widgiemooltha domes in Western Australia; Langmuir and Marbridge in the Abitibi belt; and Damba, Epoch, and Shangani deposits in the Zimbabwean greenstone belts.

Group II: Medium sized (10 to 40 million tonnes) fairly high grade (1,5% to 2,5% Ni) ore deposits located at the base of intrusive dunitic or peridotitic lenses which in many cases, are thought to represent feeders for the komatiitic volcanism. These deposits may contain massive and/or disseminated mineralization. Examples of this type of deposit include the deposits of the Proterozoic Cape-Smith-Wakeman Bay greenstone belt (Ungava nickel belt), the Manitoba nickel belt, and the Perserverance deposit in Western Australia.

Group III: Very large (100 to 250 million tonnes) low grade (0,6% Ni) deposits spatially associated with dunitic lenses which are interpreted as intrusive, sill-like bodies feeding komatiitic volcanism. Examples of this type of deposit include the Mt. Keith, Six Mile, and Yakabindie deposits in Western Australia.

Setting IV: Tholeiitic intrusions which are generally synchronous with orogenesis in Phanerozoic orogenic belts host deposits of lesser importance. These include the Rhonå deposit in Norway and the Katahdin gabbro in Northern Maine.

The relative importance of the different petro-tectonic settings as hosts for nickel-copper sulphide ores is illustrated in Fig. 1.2. Three classes dominate; the Sudbury nickel camp (Setting I), those deposits associated with flood basalt magmas and intracontinental rifting (Setting II), and those deposits spatially associated with komatiitic rocks in Precambrian and Proterozoic greenstone belts (Setting III). The chapters that follow will primarily concentrate on these three types of deposit.

Alpine-type bodies, Alaskan-type bodies and alkalic ultramafic rocks are unlikely hosts for significant deposits of nickel sulphides on the basis of past experience (Naldrett et al., 1980a). It should be noted however, that deposits near the basal contact of the Stillwater and Duluth complexes have great economic potential if environmental considerations are overcome (Naldrett et al., 1980a). These deposits however, constitute low grade disseminated deposits which will require large scale mining and processing if they are ever to become economic.

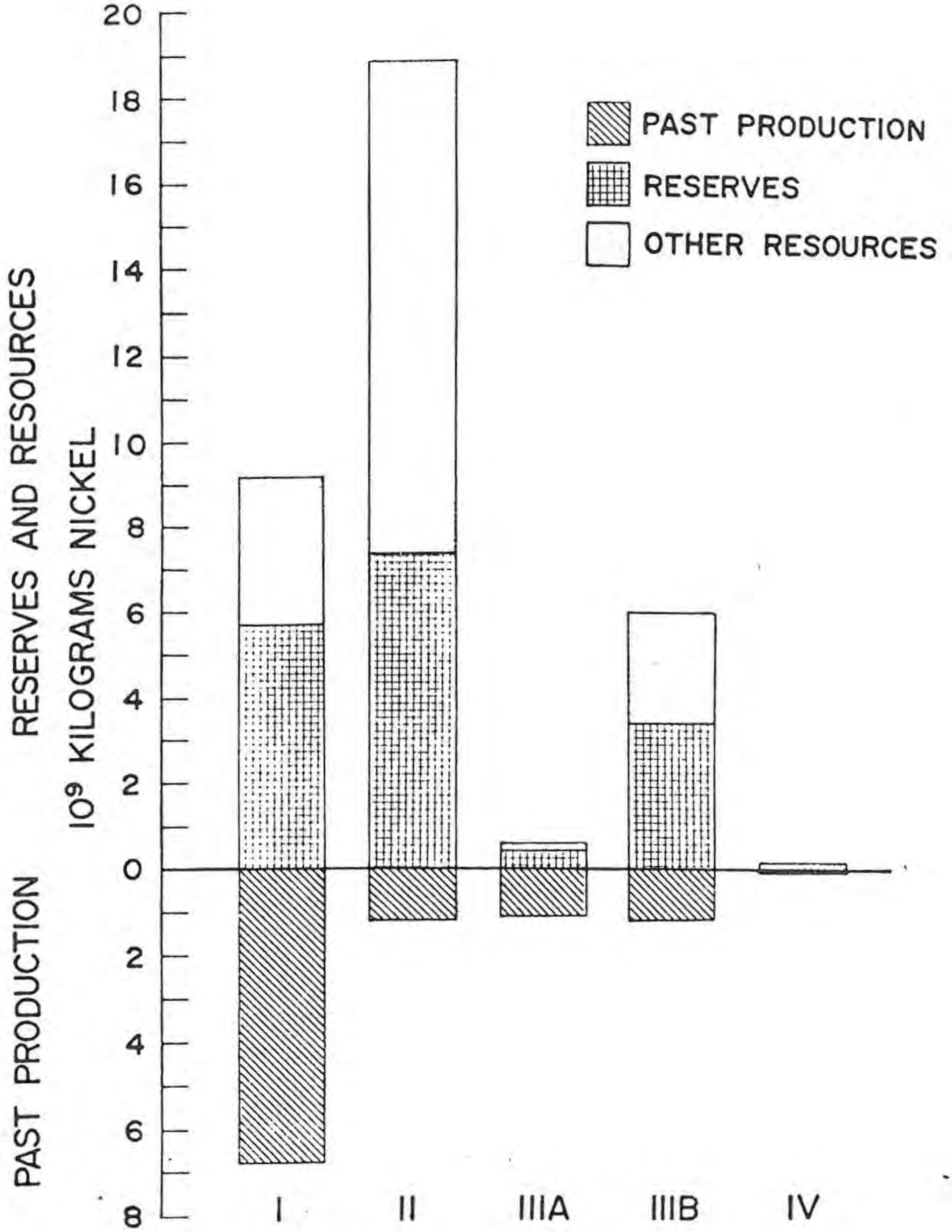


Fig. 1.2. Quantity of Ni metal contained in total past production, present reserves, and other identified resources of magmatic sulfide deposits. The deposits are classified according to their petrotectonic settings as described in the text. Reserves comprise known ores that are currently mineable at a profit, whereas other resources include those known deposits that are economically viable at present but which are likely to undergo development in the foreseeable future. The other resources present at Sudbury (setting I) and at Noril'sk (included in setting II) are not known but have been conservatively estimated to be one-half of the reserves (after Naldrett and Duke (1980), from Naldrett, 1980).

2. THE BEHAVIOUR OF NICKEL IN SULPHIDE AND SILICATE MELTS

2.1 The partitioning of Cu, Ni, and Co between sulphide and silicate melts

One characteristic feature of nickel-sulphide deposits is that the composition of the ores is directly related to the geochemistry of the associated host rocks. Cu/(Cu + Ni) ratios in many deposits show a general increase with decreasing MgO content of the host igneous rocks (Naldrett, 1973). Naldrett and Cabri (1976) demonstrated this relationship graphically and found a negative correlation between the MgO content and the Cu/(Cu + Ni) ratios (Fig. 2.1). Therefore, deposits

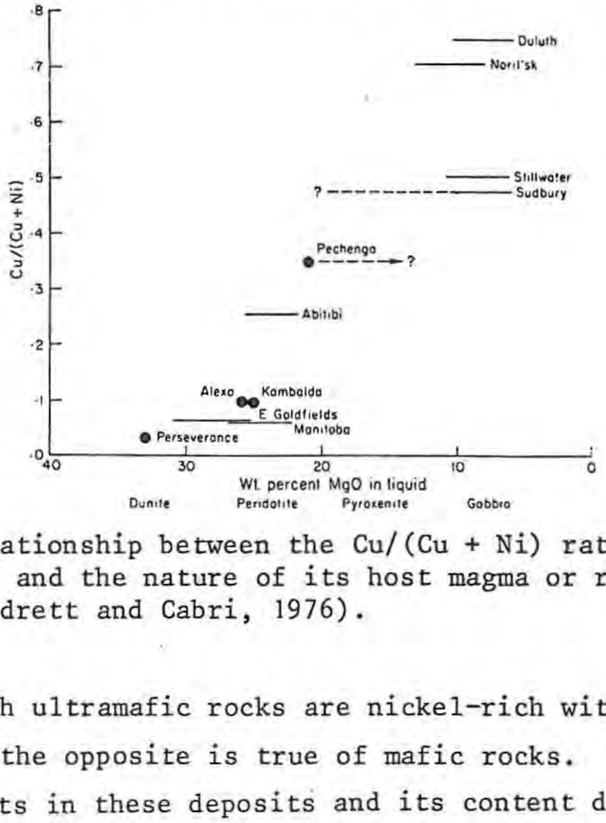


Fig. 2.1. Relationship between the Cu/(Cu + Ni) ratio of s sulphide ore and the nature of its host magma or rock (after Naldrett and Cabri, 1976).

associated with ultramafic rocks are nickel-rich with low Cu/Cu + Ni ratios, while the opposite is true of mafic rocks. Cobalt is present in minor amounts in these deposits and its content does not seem to vary significantly with associated rock type (Rajamani and Naldrett, 1978). Therefore, Ni/Co ratios in these deposits decreases with the decreasing basicity of the host rocks.

Fig. 2.2 illustrates the variation in the Ni and Cu contents in what are believed to be the successive liquids of a fractionally crystallised komatiitic magma, plotted as a function of the weight percent MgO in the liquids. Much of the compositional change exhibited by these liquids is interpreted as the result of the

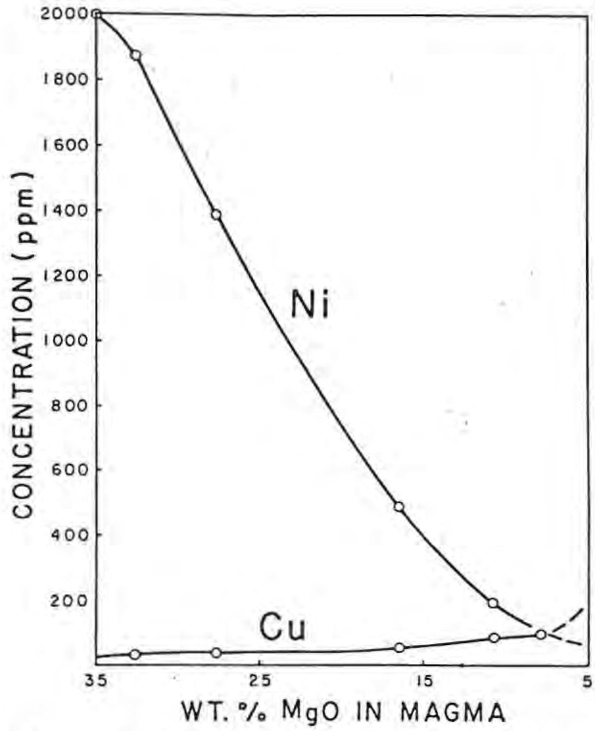


Fig. 2.2. Variation of Ni and Cu with weight percent MgO in the successive liquids of a fractionally crystallized komatiitic magma, based on the composition of komatiitic rocks of Yakabindie, Western Australia (after Rajamani and Naldrett, 1978).

crystallization and removal of olivine (Rajamani and Naldrett, 1978). The strong preference of Ni^{2+} for olivine relative to the silicate liquid accounts for the marked depletion of Ni in the residual liquids. Cu on the other hand tends to build up in the residual magma because Cu^{+} does not have any preference for the early crystallizing ferromagnesian silicates. Therefore, the Ni/Cu ratio decreases rapidly during the fractional crystallization of ultramafic and mafic magmas.

Rajamani and Naldrett (1978) also calculated the variation in the Cu/(Cu + Ni) ratio of the sulphide liquid segregating from the successive liquids of a fractionally crystallizing komatiitic magma and superimposed it on the data known for natural ore deposits (Fig. 2.3). The composition of the sulphide liquid separating from the komatiitic magma is in reasonable agreement with the observed composition of the various deposits and supports the contention that these ores are of magmatic origin.

MacLean and Shimazaki (1976) investigated the partitioning of Ni, Cu, Co, Fe, and Zn between the immiscible sulphide and silicate melts in the system $FeS\text{-}FeO\text{-}SiO_2$ at $1150^{\circ}C$ and found that the first

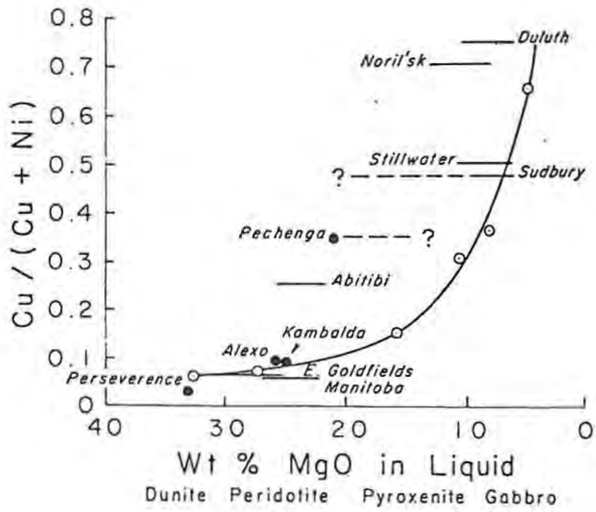


Fig. 2.3. Calculated relationship between the Cu/(Cu + Ni) ratios of sulphide liquids and weight percent MgO of komatiitic magma, superimposed on Fig. 2.1. The open circles represent the calculated ratios (after Rajamani and Naldrett, 1978).

four elements strongly favoured the sulphide liquid. The preference of the transition metals for the sulphide liquid was found to be Ni > Cu > Co > Fe > Zn. These authors interpreted the preference as a consequence of the transition metals forming π bonds with sulphur. These have higher stabilization energies than ionic bonds formed with oxygen. The partitioning may be more quantitatively defined by using the Nernst partition coefficients (D or K_{me}), which are defined as (Rajamani and Naldrett, 1978):

$$D(\text{or } K_{me}) = \frac{\text{Wt \% metal in the sulphide liquid}}{\text{Wt \% metal in the silicate liquid}}$$

The values for Ni and Cu are both strongly positive (Fig. 2.4). It should be noted that Rajamani and Naldrett obtained much larger partition coefficients. Their D^{Ni} was 275, and D^{Cu} was 240 for a melt of basaltic composition.

These findings are in agreement with the situation in natural nickel-sulphide ores where the most abundant metals present, Ni and Cu, show the greatest partitioning into the sulphide phase (Reynolds, 1982). Cobalt is fairly common accessory and shows a weak partitioning. Zn shows a slight preference for the silicate phase and is rarely encountered in nickel sulphide deposits. The ores contain large amounts of iron sulphide even though it has a very low partition

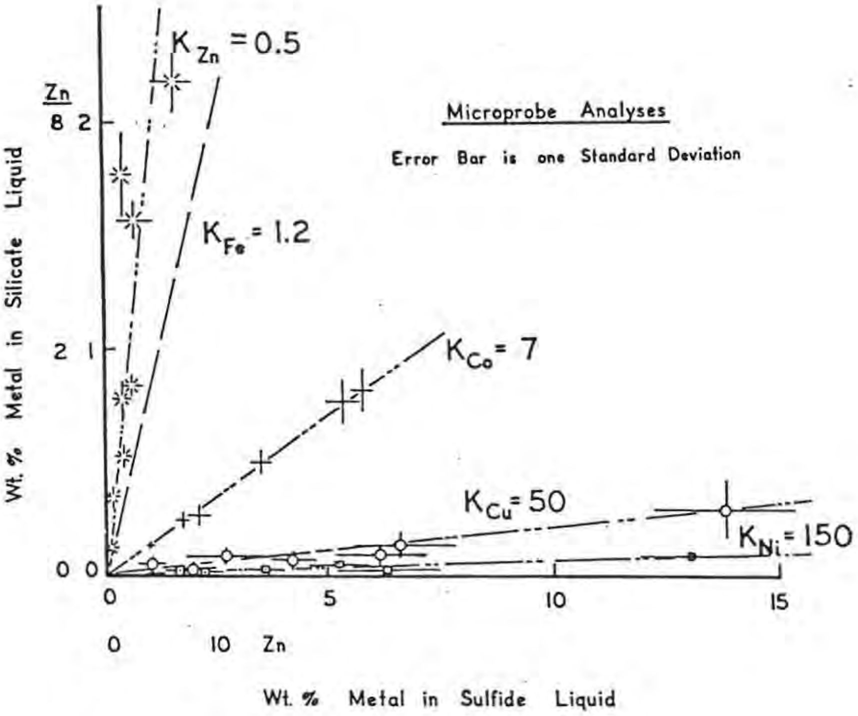


Fig. 2.4. Plot of the experimental data on the partitioning coefficients. The error bars are one standard deviation of X-ray counting statistics (after MacLean and Shimazaki, 1976).

coefficient. This is because of the large amount of iron present in mafic and ultramafic magmas.

The observations described above are of profound importance in the genesis of nickel sulphide deposits. Only if a magma contains sulphur will nickel selectively partition into the sulphide phase, if the magma contains no sulphur, nickel will selectively partition into olivine and no sulphide deposit will form.

The chrondrite normalized platinum group element patterns of these deposits is systematically related to the composition of their host rocks (Naldrett et al., 1979; Naldrett, 1981). The sulphides associated with peridotitic komatiites, which have crystallized from magmas containing more than 20% Mg, have (Pt + Pd)/(Ru + Ir + Os) ratios of 3,0 or less. Ratios of 12 or more are characteristic of magmatic sulphides related to gabbroic rocks that have crystallized from magmas containing less than 12% MgO. This generalization only applies to ratios. The absolute levels of P.G.E. in deposits vary by several orders of magnitude with respect to both komatiite-related and gabbro-related deposits. This correlation is best explained as the result of Ru, Ir, and Os behaving much more "compatibly" with respect to mantle mineralogy during partial melting than Pd and Pt, which partition into early-formed melts. It is possible that the compatible nature of the former is due to their presence in alloys which are reluctant to dissolve in early mantle melts.

2.2 Sulphur solubility in mafic and ultramafic magmas

Nickel sulphide deposits are thought to have formed as the result of the high temperture separation of an immiscible sulphide melt. This process has been observed in currently active lava pools on Hawaii by Skinner and Peck (1969). Sulphur, as sulphide, is most readily dissolved in silicate liquids by displacing the oxygen bonded to ferrous iron (Fig. 2.5) by the reaction (MacLean, 1969):

$$FeO_{(melt)} + \tfrac{1}{2}\,S_2 = FeS_{(melt)} + \tfrac{1}{2}\,O_2$$

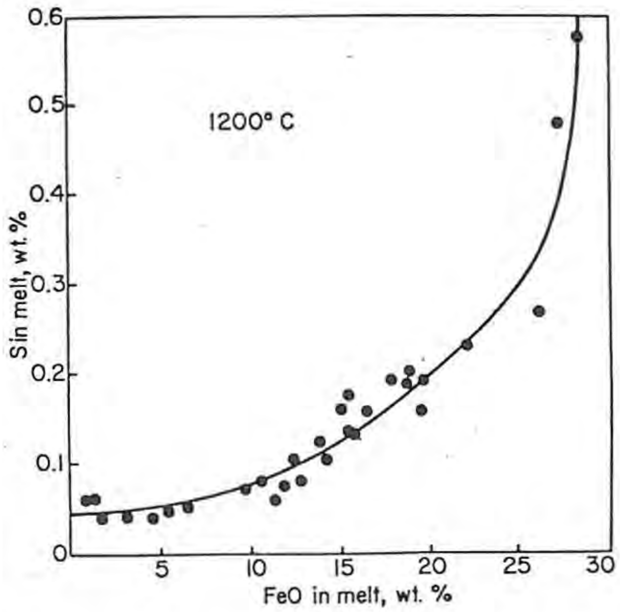


Fig. 2.5. Sulphur and FeO contents of a basaltic melt in equilibrium with varying Fe-S-O liquids at 1,200°C (after Haughton et al., 1974).

Haughton et al. (1974) reported that $f(O_2)$, $f(S_2)$, temperature, and composition of the melt are the principal controls on the solubility of sulphur in a mafic magma. Shima and Naldrett (1975) found that Fe^{2+} content is the major factor controlling the solubility of sulphur in ultramafic rocks. The lower $f(O_2)$ conditions present also lead to higher sulphur solubilities and most ultramafic magmas contain somewhat more dissolved sulphur than mafic magmas.

An immiscible sulphide melt may form in a number of different ways. A 5 times to 7 times decrease in the solubility of sulphur is experienced with every 100°C drop in temperature assuming a constant ratio of $f(O_2)$ to $f(S_2)$ (Haughton et al., 1974). A magma rising from the mantle or base of the crust will undergo both a decrease in pressure and in temperature (Haughton et al., 1974). As the magma cools, it may eventually reach saturation and commence precipitation of an immiscible sulphide liquid. The optimum conditions for forming a large concentration of sulphide would be in large relatively stable magma chambers. Continuous tectonic movements will probably result in the continued suspension of the sulphide crystals and consequently, no major accumulation of sulphide will form.

Assuming the system is closed to sulphur, the crystallization of any oxides or silicates would increase the relative concentration of sulphur in the melt and allow the separation of an immiscible sulphide phase (Haughton et al., 1974). In contrast however, separation of plagioclase and pyroxene which are less iron-rich than the parent magma will cause the magma to become enriched in FeO and this results in increased amounts of sulphur being dissolved.

Any change in the magma that would promote precipitation of magnetite, chromite, and/or ilmenite would decrease the FeO content of the magma and would therefore decrease the capacity of a sulphide-saturated magma to dissolve sulphur (Buchanan and Nolan, 1979). These changes may ultimately lead to super-saturation of the magma in sulphur and so promote the formation of an immiscible sulphide phase.

The importance of $f(S_2)$ and $f(O_2)$ as precipitating mechanisms is difficult to evaluate (Haughton et al., 1974). Both these variables will, in general, be controlled by the magma and will tend to vary in parallel as thermal and compositional changes occur in the magma. In a closed system therefore, it is not likely that sufficiently large changes in the ratio of $f(S_2)$ to $f(O_2)$ will occur during cooling of the magma to allow separation of an immiscible sulphide phase. If the cooling magma is not a closed system however, variations in $f(S_2)$ and $f(O_2)$ can occur in a number of ways. Direct assimilation of sulphide minerals, SO_2, or H_2S by the magma could induce rapid variations in $f(S_2)$ and allow the precipitation of sulphide minerals. Assimilation of water, diffusion of H_2 out from a magma, floundering of cooled, oxidized roof rocks from a magma chamber, and direct assimilation of oxygen could all lead to an increase in $f(O_2)$ and thus, a decrease in the ferrous iron content which would allow the separation of an immiscible sulphide melt.

2.3 Modelling of olivine and sulphide fractionation

Computer modelling experiments to simulate the formation of nickel sulphide ores in komatiitic liquids have been performed by Naldrett and Duke (1978). This work was subsequently refined and extended to more mafic compositions by Duke (1979).

The calculated variation of Ni, Cu, and Co with MgO concentration in derivative liquids is shown in Fig. 2.6. The compositions of some

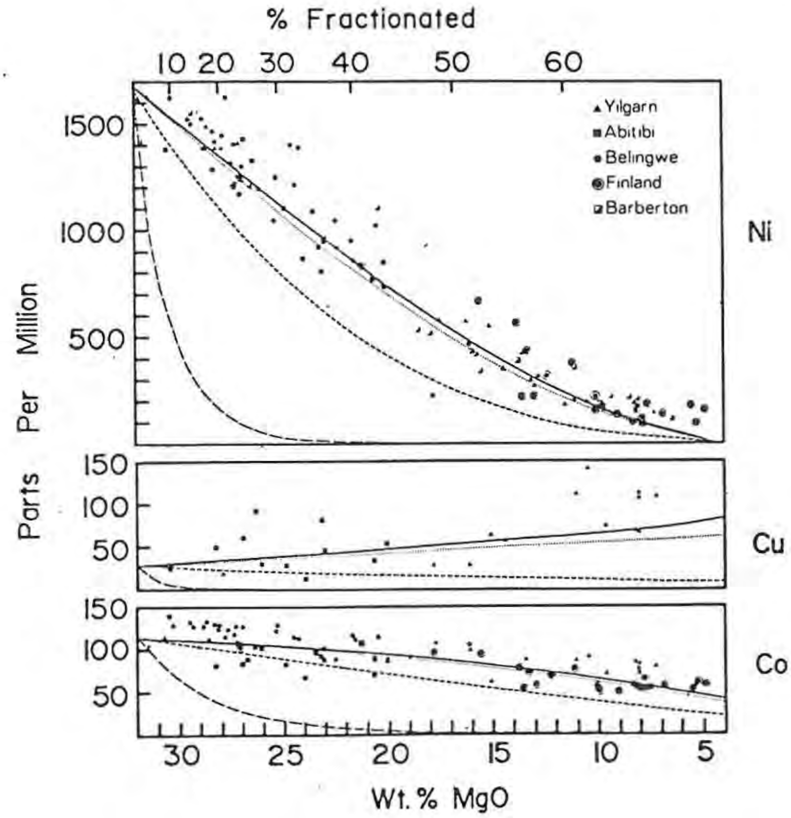


Fig. 2.6. Concentrations of chalcophile elements in derivative silicate liquids as a function of the MgO concentration in the liquid for the model komatiite system for sulphide-free fractionation (solid lines) and olivine/sulphide ratios of 1000 (dotted line), 100 (short dashed lines) and 10 (long dashed lines). The points are published analyses of natural komatiite lavas (after Duke, 1979).

natural liquid-equivalent komatiites are also plotted. Much of the variation in the chalcophile-element concentrations amongst these samples could have apparently resulted from fractional crystallization of olivine from rather similar parental magmas and therefore, the modelled data agrees fairly well with natural data.

The concentrations of Ni, Co, and Cu in the model sulphide melts are plotted in Fig. 2.7. Consider a parental silicate liquid containing 32 wt % MgO and 1600 p.p.m. Ni which is saturated in both olivine

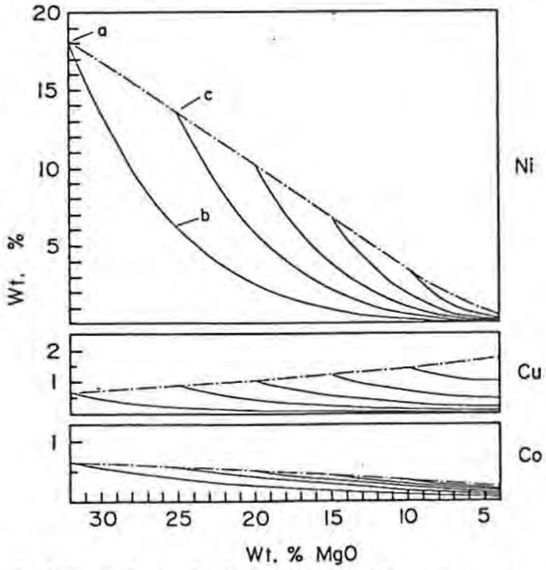


Fig. 2.7. Composition of initial sulphide melt to form from silicate liquid which becomes sulphide-saturated at given MgO concentration (dash-dot curve), and compositions of subsequent sulphide melts. Points a, b and c relate to text (after Duke and Naldrett, 1978).

and molten sulphide. The initial increment of sulphide to exsolve from this silicate liquid will contain 18,2 wt % Ni (Fig. 2.7 point a). As the fractionation of olivine and molten sulphide proceeds, the concentration of MgO in the silicate liquid decreases. At the stage when it has reached 25 wt %, the increment of (subsequent) sulphide melt which forms contains only 6,1 wt % Ni (point b). Consider on the other hand, a similar parental liquid which contains some sulphur, but is not sulphur saturated. As olivine fractionation proceeds, the sulphur concentration increases in successive residual liquids and the sulphide solubility decreases as a result of the changing liquid composition and decreasing temperature, and the silicate liquid may eventually become saturated with sulphide. If the silicate liquid first reaches sulphide saturation when the MgO content is 25 wt %, the initial sulphide increment to form would contain 13, 6 wt % Ni (point c). Thus the Ni, Cu, and Co grades in any one nickel-copper sulphide deposit is clearly dependent on the amount of sulphur initially present and the MgO content and time when sulpide saturation was achieved.

The corresponding Ni/Cu ratios of the modelled systems are plotted in Fig. 2.8. From a study of this diagram it is clear

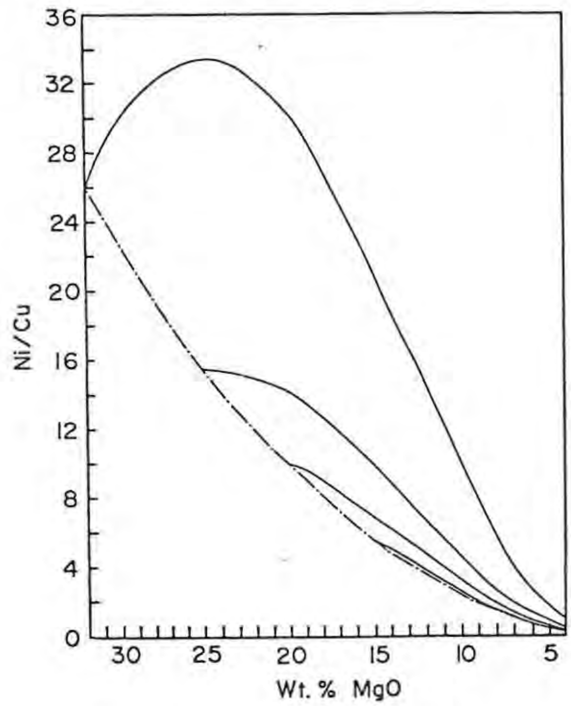


Fig. 2.8. Ni/Cu ratios of initial sulphide melts (dash-dot curve) and subsequent sulphide melts (solid curves) as function of MgO concentration of coexisting silicate liquid (after Duke and Naldrett, 1978).

that the Ni/Cu ratios are also very dependent on whether sulphide saturation occurred at a very early stage (high MgO content) or at a later stage (lower MgO content). Therefore, although the Ni/Cu ratio varies markedly between ultramafic and mafic rocks as a result of olivine fractionation, considerable local variation may be found within any one ore deposit or in ore deposits hosted by similar rocks as a result of the relative timing of sulphide saturation.

2.4 Crystallization of magmatic sulphide liquids

The sulphide assemblages found in nickel sulphide ores develop from a high temperature sulphide liquid that intially solidifies as a single high temperature phase referred to as a monosulphide solution.

The breakdown of this solid solution with decreasing temperature gives rise to the main sulphide phases encountered in nickel sulphide deposits.

The magmatic sulphide liquid can be represented by compositions within Fe-Ni-Cu-S quaternary system. Phase relationships above 350°C are well known and have been investigated by Craig (1973), Craig et al. (1968), Kullerud (1963), Kullerud et al. (1969) and Naldrett (1969). A summary of their work is to be found in Reynolds (1982).

Crystallization of the Fe-rich monosulphide solution (M_{ss}) commences at temperatures slightly above 1100°C and becomes more nickel-rich with falling temperature. Magnetite is able to co-precipitate with the monosulphide solution, but the amount formed is largely a function of the degree to which the oxygen fugacity is buffered by the other phases. The crystallization of chalcopyrite commences at about 970° and there is a possibility that a Cu-rich sulphide liquid may separate from the melt between 1190° and 950°. At 862°C a phase of the composition $(Ni, Fe)_{3 \pm x} S_2$ crystallizes. On cooling to 610°C, the M_{ss} and $(Ni\ Fe)_{3 \pm} S_2$ phases react to form pentlandite which now enters as the stable phase. Cubanite will begin to exsolve from chalcopyrite below 590°C. Below 300°C the monosulphide solution finally decomposes to yield pyrrhotite and pentlandite. The pyrrhotite commonly decomposes on further cooling to form an intimate mixture of hexagonal and monoclinic pyrrhotite.

2.5 The 'Billiard Ball Model' for nickel sulphide mineralization

Many nickel sulphide deposits contain a basal accumulation of massive sulphide in sharp contact with an overlying net-textured zone comprising a continuous network of sulphides interstitial to olivine phenocrysts. The latter is in sharp contact with an overlying zone containing a weaker discontinuous dissemination of sulphide.

These observations can be explained with reference to a very simple model-based on gravitational settling (Naldrett, 1973). Consider a large beaker partly full of billiard balls (Fig. 2.9), imagine that this is then filled with water and that the balls are denser than the water so that they remain at the bottom. If mercury is then poured into the beaker it will sink to the bottom and the

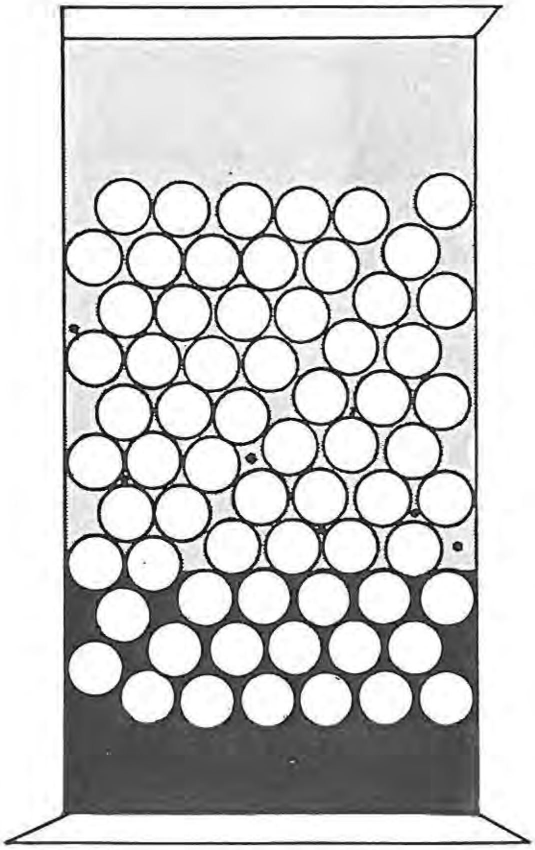


Fig. 2.9. The "billiard ball" model (after Usselman et al., 1979).

balls will tend to float on top of this. The weight of the overlying balls will force the lowest ones down into the mercury to an extent necessary to provide floatation for those above the mercury. A few small drops of mercury may get trapped against the overlying balls which are primarily enclosed in water. If the beaker is then frozen before all the mercury has had a chance to percolate to the bottom, the end product will resemble that shown in Fig. 2.9.
In this model an analogy is drawn between the mercury and the massive sulphides, between the overlying zone of balls immersed in mercury and the net-textured ore, between the water enclosing the billiard balls and the silicate liquid, and finally between the low grade disseminated zone and the small drops of mercury trapped between the billiard balls.

The ore sequence can be explained by dynamic modelling (Usselman et al., 1979). Heat loss through the bottom of the flow/intrusive pulse causes the sulphide liquid to freeze upwards and produces the massive ore. At the same time olivine accumulates on the top of the sulphide liquid as a result of heat loss through the top of the flow/intrusion. The ever-growing olivine cumulus pile forces some of the olivine crystals into the sulphide liquid resulting in the development of the net-textured zone. The relative thicknesses of these two ore units are dependent on the rates of massive ore solidification and olivine accumulation, and on the percentage of olivine that had crystallized prior to the onset on gravitational settling (Usselman et al., 1979).

3. NICKEL SULPHIDE DEPOSITS ASSOCIATED WITH THE SUDBURY IRRUPTIVE

3.1 Regional geological and tectonic setting of the Sudbury basin

The Sudbury Nickel Irruptive has been the world's single most important source of nickel since 1903 (Fig. 3.1). The Sudbury Complex is also a very important source of copper and platinum group

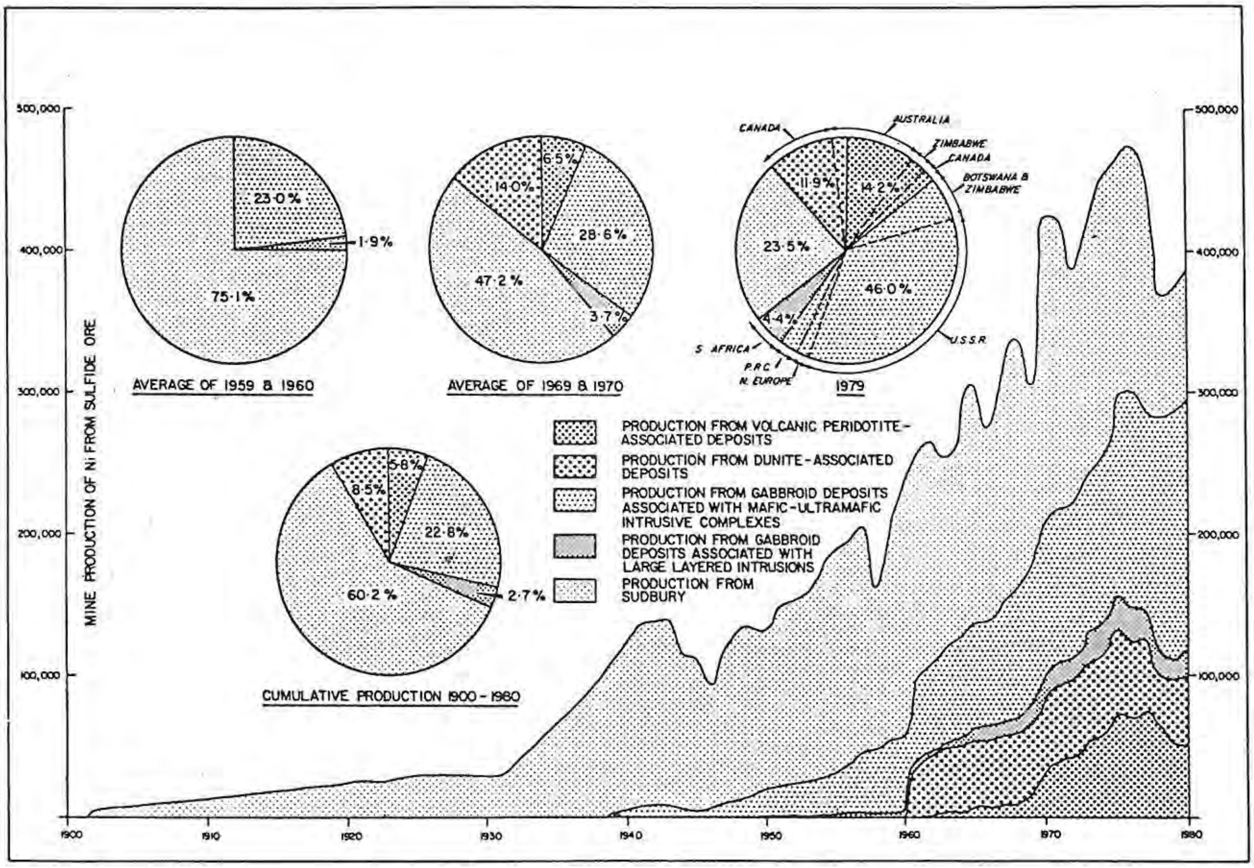


Fig. 3.1. World mine production of sulphide Ni since 1900 subdivided by deposit type (after Ross and Travis, 1981). Note that the gabbroic deposits associated with mafic-ultramafic complexes includes deposits from Phanerozoic orogenic belts and greenstone belts.

elements. Furthermore, this small portion of the earth's crust contains a substantial amount of the world's proven nickel sulphide reserves (Fig. 3.2).

The Sudbury basin comprises the Nickel Irruptive and the sedimentary rocks of the Whitewater Group. The Nickel Irruptive is an intrusive body which outcrops in the form of an elliptical ring about 60 km long and 27 km wide with its long axis trending east-northeast

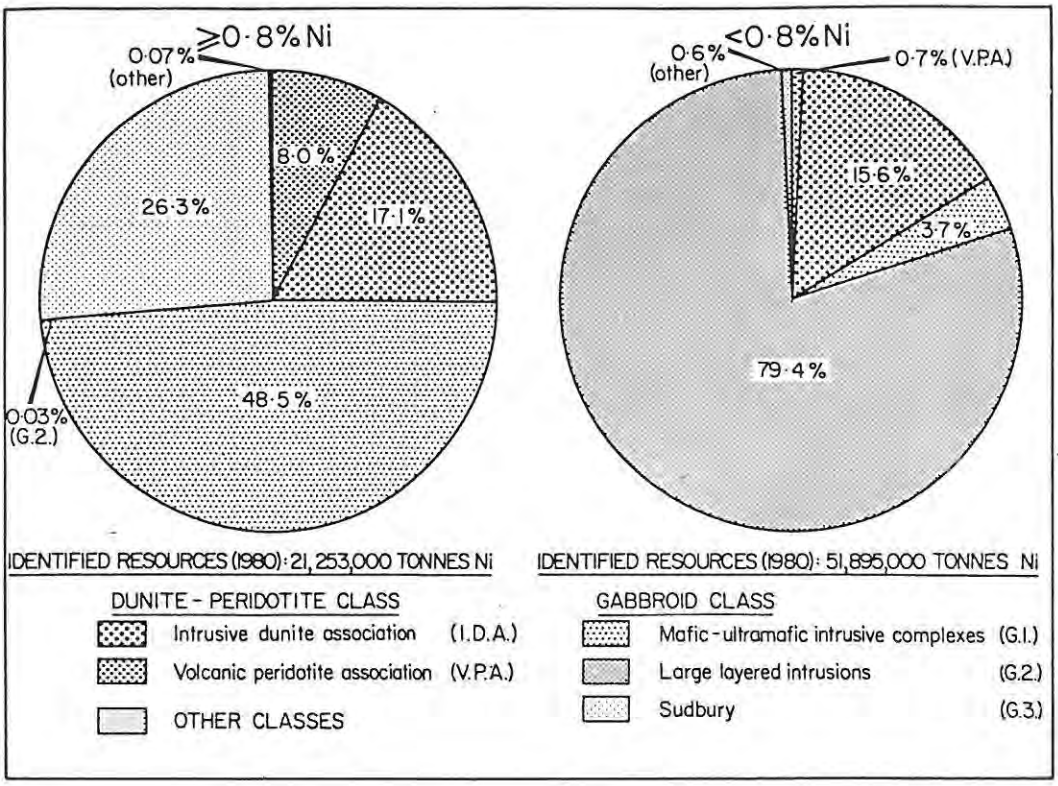


Fig. 3.2. The world total of identified resources of sulphide nickel by deposit type in ores with $\geq$ 0,8% Ni and $\leq$ 0,8% Ni (after Ross and Travis, 1981). The gabbroic deposits associated with mafic-ultramafic intrusive complexes are defined as in Fig. 3.1.

(Fig. 3.3). The Irruptive consists of an outer ring of noritic rocks and an inner ring of granophyre or micropegmatite with a transitional zone of granophyre-rich gabbro between. The outer contact of the Irruptive dips 30^{o} to 50^{o} towards the south on the north limb (North Range), and 45^{o} to 70^{o} towards the north on the south limb (South Range), although locally on the south limb dips may be vertical or even southward dipping (Card and Hutchinson, 1972). The outer surface of the Irruptive plunges steeply south-westward at the north-east closure and moderately north-eastward at the south-west closure (Brocoum and Dalziel, 1974). Consequently, the Irruptive is thought to have the form of an assymmetric funnel in cross-section and has been interpreted variously as the surface expression of a folded differentiated sill, a ring dyke complex, a differentiated funnel shaped intrusion, or the result of a meteorite impact (Naldrett and Kullerud, 1967; Deitz, 1964).

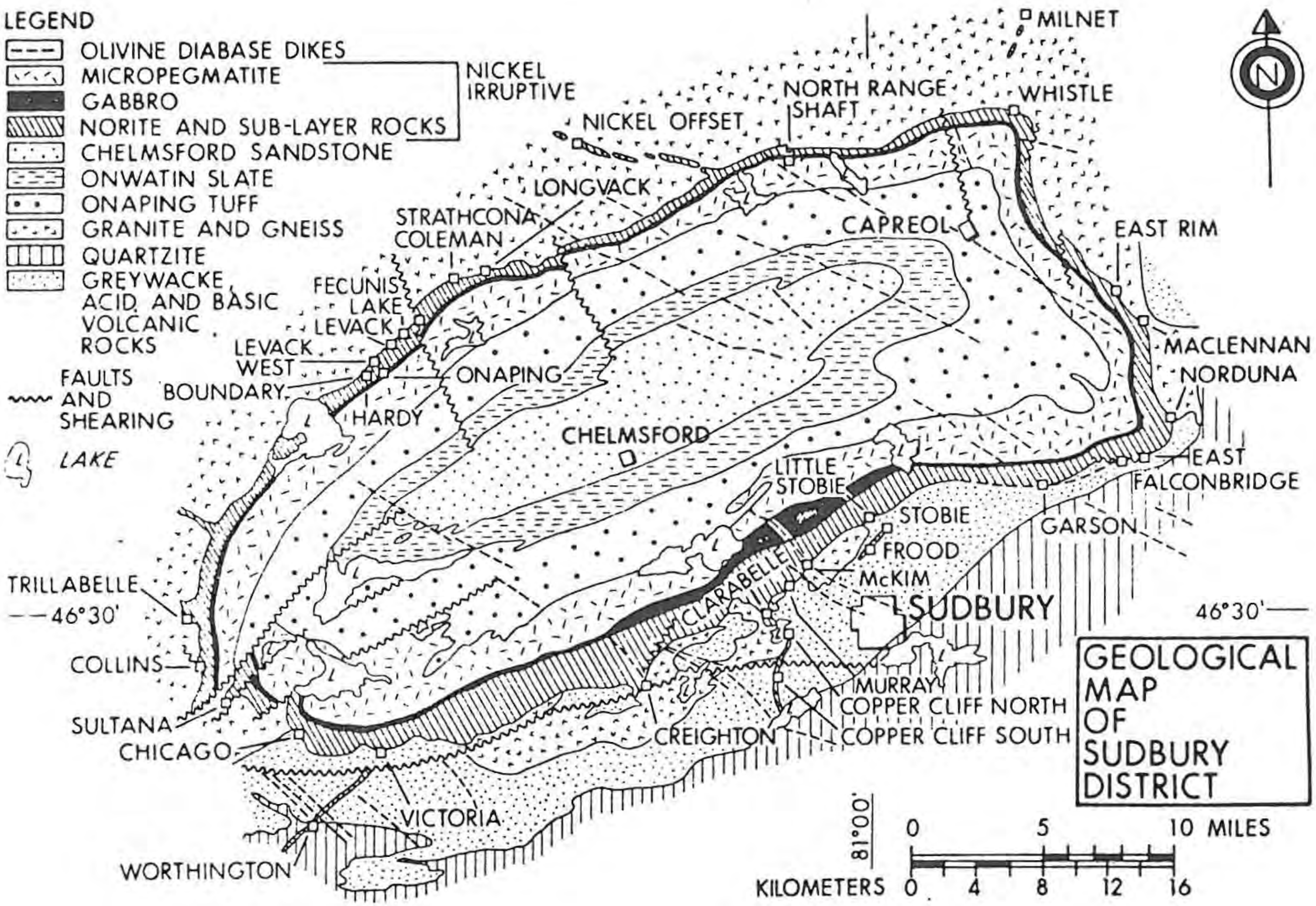


Fig. 3.3. Geological map of the Sudbury basin (Naldrett, 1980).

In the north the Nickel Irruptive intrudes Archaean granitic and migmatitic rocks of the Superior Province, while in the south, the Irruptive is intrusive into Proterozoic greenstones and greywackes of the Huronian Supergroup as well as felsic and mafic intrusions of various ages. The Irruptive therefore, has been preferentially emplaced along the unconformity separating the Archaean from the Proterozoic.

Near Sudbury there are marked changes in the character of the Huronian sequence. The upper portions of the sequence, which consists of gross repetitions of conglomerates, pelites, and orthoquartzites, thickens south-eastwards at the expense of the lowermost portion of the sequence which consists of several hundreds of metres of mafic and intermediate flows, felsic volcanics and related volcanogenic sediments including sulphide-facies iron formation and distal to proximal turbidites. It has therefore been suggested that the Sudbury area may have marked the site of a domical volcano-sedimentary complex which was flanked by relatively stable platformal areas (Card and Hutchinson, 1972). This is further substantiated by the occurrence of Pb-Zn-Cu deposits in the Whitewater group, namely the Errington and Vermilion Lake Mines (Martin et al., 1957).

Radiometric dating of the Irruptive has yielded ambiguous results with a wide range of indicated ages between 1,68 and 2,02 (Naldrett et al., 1980). Fairbairn et al. (1968) reported a Rb-Sr whole rock age for samples of granophyre and norite from the Irruptive of 1704 My ± 19 My. Souch et al. (1969) obtained a minimum U-Pb age of 1900 My for the Sublayer from the South Range which was close to the U-Pb age of 1844 My ± 2 My for the Irruptive later determined by Krogh and Davis (1974). Gibbins and McNutt (1975) obtained a Rb-Sr age on samples from the Copper Cliff offset and Murray mine of 1957 My ± 15 My.

The sediments of the Whitewater Group occur in the centre of the basin, but have defied correlation with any rocks outside the basin (Naldrett et al., 1970; Naldrett et al., 1980). The Whitewater Group includes three entirely conformable formations which have an overall thickness of some 2700 m (Naldrett et al., 1980; Brocoum and Dalziel, 1974). A unit including quartzite breccia and certain unusual igneous rocks is developed discontinuously at the base of the Whitewater Group. This is overlain by the Onaping Formation which consists of more than 1500 m of unsorted breccia composed of fragments of various country rocks (quartzite, granite gneiss, gabbro, and devitrified glass shards), many of them shock metamorphosed, set in a finer-grained matrix of smaller rock fragments and devitrified glass shards. Sharply divided views exist on the origin of the Onaping Formation. Stevenson (1972) regards the Onaping as being a sequence of ash fall tuffs, that is, the products of violently explosive volcanism. On the other hand, Peredery (1972) believes the Onaping was derived from the products of fall out after a meteorite impact. The Onaping is overlain by finely laminated pyritic carbonaceous argillite, limestone and chert which comprise the Ontwatin slate. Coarser-grained bands occur in the upper part of the slate which then grades upwards into the overlying Chelmsford sandstones and greywackes occupying the most central portions of the basin. Rousell (1972) has interpreted the Chelmsford Formation as representing the depositional products of turbidity currents. All the formations within the Sudbury basin are cut by a swarm of olivine diabase dykes (Nipissing diabase).

The Sudbury basin occupies a unique tectonic setting in that it lies at the junction of three major structural provinces on the Canadian Shield (Fig. 3.4). Of particular importance is the close proximity of the Sudbury Irruptive to the Grenville front which represents a fundamental crustal discontinuity initiated some 1800 My ago. This zone is characterized by a complicated history of repeated deformation and intrusion. Movements along this zone have brought highly metamorphosed and deformed rocks of the Grenville Province into juxtaposition with relatively mildly deformed rocks of the Southern Province and have rotated and partly obliterated earlier structural trends in both provinces (Card and Hutchison, 1972).

The Sudbury structure lies along the junction of the major fault systems, the easterly to north trending Murray System and the north-northwesterly striking Onaping system (Fig. 3.4). The major and minor axes of the basin parallel these two fault systems. There is evidence from Huronian stratigraphy and sedimentology that the Onaping

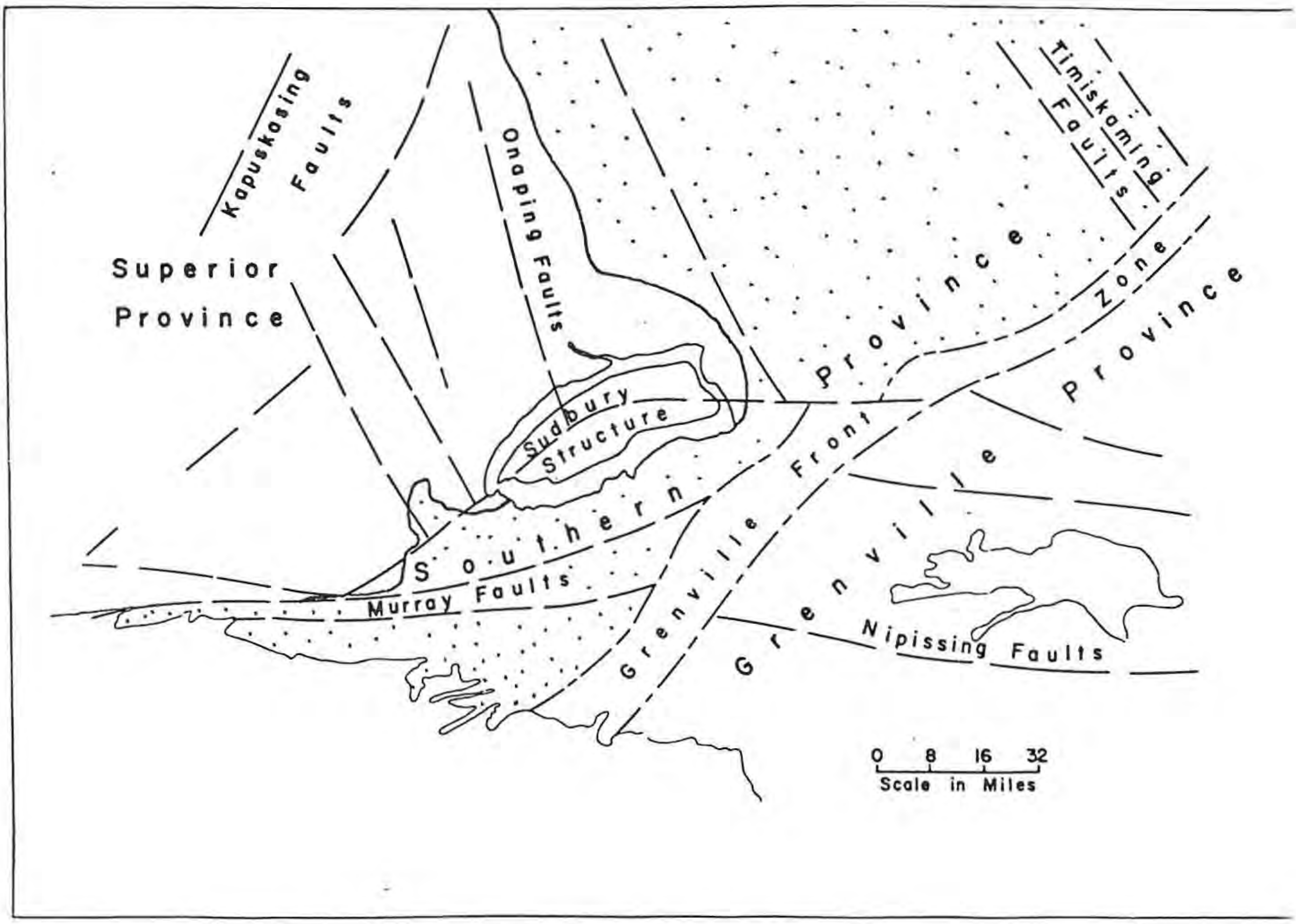


Fig. 3.4. Location of the Sudbury structure with respect to structural province boundaries and major fault systems (modified after Card and Hutchinson, 1972).

and Murray fault systems originated prior to Huronian sedimentation and were initially bounding faults to graben-like basins in which the Huronian sediments were deposited (Card and Hutchinson, 1972). Card and Hutchinson present convincing evidence that the Murray and Onaping fault systems were possibly part of a much larger continental rift system, the Lake Superior Rift System, that originated during the early Proterozoic some 2300 to 2500 My ago (Fig. 3.5). Various portions of the rift system exhibited a history of complex reactivation during later times.

Furthermore, the Sudbury Irruptive lines at the junction of two major structural arches which are thought to have been positive features from the early stages of Huronian sedimentation (Card and Hutchinson, 1972)(Fig. 3.6).

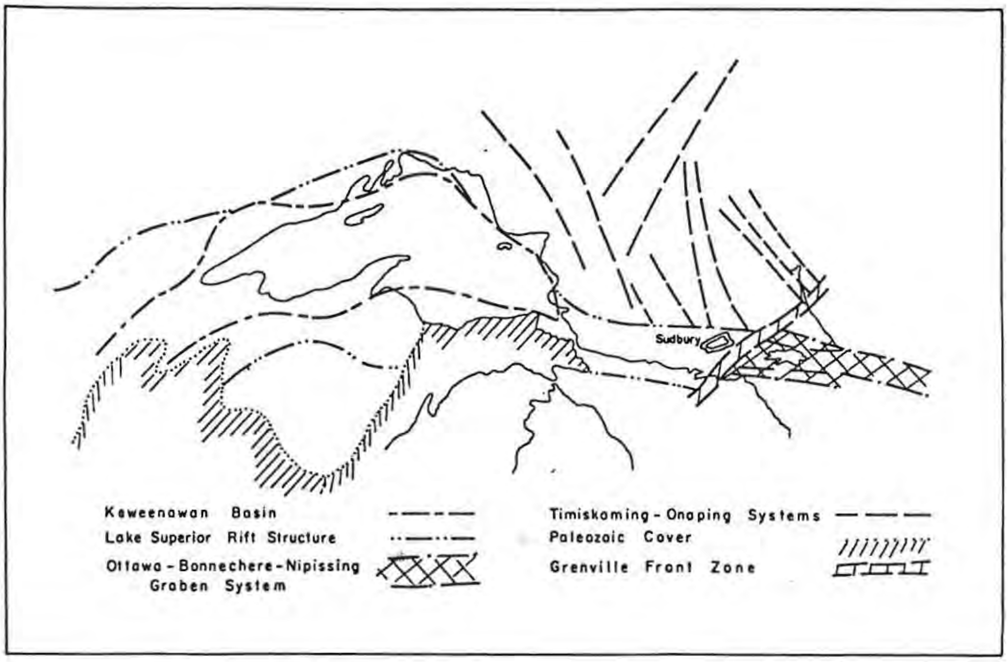


Fig. 3.5. Possible Precambrian Lake Superior Rift System (after Card and Hutchinson, 1972).

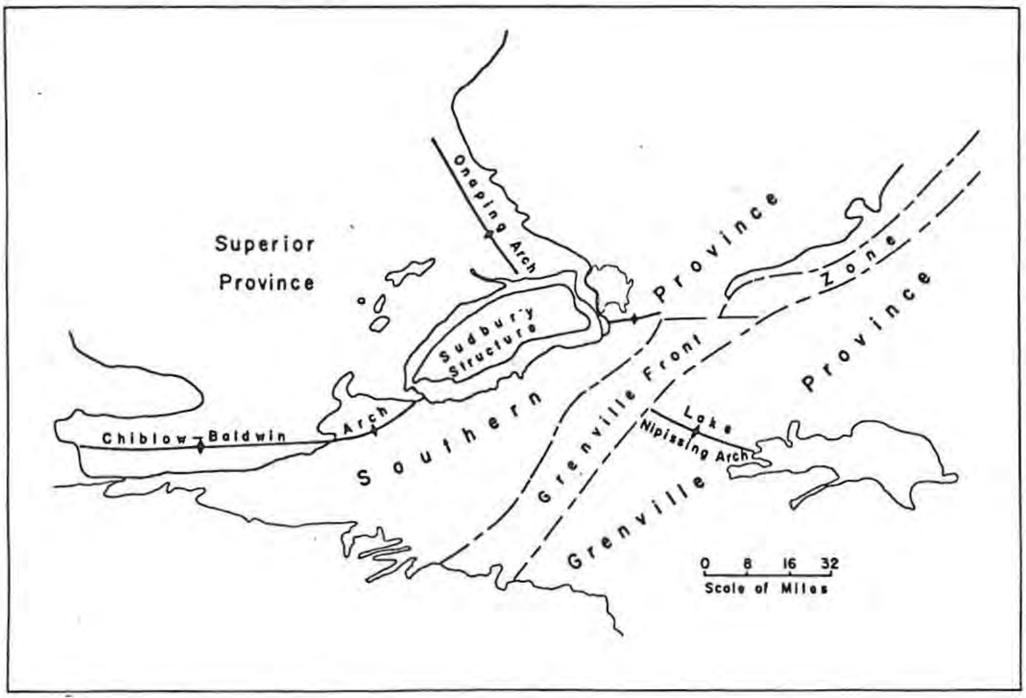


Fig. 3.6. Sudbury in relationship to structural province boundaries and major structural arches (after Card and Hutchinson, 1972).

The intersection of the two fault controlled graben systems and arches within the grabens would have provided a very favourable site for the ensuing igneous activity that initially formed the Sudbury Irruptive.

The influence of the Precambrian Superior Rift System and it's eastward extensions on the emplacement of mafic intrusions of widely differing ages is shown in Fig. 3.7. Many of these bodies are nickeliferous and include the well known Duluth Complex and Great Lakes nickel body. It is significant that alkalic intrusions which characterize many of the world's rift systems occur along and adjacent to the Superior structure (Fig. 3.7).

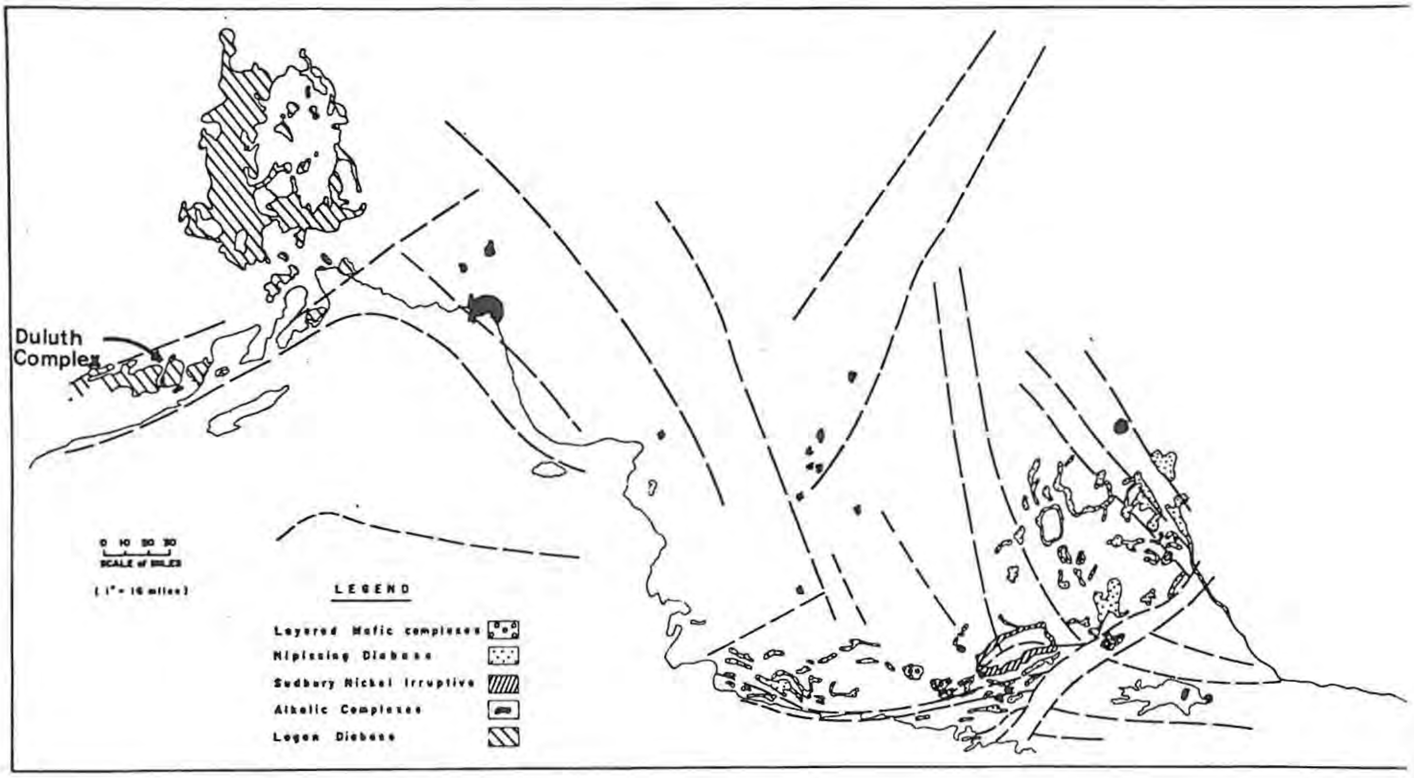


Fig. 3.7. Sudbury in relationship to the Precambrian Lake Superior Rift System and related intrusions (after Card and Hutchinson, 1972).

Reactivation along the Onaping and Murray fault systems resulted in portions of the Nickel Irruptive being displaced (Fig. 3.8). The north-westerly striking faults usually dip vertically or steeply westward. The central Cameron Creek - Airport Fault zone has resulted in an upward displacement of South Range relative to the North Range of some 4.8 km (Souch et al., 1969). This has been verified by regional gravity surveys which indicate that the main body of norite extends to a depth of about 9 km on the northern side of the Cameron Lake - Airport fault zone, whereas it's vertical extent on the South Range is probably less than 5 km.

All the rock types within the Sudbury basin, including the various types of breccia related to the mineralization, have been deformed during the Penokean orogeny (1,7 - 1,8 by). The deformation is concentrated in the southern-most two thirds of the basin. The deformation is characterized by various styles and includes penetrative slaty cleavage axial planar to doubly plunging open upright folds in the Whitewater Group which forms a complex synclinorium in the central portions of the basin, a penetrative foliation axial planar to doubly plunging domes and basins in the Huronian rocks of the southern Province which become isoclinal as the Grenville Front is approached, and early isoclinal folds with a mylonitic axial planar foliation in rocks of the Grenville Province (Brocoum and Dalziel, 1974 and Rousell, 1975). In the vicinity of the Grenville Front, east-northeasterly striking Z-shaped assymetric folds deform these structures. It should be noted that because of their comppetent nature, the noritic rocks of the Irruptive show little effects of this deformation, and consequently the ore bodies are relatively undeformed.

The rocks of the Sudbury basin have been metamorphosed only to lowermost greenschist facies. The highest grade is attained in the eastern-most two-thirds of the South Range where biotite makes it's first appearance in the rock of the Onaping Formation (Rousell, 1975) (Fig. 3.8).

3.2 The petrology of the Nickel Irruptive

The nickel-copper sulphide ores are associated with an inclusion-rich suite of rocks known as the Sublayer (Naldrett and Kullerud, 1967; Souch et al., 1969; and Naldrett et al., 1980a). The Sublayer lithotypes are encountered along the outer margin of the Irruptive (Fig. 3.9). They occur as irregular flat lenses, laterally extensive sheets, small bodies occupying embayments or troughs in the footwall, and as offset dykes that extend into the footwall for many kilometers (Pattison, 1979). Many offsets extend radially outward from the Irruptive-footwall contact (Pattison, 1979). An exception is the

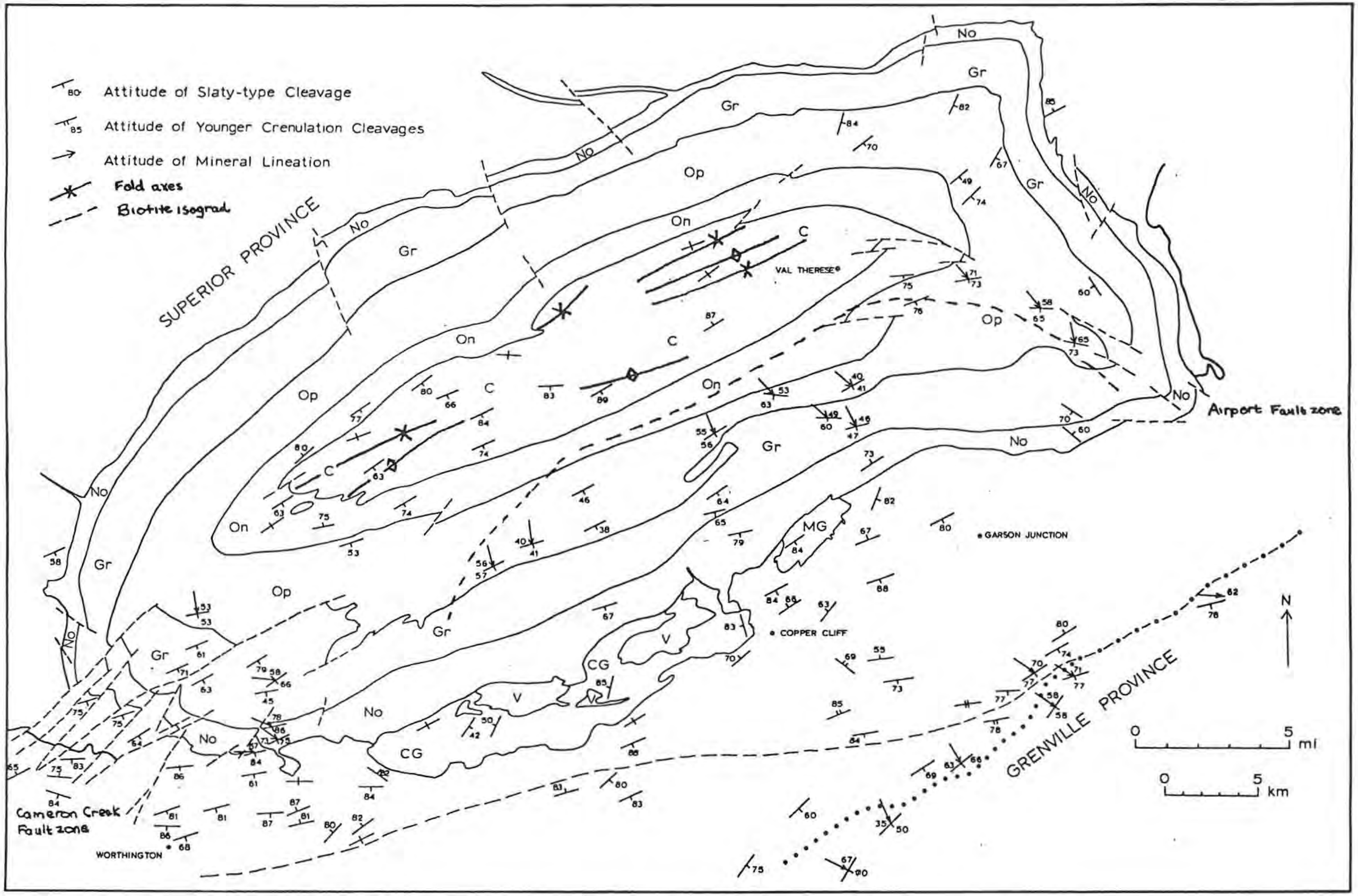


Fig. 3.8. Structural geology of the Sudbury basin (after Brocoum and Dalziel, 1974).

Frood-Stobie offset which is almost parallel to the contact (Fig.3.9).

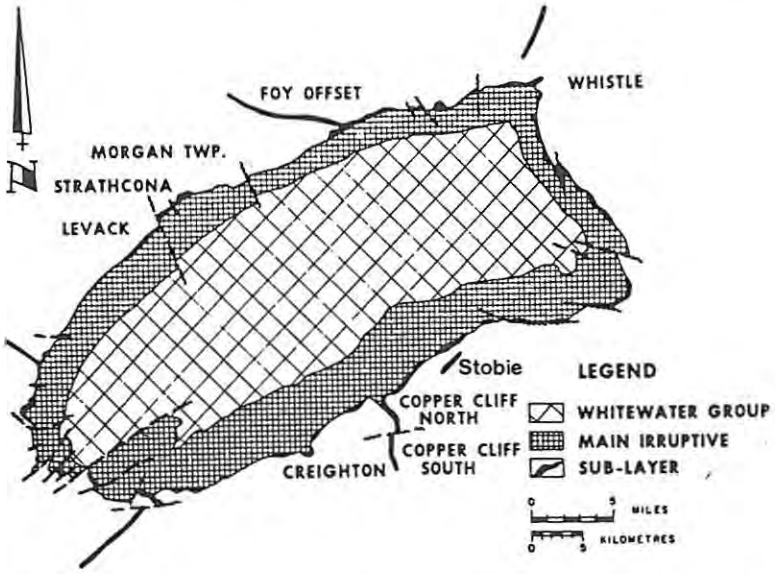


Fig. 3.9. Generalized geological map of the Sudbury basin showing the distribution of major occurrences of Sublayer material (thickness somewhat exaggerated) (after Pattison, 1979).

Two major facies can be distinguished in the Sublayer (Naldrett et al., 1972): (a) igneous sublayer, a group of igneous textured gabbroic, noritic and dioritic rocks; and (b) leucocratic breccias, a group of metamorphic-textured felsic to mafic breccias. Both facies are characterized by the presence of Fe-Ni-Cu sulphides and by the presence of xenoliths of recognizable footwall rocks as well as xenoliths of ultramafic and mafic composition whose exact origin is uncertain (Pattison, 1979). The composition of these cumulate-textured exotic fragments ranges from dunite, through harzburgite and lherzolite, to orthopyroxenite, and websterite (Naldrett et al., 1972). The nature of these inclusions suggests that they are probably disrupted blocks of a deeper more mafic zone of the Sudbury intrusion (Naldrett and Kullenud, 1967).

Two varieties of igneous sublayer have been identified (Pattison, 1979): (a) the two pyroxene gabbro-norites of the marginal deposits, and (b) the hornblende-bitotite-quartz diorites associated with the offsets. The composition of the North Range mafic sublayer varies from an augitite-norite to a hypersthene-gabbro. Less petrological information is available about the South Range sublayer, which is described by Souch et al. (1969) as noritic.

Pattison (1979) reports that similar, although not identical, sequences of rock type to those in the North Range are found in the South Range embayment structures. Primary olivine is not a common constituent of the igneous Sublayer. The Sublayer norites can be distinguished from the overlying Main Irruptive norites by the fact that they contain negligible amounts of quartz, K-feldspar, and granophric intergrowth, and are richer in clinopyroxene (Naldrett et al., 1980) (Fig. 3.10).

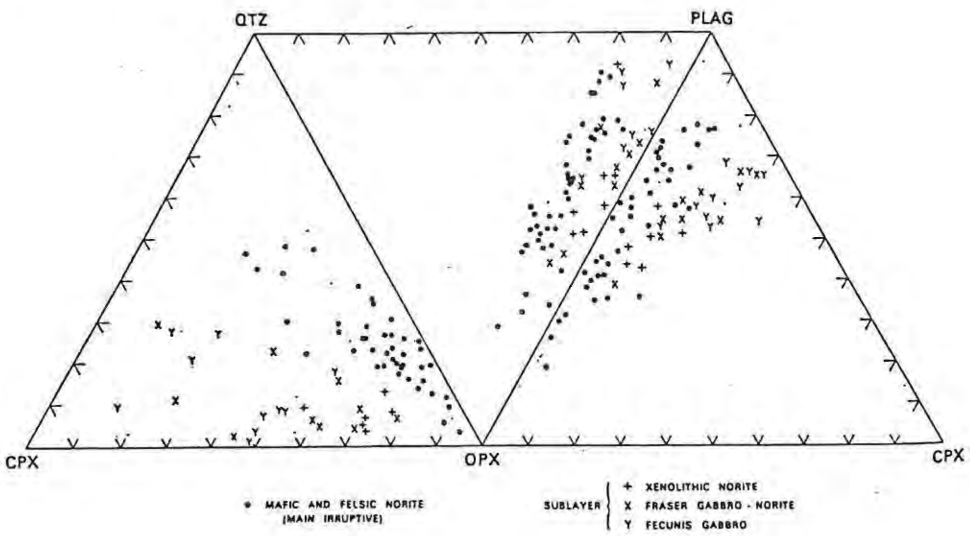


Fig. 3.10. A comparison of the modal proportions of quartz, plagioclase, clinopyroxene and orthopyroxene in the mafic and felsic norites and the sub-layer rocks from the Strathcona-Fecunis area (after Naldrett et al., 1972).

Recent mapping has shown that the gabbro-norite Sublayer is a common constituent of the North Range offsets and much of the hornblende typical of the South Range offsets is pseudomorphic after primary pyroxenes. Therefore, the marginal gabbro-norites and offset quartz-diorites can be considered as part of the same intrusive pulse, the latter representing deuterically altered gabbro-norite.

Within the marginal deposits of the Sublayer there is a distinct increase in silica and the Fe content of the clinopyroxene and orthopyroxene towards the footwall. This trend is also exhibited by the offset deposits whose margins show similar enrichment trends.

A large number of breccias occur in the footwall of the Irruptive along the North Range. Many textural and compositional variants of these breccias can be defined locally. Contradictory cross-cutting and gradational contact relationships between these and the spatially associated igneous Sublayer and basal Main Irruptive units are encountered (Pattison, 1979). The main types of breccia are listed below in their approximate chronological sequence (Naldrett et al., 1972):

(i) Migmatites related to felsic plutons in the sequence.

(ii) Levack breccia, correlatable with the Sudbury breccia of the South Range, and thought to have been formed by the event, either meteoric or crypto-volcanic, which formed the Sudbury structure. The offset deposits appear to be located in zones of abnormal concentrations of these breccias.

(iii) Agmatite occurring around the outer margin of the North Range.

(iv) A group of breccias referred to locally as "footwall breccia", "granite breccia","late granite breccia", and "grey breccia".

Various factors contribute to the diversity of these leucocratic breccias. These include variations in bulk composition, fragment-matrix ratio, fragment size and lithology, and matrix texture, together with the presence or absence of exotic fragments and sulphide mineralization (Pattison, 1979). The major petrographic characteristics of the matrices of these breccias are granoblastic metamorphic textures and heterogeneous modal compositions. Generally, the matrices consist of highly variable proportions of intermediate plagioclase, quartz, pyroxene, and amphibole (Pattison, 1979). Whole rock geochemical data for the breccias indicate that they may have bulk compositions similar to those of the Sublayer, for example the Foy offset, but some, for example the Levack breccia, may have compositions similar to that of the footwall (Pattison, 1979).

The relationships between the major facies of the Sublayer in the various embayment and sheet deposits are complex and contacts tend to be diffuse and gradational. A complete section through an idealized sublayer occurrence would consist, from hangingwall to footwall of (Fig. 3.11): (i) contaminated hybrid basal Irruptive, (ii) igneous Sublayer, (iii) leucrocratic breccia which gradually passes downwards by an increase in the size of the footwall blocks into (iv) a megabreccia which contains interblock dykes of leucocratic breccia.

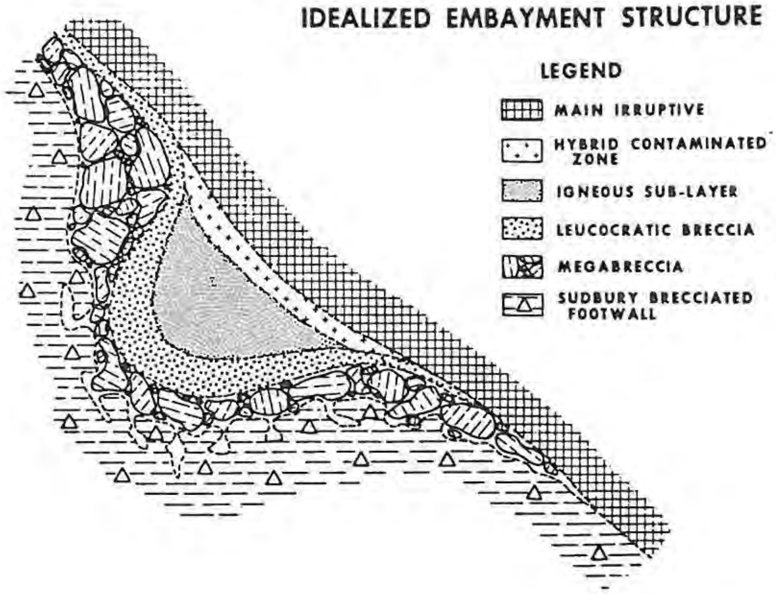


Fig. 3.11. Cross-section through an idealized Sublayer occurrence on North Range of the Sudbury structure (after Pattison, 1979).

The relative ages of the mafic Sublayer and overlying Main Irruptive are uncertain. The main evidence in favour of a post-Irruptive age for the Sublayer is the presence of xenoliths of Irruptive mafic norite in the leucocratic breccias of the Strathcona Mine (Pattison, 1979). However, considerable evidence points to a pre-Irruptive age for the Sublayer (Pattison, 1979):

(i) Inclusions of the various facies of the Sublayer as well as inclusions of sulphide are encountered within the Main Irruptive.

(ii) Basal Irruptive units contain copper-nickel sulphide mineralization only where in contact with the mineralized sublayer.

(iii) On occasion the hybrid unit at the base of the Main Irruptive consists of discrete blocks of Sublayer veined and permeated by basal Irruptive rock.

(iv) The offset dykes only contain Sublayer material and never rocks from the Main Irruptive. As the offsets are emplaced in pre-Irruptive breccia zones it seems probable that they would have been filled with Irruptive material if this has been the first intrusive pulse.

(v) Internal contacts within the Sublayer are truncated by the basal Irruptive contact.

(vi) The offsets never cut the Irruptive itself.

The Main Irruptive rocks of the North and East Ranges of the ring resemble one another and are distinctly different from those in the south (Naldrett et al., 1970).

On the East and North Ranges, 1000 ft to 1500 ft of felsic norite, a plagioclase-hypersthene orthocumulate, is overlain by 700 ft of oxide-rich gabbro, a plagioclase-augite-ulvospinel orthocumulate, which then grades by an increase of micrographic intergrowth into an overlying micropegmatite which reaches 4500 ft thick (Naldrett et al., 1970)(Fig. 3.12). A thin impersistent mafic norite unit may be found directly overlying the Sublayer rocks.

On the Southern Range the upper gabbro is similar to the oxide-rich gabbro which then also grades upwards into a micropegmatite. (Naldrett et al., 1970). The latter is similar to that developed on the North Range except that it is more strongly sheared. The upper gabbro is underlain by the South Range norite, a plagioclase-hypersthene mesocumulate, which is separated from the underlying Sublayer by a thick layer of quartz-rich norite (Naldrett et al., 1970)(Fig. 3.12). This unit has many similarities with the mafic norite of the North Range (Naldrett et al., 1980). The exact thickness of the various units in the South Range are unknown and only horizontal distances are quoted in Fig. 3.12.

As stated above, the South Range norite, the felsic norite, the upper gabbro, and the oxide-rich gabbro are cumulate rocks. Cryptic variation in the composition of hypersthene, augite, and plagioclase are present (Naldrett et al., 1970). This combined with the occurrence of broad scale phase layering (ordered appearance and disappearance of cumulus minerals) and igneous foliation suggest that the body is a gravity differentiate (Naldrett et al., 1972; Naldrett et al., 1980). These variations are shown in a number of different ways (Fig. 3.12): by a gradual decrease in hypersthene content the norite gradually passes up into the gabbro; the outer margins of the gabbro are characterized by an abrupt increase in

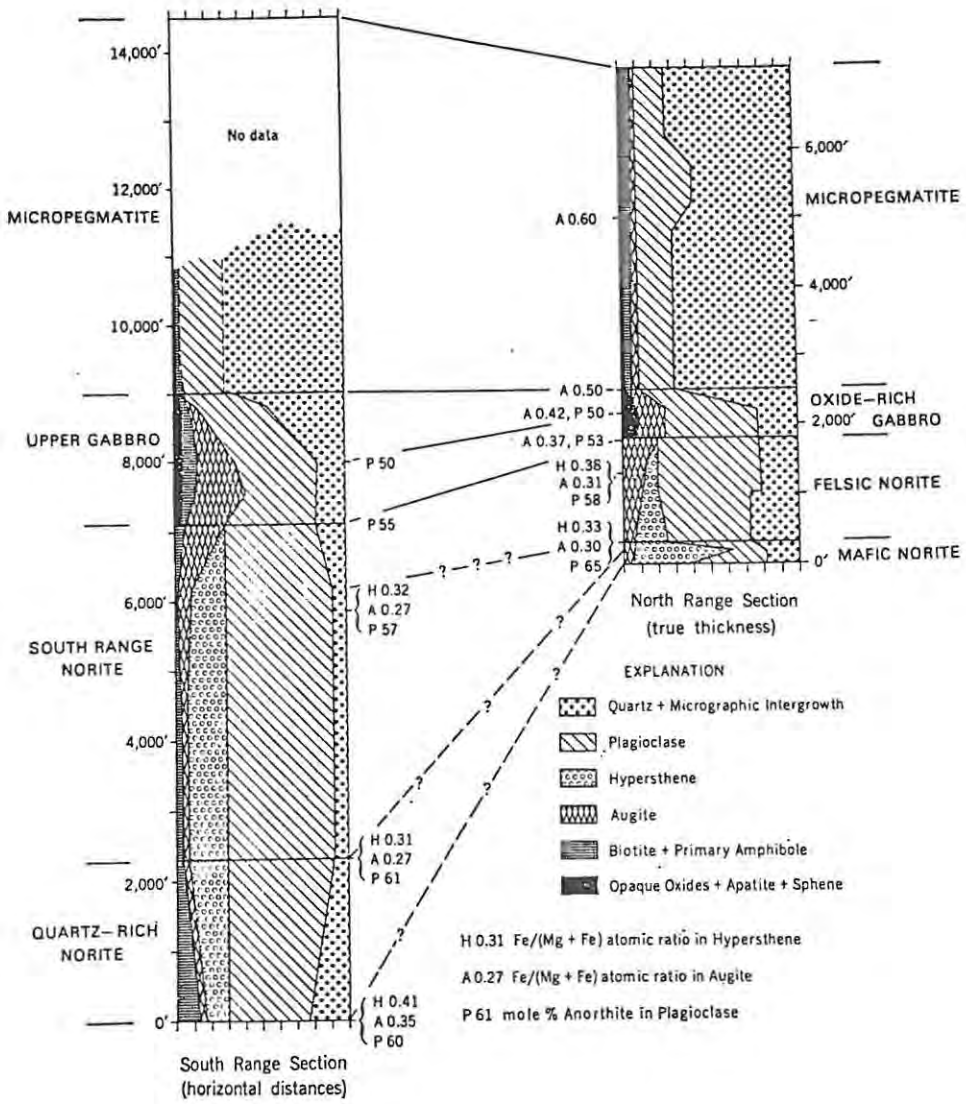


Fig. 3.12. Comparison and correlation of partially idealized sections through the rocks of the North and South ranges. The columns indicate variation in modal composition of the rocks (after Naldrett et al., 1972).

magnetite, ilmenite, and apatite; and the upper portions of the gabbro show a gradual increase in micrographic intergrowth (Naldrett et al., 1980b; Naldrett et al., 1970).

Cumulate textures and igneous lamination are absent from the quartz-rich norite and are only present in the uppermost mafic norite, and both units are considered to represent a rapidly cooled marginal facies (Naldrett et al., 1980a). The quartz-rich norite shows similar compositional trends to the Sublayer. There is an increase in quartz content from 8% to 20% and an increase in the

Fe/Mg ratio of the augite and hypersthene towards the footwall (Naldrett et al., 1980b)(Fig. 3.12).

Two distinct phases of micropegmatite are recognized (Peredery et al., 1975): a granophyre-rich phase (the granophyric micropegmatite) and a plagioclase-rich phase. Discontinuous bands and isolated blocks of the latter exist in the granophyric micropegmatite, and apophyses of the plagioclase-rich rock extend into the Whitewater Formation.

Modally the plagioclase-rich rock is distinguished from the granophyric micropegmatite by its higher plagioclase and ferromagnesian mineral content. The augite of the plagioclase-rich rock is MgO-rich in comparison with that of the granophyric micropegmatite and it has FeO/(FeO + MgO) ratios similar to those encountered in the oxide-rich gabbros. The plagioclase-rich rock is compositionally similar to the upper part of the oxide rich gabbro in the normative content of its plagioclase and in total Na_2O, K_2O and CaO (Peredery et al., 1975). Therefore, it has been postulated that the plagioclase-rich rock is a phase belonging to the upper part of the oxide-rich gabbro which was split off from the remainder of this unit by a later injection of granophyric micropegmatite (Peredery et al., 1975). This micropegmatite is thought to be an extreme differentiate of the Irruptive that collected at its top.

In comparison with other large layered intrusions, the Irruptive is unusual in three important aspects (Naldrett et al., 1980b): the absence of small scale (< 70 m) cyclical units, the absence of visible layering resulting from the variation in the proportions of minerals, and the very high quartz content of the rock. In Fig. 3.13 the normative proportions of olivine, hypersthene, and quartz in cumulus rocks from a number of large layered intrusions are plotted against the Fe/Fe + Mg ratio of their augite. Where available, the Fe/(Fe + Mg) ratio of the hypersthene and the An content of the plagioclase is also plotted. The compositions of these minerals vary in a systematic manner with augite, all three compositions serving as indicators of the degree of differentiation of the magma from which they crystallized. The siliceous nature of the Sudbury magma is immediately apparent. However, it may be argued that because the

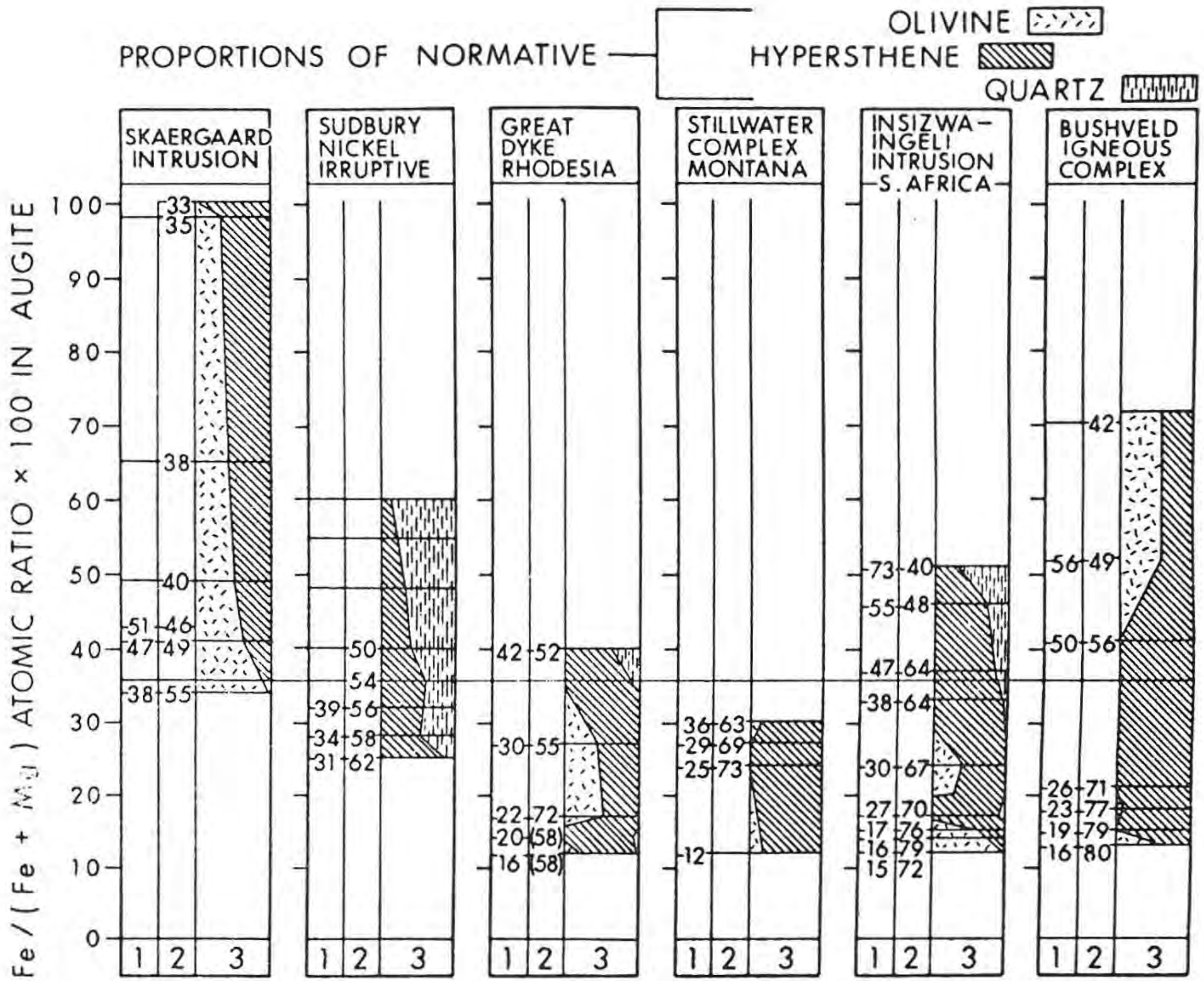


Fig. 3.13. Comparison of the normative olivine, hypersthene and quartz contents of various layered intrusions on the basis of the Fe/(Fe+Mg) atomic ratio of the augite that they contain. Column 1 indicates the same ratio for orthopyroxene where it is present and column 2 the anorthite content of plagioclase (after Naldrett et al., 1972).

silica content of a magma is also an indicator of the degree of its differentiation, the Sudbury magma merely represents a more differentiated magma. If this were true however, the compositions of the pyroxenes and plagioclases should also indicate an advanced stage of differentiation, which they do not. A possible explanation for this anomalous situation may be that the Sudbury magma became highly contaminated with quartz-rich material, resulting in an increase in SiO_2 but no corresponding increase in the Fe/Mg ratio (Naldrett et al., 1980b). The presence of numerous partially digested inclusions within the Irruptive (Stevenson and Colgrove, 1968) and the relatively high Sr^{87}/Sr^{86} ratio of 0,706 for the norite (Gibbins and McNutt, 1975) support this view. The high original silica content would result in a highly viscous magma which would inhibit convection and the winnowing effect of vertical magma currents which would give rise to the cyclical units and visible layering (Naldrett et al., 1980b). This high silica content is of profound importance as an original control of grade of mineralization within the Sudbury deposits and this will be discussed in more detail in a later section.

3.3 The North Range ore deposits

The Sudbury nickel camp embraces some 61 nickel-copper occurrences. Most of the ground covering the contact and its dip projection is held by the International Nickel Corporation and Falconbridge Nickel. The former has 11 producing mines and three mines on standby, whilst Falconbridge has six mines in production and four on standby (E.M.J. Staff, 1981).

Extensions to existing mines are constantly being found and the E.M.J. Vice-President of Mining and Milling for Inco's Ontario Division is fortunate in being able to say: "You have to look at the whole of Sudbury as a mine .... when one mine phases out, you bring in another one" (E.M.J. Staff, 1981).

The North Range deposits are preferentially clustered in an extensively mineralized 8,2 km long segment on the north-western side of the basin (Fig. 3.14).

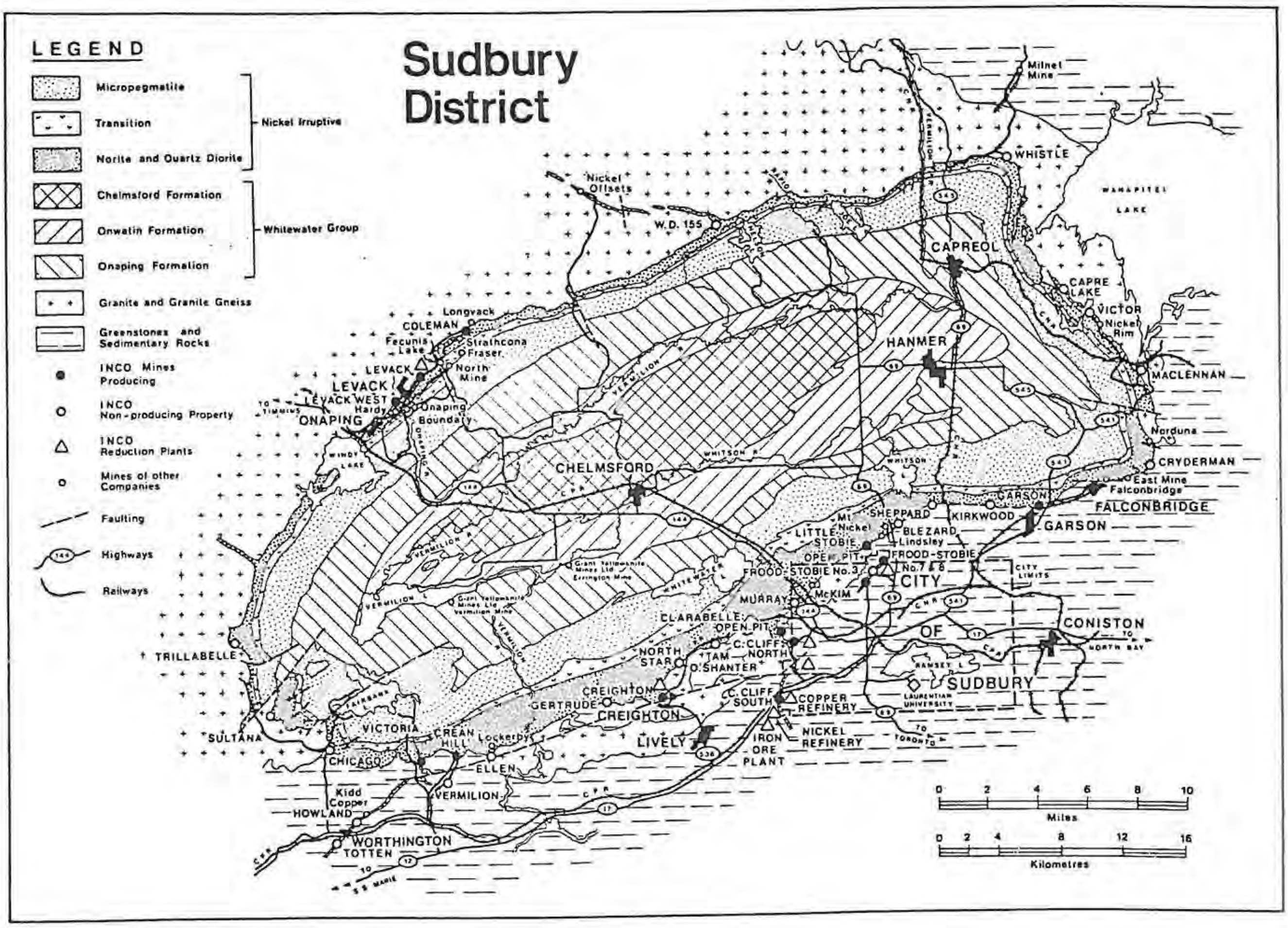


Fig. 3.14. The location of the mineral deposits in the Sudbury basin (after C.M.J. Staff, 1977).

The ores of the North Range marginal deposits are found not only with the Sublayer rocks, but also within the brecciated footwall rocks.

The 800 m long Strathcona orebody (Fig. 3.14) is associated with an embayment in the footwall of the Irruptive and has an irregular rolling dip of 20^{o}S to 60^{o}S (Abel et al., 1979). Strathcona is Falconbridge's largest producing mine and processes some 1,7 million ton/yr.

Four types of orebody are present at the Strathcona mine (Abel et al., 1979): the hanging wall orebodies, the main ore zone, the deep ore zone, and the Strathcona copper zone.

The hangingwall orebodies occur as irregular discontinuous sulphide lenses predominantly in dark norite breccia (hangingwall breccia) and to a much lesser extent in dark norite (Abel et al., 1979) (Fig. 3.15). The hangingwall breccia forms the basal portion

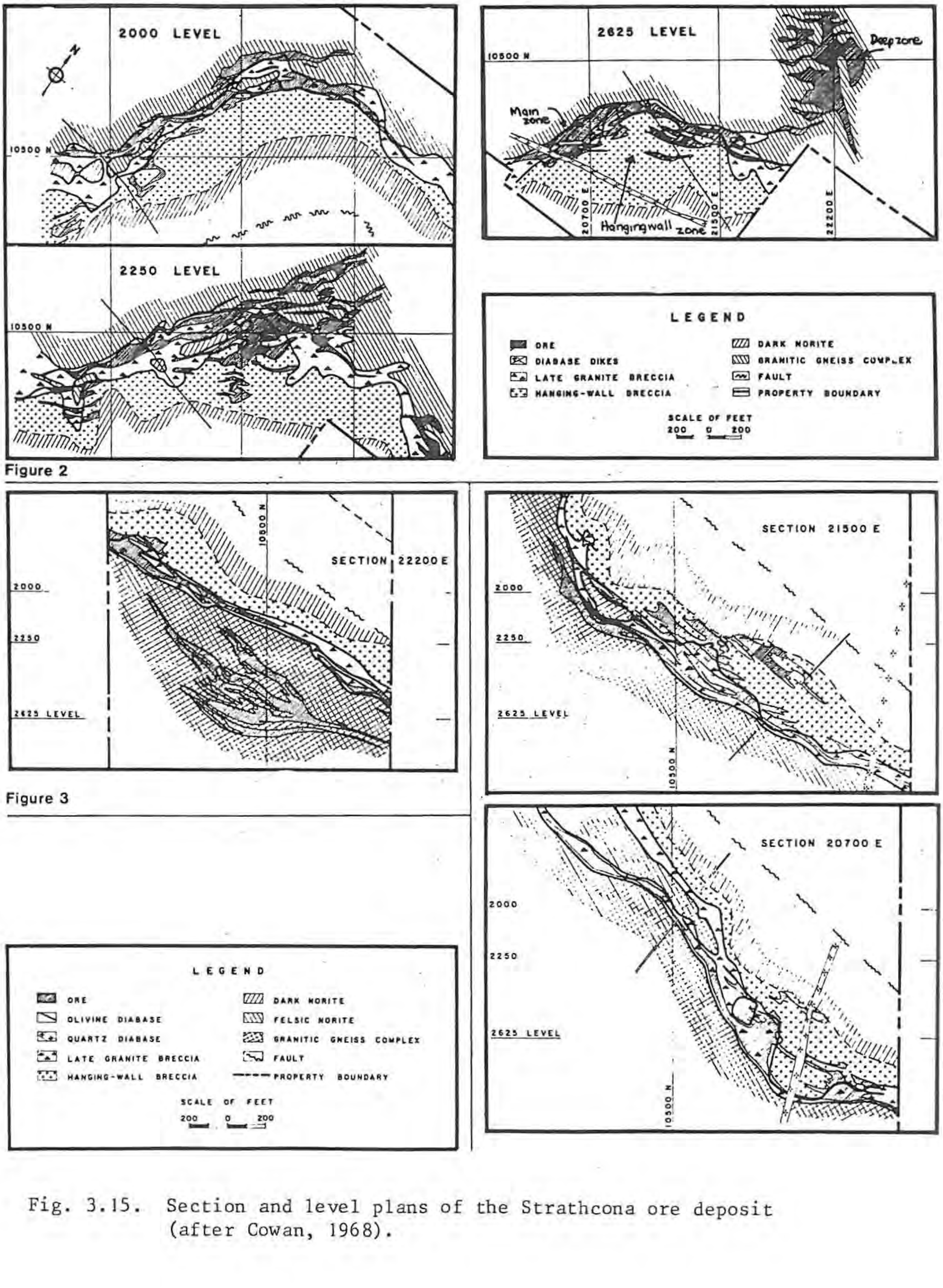


Fig. 3.15. Section and level plans of the Strathcona ore deposit (after Cowan, 1968).

of the Sublayer and comprises a rock containing more than 30% of mafic and ultramafic fragments by volume (Cowan, 1968). The hangingwall breccia is best developed in zones of strong irregularity in the footwall contact and is thin or absent outside the embayment structure (Cowan, 1968). A concentration of the hangingwall lenses occurs directly above the axial plane of the embayment where they are associated with a sharp increase in the volume of ultramafic inclusions (Cowan, 1968) (Fig. 3.15). Further concentrations of ore are found near the flanks of the embayment where there is an abrupt flattening in the dip of the basal contact of the Irruptive (Fig. 3.15).

The main ore zone comprises about 70% of the ore within the deposit and is confined to a zone of late granite breccia between the Irruptive and underlying feldspathic gneiss complex (Abel et al., 1979). The breccia varies from 10 m to 60 m in thickness and is composed of fragments, mainly of footwall lithologies, set in a quartz-rich matrix. The breccia parallels the embayment in the basal contact in both dip and strike. This zone is composed of a series of lenticular en echelon lenses of ore which are linked together to form a more or less continuous sheet paralleling the strike and dip of the granite breccia (Fig. 3.15) (Cowan, 1968). The dip of the ore lenses vary from 60^{o} south in the west, through horizontal, to 30^{o} south in the east and have a dip length of over 330 m (C.M.J. Staff, 1978). In essence therefore, the shape of the main zone is that of an inclined trough which is heavily mineralized in the nose and less strongly mineralized on the more steeply dipping flanks. Individual ore lenses pinch and swell and vary in thickness from 2 m to 16 m (Fig. 3.15). They are often separated from one another by weakly mineralized granite breccia, but where they join they may form composite lenses up to 50 m in thickness. The greatest concentration of ore in the main zone usually occurs on the footwall side of the breccia and is generally separated from the hangingwall mineralization by a zone of barren granite breccia (Cowan, 1968). However, in areas where the dip of the basal contact flattens, particularly in the nose of the embayment, the main ore zone merges with the hangingwall zone (Fig. 3.15). In addition, some ore lenses may be encountered within the feldspathic gneiss Levack breccia footwall paralleling the contact of the granite breccia (Fig. 3.15).

The deep ore zone accounts for 20% of the ore reserves and is an irregularly shaped concentration of lenses and stringers of massive sulphide located some 150 m to 200 m below the base of the Irruptive. The ore is present within dilational and shear fractures within the footwall gneiss complex. The zone is adjacent to the eastern flank of the structural embayment and in detail it is composed of arcuate flat-lying en echelon bands of massive sulphides separated by barren granitic gneisses (Fig. 3.15) (Cowan, 1968). The deep zone is separated from the main zone by barren granitic gneisses, but on occasion individual stringers in the upper portion of the deep zone are interfingered with and join sulphide stringers of the main zone (Fig. 3.15). The ore zone pinches out with depth and bottoms on the 2750 level, some 220 m vertically below the basal contact of the Irruptive (Cowan, 1968). En masse, the deep ore zone plunges at 48° south-westwards.

The Strathcona copper zone was discovered in 1976 by tracing, through diamond drilling, the upward extension of narrow subeconomic stringers of millerite and chalcopyrite which had been intersected in the mine openings on 3050 level (Abel et al., 1979). Probable diamond drill indicated ore reserves amount to 910 000 tons grading at some 9,09% Cu, 0,52% Ni, and 34,3 g/t Ag (Abel et al., 1979). The vein sulphides occupy a system of fractures that can arbitrarily be confined to a block having horizontal dimensions of 250 m by 150 m and a dip slope length of 215 m (Fig. 3.16). Individual veins within the system range in width from a few millimeters to approximately 6 m (Abel et al., 1979). Some veins are straight and maintain a consistent width for many meters, whereas others are more irregular and exhibit marginal apophyses extending for short distances into the host rock (Abel et al., 1979). The individual veins may be structurally classified as follows (Abel, 1981):

(1) Set 1, containing important tonnages of ore, strikes N84°W and dips 68°S.

(2) Set 2, also containing important tonnages of ore, strikes N84°W and dips 68°S.

(3) Set 3, which contains subeconomic amounts of ore, but which is the main ore carrier in the deep zone, strikes N16°W and dips 77°E.

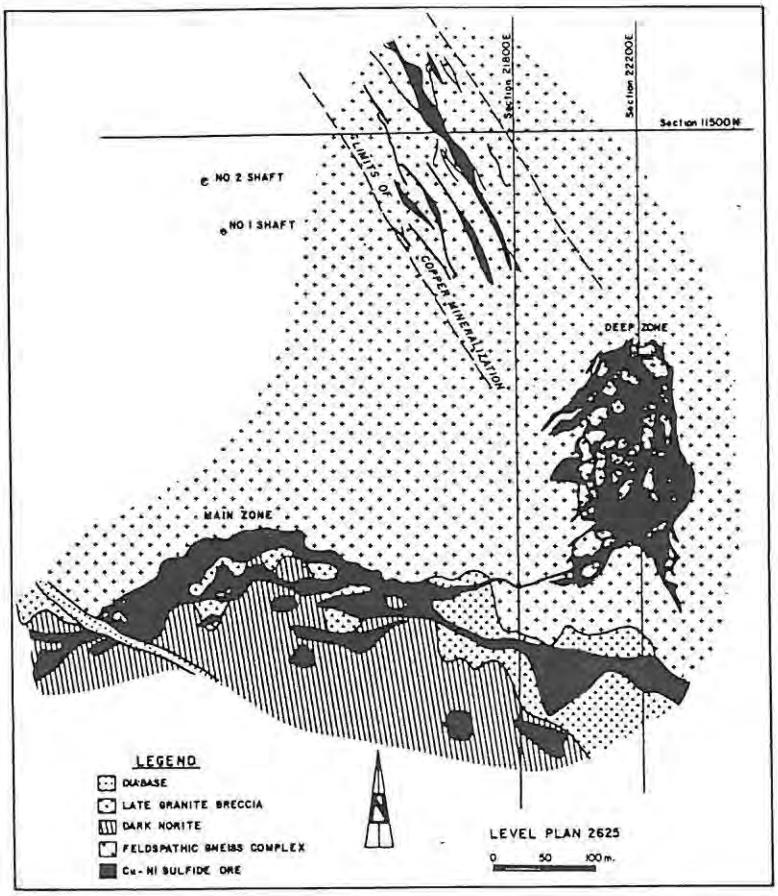


Fig. 3.16. Level plan 2625, Strathcona mine (after Abel et al., 1979).

(4) Set 4 can be subdivided into two groups.

(a) Narrow stringers branching at an angle of about 80° from sets 1 and 2 have a strike of N17°E and a dip of 38°W.

(b) A group with important widths of ore, but comprising only a small part of the reserves, has a strike of N9°E and a dip of 50°.

The principal ore shoots of sets 1 and 2 are generally quite straight and maintain consistent strikes and dips for as much as 50 m (Abel, 1981). Set 3 are considered to be shear fractures conjugate to sets 1 and 2 (Abel, 1981). Dip slip movement along sets 1 and 2 produced dilatant sections into which the sulphides could migrate. Set 4 represents dilatant tension fractures (Abel, 1981).

The mines constituting Inco's Levack Complex (Fig. 3.14) similarly exhibit a close relationship with embayment structures within the Sublayer. The Levack deposit is found within norite which occupies a pronounced depression in the footwall (Fig. 3.17). The orebodies are preferentially located where secondary bulges within the embayment make their deepest penetrations into the footwall (Boldt et ál., 1967). The orebodies at Levack West mine, some 2,4 km southwest of the Levack mine, are related to a suite of inclusion-rich two pyroxene gabbros and leucocratic breccias which lie below the basal mafic norite of the Main Irruptive. The predominant Sublayer phase is the leucocratic breccia which is granodioritic in composition and hosts numerous footwall as well as mafic to ultramafic inclusions (Hoffman et al., 1979). The bulk of the ore at Levack West mine occupies a prominent embayment in the footwall

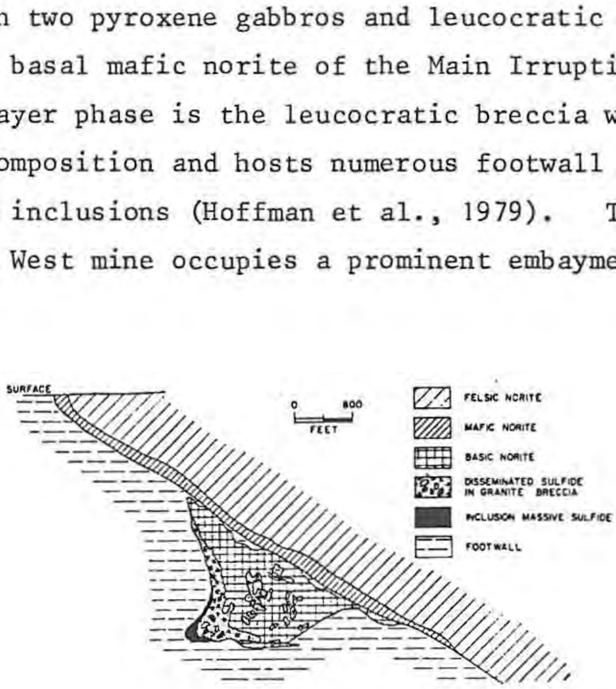


Fig. 3.17. Generalized section through a typical Levack Mine ore body, looking east (after Souch et al., 1969).

rocks between the 800 and 1200 levels where the ore assumes a nearly horizontal atitude (Fig. 3.18). Adjacent to the main embayment are sheet-like lenses which strike in a north-easterly direction and dip from 30^{o} to 40^{o} south. The footwall ore zone consists of sulphide filled fractures in the Levack breccia. The fractures vary in width from 1 mm to 2 m and the larger veins parallel the trend of the overlying main zone and dip steeply to the south-east (Hoffman et al., 1979).

The ore at Hardy mine occurs almost entirely within the mafic and granitic footwall gneisses (Mitchell and Mutch, 1957). The mineralization is spatially associated with a quartz diorite rock, similar to that observed in the offset deposits, which reaches its

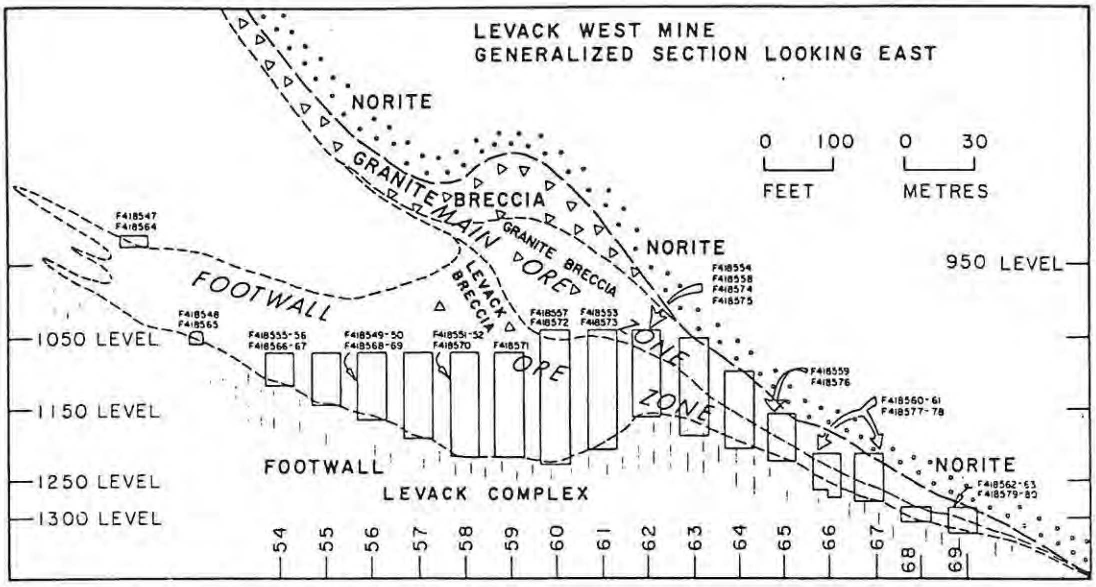


Fig. 3.18. Generalized section of the Levack West mine (after Hoffman et al., 1979).

greatest thickness in the vicinity of the deposit (Fig. 3.19). Where this rock type is absent the contact is barren. The orebody is strongly controlled by distortions in the footwall contact of the biotitic norite (Fig. 3.19 and Fig. 3.20). The distortions are related to a prominent north-westerly striking and north-easterly dipping cross fault. The distortions are pre-ore in age and the fault appears to be a reactivated pre-ore fault (Mitchell and Mutch, 1957). The ores characteristically swell into the footwall below the distortions in the contact and very little ore is found east of the distortion area (Fig. 3.20). The Hardy orebody is tabular in shape, about 330 m long, up to 45 m wide, and extends some 400 m below surface at an average dip of 35^{o} (Popoff, 1967). In detail the body is made up of a number of lenses which characteristically show irregular lateral terminations (Fig. 3.20). Along strike, particularly in the area of the cross fault, some of the ore swings into the norite to terminate in zones of quartz diorite breccia and dykes of contact breccia (Fig. 3.19). Fins of ore up to 3 m wide may extend for up to 15 m into the hangingwall norites along similar structural trends utilized by the aplitic dykes (Fig. 3.20). The ore has a strong affinity for Levack breccia, a common constituent of the footwall of the other two deposits discussed, which commonly consists of footwall fragments of all sizes set in dark very fine grained groundmass. The ore does not restrict

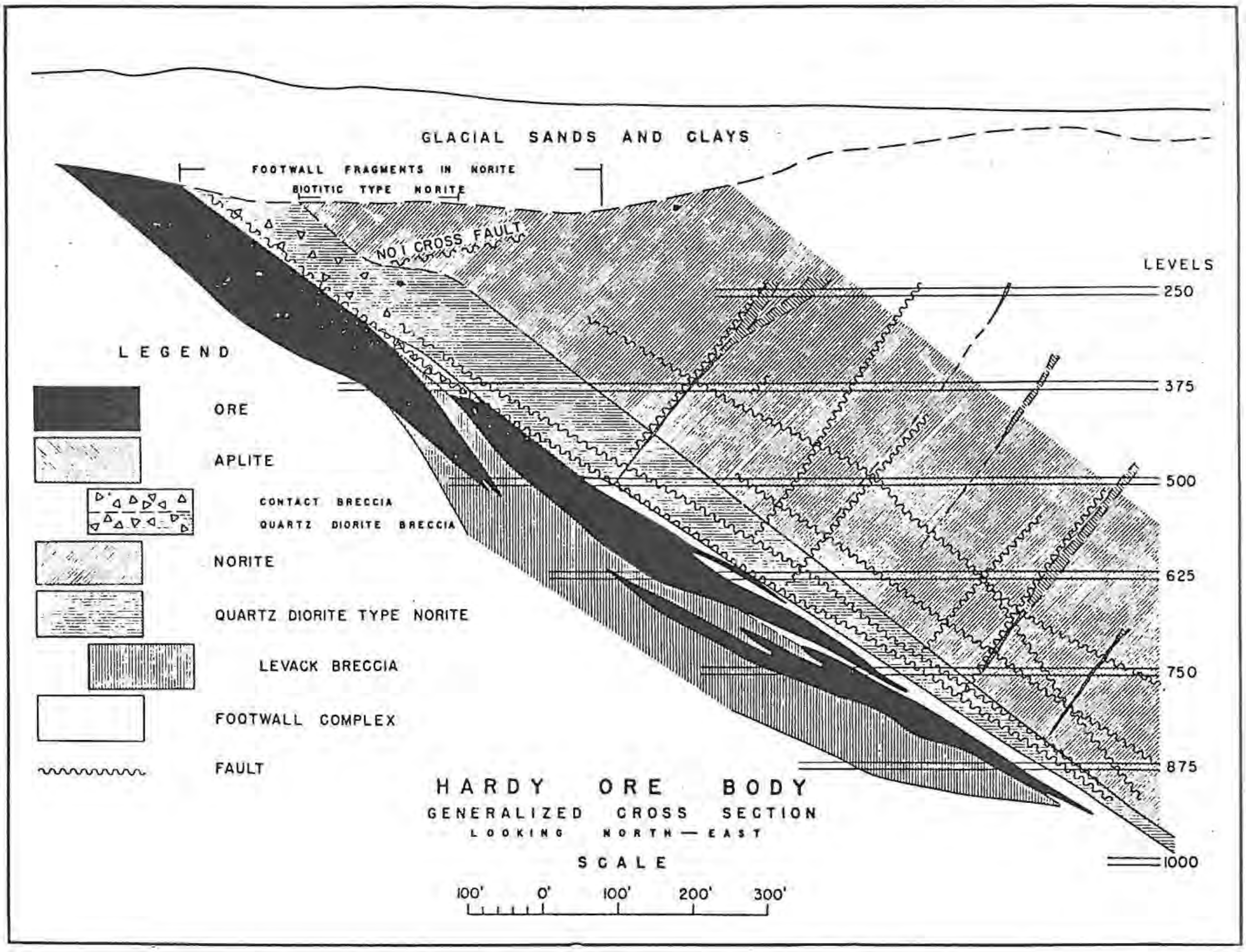


Fig. 3.19. Generalized cross-section, Hardy orebody (after Mitchell and Mutch, 1957).

itself to this rock type and in the western part of the mine it is found entirely within granite (Mitchell and Mutch, 1957). Very little ore occurs in the greenstone and in fact pinches in the western ore shoot take place where rocks are of this type.

Tonnage figures for the individual deposits in the Sudbury camp are not commonly reported in the literature. Proven and probable ore reserves are estimated at an incredible 500 million tons of which the major holder is Inco, while Falconbridge holds some 81 million tonnes. Inco extracts some 15 million tonnes of ore per year from its Sudbury operations which represents 25% of the total non-Communist World's capacity (E.M.J. Staff, 1981). Falconbridge mines some 3,1 million tonnes of ore per year from its Sudbury operations

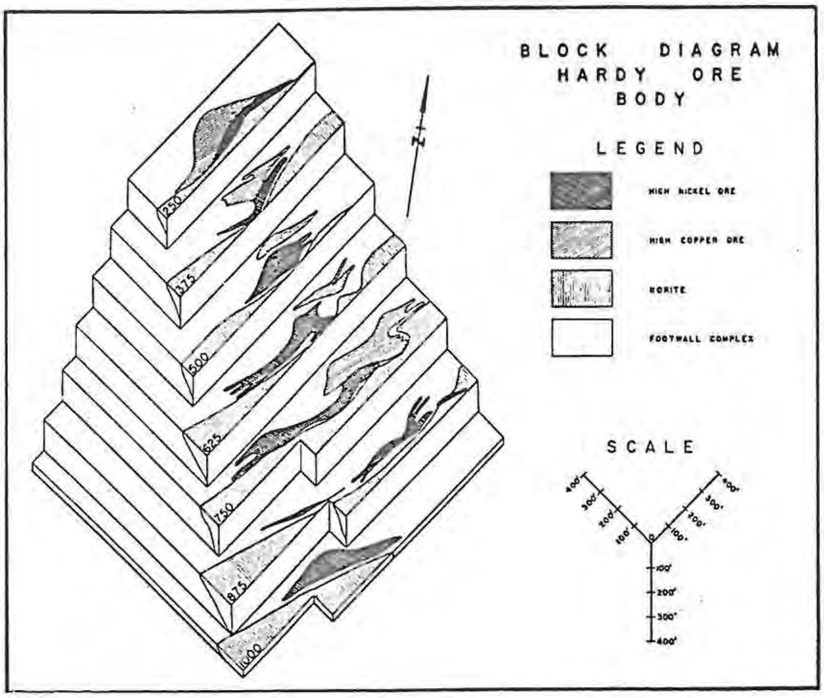


Fig. 3.20. Block diagram, Hardy orebody (after Mitchell and Mutch, 1957).

and by the end of 1977, it had extracted 81,732,241 tonnes of ore from the Sudbury field (E.M.J. Staff, 1981; E.M.J. Staff, 1978).

From the above discussion it is evident that the orebodies vary considerably in size, have a highly irregular shape, lack both lateral and vertical continuity and vary considerably in atitutde in a down dip dimension. For these reasons the orebodies are difficult to evaluate and mine.

The orebodies of the North Range are characteristically texturally heterogeneous and a number of textural variations are present within any one orebody.

The hangingwall zone of the Strathcona ore body is typically composed of a disseminated type of mineralization which embraces blebs, composite grains and patches of sulphide in a noritic matrix (Cowan, 1968). Stringer ore and breccia ore may be locally present. Adjacent to the hangingwall breccia and granite breccia contract the sulphides may be locally banded. The banding is defined by alternating pyrite and pyrrhotite layers.

The Levack orebody similarly contains patches of sulphide interstitial to the silicate minerals in the Sublayer norite (Souch et al., 1969). These patches are generally sparsely distributed, but in some inclusion-rich areas they are sufficiently concentrated to constitute ore. The Levack West deposit is atypical however, in that it does not have any equivalent of the disseminated sulphide mineralization in the hangingwall norite (Hoffman et al., 1979).

The presence of this disseminated mineralization in the hangingwall results in the upper portions of mineable ore in any one deposit being defined by an irregular assay cut-off rather than by a sharp geological cut-off.

The Main ore zone at Strathcona is predominantly composed of breccia ore which consists of patches and stringers of sulphides with numerous rock fragments (Cowan, 1968). Disseminated ore may also occur in this zone and is restricted to the quartz-rich matrix of the granite breccia. Bands of inclusion massive sulphide containing some rock fragments are commonly encountered along the footwall of the main zone and within the gneissic footwall.

Granite breccia ore containing sulphide blebs that locally coalesce into pods of a network of braided stringers accounts for two-thirds of the ore at Levack mine (Fig. 3.17). This ore grades downwards into inclusion massive sulphide which occurs in the nose of the embayment (Fig. 3.17). The ore, which constitutes one-third of the reserves, contains scattered footwall inclusions and leuconorite (Souch et al, 1969). The Levack West deposit contains a prominent zone of granite-breccia ore containing both disseminated and massive sulphides (Fig. 3.18).

Granite breccia ore is not common at the Hardy mine. Little development is carried out on this ore because of its poor grade and irregular distribution (Mitchell and Mutch, 1967). Most of the ore reserves are contained in lenses of massive sulphides which have a sieve-type texture due to the presence of foreign inclusions (Mitchell and Mutch, 1957). Minor galena-sphalerite-calcite mineralization is found in small fractures and veins cutting across the massive ore.

Typically, as outlined above, the main ore zones show a gradual enrichment of sulphide towards the footwall where massive sulphides occur. Therefore, the basal contact of the ore zone is defined by a sharp geological cutoff. The upper boundaries of the ore zone is defined by an assay cutoff and coincides with that area where the abundance of fragments constitutes a serious dilution factor to the tenor of the ore.

The deep zone at Strathcona consists of stringers and veins of massive sulphide containing fragments of feldspathic and mafic gneiss from 20 cm up to 7 m (Cowan, 1968). The footwall ore zone at Levack West is thought to be equivalent to the deep zone at Strathcona (Fig. 3.18). Three textural classes of ore occur (Hoffman et al., 1979); massive sulphide stringers in the Levack breccia, atypical copper stringer ore in the Levack breccia, and disseminated ore. The last two types of ore are not significant volumetrically.

The mineralization in the veins of the Strathcona copper zone is almost entirely massive and has extremely sharp contacts with the host rocks (Abel et al., 1979). Minor disseminated sulphides in the wall rock are restricted within a few centimeters of the veins.

Compositionally, the ores of the North Range are relatively simple. The major sulphides are chalcopyrite, pyrrhotite, pentlandite and cubanite. Common accessory sulphides include magnetite, ilmenite and pyrite. The Cu:Ni ratio varies considerably between deposits, but generally falls between 1:1.5 and 9.5:1 (Falconbridge Staff, 1959).

The hanging wall disseminated ores at Strathcona are composed predominantly of pyrrhotite and lesser amounts of pentlandite (Cowan, 1968). Chalcopyrite is a relatively minor constituent of these ores which also contain an average of 2% pyrite and 15% magnetite.

The main ore zone at Strathcona has a similar mineralogy to the hangingwall ore and is composed of 30% pyrrhotite, 4% pentlandite, and 1,5% chalcopyrite (C.M.J. Staff, 1978). Minor amounts of magnetite, pyrite, millerite, bornite and cubanite occur. The magnetite is preferentially concentrated in the footwall gneisses. The pyrite is around the margins of fragments and as bands within the more massive ores. At Hardy pyrrhotite accounts for some 75% of the total massive ore assemblage, the remainder being composed of pentlandite, chalcopyrite, magnetite, and pyrite (Mitchell and Mutch, 1957).

The most significant differences between the ore of the Strathcona deep zone and that of the main zone are increases in grain size and an increase in the amount of chalcopyrite and magnetite (Cowan, 1968). The magnetite which may constitute up to 10% of the ore, is often concentrated in bands up to 20 cm thick. The footwall ore at Levack is strikingly similar but also contains millerite (Hoffman et al., 1979).

The sulphide veins of the Strathcona copper zone consist of 67% chalcopyrite, 18% cubanite, 3,5% pyrrhotite, 1,5% pentlandite and 0,5% sphalerite (Abel et al., 1979). Magnetite, which may constitute up to 5% of the ores, occurs as late stage veinlets cutting across the ore and as disseminated crystals in the ore.

Texturally, the copper-nickel sulphide ores are complex (Cowan, 1968). Pentlandite typically occurs as fine exsolved flames along the basal cleavage of the pyrrhotite, as interstitial grains within the pyrrhotite, more rarely as large blocky crystals 10 cm in diameter, and as grains preserved at the junction of chalcopyrite and cubanite crystals. Chalcopyrite occurs as discrete grains mantling all the other sulphides in the massive and stringer ore, surrounding fragments within the breccia ore, or as veinlets containing inclusions of pyrrhotite and pentlandite in the footwall gneisses. Blebs of chalcopyrite are common in the footwall copper rich zones. In the other sulphides cubanite is invariably found as coarse blades concentrated along prominent crystallographic directions in the chalcopyrite. Pyrite invariably encloses inclusions of pyrrhotite, pentlandite, and chalcopyrite. The sphalerite often hosts blebs of exsolved chalcopyrite.

The platinum group elements and precious metals present within the ores are recovered as a by-product and provide a valuable additional source of income for many mines. The Sudbury ores have (Pt + Pd)/(Ru + Os + Tr) ratios ranging from 12 to 10 and Pt and Pd levels ranging from 0,4 to 4 x chrondritic (Naldrett, 1980). The ores at Levack West are marked by fairly high concentrations (relative to chrondritic levels) of Au, Pd, Pt, and Rh and very low concentrations of Ru, lr, and Os (Hoffman et al., 1979). The values for the various platinum group elements range from a few p.p.b. to a few thousand p.p.b. Data from the nearby Strathcona deposit indicate values of close to 400 p.p.m. for both Pt and Pd, approximately one-third of the levels at Levack West. The most common platinum group-bearing minerals in the north range deposits are the tellurides : moncheite (Pd Bi Te) and moncheite (Pt Te_2) (Cabri and Laflamme, 1976). These minerals are commonly found as very tiny inclusions in chalcopyrite and reach a maximum size of 300 x 660 microns. This data is supported by the studies of Keays and Crockett (1970) who found that most of the Pb and Pd reported with the chalcopyrite, but contrasts strongly with the data of Chyi and Crockett (1979). The latter mentioned, in a later study of the Sudbury ores, found that for Pd and Au, the noble enrichment trend followed the sequence pentlandite > chalcopyrite > pyrrhotite > magnetite; and for Pt and lr the trend followed the sequence chalcopyrite > pentlandite > pyrrhotite > magnetite. Most of the silver in the Sudbury ores reports with the chalcopyrite (Hawley, 1962).

Very little data is available on the actual grade of individual deposits in the Sudbury camp. The mill head grades at Strathcona average some 1,40% Ni and 0,67% (C.M.J. Staff, 1978). The ores mined by Falconbridge in the Sudbury camp are reported to have an average grade of 1,5% Ni and 0,80% Cu (C.M.J. Staff, 1978). During 1980 Falconbridge Nickel milled 2182765 tonnes of ore at an average grade of 0,94% Cu, 1,20% Ni, 0,07 g/t Au, and 3, 43 g/t Ag from its six producing mines (C.M.J. Staff, 1982). During the same period Inco milled 10 608 827 tonnes at an average grade of 1,30% Cu, 1,39% Ni, 0,17 g/t Au and 4,46 g/t g from its 11 producing mines (C.M.J. Staff, 1982). The average grade of Inco's mines is reported to be some 2½% Cu + Ni, with both present in roughly equal amounts (C.M.J. Staff, 1977). The grades reported above are not too dissimilar from the average grades of all the ore mined in the Sudbury basin and the average grade of the ore held in reserve. For example, the total ore mined by Falconbridge up to the end of 1976 graded at 1,46% Ni and 0,77% Cu, while the 80 670 000 tons the company holds in reserve has a grade of 1,46% Ni and 0,77% Cu.

Likewise, very little information is available on the amount and grades of the P.G.E. and precious metals recovered. The gold and silver recovered over the 10 year period 1947-1956 included some 41 000 oz. of Au and 1,2 million oz. Ag, implying a ratio of Au:Ag produced in the order of 1:31 (Hawley, 1962). Inco recovered an average grade 0,69 p.p.m. Pt between 1966 and 1971. Hawley (1962) calculated the average grade of platinum recovered was between 0,65 p.p.m. and 0,9 p.p.m.

The orebodies of the North Range exhibit a well defined compositional and mineralogical zonation. Within any deposit there is a gradual increase in the Cu:Ni ratio from the hangingwall orebodies to the footwall orebodies. At Strathcona the Cu:Ni ratio in the hangingwall zone is 1:2, in the Main Zone 1:2 and in the Deep Zone 1:1 (Abel et al., 1979). There is a crude zoning in the Cu:Ni ratio at Levack West (Hoffman et al., 1979). The Cu:Ni ratio over the granite breccia ore (main ore zone) at Levack West is 3:3, while the ratio over the Levack breccia ore (footwall ore zone) is 3:5. The copper content is highest in the atypical chalcopyrite-rich stringer ore at the base of the footwall ore zone and nickel is strongly depleted with respect to the typical Levack breccia ore and granite breccia ore. Similarly, at Hardy the lowest Cu:Ni ratio occurs in the hangingwall and the highest in any random mineralization in the footwall complex (Mitchell and Mutch, 1957). Within an individual orebody there seems to be an enrichment of Cu towards the footwall side of the zone. For example, the Cu:Ni ratio increases markedly at the base of the Main and Deep zones where stringers of almost pure chalcpyrite may be encountered (Cowan, 1968). This is not always true, as the distribution of Cu and Ni in any one shoot at the Hardy mine shows considerable variation, and changes in the Cu:Ni ratio from 1:20 to 1:1 across a shoot are very common (Mitchell and Mutch, 1957). In some ore bodies there is a strong variation in the Cu:Ni ratio with increasing depth (Falconbridge Staff, 1959). At Hardy an average Cu:Ni ratio ranges from 1:1,5 in the upper levels to 1:5 in the lower levels. At the Boundary mine the Cu:Ni ratio varies from 1:2 in the upper levels to 1:5 in the lower levels.

Both Strathcona and Levack West, are typically zoned with respect to P.G.E. and precious metals (Naldrett, 1981). Pt, Pd, and Au increase away from the Irruptive hangingwall into the footwall and Rh, Ru, Ir, and Os increase in the opposite direction. Consequently, the greatest concentration of Pd and Pt at Levack West is found in the atypical chalcopyrite-rich stringer ore. The concentration of P.G.E. in any one single orebody is greatest on its footwall side. At Strathcona for example, there is a marked increase in the volume of P.G.E. in chalcopyrite-rich ore at the base of the main and deep ore zones.

The Ni:Co ratio shows an increase from hangingwall to footwall both at Levack and Strathcona. The average Ni:Co ratio in the hangingwall ore at Strathcona is 15,7, in the main zone 21,6, and in the deep zone 43,5.

There is a pronounced zoning in the pentlandite:pyrrhotite ratio at Strathcona (Abel et al., 1979). The Ni content of the iron-nickel sulphides is lowest in the hangingwall zone (2,5% - 3,0%) and highest in the main zone (3,0% - 5,0%) (Fig. 3.21). The individual values within the main zone show a strong zonation with the highest values occurring along the basal contact (Cowan, 1968). The zoning is laterally away from the Irruptive contact and there is little change in the values in a down dip dimension. The individual contours parallel

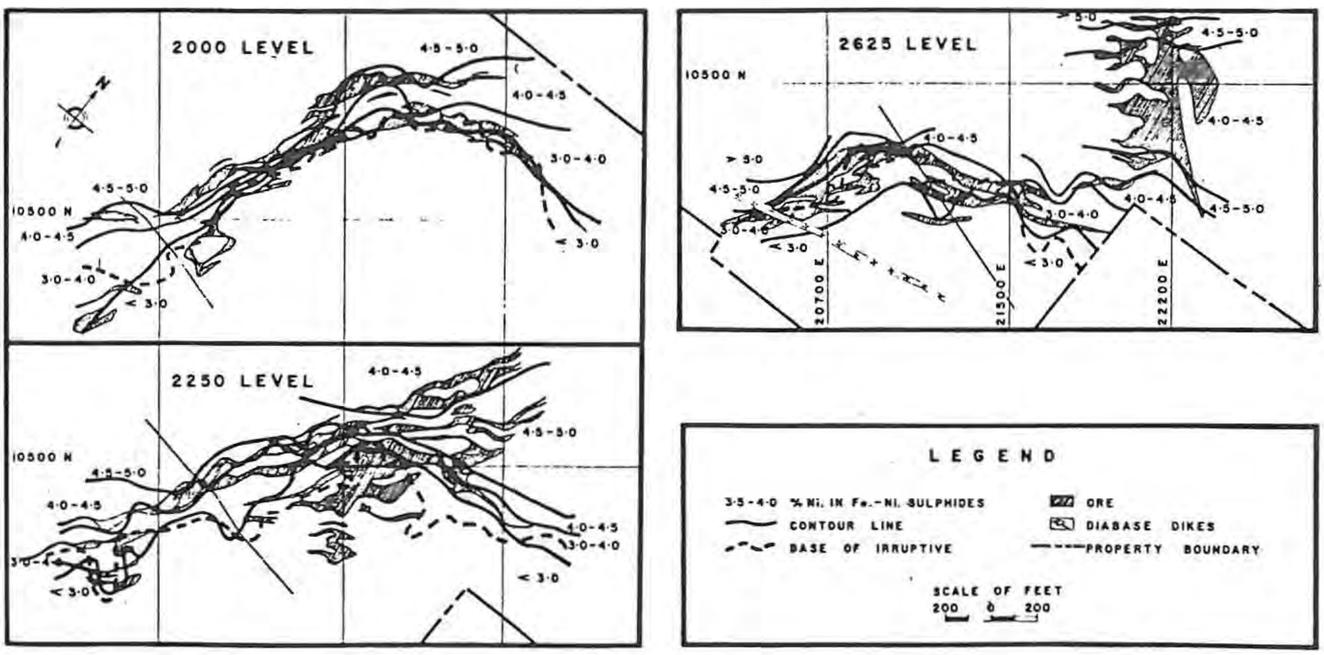


Fig. 3.21. Contour plans showing the percentage and distribution of nickel in iron-nickel sulphides at Strathcona (after Cowan, 1968).

the contact between the hangingwall and the granite breccia even where strong irregularities are present in the contact. However, individual ore lenses do not have a characteristic value as they are often cut across by the contours. The bulk of the deep zone possesses similar ratios to the main zone except that the base of the deep zone is strongly zoned and a maximum value of 6 occurs here. The nickel content of the sulphides increases towards the footwall side of any individual vein in the copper zone. The type of zonation is not universally present, and at Hardy the variation in the ratio of pyrrhotite to pentlandite is small.

At Strathcona there seems to be a broad zonation of hexagonal (strongly magnetic) and monoclinic (weakly magnetic) pyrrhotite across the deposit although the distribution of these vary on a local scale (Cowan, 1968). The ore zones in the hangingwall contain significant amounts of hexagonal pyrrhotite (Fig. 3.22). The main zone contains only small amounts of hexagonal pyrrhotite which then increases towards the hangingwall side. The amount of hexagonal pyrrhotite increases towards the base of the deep zone where it makes up more than 40% of the total pyrrhotite. The distribution of hexagonal pyrrhotite has no direct correlation with the amount of Ni in the iron-nickel suphide.

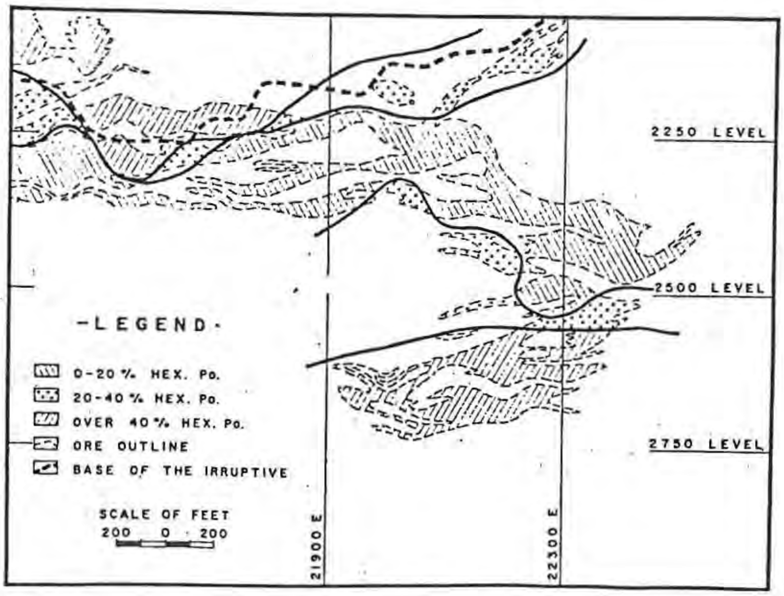


Fig. 3.22. Part of west-east vertical section 10560N, illustrating the distribution and percentage of hexagonal pyrrhotite (after Cowan, 1968).

All the country rocks surrounding the ore zone are relatively unaltered from hangingwall to footwall and even below the ore zone. Narrow selveges of alteration 2mm to 5 mm in width are observed in the wallrock and inclusions within the ore zones. These consist of varying proportions of chlorite, talc, biotite, epidote, hornblende and spessartite or grossularite garnet. Chloritic veinlets may be found parallel to the sulphide/host rock contact in the springer type mineralization in the footwall.

Glacial erosion has removed most of the oxidized portions of the orebodies and consequently supergene alteration is not conspicuous in the deposits of the north range. Only in the vicinity of sparsely distributed open faults does pentlandite oxidize to violarite. In some cases millerite may form as replacement along cracks in the violarite (Hawley, 1962).

3.4 The South Range deposits

Many of the South Range deposits show a strong spatial relationship with irregularities at the base of the Sublayer. The Murray orebodies (Souch et al., 1969) occur in an ultramafic and mafic inclusion-bearing contact breccia zone occupying the lower portions of a gentle depression at the base of the Irruptive (Fig. 3.23). The ore zone terminates abruptly, but with an irregular contact, against the overlying quartz-rich norite. The tabular-shaped orebody extends down to a depth of 1000 m, averages 500 m in length, and has a maximum horizontal thickness of 170 m.

Although footwall embayments are the dominant control on the shape and size of many deposits, local shear zones may also exert a strong control. The Creighton orebody occupies a trough-like depression at the base of the Irruptive. The Sublayer rocks, which may reach 150 m in thickness, form an irregular branching sheet along the margins of troughs between the quartz-rich norite and the footwall granite-greenstone (Fig. 3.24). The greatest concentration of ore is found in a funnel-like portion of the embayment, where it joins an off-set, and in the underlying footwall rocks (Boldt et al., 1967). The

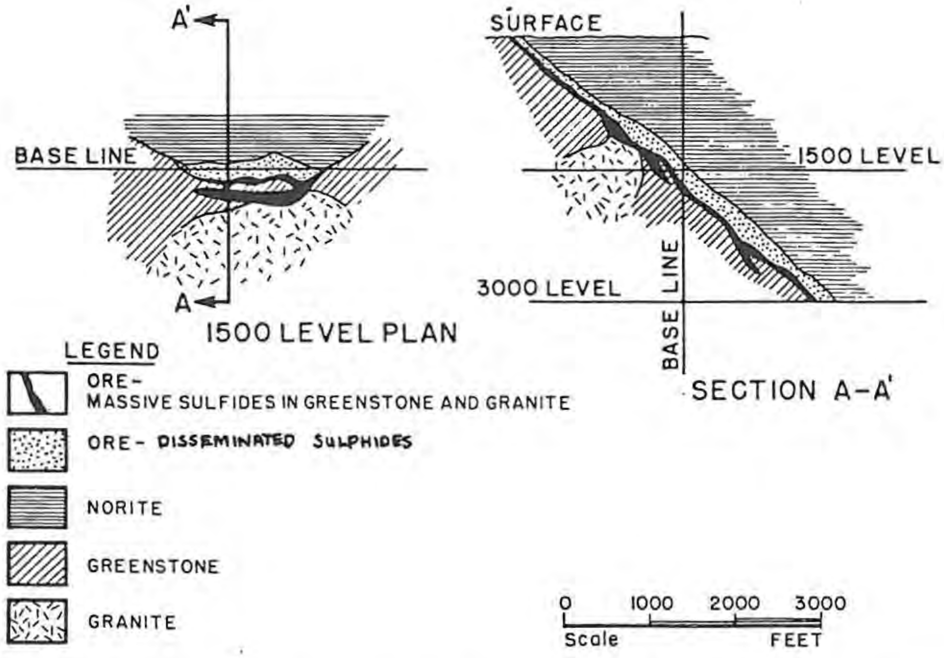
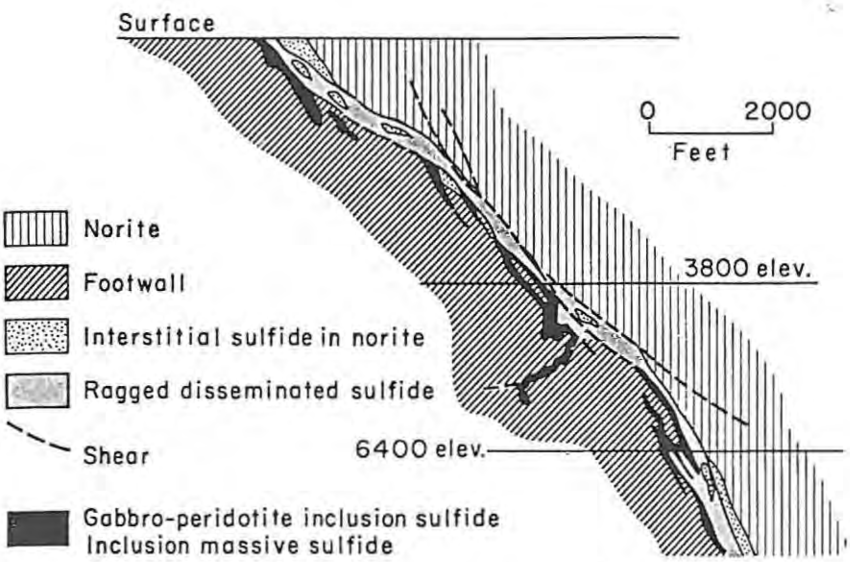


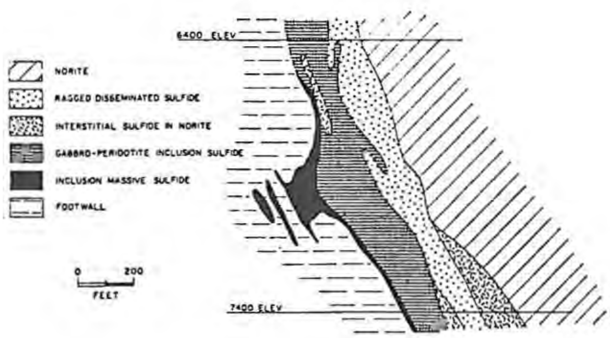
Fig. 3.23. Generalized geological level plan and section, Murray mine (modified after Boldt et al., 1967).

distribution of ore in these zones is partly controlled by a system of "horse-tailing" shears that cut across the embayment. The tabular-shaped orebody has a depth extent of nearly 3 km and the Creighton No. 9 shaft is the deepest continuous shaft in the western hemisphere (C.M.J. Staff, 1977). The Garson deposit is associated with an embayment structure and a local shear system that together outline lobe-like bodies of sulphidic quartz-rich norite (Fig. 3.25).

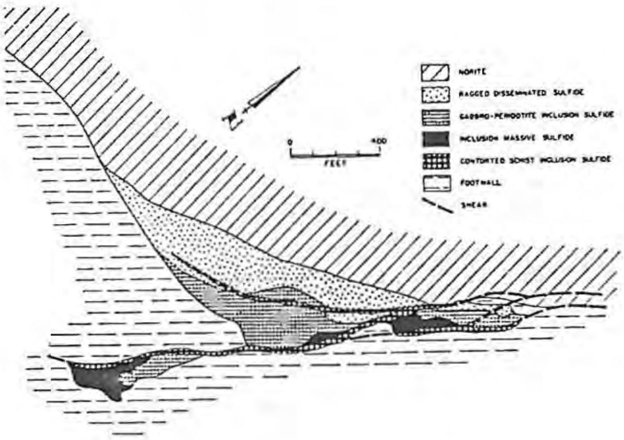
Some orebodies, for example East and Falconbridge, occupy prominent pre-existing fault or shear zones that preferentially developed at the margins of the basin now represented by the norite-greenstone contact. It is thought that the porous and brecciated rocks adjacent to the fault zone acted as a locus for ore deposition. The Falconbridge deposit is individualistic in that it is composed of a continuous well defined sheet of sulphides some 1600 m wide and 1900 m deep (Lockhead, 1955). Along strike, both to the east and west, the fault zone diverges from the contact and at the points of diversion the sulphides cease. Some 700 m east of this point another mineralized shear zone is found along the norite-greenstone contact. This corresponds to the East Mine which is similar in all respects to the Falconbridge



(a) Generalized section through the ore zone, looking west.



(b) Detailed section through the ore zone, looking west.



(c) Plan of 3400 level, showing relationship of ore to shearing.

Fig. 3.24. Sections and level plans of the Creighton ore zone (after Souch et al., 1969).

deposit. The fault zones exhibit evidence of a complex history of reactivation subsequent to ore deposition, and much of the ore in the vicinity of the faults is sheared, folded and brecciated. The wall rock adjacent to the faults is silicified and carbonated as a result of those repeated movements, much of the alteration being pre-ore in age. The ore zone at Falconbridge varies in thickness from a few centimeters to over 33 m, but generally averages 5 m. The rolling ore zone varies its dip from almost vertical to 65° or 30°S. Subsidiary

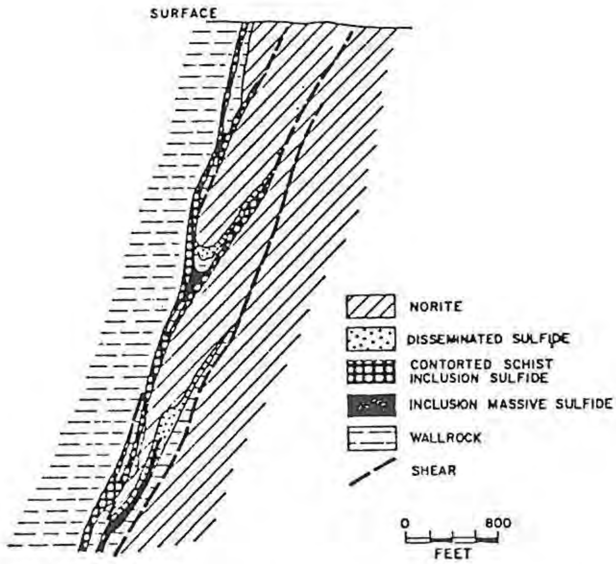


Fig. 3.25. Generalized section through the Garson ore zone, looking west (after Souch et al., 1969).

tangential shears are concentrated in the vicinity of marked variations in dip and strike. In the lower levels of the mine where highly sheared greenstone is the dominant lithotype, stringers and branching or isolated ore shoots extend for up to 33 m along the shears into the greenstone (Figs. 3.26 and 3.27). In the upper levels of the mine norite is the predominant lithology. Where the shears break away into the norite they do not produce shoots, but merely result in the widening of the ore zone - a reflection of the partially cooled nature of the norite at the time of deposition (Fig. 3.26).

The Little Stobie mine is made up of two orebodies of strongly contrasting character (Hoffman et al., 1969). The No. 1 orebody which lies between the footwall granite-greenstone complex and the Main Irruptive norite, resembles other marginal Sublayer deposits (Fig. 3,25). The ore zone dips at 55° to the north, has a strike length of 610 m, a depth extent of 792 m, and an average width of 30 m. The No. 2 deposit, which occurs entirely within the footwall rocks and has been preferentially emplaced between the meta-basalts and a granite boss, greatly resembles the offset deposits (Fig. 3.28). This orebody lies between 91 m and 366 m below the surface (Fig. 3.29), has a strike length of 273 m and an average width of 52 m.

The late intrusive olivine diabase dykes may severely modify the shape and continuity of the orebodies. The McKim mine (Fig. 3.30)

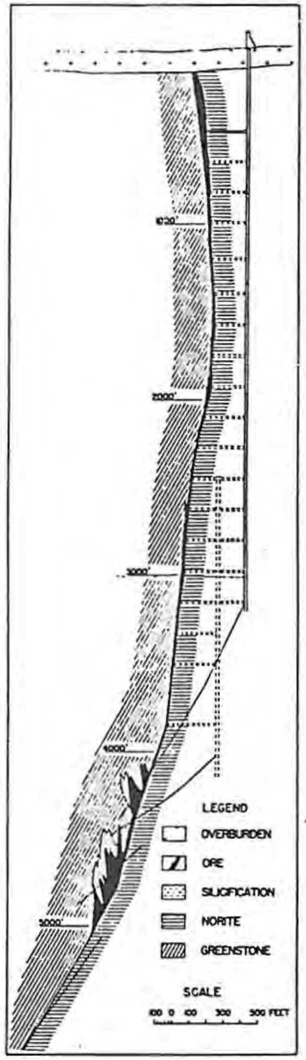


Fig. 3.26. Geological cross-section through No. 5 shaft - Falconbridge mine (looking west) (after Lochhead, 1955).

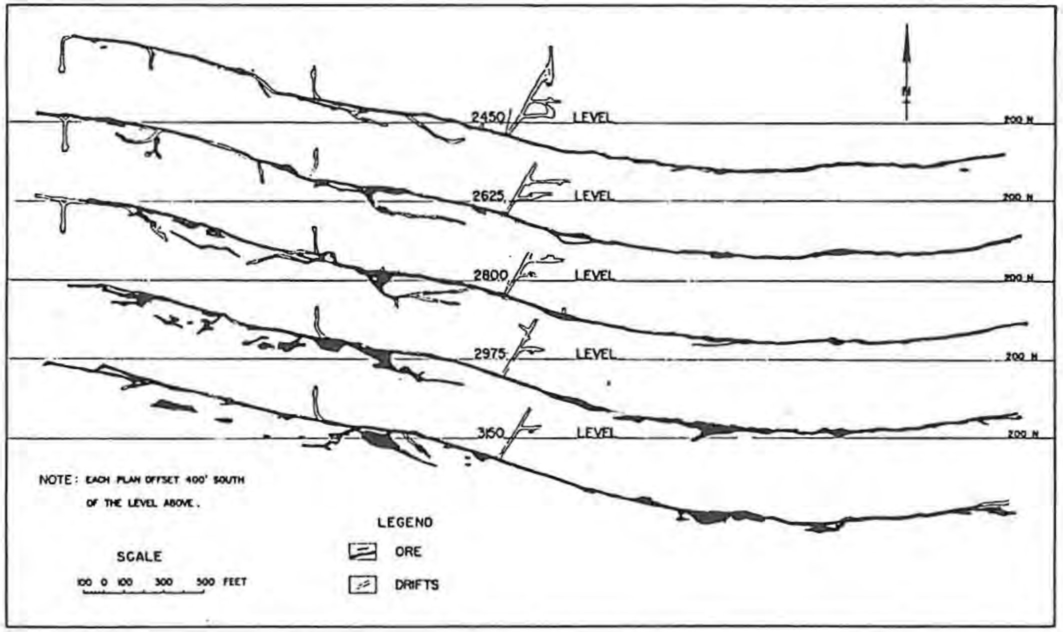


Fig. 3.27. Series of lower level plans - Falconbridge mine (after Lochhead, 1955).

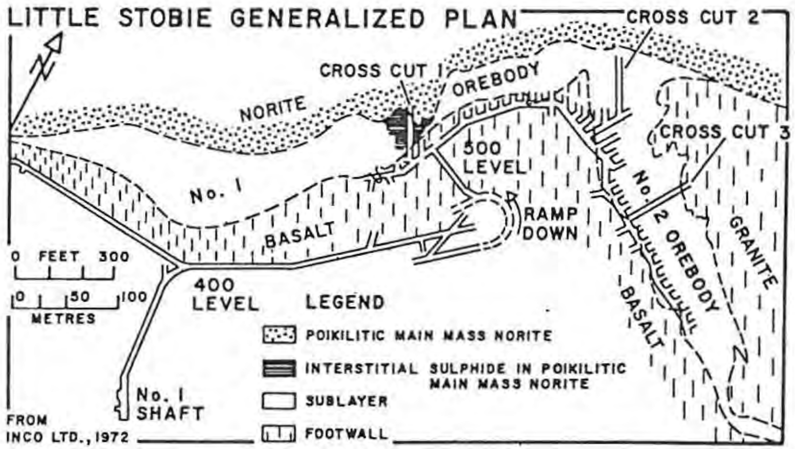


Fig. 3.28. Generalized plan of the Little Stobie mine (after Hoffman et al., 1979).

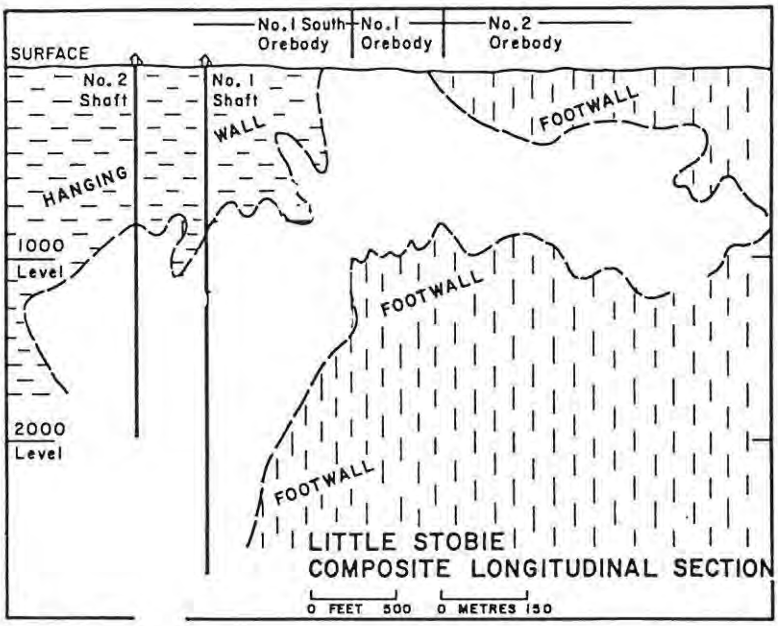


Fig. 3.29. Composite longitudinal section of the Little Stobie mine, showing sample locations (modified after Hoffman et al., 1979).

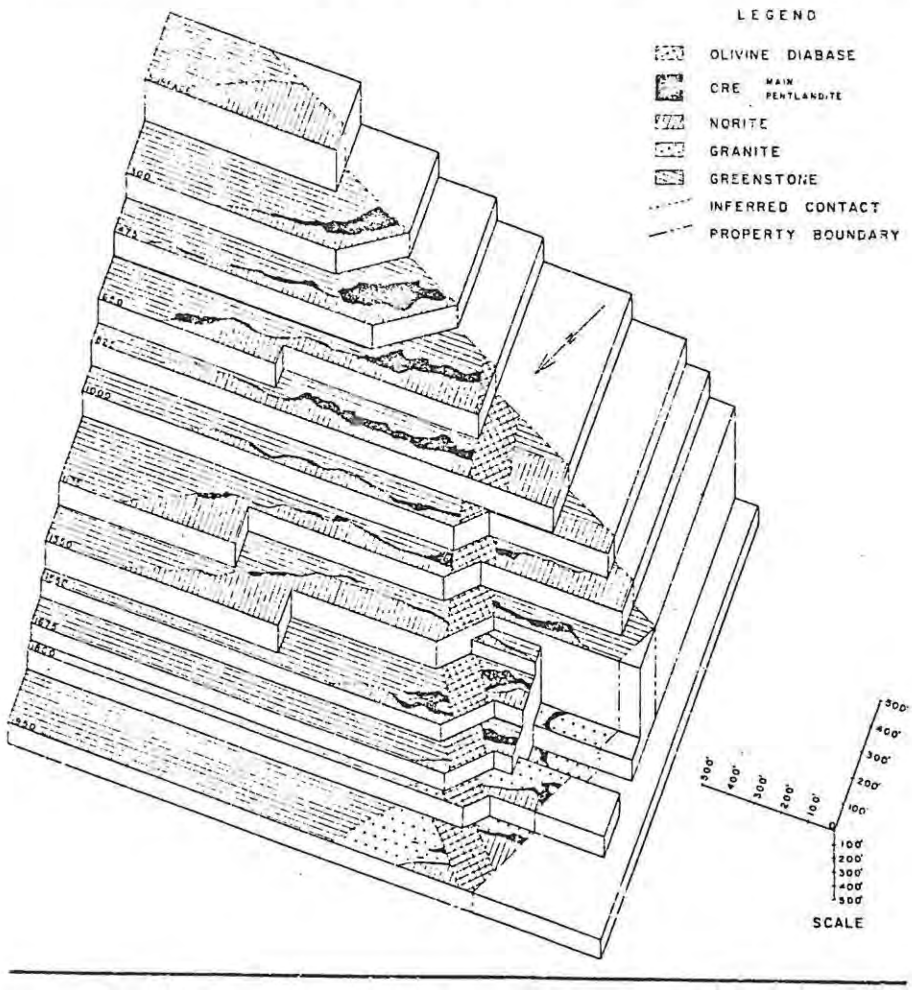


Fig. 3.30. McKim Orebody - Block Diagram (after Falconbridge Staff, 1959).

is located on the contact of the Sublayer norite and granite-greenstone complex (Falconbridge Staff, 1959). The 900 m by 42 m ore zone has an average dip of 45°S. Localized flexuring may shallow the dip to 15° or steepen it to 70°. The tabular orebody is made up of a family of shoots which are preferentially located within small irregularities in the footwall contact and are interconnected by low grade stringer mineralization. In the deeper levels of the mine off-shoots and isolated zones of mineralization occur in the footwall granite. Fig. 3.30 clearly shows the effects of the late dyke on the continuity ore the McKim orebody.

In sharp contrast with the North Range deposits, no footwall copper-rich zones such as the Strathcona copper zone have been found.

The size of the bodies is variable as indicated by the tonnages mined per day (E.M.J. Staff, 1981): Creighton mines some 7100 t/d, and is Inco's second largest producer, Garson 4100 t/d, Little Stobie 3100 t/d, East 250 000 t/yr, and Falconbridge 500 000 t/yr.

From the above description it can be concluded that the South Range orebodies greatly resemble the North Range deposits in that they lack both vertical and lateral continuity, vary considerably in size, and often vary their atitude down dip.

A distinct number of ore types are present in the South Range deposits and at the Creighton, Murray, and Little Stobie deposits these include, from hangingwall to footwall (Souch et al., 1969; Hoffman et al., 1979): disseminated sulphide, ragged disseminated sulphide, interstitial sulphide, gabbro-peridotite inclusion sulphide, and inclusion massive sulphide (Figs. 3.31 and 3.24).

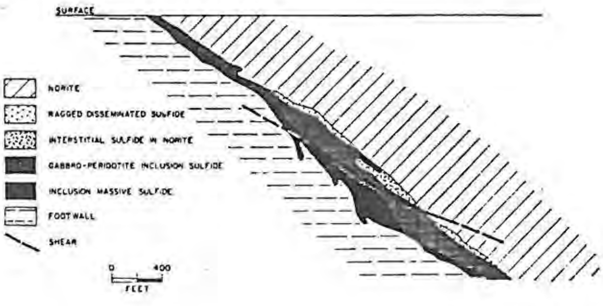


Fig. 3.31. Generalized section through the Murray ore zone, looking west (after Souch et al., 1969).

Disseminated sulphide may locally occur in the hangingwall quartz-rich norite where it is populated with inclusions. This type of ore is not present at the Murray Mine. Most of the hangingwall portions of the orebodies consist of ragged disseminated sulphide which consists of crescent or cusp-like masses of sulphide and norite filling the space between gabbroic inclusions. The inclusions range in size from a fraction of a centimeter to several centrimeters. Both the disseminated and ragged disseminated ores contain lenses of interstital sulphide ores which comprise irregular masses of norite containing variable amounts of sulphide filling the interstices between euhederal plagioclase and pyroxene. The ragged disseminated sulphide grades downward into gabbro-peridotite inclusion sulphide. In the latter, the ratio of matrix to inclusions increases and consequently it contains a greater proportion of sulphides in the matrix, the size of the inclusions increases (up to a few meters), and there is a marked increase in the proportion of peridotitic and pyroxenitic fragments with respect to gabbro. The gabbro-peridotite inclusions massive sulphide grades into inclusion massive sulphide towards the footwall. This class of ore consists of massive sulphide containing rare footwall and ultramafic fragments. This ore occurs discontinuously along the footwall contact and in the footwall as isolated pods, stringers, and fracture fillings. The contorted schist inclusion sulphide represents portions of the main ores that are present along shears cutting the footwall rock. The ore itself is not schistose but tends to be finer-grained and contains finer rock particles than the surrounding ore zones. This class of ore is rarely encountered at Murray and is not present at Little Stobie.

Contorted schist sulphide and inclusion massive sulphide make up four-fifths of the ore at Garson (Fig. 3.25). The former greatly predominates and is found in braided fault zones and shear zones adjacent to the noritic lobes. The remaining one-fifth includes interstitial and ragged disseminated sulphide which occur at the base and part way up the flanks of each lobe.

The ore at the Falconbridge and East deposits includes disseminated and breccia sulphides, the latter occurring as matrix sulphide filling the interstices between fragments (Lockhead, 1955).

Four classes of ore are present at McKim : massive ore, breccia ore, disseminated pentlandite breccia ore, and disseminated sulphides

(Falconbridge Staff, 1948). Types 1, 2 and 4 are found in the main ore zone and types 2 and 3 in the footwall shoots. Disseminated ores occur to a very limited extent on the hangingwall side of the ore zone. The sulphide breccia ores consist of fragments of wall rock with minor amounts of quartz and carbonate cemented by a sulphide matrix. The disseminated pentlandite breccia ore is similar to this, but has a matrix of feldspar, quartz, carbonate and basic rock fragments, all of which contain disseminated pentlandite.

As in the North Range, the orebodies are characterized by a high grade sharp geological footwall cutoff but a low grade "assay cutoff" hangingwall contact.

The principal ore minerals in the South Range deposits includes pyrrhotite, pentlandite, chalcopyrite, with lesser amounts of pyrite, magnetite, and ilmenite (Hawley, 1962). Pyrite is not as common as in the North Range. Magnetite may be a major constituent of some ore types and at Creighton it can comprise 20% by volume of the ore. The average Ni:Cu ratio in the South Range deposits is not as variable as that in the North Range and varies from 1:1 at Garson; 2:1 at Falconbridge, East, and Murray, to 4:1 at McKim. Post-ore fractures filled with quartz, pyrite, sphalerite, galena and marcasite and carbonate are present in some deposits, especially at Falconbridge and McKim. Arsenides, especially niccolite and maucherite, are a common constituent of some ore types at Falconbridge and Garson. The textural relationships of the ore minerals and grades are very similar to those of the North Range.

The P.G.E. mineralogy of the South Range deposits is in distinct contrast to that of the North Range (Cabri and Laflamme, 1976). Most of the P.G.E. are locked up in sperrylite, arsenides, and sulpharsenides of the transition elements and are rarely encountered in the tellurides. In the North Range there is significant substitution of Pd for Pt and visa versa; this is absent from the South Range. Sb and Sn may form important components of the P.G.E. geochemistry in the South Range, but are rarely encountered in the north. Sperrylite, the most common bearing mineral is invariably found embedded in chalcopyrite.

As in the North Range deposits, the most prominent zonal trend is a marked increase in the copper content towards the footwall. For example, the Cu:Ni ratio at Creighton varies from 0,7:1 to 0,5:1 in the upper portions to 3:1 in the lower levels of the orebody (Hawley, 1962). Although the hangingwall ore shoots are enriched in copper at Falconbridge, it must be remembered that because of the reversal dip, this is in fact the structural hangingwall. The P.G.E. are zoned in an identical way to the North Range deposits. For example, the Little Stobie No. 1 body shows a distinct enrichment of Pd, Pt, and Au in the footwall copper-rich stringer ore at the base of the massive sulphide, although these stringers are not nearly as abundant as in other Sudbury ore deposits (Hoffman et al., 1976). There is a distinct lateral zonation of P.G.E. between the No. 1 and No. 2 orebodies. The latter is distinctly enriched (2 x) in all P.G.E. except Pt; although there is no corresponding increase in copper mineralization and in fact no copper-stringer ore is present at the base of this orebody. The Falconbridge deposit is anomalous as far as platinum zonation is conerned (Naldrett, 1981). Average data obtained resemble those of the hangingwall ores at Strathcona, both in a low (Pt + Pd)/(Ru + lr + Or) ratio of 2:3 and in a low Cu:Ni ratio. Naldrett (1981) has proposed that the Pt-rich footwall portion has been faulted off.

Hypogene alteration is not a conspicuous feature of the deposits, but quartz and carbonate may occur in above normal quantities in the vicinity of faults. As at Fecunis Lake in the North Range, the olivine diabase dykes cutting through the orebodies at Garson and McKim have had little effect on the distribution of Co, Ni, Cr, Ti, V, or S (Hawley, 1962). Ag does seem to be slightly enriched at the margins of the dykes. Local recrystallization and mobilization of the ore may occur in the immediate vicinity of the dykes.

Supergene alteration is not conspicuous and the deposits are characterized by relatively shallow oxidation profiles. Significant alteration does however occur at the Falconbridge deposit where pyrrhotite and pentlandite have been altered by supergene solutions, flowing along cross-fractures and faults, into a complex nickeliferous pyrite, marcasite assemblage (Hawley, 1962). This halo may extend from 1 m to $3\frac{1}{2}$ m laterally on either side of the faults.

3.5 The Offset Deposits

The offset deposits occur sporadically along quartz-diorite dykes that extend radially outward from the Irruptive, and are preferentially concentrated on the southern side of the basin. Deposits of commercial grade are known to exist up to 7 km from the outer contact of the Irruptive.

The orebodies are lens-like or pipe-like in form and in most cases have near vertical attitudes and poor lateral continuity. Unlike the marginal deposits, the offsets usually have strong vertical continuity. The ore may be concentrated at either margin of the dyke, within the dyke, or in some cases the ore even crosses from one margin to another (Fig. 3.32).

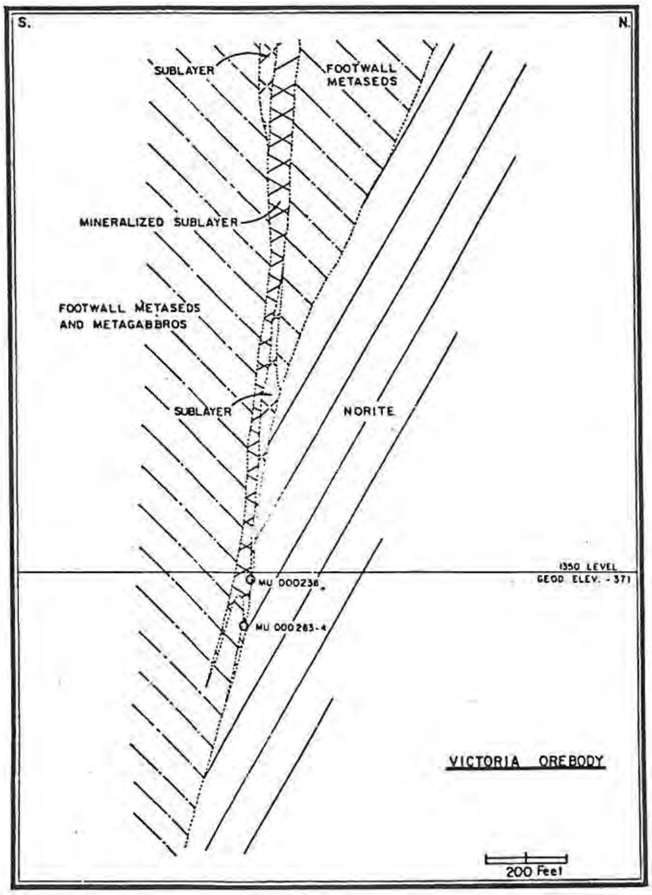


Fig. 3.32. Cross section, Victoria orebody (after Cabri and Laflamme, 1976).

The near-vertical dipping Copper-Cliff offset hosts three operating mines : the South mine, the North mine, and the Clarabelle open pit. The Murray mine is situated at the contact between offset and the marginal Sublayer. Ore bodies occurring within the dyke range in shape from thin sheets in which depth generally exceeds length, to steeply plunging or vertical pipes (Fig. 3.33). Little mineralization occurs in the country rock adjacent to the dyke.

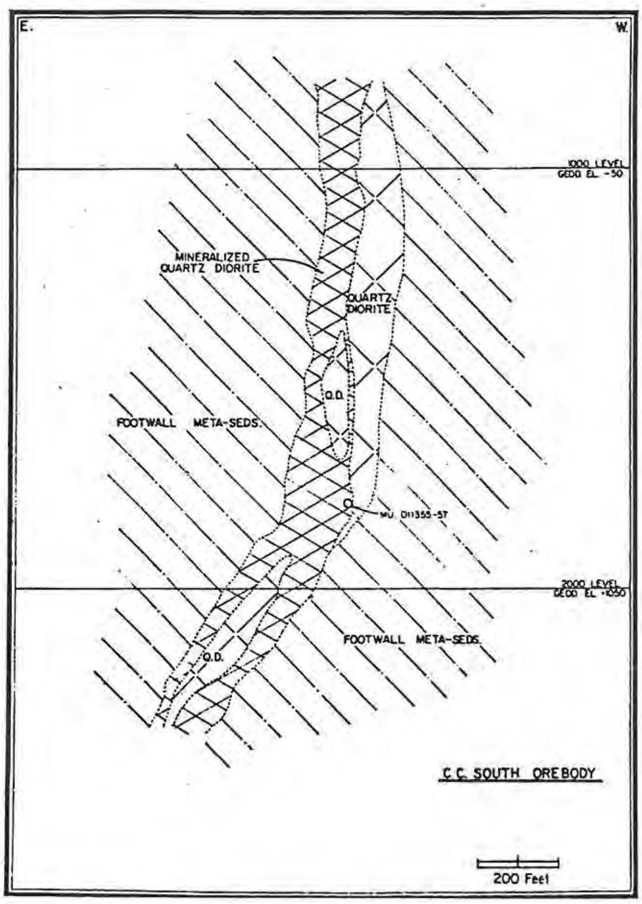


Fig. 3.33. Cross section, Copper Cliff South orebody (after Cabri and Laflamme, 1976).

The Frood-Strobie offset has been by far the most productive mining complex in the district. The inclusion-bearing quartz-diorite dyke has been preferentially emplaced into a 1,5 km wide zone of Sudbury breccia (Zurbrigg, 1957). Rhyolitic and andesitic volcanics, gabbroic sills, and interbedded sediments are also encountered in both the hangingwall and footwall. The offset strikes parallel to the southern margin of the basin and is now isolated, as erosion has removed the horizon at which continuity would have existed between the appendage and the marginal deposits (Boldt et al., 1967). The wedge-shaped body, which appears to occupy a dilantant tensional fracture, dips at 70°S to 75°S (Fig. 3.34). The body thins with depth, extending deepest in two lobes that correspond more or less to the Frood and Stobie mines (Fig. 3.35). The body is very irregular in plan (Fig. 3.36), and is huge by Sudbury standards measuring some 1430 m in length, 1170 m in depth, and 300 m across (Souch et al., 1969).

The size of the various offset deposits is very variable as indicated by the tonnes mined per day (.M.J. Staff, 1977): the South mine hoists 3500 tpd, the North mine 6700 tpd, Frood mine 6700 tpd and the Stobie, which is Inco's largest producer, 8000 tpd.

The ore in these deposits is characterized by disseminated sulphides and inclusions of foreign rock fragments, both of which vary in amount, size and character (Boldt et al., 1967). Some of the quartz diorite is essentially free of sulphides, elsewhere disseminated specks and spots occur. These range in character from sparse to numerous and may coalesce to form stringers and patches of ore.

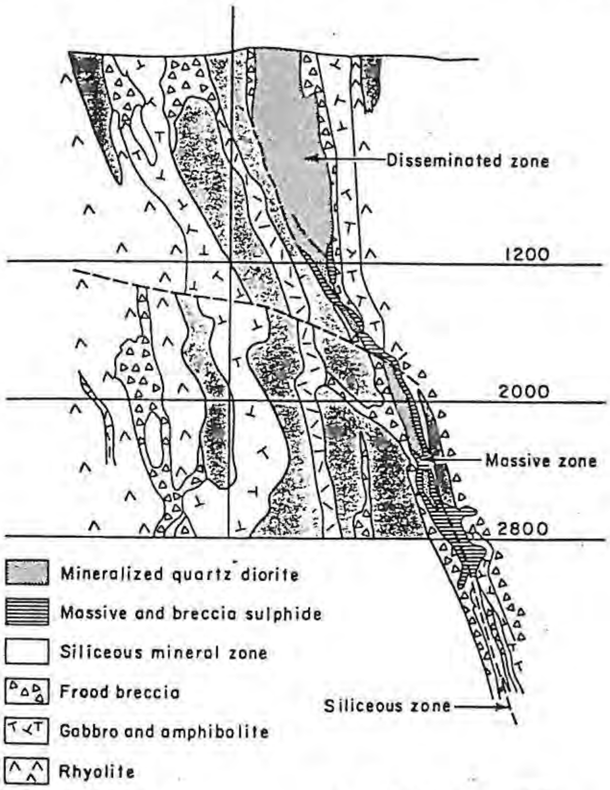


Fig. 3.34. Vertical cross section at Frood mine, showing major zones in orebody (after Zurbrigg, 1957).

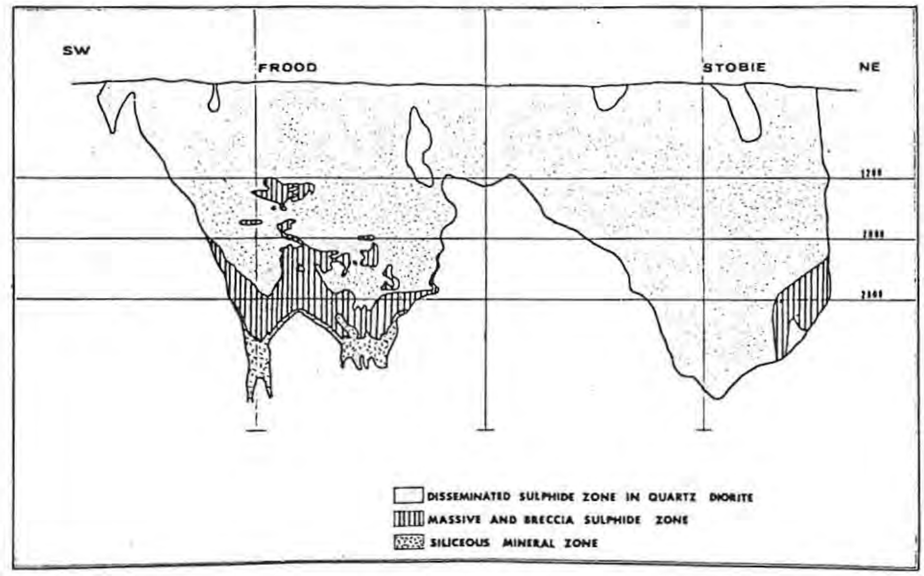


Fig. 3.35. Vertical longitudinal projection of mineralized quartz diorite and ore bodies, Frood-Strobie Offset (after Zurbrigg et al., 1957).

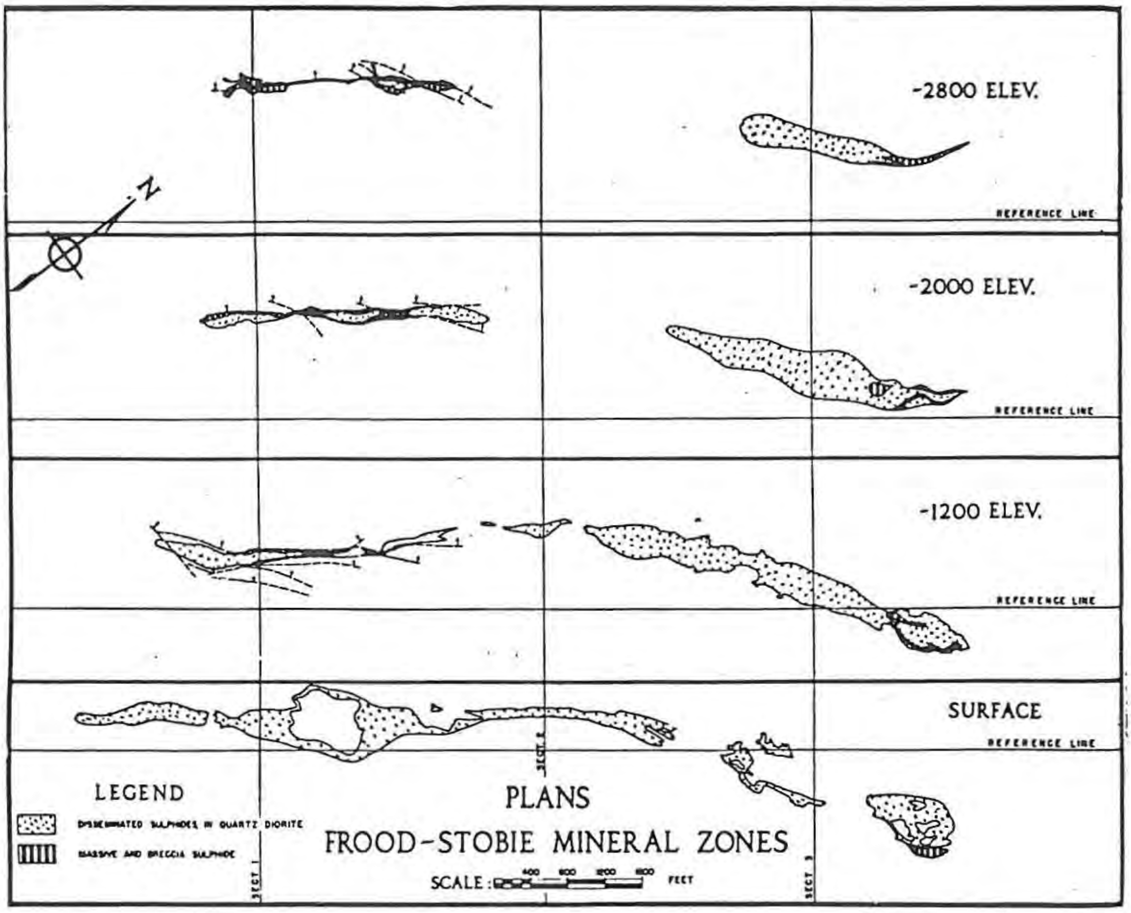


Fig. 3.36. Level plans showing the distribution of ore at Frood-Stobie (after Zurbigg, 1957).

In the Copper Cliff complex each ore body consists of a core of inclusion-bearing sulphide fringed by a zone of disseminated inclusion-bearing quartz diorite. The ore zones grade into weakly mineralized or barren, relatively inclusion-free quartz diorite, over distances of several centimetres to a few meters.

Four types of ore are recongized in the Frood-Stobie deposit (Hawley, 1965, Souch et al., 1969): disseminated sulphide, inclusion massive sulphide, contorted schist sulphide, and siliceous stringer ore (Fig. 3.37). Essentially, the ore body consists of a sulphide

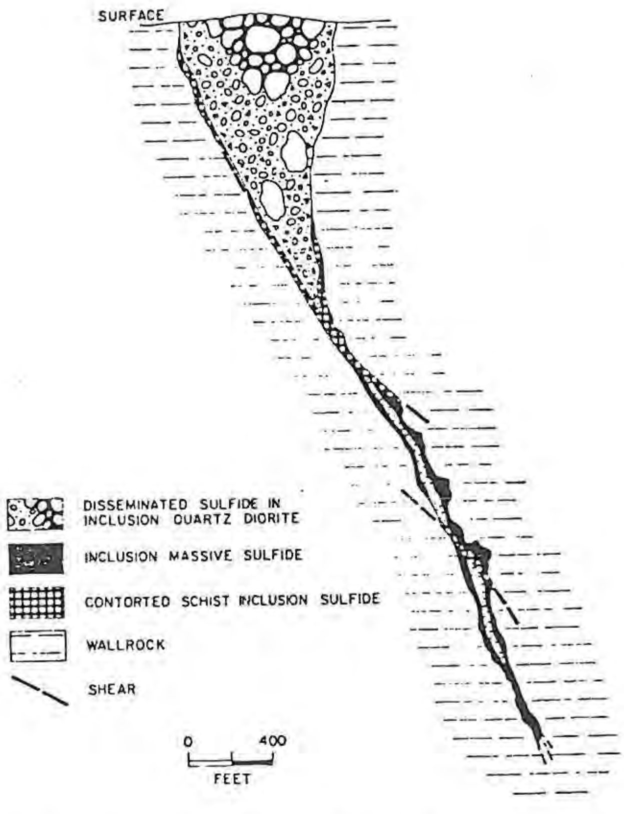


Fig. 3.37. Generalized section through the Frood ore body, looking southwest (after Souch et al., 1969).

spotted quartz diorite wedge rimmed by inclusion massive sulphide (Naldrett et al., 1980a). The disseminated sulphides occur as blebs in the quartz diorite and are sparsely distributed near the top but become increasingly abundant downward. In the lower portions of the mine the disseminated ore grades outward and downward, through an intermediate type of massive disseminated mineralization, into inclusion massive sulphide (Hawley, 1965). The greatest accumulations of massive ore are found near the bottom of the orebody and along the lower portions of the walls, especially in the deeper sections of the lobes (Boldt et al., 1967). The high grade massive ore has a number of forms (Hawley, 1965) : a breccia consisting of rock fragments in a matrix of sulphide, massive sulphide with few fragments, and sulphide stringers in the wallrock. The contorted schist inclusion sulphide is confined to local shears marginal to and cutting across the disseminated ore (Souch et al., 1969). This type of ore embraces narrow (2,5 cm to 12,5 cm) massive seams and stringers in fractures as well as fine disseminated sulphide in the matrix of the breccia. The siliceous stringer ore pentrates both the acid and mafic rocks and consists of two sections, separated by a relatively short gap, projecting downwards below the massive ore (Hawley, 1965).

The offset deposits in marked contrast to the marginal deposits may, as described above, have both low grade indistinct "assay-cutoff" footwall and hangingwall boundaries.

Compositionally, the overall mineralogy of the offset deposits is far more complex than that of the marginal deposits. This is well illustrated by the Frood-Stobie offset (Hawley, 1965). The disseminated ore zone consists of magnetite, ilmenite, pyrrhotite-containing flames of exsolved pentlandite, and chalcopyrite containing blades of cubanite. The sulphides are generally very coarse and often greater than 5 mm in diameter. The massive ores contain abundant segregations of pentlandite in pyrrhotite both along grain boundaries and along basal cleavage planes. Within the cubanite and chalcopyrite, small replacement remnants of pyrrhotite and exsolved pentlandite are found. Arsenides, particularly gersdorfsite, niccolite and maucherite are commonly found in the lower portions of the massive ores and are also a common constituent of the ores in the Worthington offset. The siliceous zone is poorer in pyrrhotite but still contains a fair amount of copper as chalcopyrite, cubanite, and bornite, and nickel as pentlandite and parkerite. The silicous zone is noted for a wide variety of minerals rich in Sn-Bi-As-Te-Pb-Zn-Au-Ag-P.G.E. Most of these rarer types are found intergrown with galena. The platinum group mineralogy of the offset deposits is strikingly similar to that of the South Range deposits.

Many of the offset deposits like the marginal deposits show a strong vertical compositional zonation. This is best illustrated by the Frood-Stobie deposit (Hawley, 1965). There is a gradual increase in chalcopyrite and a corresponding decrease in pyrrhotite downwards in the disseminated ores. Similarly, the copper content of the massive ore decreases downwards, being most noticeable at deeper levels where cubanite appears in increasing quantities. Samples from the disseminated sulphide zone have low Pb, Pd, and Au contents but high Ir contents relative to the sulphides from the massive and siliceous zones - a trend similar to that of many of the marginal deposits (Keayes and Crockett, 1970). As would be expected from the P.G.E. distribution, the arsenides are preferentially concentrated at or close to the margins of the massive ore and in stringers which penetrate the wallrock in areas where there are pronounced changes in dip.

A strong lateral zonation is also present in the siliceous ore of the Frood-Stobie deposit (Zurbrigg, 1957). The southern portions of the deposit are richer in galena, bornite, Sn, Pt, and palladium bismithides, while the northern portions are richer in arsenides and chalcopyrite-cubanite intergrowths.

Quartz and carbonate alteration is quite common in some of the offset deposits, especially Milnet and Worthington. Wall rock alteration in the quartz diorite is not conspicuous and crosscuts that have advanced to within one round of the orebody ordinarily yield no evidence of its presence, although a slight increase in the amount of quartz is often noticeable. In the vicinity of the sulphides the actinolite in the mafic rocks is often altered and garnet may be developed. Wall rock alteration is prominent in the siliceous zone at Frood and biotite, chlorite, talc, garnet and amphibole may be associated with the silicification (Hawley, 1965).

As in the marginal deposits, supergene alteration is not conspicuous although at Worthington supergene alteration consisting of violarite and millerite extends for some 50 m from the surface (Hawley, 1962).

3.6 Geological factors affecting the tonnage and grade of the deposits

The tonnage of any one deposit is critically dependent upon the size and shape of the footwall embayments. In the offset deposits, however, the tonnage is critically dependent on the size of the pre-existing dilational fracture. The tonnage also depends on the amount of inclusion massive that is present.

The nickel grade is of course strongly influenced by the ratio of pentlandite (33,15% - 32,82% Ni) to pyrrhotite (maximum 2,65% Ni). Millerite, which may be locally present, considerably upgrades the ore because of its high nickel (64,7%) Ni) content. The copper grades are influenced by the chalcopyrite: cubanite ratio as chalcopyrite contains between 34,26% and 33,68% Cu, while cubanite only contains 22,06% Cu. The grades of any particular metal within a particular portion of the orebody is a function of the metal zoning. Inclusions within the massive sulphides and brecciated blocks within the breccia ore types are deleterious to the overall ore grade.

3.7 Geological factors affecting the mining and beneficiation of the ore

A variety of mining methods are used, and have been used, in the extraction of ore from the Sublayer. However, the most widely used stoping method in the North Range and South Range deposits is mechanized cut and fill (C.M.J. Staff, 1977; C.M.J. Staff, 1978). This stoping method has a number of major advantages: the flexibility of the method allows one to readily change mining layouts to follow orebody irregularities because there is a minimum dependency on chute location, the method allows good grade control whereas any other bulk method would allow excessive dilution, development costs are relatively low, and with this method stope backs and walls are readily accessible for inspection, sampling, and support. Some mines, for example Creighton, are now mining low grade disseminated ore by blast hole open stoping (C.M.J. Staff, 1977). This large-scale mechanically intensive mining method is ideally suited to extract the more regularly distributed disseminated ore because of the competent nature of the wall rocks. Sublevel caving is the most common stoping method used in the offset deposits (C.M.J. Staff, 1977). This method is ideally suited to these orebodies because of their very steep dip, their narrow widths, and because the brecciated nature of the ore allows easy caving.

The lack of wall rock alteration greatly hampers development for hidden ore zones in complex orebodies.

The zoning of metal distribution and the great variety of ore classes hampers the grade control in the various mines. A number of methods are used to achieve a good grade control (Potapoff, 1967). As much ore as possible is located and all ore, regardless of its assumed thickness, is slashed off the walls. This sometimes uncovers additional unsuspected ore shoots that otherwise may have been left unmined. Also, where required, stope walls are tested for up to 8 m by drilling and the sludge assayed to ensure that any isolated ore zones nearby are located. The mining is drawn up for long periods in advance so that ores can be properly blended and excessive accumulations of low grade ore can be avoided. The maximum of ore and the minimum amount of waste are mined. All stopes are thoroughly cleaned of fines before being filled. Every working face is chip sampled, mapped and continually tested by drilling. Specific controls are applied during stoping, for example, rock bolting, grobbing in square sets etc.

The complex intergrowth of pentlandite and pyrrhotite results in a significant percentage of the extracted nickel being lost in beneficiation. For example, the plant at Strathcona has an average nickel recovery of 83,1% and an average copper recovery of 93,5% (C.M.J. Staff, 1978). The recovery of cobalt is largely dependent on the beneficiation characteristics of pentlandite as this is the major host for cobalt. With sufficient fine grinding and enhanced magnetic separation however, one is able to remove a significant proportion of the pentlandite intergrown with the pyrrhotite. This is supported by the studies of Hawley (1962) who reports that 1,61% Ni was present in the pyrrhotite at -65 mesh, while only 0,58% was retained at -325 + 400 mesh. During the early sixties Falconbridge established a regrind mill, which ground the ore to 85% -325 mesh, and a second stage magnetic circuit, enabling them to gain a 2% increase in nickel recovery.

The loss of nickel in pyrrhotite is offset by the fact that pyrrhotite, because of its high sulphur content, results in excessive SO_2 emissions during smelting. Companies are under governmental pressure to keep these harmful emissions to an absolute minimum. Magnetic methods do not allow an effective separation of pyrrhotite from the smelter feed as both magnetic (hexagonal) and non-magnetic (monoclinic) forms are present. Inco only recovers approximately half of the pyrrhotite from the smelter feed and has recently begun using froth floatation to effect the enhanced separation of pyrrhotite from ore concentrates (E.M.J. Staff, 1981). The arsenic-rich ores of the offset deposits are deleterious to the smelter feed as they also result in toxic emissions.

The recovery of P.G.E. is adversely affected by their small grain size; Cabri and Laflamme found that significant percentages are liberated as free grains only at -48 +100 mesh. Improved platinum recovery is a function of improved copper recovery as most of the P.G.E. occur as discrete grains in the chalcopyrite. A significant percentage of the P.G.E. is not recovered during beneficiation as they occur as inclusions in non-economic sulphides such as pyrrhotite, magnetite, and silicate.

The presence of hard silicate inclusions within many of the ore types may result in overgrinding of the sulphides at the mills and leads to excessive sliming during floatation.

Primary ore fines may contain supergene oxidation products where development is concentrated in heavily faulted ground. These products are detrimental to the floatation process and wet screening is used to segregate them from the ore.

3.8 Evaluation

A detailed account of the evaluation of the deposits owned by Falconbridge is given by Potapoff (1967). In general, all orebodies were explored and outlined by surface diamond drilling on a 66 m or 33 m square grid developed by normal underground methods. The steeper-dipping South Range deposits were outlined by drifts driven along the norite contact in the main breccia ore zone and by horizontal drillholes drilled at 16 m or 8 m spacings along the drifts. The flat-dipping North Range deposits were outlined by horizontal and inclined boreholes drilled from drifts either in the hangingwall or footwall of the ore zone and, in some cases by cross-cuts driven across the ore zone at 20 m or 33 m intervals. Both the horizontal and inclined holes were drilled on vertical sections spaced at intervals varying from 8 m to 16 m and 25 m.

The ore reserves are divided into two distinct classes: probable and proven. Probable reserves include those reserves outlined by surface exploration, while proven reserves include those calculated during underground development.

Two basic methods are used to estimate the ore reserves: the cross-sectional method and the polygonal method. The sectional method is the most widely used. The polygonal method is used on occasion and is best suited to continuous sheet-like orebodies that are flat-lying. The method has proved to be accurate enough in steeply dipping, discontinuous or lens-shaped bodies as long as the geology and structure are carefully taken into account when the polygonal area is measured.

The problem of using a proper specific gravity factor for the tonnage computation was solved by determining the specific gravity and nickel assay of a wide range of mineralized samples and plotting the results graphically for each ore deposit and, in some cases for different ore types in each deposit. All the probable reserves were diluted by the amount necessary to bring the ore widths up to a 2 m mining width. The proven reserves were diluted up to 25% for expected "slough" in addition to the dilution necessary for arriving at the 2 m minimum mining width.

Table 3.1 shows a comparison between the probable and proven ore reserves and the equivalent ore actually hoisted from the mine. The data shows that the accuracy of the probable reserves is dependent on the size and the complexity of the ore deposit. Falconbridge, the largest of all the deposits was the most accurately estimated, while Norduna, which contained low reserves was one of the least accurately estimated. The latter however, is structurally complex

Table 3.1. Comparison of probable and proven ore estimates with hoisted ore. Note that a negative sign indicates that the hoisted ore was lower in value than the original estimate, while a positive sign indicates that the hoisted ore was higher in value. Data from Potapoff (1967).

Mine	Probable Reserve			Proven Reserve		
	Tonnage	Ni grade	Cu grade	Tonnage	Ni grade	Cu grade
Falconbridge	-9	-17	+12	+21	-12	-8
East	+29	-21	-15	+7	-1,5	+5
Norduna	+46	-31	-40	+20	+2	-15
Mount Nickel	+32	-17	-1	+4	-8	-2
McKim	+54	-22	-20	+5	-16	-15
Hardy	+25	-10	-14	+12	-1	-1
Longvack	-2	+18	+18	-11	+20	+14

and a major portion of the discrepancy is attributable to the fact that the ore thickened against closely spaced faults which were not evident during drilling. The large tonnage discrepancy at McKim is the result of the orebody not being properly outlined by drilling. A good probable tonnage estimate can be obtained even in the most irregular of ore bodies, such as Longvack, if as was the case here, the boreholes are very closely spaced. Most of the probable grades mined were actually lower than the grades of the ore mined. This is a result of the underestimation of waste dilution which is a critical factor in the evaluation of these irregularly shaped bodies. This is particularly true of Norduna where the faulting has a considerable adverse effect on the amount of waste dilution.

The proven tonnage estimates at Mount Nickel and McKim and the good estimates at Hardy are attributable to a good dilution estimate, intense development work, closely spaced drillholes, negligible waste dilution, and to the fact that no additional ore was found during mining. The large discrepancies in tonnage estimates at East and Falconbridge are due to additional ore being found between development levels and partly to more waste dilution than had been predicted.

3.9 Origin of the ore

Although it is almost universally accepted that the Sudbury ores were formed via an immiscible sulphide melt derived from melting within the mantle, the origin of the Sudbury structure itself is still highly controversial. The account presented above is biased towards the idea that Sudbury was the site of a major volcanic centre, most authors now believe that Sudbury was the site of a meteorite impact (Rousell, 1981). It is not the purpose of this review to discuss the lines of evidence against and for either hypothesis. What is clear however, whether meteorite impact triggered mantle melting and the emplacement of the noritic and gabbroic rocks or whether the magma was generated at the site of the intersection of major intra-continental rift zones, the sulphides are associated with quartz-normative-rich mafic rocks. The quartz-rich nature of these rocks is most readily explainable as being the result of the assimilation of siliceous crustal material.

Irvine (1975) has pointed out that silicification of a mafic magma can induce saturation of sulphide. This point is illustrated in Fig. 3.38. The FeO-SiO_2 side of the diagram can be taken as

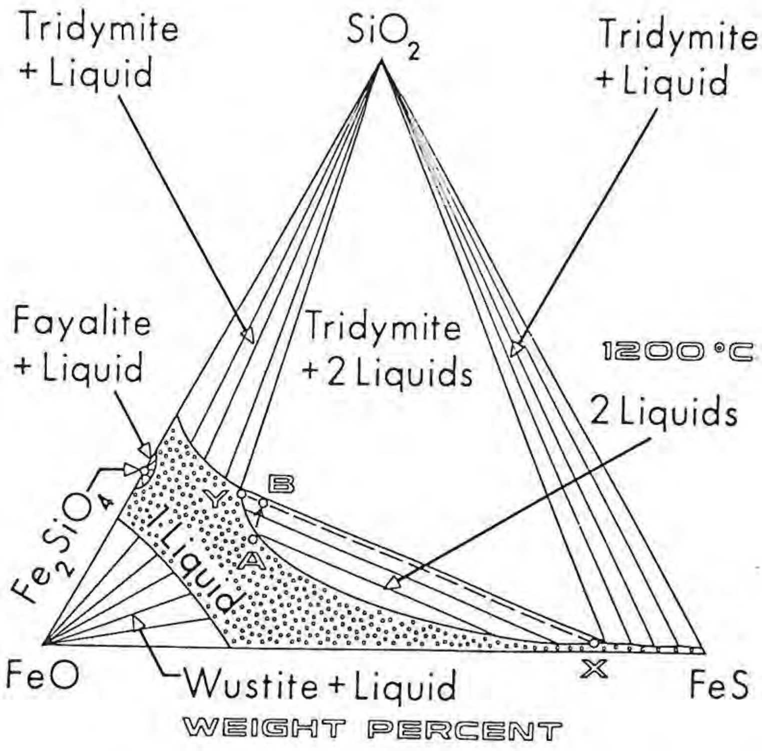


Fig. 3.38. 1200°C isotherm of the FeO-SiO_2-FeS system (drawn from the liquids diagram of MacLean, 1969) illustrating the effect of adding SiO_2 to a composition represented by point A (from Naldrett et al., 1981b).

equivalent to silicate melts and the FeS corner as the equivalent of sulphide magmas. A composition represented by point A lies in the field of a homogeneous FeO-SiO_2-FeS liquid. When enough SiO_2 is added to composition A to change it to B, the bulk composition moves out of the single-liquid field into a two phase field, in this case consisting of a silicate-rich liquid Y, rather poorer in sulphide than A, and a sulphide-rich liquid X. The sulphide melt was then emplaced into footwall irregularities and dilational fractures within the wall rocks.

The origin of the strong metal zoning in Ni, Cu, Co, and platinum is also somewhat controversial. Some authors (Hawley, 1965; Keayes and Crockett, 1970; and Chyi and Crockett, 1976) have suggested that the zoning is the direct consequence of the fractional crystallization of sulphide melt. In this model it is proposed that a copper-rich liquid into which Pt selectively partitioned, separated from the monosulphide solution at an early stage and was expelled into fractures and irregularities in the footwall. Naldrett and Kullerud (1967) and Hoffman et al. (1979) suggested that the zoning was a result of the redistribution by diffusion in response to a thermal gradient.

4. THE NORIL'SK - TALNAKH DEPOSITS

4.1 Regional geological setting

The Noril'sk-Talnakh camp is the world's second largest nickel-copper producer. The deposits also contain platinum group element values some 20 times higher than those of Sudbury district (Naldrett et al., 1980a). In the Soviet Union all data on production capacity, information on reserves and production plans of non-ferrous, precious and rare metal mines is regarded as classified information. Consequently, little information is obtainable in the West on the tonnage, grades and even the basic geology of the Noril'sk group of deposits. Known Soviet nickel reserves, half of which consist of low grade silicate ores, are estimated not to exceed 5 Mt of contained metal (Mining Annual Review, 1982). About 50% of the total reserves are contained in the sulphide ores of the Noril'sk area and in the Pechenga-Monchengork area of the Kola Peninsula. The reserves of the former greatly predominate however. The total Soviet platinum output in 1981 was estimated at 104 tonnes, the Noril'sk region supplying over 75% (Mining Annual Review, 1982).

The Noril'sk-Talnakh copper-nickel deposits are located at the extreme northwestern edge of the Siberian platform (Fig. 4.1). The platform has acted as a stable block since the end of the Palaeozoic (Naldrett et al., 1980b). The Siberian platform is separated from the Taymyr Peninsula and the Eastern European-Urals Block by the Khatanga Trough and Yenisei Trough respectively. The Taymyr Peninsula has behaved as a stable craton since the Palaeozoic, whilst the Eastern European-Urals Block has been a stable cratonic block since Middle Permian.

In the Noril'sk area the platformal cover is dominated by three stratigraphic sequences (Smirnov, 1977). The lower portions of the sedimentary fill comprise Lower Palaeozoic argillites. These are conformably overlain by Devonian evaporites and shallow carbonates of Lower Carboniferous age. The chemical sediments are unconformably overlain by Middle Carboniferous arenites and argillites which contain intercalated coal measures.

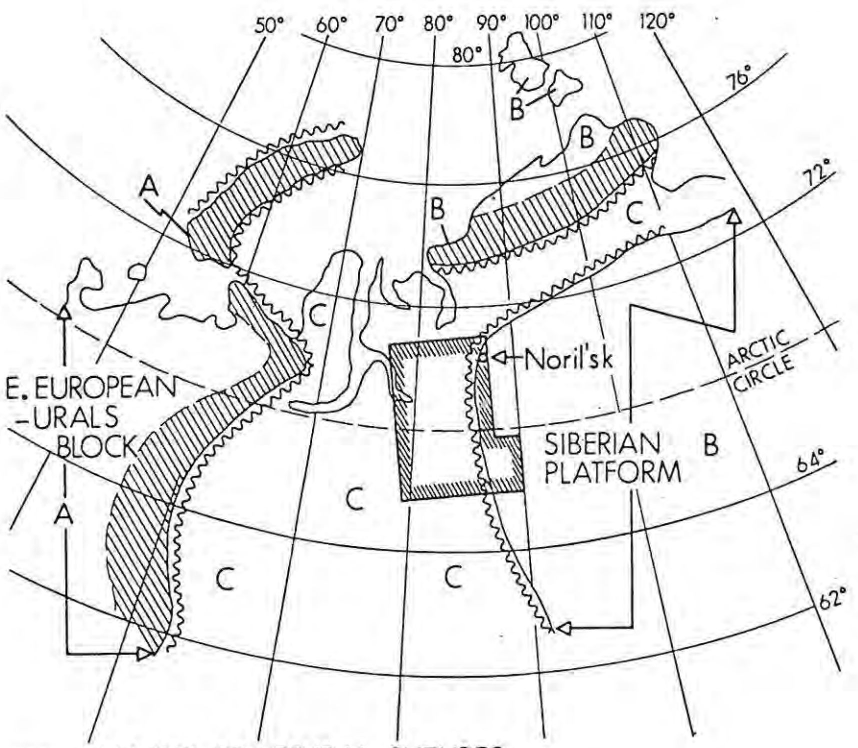


Fig. 4.2. The main tectonic features of northwestern Siberia (Maksimov and Rudkevich, 1974, from Naldrett et al., 1980b).

The sediments are overlain by an extremely large volume (approximately one million cubic kilometers) of Lake Permian and Triassic flood basalt and tuff - the Siberian traps. Sill-like tholeiitic intrusions, varying in composition from subalkaline dolerite to gabbro dolerite were emplaced contemporaneously with, and are feeders to, the extrusive volcanics (Naldrett et al., 1980b).

Four cycles of trap volcanism have been recognized (Smirnov, 1977). Permian igneous activity is marked by subalkaline titanaugite-bearing basalts and titanaugite porphyry sills. The initial stages of igneous activity in the Triassic are represented by andesitic basalts, pictritic basalts, and dolerite sills. Evidence for two later cycles of igneous activity in the Triassic are present. The former consists of basalts and the ore bearing gabbro-dolerites, and the latter consists of basalts and gabbro-dolerite dykes. The relationships between the sediments, extrusives, and intrusives in the Noril'sk region is shown in Fig. 4.2.

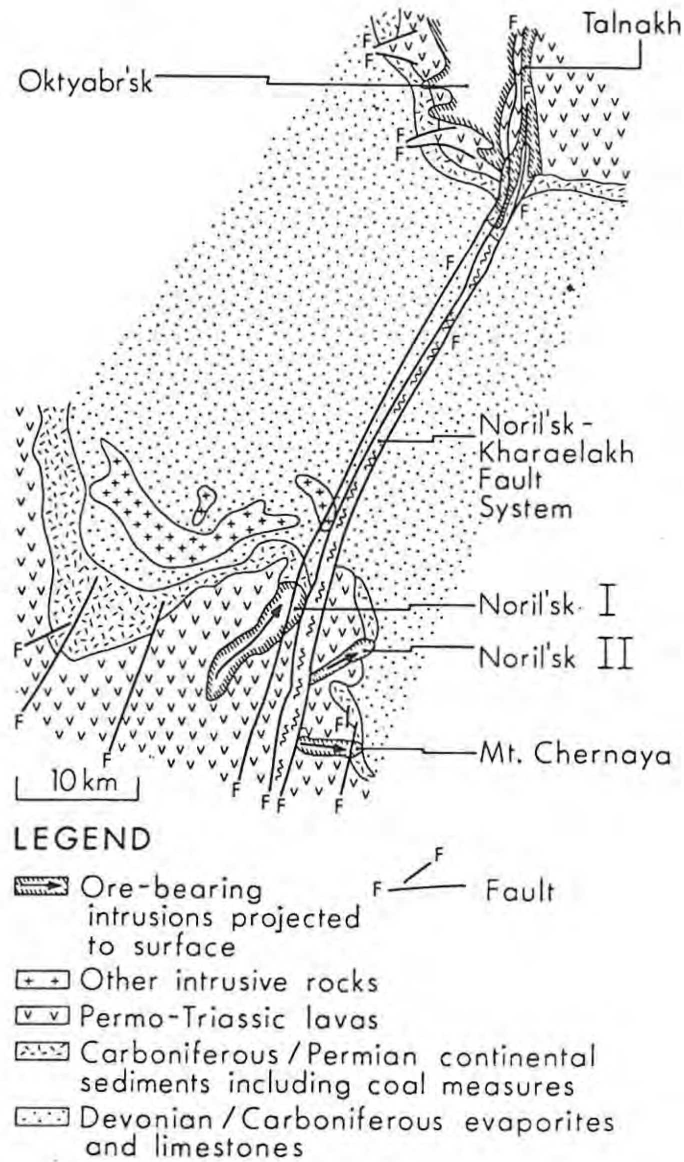


Fig. 4.2. Geology of the Noril'sk-Talnakh region (partially schematic) based on maps of Smirnov (1966) and Glazkovsky et al. (1977) (from Naldrett et al., 1980b).

Seven mineralized intrusions are known in the Noril'sk area. The sill-like intrusions may reach 12 km in length and 2 km in width (Naldrett et al., 1980b). The intrusions are distinctly layered and grade upwards from more mafic differentiates, the picritic dolerites, to more acid (hybrid rocks) (Smirnov, 1977). The mineralized Triassic intrusions represent volcanic conduits radiating outward and upward from intrusive centres and penetrating the sedimentary sequences.

The structure of the district is dominated by northeasterly trending block faults which were essentially coeval with the igneous activity (Naldrett et al., 1980b). Individual faults may be over 500 km in length and have throws in excess of 1000 m. The deposits exhibit a close spatial relationship to a prominent block fault, the Noril'sk-Kharaelakh fault (Fig. 4.2), which occurs within the Siberian platform and is parallel to the fault system forming the boundary between the platform and the Siberian Lowlands to the west. The fault zone is therefore regarded as a zone of crustal weakness up which the flood basalts and related intrusions were emplaced.

Geophysical measurements of the depth to the Mohorovicic discontinuity indicate that, despite the considerable thickness of Mesozoic and early Tertiary sediments in the area, the discontinuity is significantly shallower beneath the Yenisei and Khatanga troughs than beneath the adjacent platforms (Naldrett, 1980). The coincidence of marked subsidence with crustal attenuation is indicative of an intracontinental rift environment and a plate tectonic model involving continental rupturing is widely accepted as being the most plausible hypothesis to explain the tectonic evolution of north-west Siberia (Naldrett et al., 1980a; Naldrett et al., 1980b). Initially, downwarping resulting from crustal attenuation during Cambrian and Carboniferous times formed a large depository extending from the Noril'sk region southwards. A considerable thickness of sediments including evaporites, limestones, dolomites, marls, and continental sandstones were deposited into this basin. Uplift and peneplanation in Permian times was followed by renewed crustal attentuation in the Triassic resulting in considerable tensional faulting and the formation of a triple junction above a zone of mantle upwelling in the Noril'sk region. Considerable volumes of tholeiitic flood basalts and spatially associated kimberlites and carbonates were emplaced into the rift zone and the marginal zones of the adjacent Siberian platform.

The deposits of the Noril'sk area tend to be of lower grade than those in the Talnakh area, and in 1978 only two mines were active, the Medrizhii Ruchei (Bear Creek) open pit at the north-eastern end of the

Noril'sk I chonolith and the underground Zalpoyarni mine to the south-west (Naldrett, 1980). The deposits of Noril'sk II and Mt. Chernaya are subeconomic and are not being mined at present. The mines of the Talnakh area include Mayok, Komsomolski, Oktyabr'sk and Taimyr deposits.

4.2 The Noril'sk I deposit

The Noril'sk I deposit is located within a differentiated layered intrusion which has an areal extent of some 12 km (Smirnov, 1977). The thickness of the lensoid intrusion varies from 30 m to 350 m. The footwall rocks are composed of Permian sediments, trachydolerites, trachybasalts, and andesite-basalts (Fig. 4.3). The hangingwall lithologies are dominated by tholeiitic basalts.

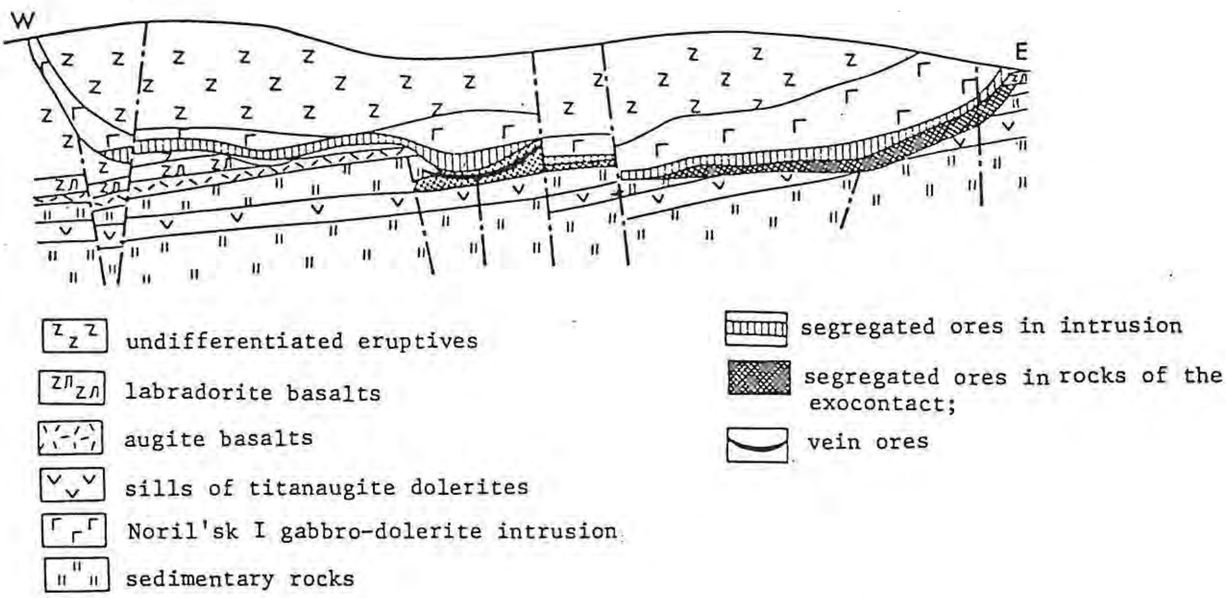


Fig. 4.3. Geological section through the Noril'sk I deposit. Scale not available (modified after A. Tarusev, 1968. From Smirnov, 1977).

The differentiated layered intrusion consists of taxitic and contact dolerites at the base, passing successively upwards into picritic gabbro- and norite-dolerites, olivine gabbros and norite-dolerites; gabbro-diorites, gabbro- and olivine-bearing dolerites; and eruptive breccias, hybrid rocks and taxitic dolerites (Smirnov, 1977).

The floor of the intrusion is highly irregular and contains troughs up to 150 m deep and 1000 m wide (Smirnov, 1977). The roof of the intrusion is more regular and irregularities are marked by gentle bulges.

The copper-nickel-platinoid mineralization is confined to the basal portions of the intrusion, that is, the picritic, taxitic, and contact dolerites, as well as the immediate footwall rocks. The main ore zone is a relatively persistent layer which invariably conforms to the irregular shape of the footwall (Fig. 4.3).

Four textural classes of ore are present and include (Smirnov, 1977): segregated ores and schlieren bodies within the intrusion, veins of massive sulphide along the floor of the intrusion and within the immediate country rocks, and veinlet-segregation ores in the footwall rocks (Fig. 4.3).

The segregated ores consist of disseminated sulphides (10% - 20% sulphide) in which layers of net-textured ore (20% - 50% sulphide) occur (Smirnov, 1977). The layers of net-textured ore are composed of sulphide replacing the matrix of the host rock. The layers may be stacked within the stratigraphy and as many as six consecutively overlying lenses have been encountered. The volume of sulphide increases towards the footwall and coarse nests and veinlets of sulphides may occur in the basal portions of the segregated ores. The segregated ores reach their greatest thickness (up to 20 m) directly above large troughs in the footwall (Fig. 4.3). The ores are predominantly composed of pentlandite, chalcopyrite and pyrrhotite. Minor minerals include cubanite, platinoids, and magnetite. The Ni:Cu ratio averages 1:1.5.

The schlieren bodies form large (200 m x 100 m x 20 m) lenses of massive sulphide along the floor of the intrusion (Smirnov, 1977). These ores however, are rare.

The sulphide-bearing veins are mainly developed in the northern half of the intrusion (Smirnov, 1977). The irregular-shaped veins may reach 6 m to 7 m in thickness. Massive ore, breccia ore, and banded ore may occur within the veins. The ores may be subdivided into a number of categories on the basis of their composition and include pyrrhotite rich, chalcopyrite-pyrrhotite rich, cubanite-pentlandite - chalcopyrite rich, cubanite-chalcopyrite rich, bornite-chalcocite rich, and millerite-pyrite rich varieties. The chalcopyrite rich ores are characterized by an anomalous platinum content. These compositional variants may exhibit a strong horizontal zonation (Fig. 4.4).

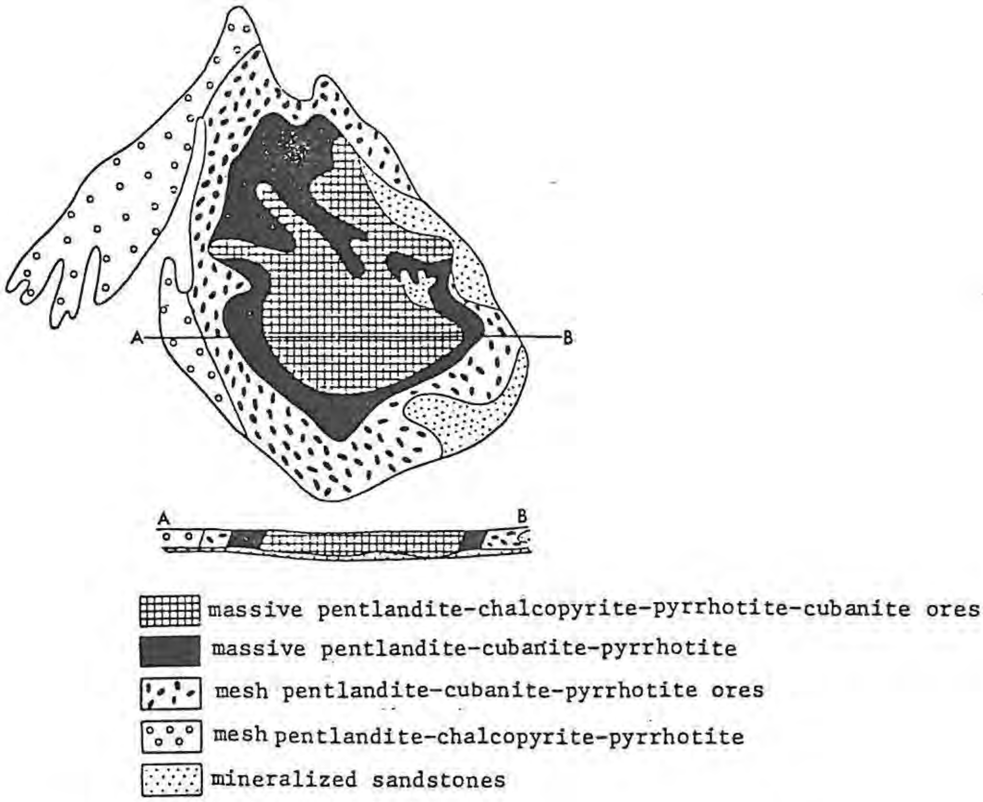


Fig. 4.4. Zonation in massive vein ore from Noril'sk I deposit. Scale not available (modified after V. Izoitko, 1968, from Smirnov, 1977).

The veinlet-segregation ores form a discontinuous aureole some 15 m wide in the footwall lithologies (Smirnov, 1977). Only the innermost 8 m however, are of economic grade. The texture and morphology of the various orebodies within the aureole is a direct function of host lithology. The sandstones and argillites are characterized by a fine to coarse dissemination of sulphide and by large lenticular bodies composed of sulphide veinlets. The amygdales in the basalts have been preferentially replaced by sulphide and where concentrated, they form discontinuous bands of high grade ore. In the titanaugite dolerites the sulphides occur as fine veinlets.

Alteration products within the various orebodies in the deposit include chlorite, biotite, albite, and microcline. The alteration however, is not very conspicuous.

The high grade massive veins and massive schlieren bodies contain an average of 2,16% Cu and 1,23% Ni together with 10,4 g/t of Pt (Buchanan, 1980). Lower grade disseminated and net-textured ores however, are the main focus of production. In these ores the average grade is 0,1% Cu, 0,3% Ni, and 3,8 g/t Pt (Buchanan, 1980). The mineralogy of the very fine-grained platinum minerals is exceedingly complex. Native platinum, ferroplatinum, compounds of Pd with tin, lead, copper, nickel and sulphur, and arsenides, antimonides, bismuthides, and tellurides of platinum and palladium are the most common. Considerable mining problems are experienced when development is concentrated in the incompetent footwall sediments.

The Noril'sk ores contain significantly higher concentrations of Cu, Pt, Pd, and Au than any other nickel sulphide deposits and are consequently, very good exploration targets. The high Cu contents are attributable to strong fractional crystallization of the host magmas in their subvolcanic chamber and to their derivation from pristine subcontinental mantle (Naldrett, 1981). The characteristic enrichment of the footwall stringers in Cu and P.G.E. is attributable to fractional crystallization from a monosulphide solution.

The shape, ore classification, mineralogy, and zonation of the Noril'sk ores is strikingly similar to the Sudbury deposits. Consequaently, similar factors are likely to affect the grade and tonnage distribution, as well as the beneficiation and evaluation of the ores.

4.3 Origin of the Noril'sk ores

The Noril'sk ores are strongly enriched in the S^{34} isotope (Kovalenker et al., 1975). Most investigators attribute the unusual enrichment to the contamination of the primordial magma by the assimilation of sulphate from the evaporites during ascent. Calculations have shown that the magma has assimilated 30% to 40% of crustal sulphur. The narrow variation in the S^{32}/S^{34} ratio is attributable to homogenization of the sulphur in an intermediate magma chamber located at depth below the Noril'sk-Kharayelakh fault zone. Assimilation of carbon from the coal measures reduced the sulphate ions and provided sulphide ions which resulted in the formation of immiscible iron sulphide droplets. These than acted as collectors for Ni, Cu, and P.G.E. (Naldrett et al., 1980a; Naldrett et al., 1980b).

5. NICKEL-COPPER SULPHIDE DEPOSITS HOSTED BY KOMATIITIC ROCKS

5.1 Deposits associated with Archaean komatiitic flows

Komatiitic-volcanic associated nickel-copper sulphide deposits are virtually restricted to the younger granite-greenstone belts, that is, those formed at approximately 2,7 By ago (Marston et al., 1981). This is particularly evident in the Rhodesian craton where deposits are restricted to the younger 'Upper greenstone sequence' (Wilson, 1979). This type of deposit is extremely rare in two of the oldest (3,3 to 3,5 By) greenstone belts in the Barberton Mountain Land and the Pilbara Block, although one small subeconomic deposit related to komatiitic volcanism occurs at Ruth Well in the latter (Nisbet and Chinner, 1981).

The komatiitic volcanic associated deposits are not uniformly distributed between Archaean greenstone belts but are concentrated in the Western Goldfields Province of the Yilgarn Block, western Australia (Fig. 5.1); the Zimbabwean greenstone belts (Fig. 5.2), and the Abibtibi belt in the Superior Province of the Canadian Shield (Fig. 5.3) (Groves and Hudson, 1981). Furthermore, the distribution within these well mineralized greenstone belts is not uniform and the deposits tend to occur to well defined clusters. The Australian deposits are very well documented, but both the Canadian and Zimbabwean deposits in contrast are very poorly documented. Consequently, this account will be biased towards the Australian deposits.

The mineralized Australian greenstone sequences have a strong linear aspect in plan view and are charactertized by a complex stratigraphy. They contrast markedly with the older unmineralized greenstone belts which consist of broader synformal keels situated between large equi-mensional granite domes and which are characterized by a fairly simple stratigraphy on a broad scale (Groves and Hudson, 1981). The major deposits all occur within, or adjacent to, a single structural province, the Kalgoorlie subprovince, within the Norseman-Wiluna greenstone belt (Groves and Hudson, 1981). This zone is bounded by highly deformed and strongly metamorphosed belts (Binns et al., 1976) and has been interpreted as being a prominent zone of rifting during greenstone development

(Archibald et al., 1978). The mineralized greenstone sequences in Canada and Zimbabwe are also thought to have originated in an environment dominated by rifting (Wilson, 1979; Groves and Hudson, 1981).

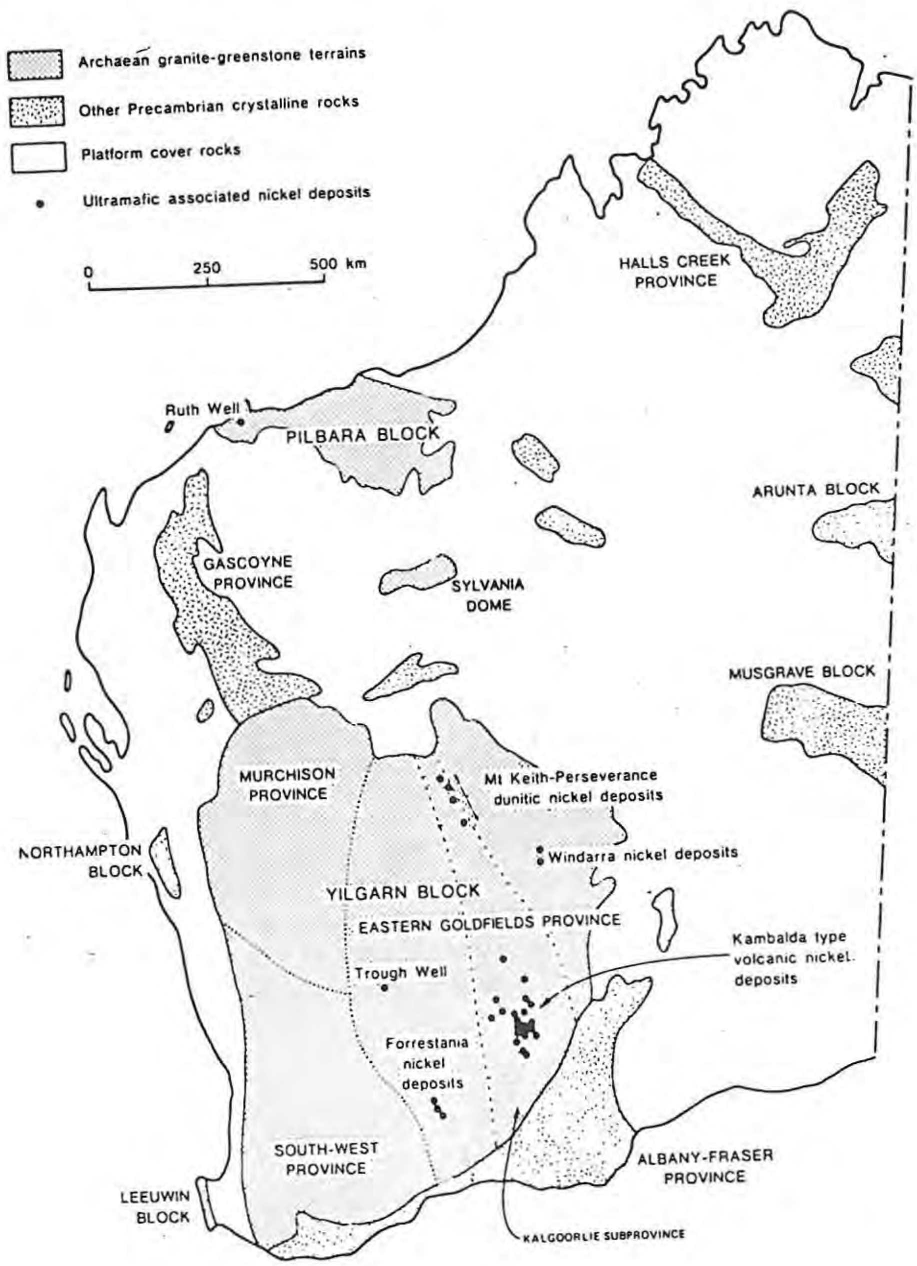


Fig. 5.1. Location of ultramafic-associated nickel deposits in Western Australia in relation to major tectonic units. The large majority of volcanic-associated Ni-Fe-Cu sulphide ores occur within the Kalgoorlie Subprovince of the Eastern Goldfields Province of the Yilgarn Block (after Groves and Hudson, 1981).

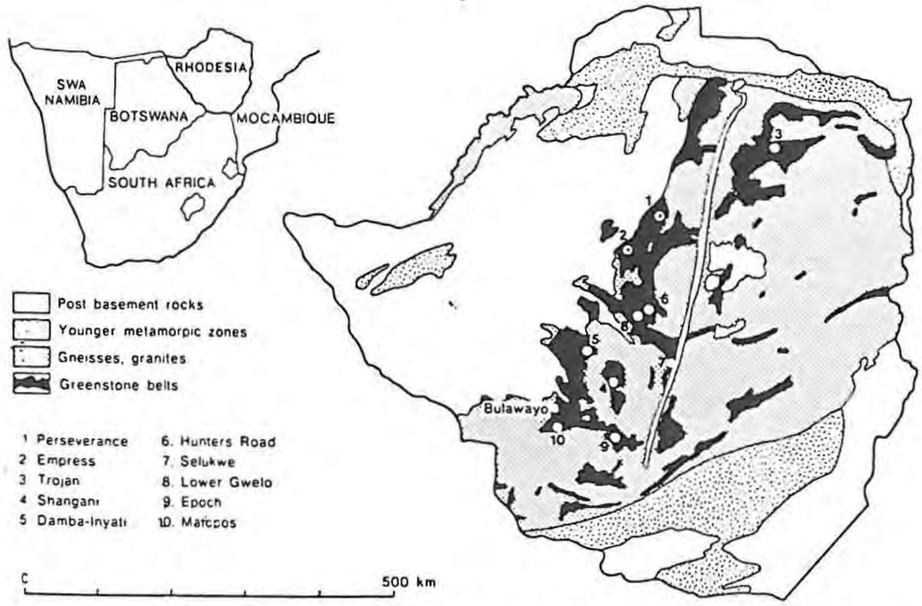


Fig. 5.2. Location of volcanic-associated Ni-Fe-Cu sulphide ores (localities 3-10) and other nickel sulphide ores in Rhodesia in relation to major tectonic units (after Williams, 1979). Localities 1 and 2 represent deposits in komatiitic (?) stratiform sills.

Fig. 5.3. Location of ultramafic-associated nickel deposits in Canada in relation to major structural provinces of the Canadian Shield (after Kilburn et al., 1969; from Groves and Hudson, 1981).

Major north-northwesterly and south-southeasterly trending strike faults appear to have exerted an important control on the distribution of the Australian deposits (Marston et al., 1981) and may have provided channelways along which sulphide charged magmas could have ascended from the mantle. O'Discoll (1981) has shown that the Kambalda group of deposits lie at the intersection of the above mentioned faults and a major west-northwesterly trending continental lineament, the Kalgoorlie-Shark Bay lineament. This narrow belt of disturbance also contains Western Australia's biggest goldfield, the Kalgoolie goldfield, it's biggest known volcanogenic massive sulphide deposit, Golden Grove, and it's only known molybdenum producer and is obviously a zone of major structural weakness along which metalliferous solutions from the underlying mantle could have ascended. The association of the Western Australian deposits with this major continental lineament is not purely coincidental as the Mt. Windarra group of deposits lie at the intersection of a smaller 150 km long lineament, which trends parallel to the Kalgoorlie-Shark Bay lineament and is thought to be subsidiary to it, and a prominent east-northeasterly trend outlined by a dolerite dyke swarm (O'Driscott, 1981).

The metamorphic grade in the Eastern Goldfields regions varies from prehnite-pumpellyite facies in areas characterized by low strain to high amphibolite-granulite facies transition in areas characterized by high strain rates (Binns et al., 1976). Metamorphism appears to have played a prominent role in the upgrading of the deposits as most economic deposits occur in zones of high strain accompanied by mid- to high-amphibolite facies metamorphism (Fig. 5.4) (Barrett et al., 1977). A notable exception is the Kambalda group which occurs in a low strain area characterized by lowermost amphibolite facies metamorphism. The lower tenor Rhodesian deposits are found in greenschist facies (Williams, 1979) with the exception of Perseverance where mid-amphibolite facies metamorphism occurs (Anderson et al., 1979). The smaller Canadian deposits occur in greenschist- or even subgreenschist-facies of metamorphism (Muir and Comba, 1979).

Stratigraphic studies of the greenstone belts between Kambalda and Norseman suggest the strong possibility that the volcanic komatiitic deposits in Western Australia are broadly stratigraphically controlled (Gemuts and Theron, 1975). Similarly, the Zimbabwean deposits show a

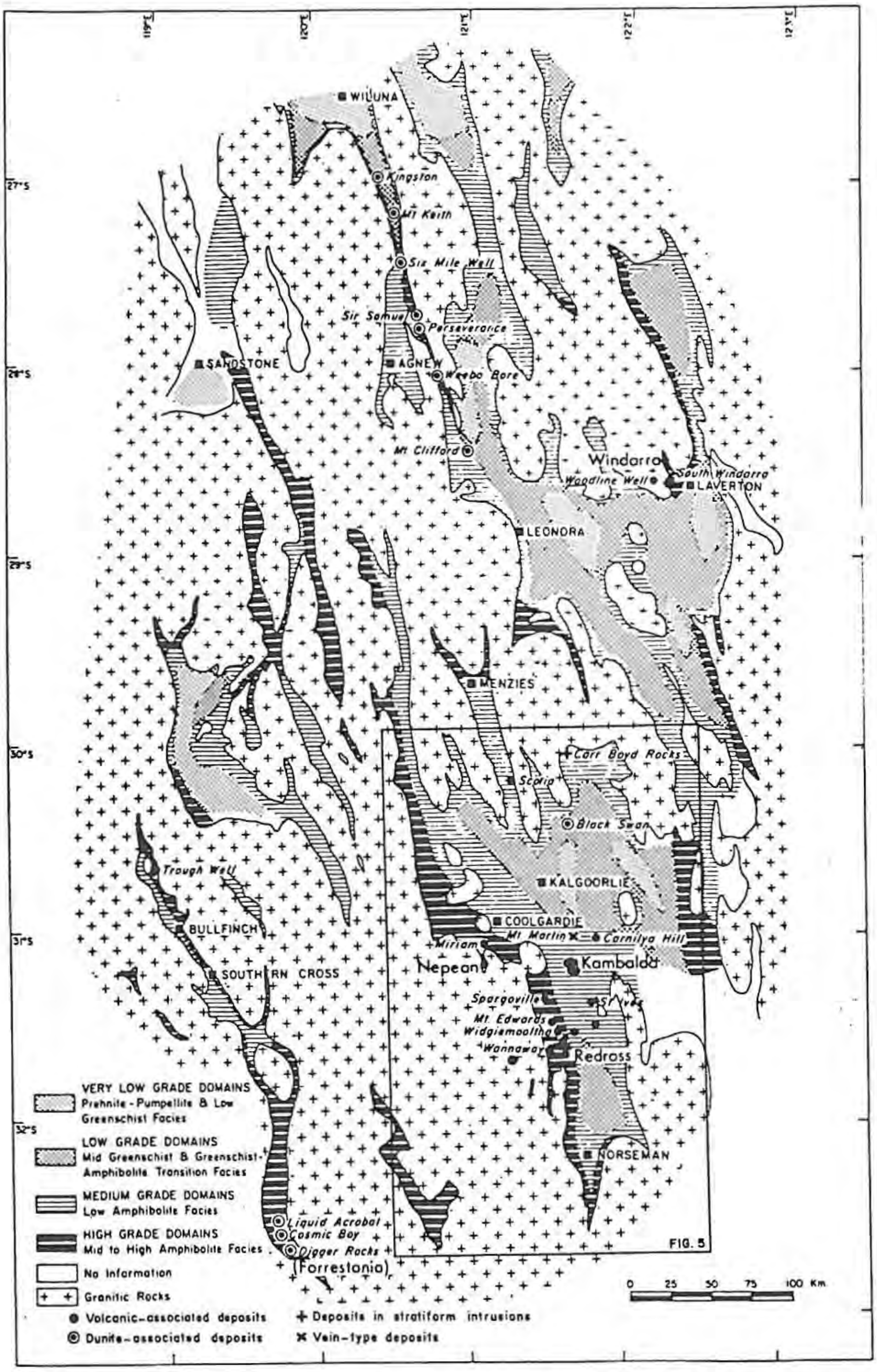


Fig. 5.4. Various classes of Ni-Fe-Cu sulphide deposits of the Eastern Goldfields Province of the Yilgarn Block, Western Australia, in relation to metamorphic grade (after Barrett et al., 1977).

strong stratigraphic control with the Damba, Shangani, Epoch, Selukwe, Hunters Road, Lower Gwelo, and Noel deposits, occurring at or near the same regional contact and appear to form an integral part of the very first period of komatiitic volcanism within the Bulawayan Group (or Upper Greenstone Group)(Wilson, 1979; Williams, 1979).

The komatiitic rocks found in granite-greenstone belts have been classified on the basis of their MgO content into (Naldrett, 1981): peridotitic komatiites (20-40% MgO), basaltic komatiites (12-20% MgO), magnesian basalt (10-12% MgO) and basalt (< 10% MgO). The sulphide ores occur towards, or at, the base of thick peridotitic komatiite units that in most cases represent the basal, less commonly the second or third, flows in thick (for example 600 to 700 m at Kambalda, Scotia and Windara) sequences of progressively thinner and less magnesian peridotitic and pyroxenitic flows.

The field characteristics of peridotitic komatiites has been described by Arndt et al (1979). The individual lava flows range from less than one metre to over 20 m and may extend laterally for hundreds of metres or terminate abruptly. They comprise two main types: spinifex-textured flows, which commonly host the mineralization, and massive flows. Only the former will be discussed below.

Spinifex textured flows have a chilled flow top (A_1 zone) containing a small proportion of solid olivine phenocrysts and a large proportion of skeletal hopper olivine grains in an augite-glass matrix (Fig. 5.5). The flow top exhibits polyhederal jointing. Underlying the chilled zone is a spinifex-textured lava in which two divisions may be recongized: an upper division (A_2) containing relatively small random orientated chain-like crystals (random spinifex) and a lower division (A_3) in which larger platy crystals are arranged in intersecting upward-pointing cones. The lower cumulate section (B zone) is characterized by the development of an uppermost portion (B_1) containing hopper grains orientated roughly parallel to the flow top. In some flows, a knobbly weathered zone (B_3) that contains irregular patches of pyroxene-glass material occurs half way through the olivine cumulate zone, dividing it into two similarly textured divisions (B_2 and B_4). Each of these consist of polyhederal or granular olivine in a sparse-augite glass matrix. A thin basal chill zone consisting of a aphanitic rock containing fine skeletal olivine grains may be present at the base of the flow. Thick (> 10 m) peridotitic komatiite units are characterized by poorly developed A zones, while thin units (< 10 m) are characterized by well developed A zones. Spinifex-textured lava flows are believed to form by extrusion of an ultramafic magma containing a small number of olivine phenocrysts. These settle towards the base of the flow, grow, and are joined by additional

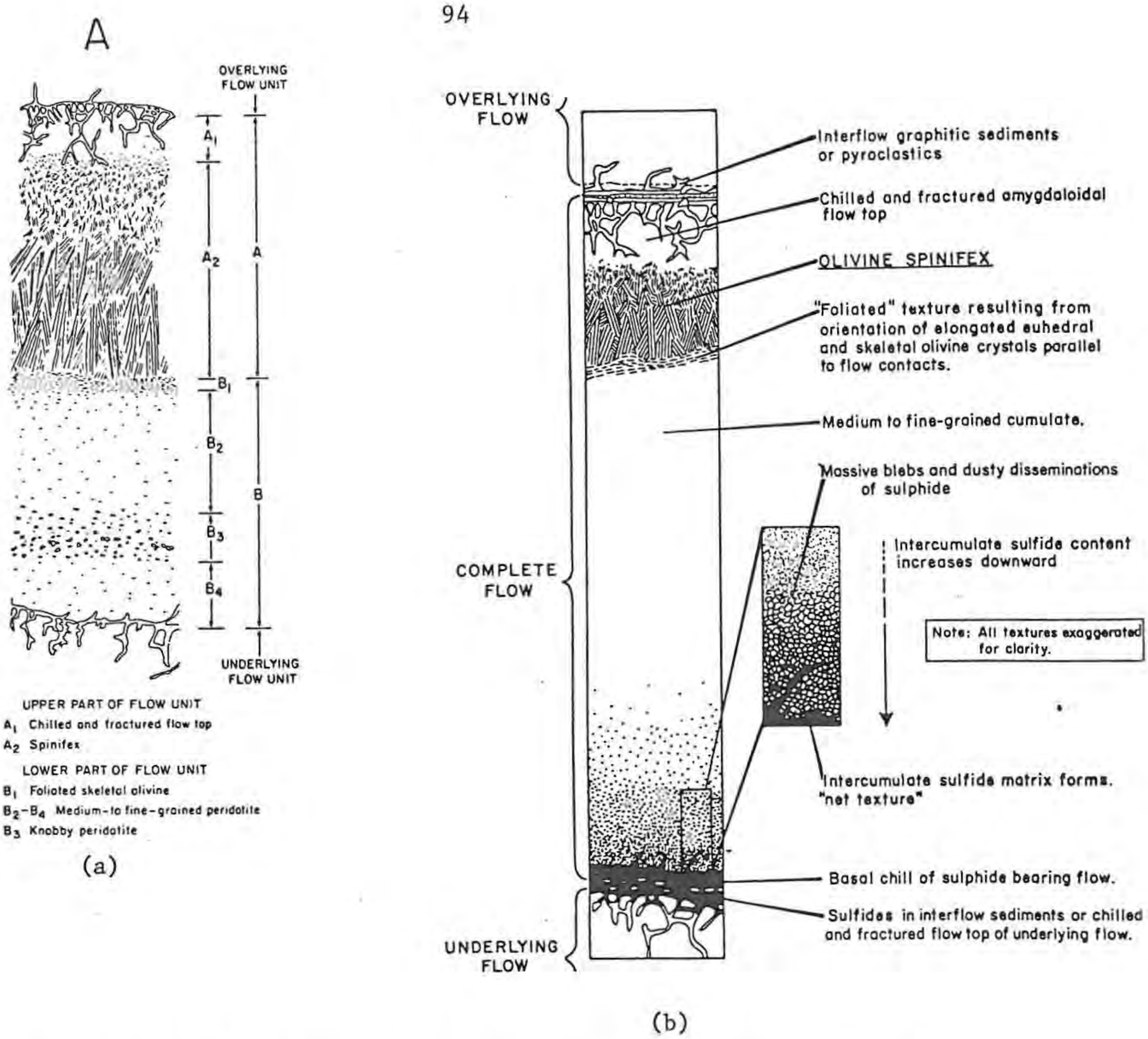


Fig. 5.5. (a) A typical section through a peridotitic komatiite flow and (b) a typical mineralized flow from the Dundonald deposit (modified after Arndt et al., 1979 and Muir and Cromba, 1979).

olivine grains that crystallize from the melt and consequently, result in the formation of a basal cumulate zone. In the phenocryst-free upper sections of lava flows, where temperature and perhaps concentration gradients are steep, the rapid growth of olivine crystals downward from the chilled flow top results in the formation of the characteristic spinifex texture.

The rocks are normally thoroughly altered (Groves and Hudson, 1981). In low grade to medium grade areas, serpentinites and talc-magnesite rocks are typical of the B zone lithologies with the proportion of chlorite, tremolite-actinolite and calcite-dolomite increasing in the upper zones. In the higher-grade environments olivine (some of which may be metamorphic), talc ± anthophyllite ± enstatite rocks constitute the cumulate zones, while tremolite-chlorite-olivine rocks represent the less magnesian lithologies. Retrogressive serpentinization may be widespread in high-grade metamorphic rocks. In talc-carbonate hosted ores, the high talc content of the ore zone may complicate the grinding circuit by rendering it physically difficult to comminute to the grain size required, and when floated, the talc shows a tendency to carry ultra-fine particles of sulphide that are embedded in it or attached to it. This results in poor recoveries and at the Trojan mine recoveries from 70% to 80% are only obtained because of the high talc content of the ore zone. The cut-off grade is adversely affected and caution must be exercised when evaluating deposits hosted by high altered serpentinized or talc-carbonated rocks (de Kock, 1964).

Systematic variation in the geochemistry of the units occurs as a result of fractional crystallization and the gravity settling of olivine. In an individual flow (Fig. 5.6) the B zone is characterized by higher MgO and Ni; lower CaO, Al_2O_3, Cr, and total Fe than the A zone or basal chill zone where present.

The ore-bearing basal ultramafic units show a number of characteristics which differentiate them from their unmineralized equivalents. They are typically the thickest in the sequence, ranging from 20 m (Nepean) to about 150 m (Juan shoot, Kambalda) thick. The thickness of the ultramafic units overlying the mineralization is typically 50 m (Table 5.1). The ore-bearing ultramafic tends to be lenticular along strike. At Windarra, the mineralized unit appears to be continuous for over 1500 m along strike and over 800 m downdip (Roberts, 1975). At the Lunnon shoot the mineralized ultramafic unit is at least 300 m wide and 1500 m long (Ross and Hopkins, 1975). Christie (1975) reports that the mineralized unit at Scotia is a lens up to 50 m thick extending for some 500 m along strike and more than 450 m downdip. The units are texturally similar to other units within the sequence, but are all characterized by a thick cumulate (B) zone and a thin telescoped upper (A) zone (Groves and Hudson, 1981). The mineralized flow units tend to display better developed textures and are more strongly differentiated (Gresham and Loftus Hills, 1981). Basal chill zones are commonly absent or poorly defined. The mineralized units are the most magnesian in the

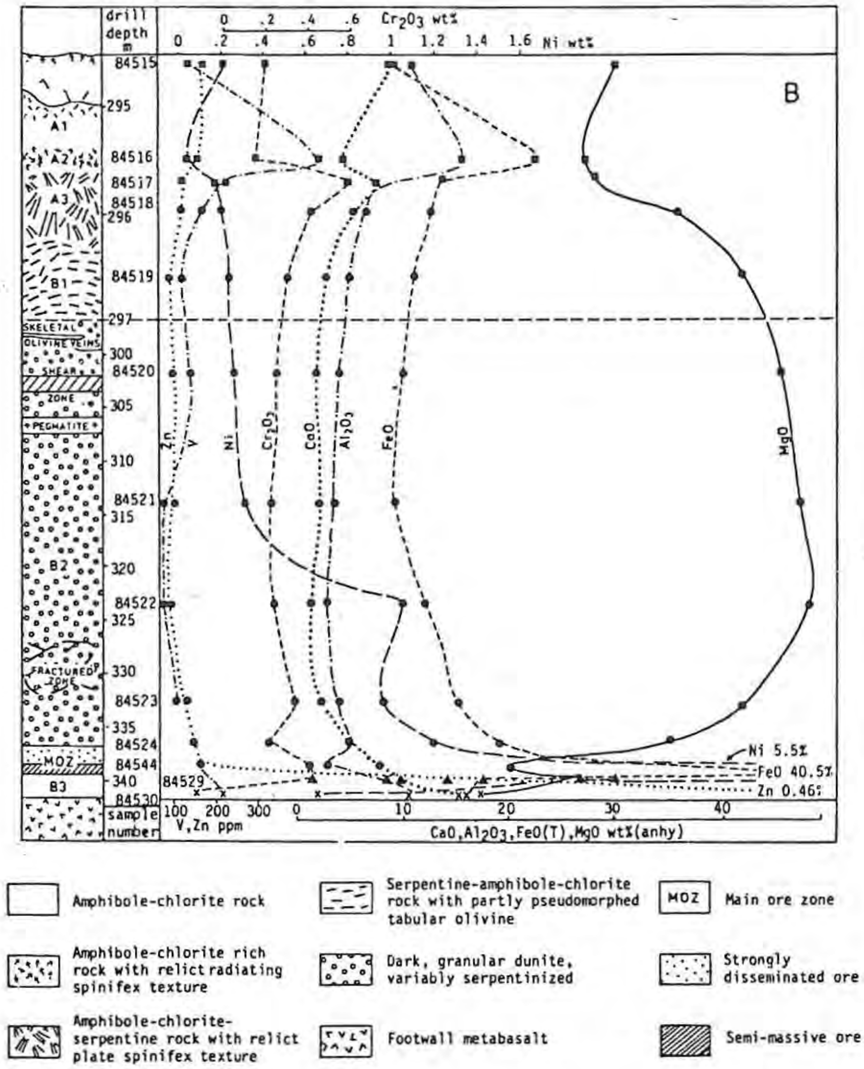


Fig. 5.6. Geochemical profile through a mineralized ultramafic sequence, Wannaway deposit, Widgiemooltha Dome (after McQueen, 1981a).

ultramafic sequence and characteristically contain 42% to 45% MgO (Table 5.1 and Fig. 5.7) and less than 5% combined Al_2O_3 and CaO (Groves and Hudson, 1981). They are characteristically depleted in TiO_2 and contain lower Fe_2O_3 than unmineralized equivalents (McQueen, 1981). The mineralized komatiites have flat heavy rare earth distribution patterns and are depleted in light rare earth elements (Marston et al., 1981). It should be noted here that komatiitic rocks from the Pilbara Block and the Barberton Mountain Land have higher CaO/Al_2O_3 ratios, lower Al_2O_3/TiO_2 ratios, and are depleted in Al and heavy rare earth elements (Marston et al., 1981). Zinc-rich chromites characterize most mineralized sequences and the upper zones are commonly enriched in chromite relative to the cumulate

Table 5.1. Thickness of mineralized ultramafic units and of associated basaltic formations for volcanic peridotite-associated deposits (after Marston et al., 1981).

Deposit group of deposit name	Mineralized ultramafic formation thickness (m)	Mineralized ultramafic unit maximum thickness (m)	Mean MgO (wt %) mineralized ultramafic unit	Hanging wall metabasalt thickness (m)	Footwall metabasalt thickness (m)
Kambalda	150-800	200	ca. 40	260-700	>1,500
St. Ives	100-200	100	ca. 40	greater than Kambalda	>500
Tramways	90-480	40	ca. 40	greater than St. Ives	>500
Republican-Bluebush	150-450	150		50-250	150-300
Widgiemooltha	upper: 60-120 lower: 100-600	50	ca. 40	250	100-450
Mt. Edwards*-Spargoville	100-650	60	ca. 40*	0-200	100-450 (?)
Nepean	40	40	35	50	40-70
Scotia	500-600	45	45 (?)	absent	150
Ringlock-East Scotia	30-270	180		50	200
Carnilya Hill	max. 630	30	34 (?)	absent	>350
Windarra	max. 300	25-130	ca. 40	200	absent

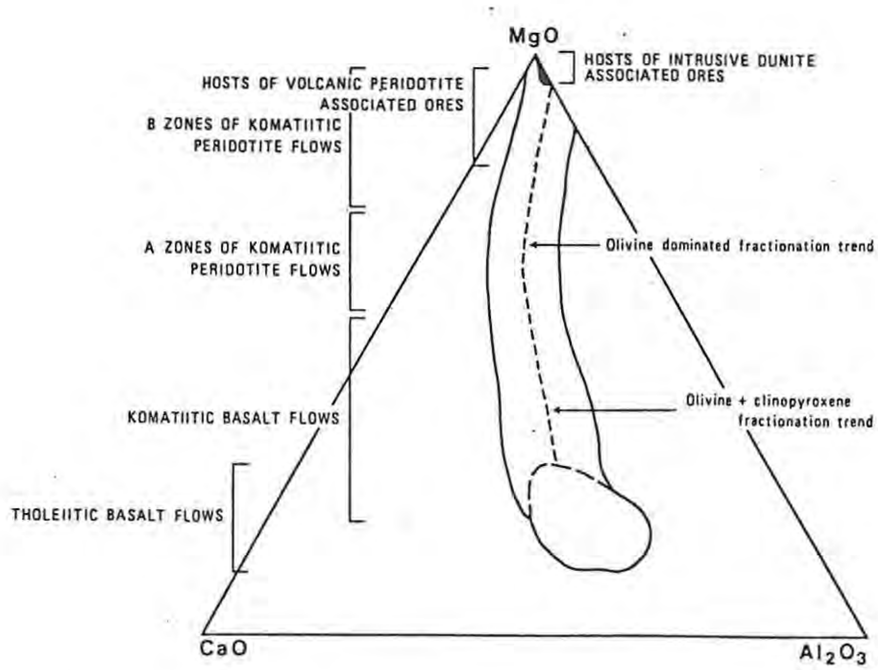


Fig. 5.7. MgO-CaO1Al_2O_3 plot of rocks associated with intrusive dunite and volcanic peridotite nickel deposits (modified after Groves and Hudson, 1981, from Marston et al., 1981).

zones (Groves et al., 1977). Olivines associated with the sulphide-bearing ultramafics tend to be more iron-rich (Barrett et al., 1976). The mineralized komatiitic flows appear to be sulphur-saturated (0,2 - 0,4 wt%S), whereas most overlying unmineralized units and the spinifex-textured zones of flows from unmineralized sequences appear to be sulphur-undersaturated (Groves and Hudson, 1981). The komatiites at Kambalda, whether from mineralized or unmineralized units, are significantly depleted in chalcophile elements relative to unmineralized sequences and to the theoretically modelled komatiite system (Lesher et al., 1981).

Sulphidic metasediments commonly occur as thin units from a few centimetres to ten meters thick at the interfaces between successive ultramafic and/or mafic flows. These sediments have been well documented in the Australian deposits but have received little attention in both the Canadian and Zimbabwean deposits. They are invariably broadly lenticular and correlate poorly laterally (Bavinton, 1981), but on rare occasions, especially where they form the contacts between major breaks in volcanic activity, for example the lower ultramafic-mafic contact, they are correlatable over distances of several kilometers (Groves and Hudson, 1981). Although metasediments occur in both the footwall and hangingwall basalts, they are invariably concentrated in the lower third of the ultramafic succession (Fig. 5.8) (Bavinton and Keays, 1978). Here the metasedimentary

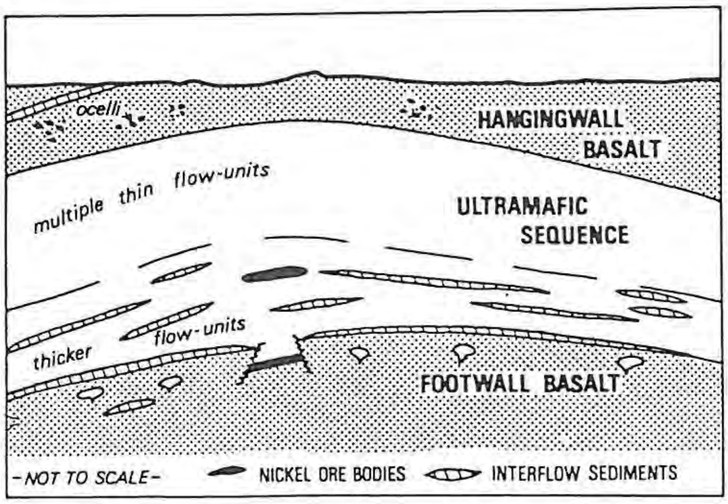


Fig. 5.8. Generalized geological cross-section through a Kambalda-type sequence showing the two basalts enclosing the central ultramafic sequence (after Bravinton and Keays, 1978).

horizons occur in two stratigraphic positions, as do the nickel ores, either at the base of the ultramafic pile on the contact with the footwall basalt (the contact situation), or within the ultramafic pile almost exclusively at the interflow boundaries (the 'internal' situation) (Bavinton and Keays, 1978). They are however, absent from the immediate ore environment and only on rare occasions do the nickel bodies touch or even overlie the sedimentary horizons (Groves et al., 1978). Commonly a sedimentary lens occurs lateral to, and at the same stratigraphic horizon as the ores (Bavinton and Keays, 1978). This rule does not appear to hold for the deposits in the Abitibi belt. Pyrrhotite-pyrite bearing graphitic cherty iron fromations are abundant as interlayers within the ore zone at the Hart mine, at the Langmuir deposit a significant amount of ore is hosted by the iron formation, and at the Dundonaldson deposit the highest grade ore is found along interflow horizons consisting of graphitic-bearing tuffaceous material (Muir and Comba, 1979; Green and Naldrett, 1981).

The interflow sediments from Western Australia may be subdivided into three gradational types (Bavinton and Keays, 1978). The most common is a cherty variety, next in abundance is a carbonaceous, and the least abundant is actinolite- or amphibole-rich variety. Felsic fragmental types are less common but are present at Scotia (Stolz and Nesbitt, 1981). Individual zones may be comprised of only one variety or may consist of an intercalation of the various types. They have high FeO, Al_2O_3, and TiO_2 contents, variable but generally high MgO, CaO, Na_2O, S, and C contents, but very low MnO and P_2O_5 contents over a wide range of SiO_2 values (Groves et al., 1978). In comparison with other lithologies, the interflow sediments are enriched in Au, both in absolute terms (average content 146 ppb) and relative to Pd and Ir (Bavinton and Keays, 1978). Bavinton (1981) interpreted the sediments to be a mixture of : local (mafic-ultramafic) and distant (felsic-granitic) detritus; S, Pb, Zn, Fe and Cu from ultramafic exhalations; S, Co, Ni, and Cu from local seafloor leaching of ultramafics; a biological carbonaceous component; and probably minor chemical silica.

In Western Australia, the footwall series is normally a thick, monotonous sequence (2000 m + at Kambalda) of pillowed, violaritic, and amygaloidal tholeiitic metabasalts, commonly terminated by, and comonly containing, thin interflow sulphidic metasedimentary units (Fig. 5.8 and Table 5.1) (Groves and Hudson, 1981). A major exception is Windarra, where the mineralized ultramafic unit overlies an interflow metasediment above a barren ultramafic unit. This is in turn underlain by a thick banded iron formation sequence (Roberts, 1975). Footwall rocks in Zimbabwe and the Abitibi belt differ markedly from those in Western Australia. They are normally felsic to intermediate volcanoclastic sequences containing agglomerates, tuffs, and volcanoclastic metasediments, and the mineralized ultramafic unit commonly appears to represent the start of a new cycle of mafic/ ultramafic volcanism (Williams, 1979; Green and Naldrett, 1981).

The ultramafic sequence hosting the ores is generally overlain by a mixed theoleittic and komatiitic basalt assemblage, which may reach 280 m to 380 m thick at Kambalda (Fig. 5.8 and Table 5.1) (Groves and Hudson, 1981). The metabasalts are texturally similar to the footwall metabasalts. Not all hangingwall metabasalts have komatiitic affinities and include the Widgiemooltha deposits, Mt. Edwards, and Spargoville (Marston et al., 1981).

A variety of metamorphically recrystallized felsic and mafic intrusives occur in the ore environments (Groves and Hudson, 1981). The most common intrusives are felsic in composition and include sodic rhyolite porphyries and dacites at Kambalda (Ross and Hopkins, 1975), feldspar porphyry at Windarra (Roberts, 1975), and pegmatites and apilites at Nepean (Sheppy and Rowe, 1975). Biotite-rich, amphibole-rich, and chlorite-rich alteration zones may be found for up to a metre from the contacts of the felsic dykes. Alteration as a result of the emplacement of the sulphide ores is lacking and hampers both surface exploration and underground development in geologically complex areas.

The komatiitic volcanic deposits appear to preferentially occupy near-vent positions within any ultramafic pile. Definite feeder vents and volcanic necks have been recognized underlying many of the Zimbabwean deposits and will be described later on. The southern end of the Langmuir No. 2 deposit is underlain by andesitic rocks, while the northern portion is underlain by ultramafics (Fig. 5.9). A discordant wedege of ore-bearing ultramafic rock connects the footwall ultramafic to the

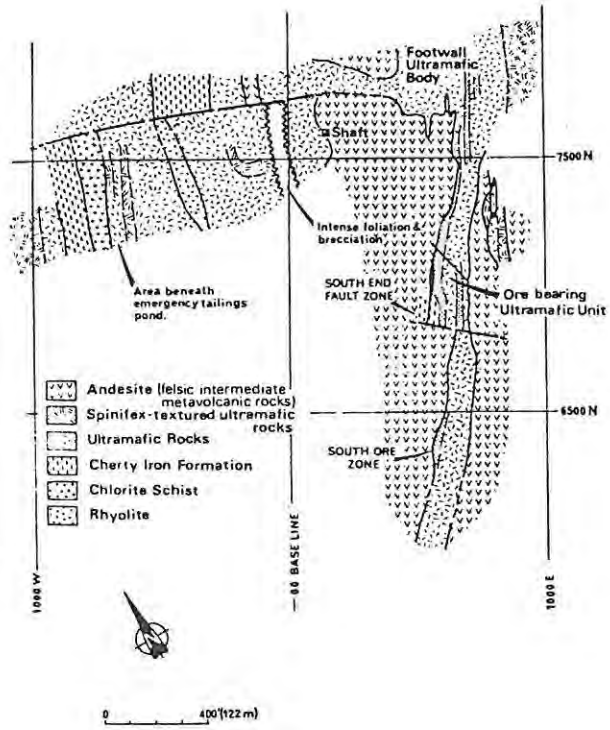


Fig. 5.9. Geologic plan of 320 m level at Langmuir No. 2 deposit showing the possible feeder zone to overlying main ore-bearing ultramafic unit (after Green and Naldrett, 1981).

ultramafic flows of the main ore zone and may represent a connecting feeder between a chamber, the footwall ultramafic body, and the overlying flows (Green and Naldrett, 1981). At Kambalda, the ordering and thickness of both members of the ultramafic formation differ in sections above and lateral to the mineralization. The systematic vertical ordering is replaced by a partly disordered internal stratigraphy in the mineralized areas and is consistent with the ponding of flows near volcanic vents and the restriction of more viscous, magnesian rich flows to sites near eruptive fissures (Gresham and Loftus-Hills, 1981). Ultramafic pyroclastics, sharply defined peridotitic komatiite flows, and a cross-cutting olivine peridotite unit dominate a locally thickened sequence overlying the ore zone at the Scotia deposit (Page and Schmulian, 1981). These features are indicative of a proximal 'vent-type' environment and are further substantiated by the absence of interflow sediments, which are only found higher up in the stratigraphy and along the flanks of the pile.

The orebodies in the Yilgarn Block are typically clustered around granitoid-cored domes which show a strong north-south elongation (Lambert and Groves, 1981) (Fig. 5.10). The domes may represent the sub-volcanic expression of felsic volcanics rather than a post-intrusive granitoid (Archibald et al., 1978). The ores around these domes exhibit a marked structural control, being essentially tabular bodies that have their greatest elongation parallel to the penetrative linear fabrics in the enclosing footwall rocks and/or to the trend and plunge of both regional and parasitic folds (Barrett et al., 1977) (Fig. 5.11). Many of the deposits in the Abitibi belt exhibit a preferential clustering around felsic or mafic volcanic-cored domal structures (Green and Naldrett, 1981). This relationship is not as clear on the Rhodesian Craton, but some deposits, for example Hunters Road, do occur on the flanks of granite batholiths (Moubray et al., 1979).

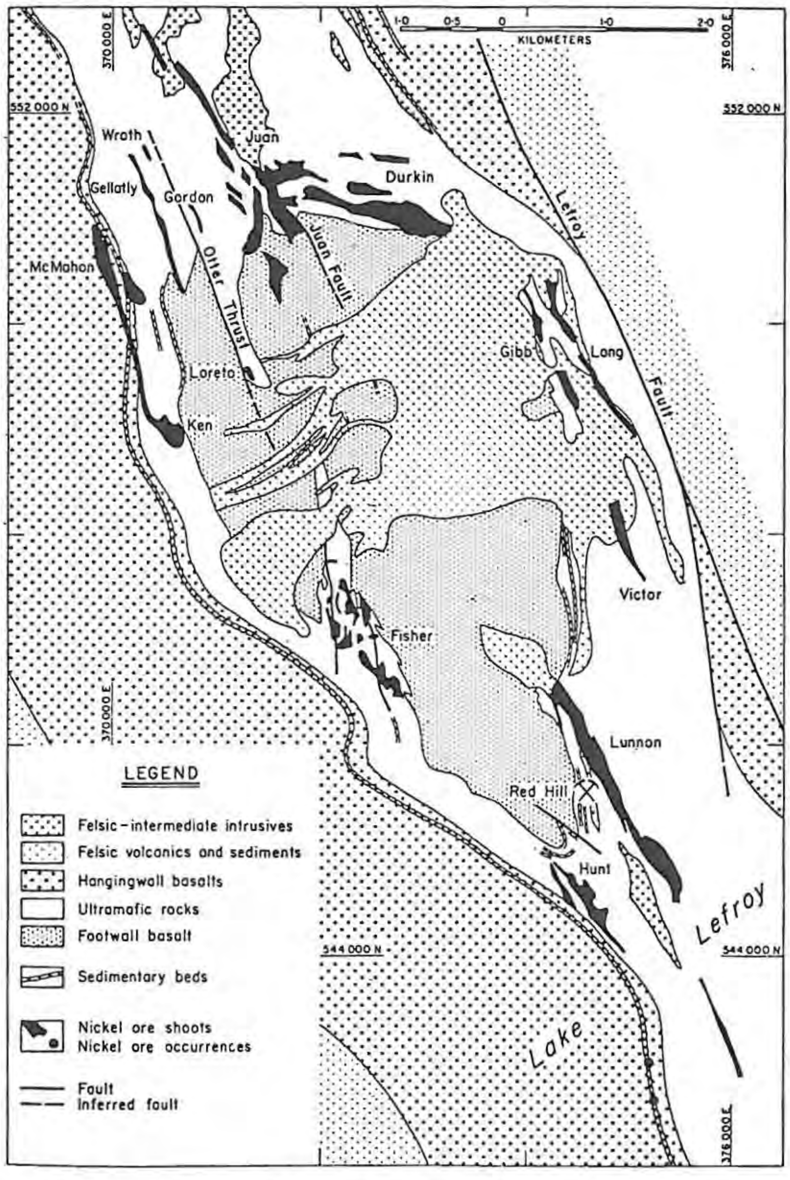


Fig. 5.10. Geologic plan of the Kambalda dome showing the nickel shoots in plan projection, and the position of the Red Hill gold mine (after Gresham and Loftus Hills, 1981).

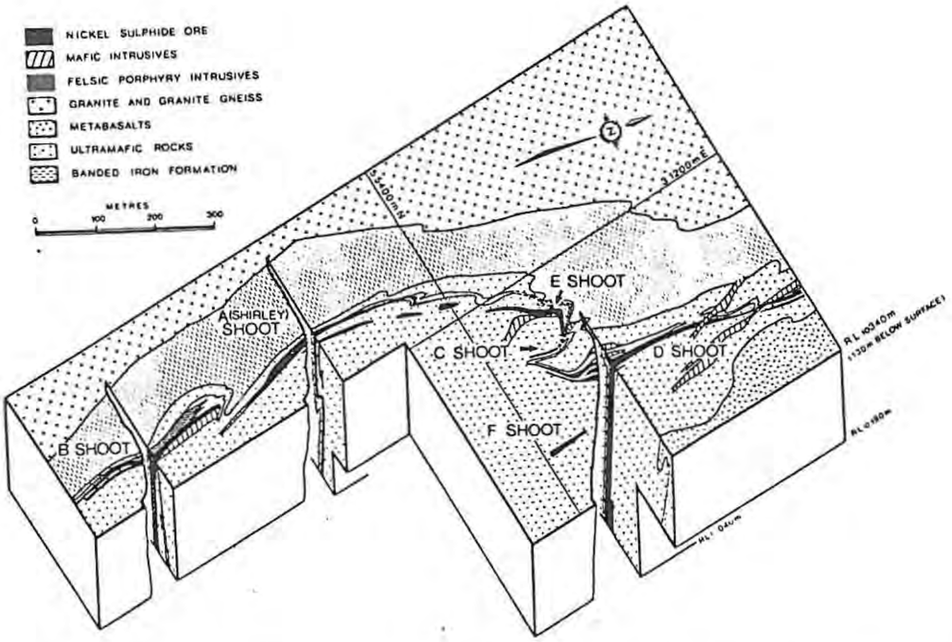


Fig. 5.11. Isometric projection Mount Windarra deposit (after Roberts, 1975).

The deposits vary widely in size and some consist essentially of one shoot (Nepean, Scotia, Wannaway, and Redross) while others consist of several shoots (Kambalda and Windarra) (Tables 5.2 and 5.3). Ore tonnages range from 500 000 to 5,0 million metric tonnes (Marston et al., 1981). Although the grade may exceed 5% Ni, most shoots contain from 1,5% to 3,5% Ni (Marston et al., 1981). The Zimbabwean deposits tend to be much larger and of lower grade, for example, Shangani contains 20 million tons at 0,9% Ni. The Canadian deposits show very variable nickel tenors and most of the deposits seem to be small, with the exception of Texmont which contains 3,8 million tonnes (Naldrett and Gasparinni, 1971).

Most ore bodies are confined to trough-like embayments in the footwall rocks and their size, continuity and regularity are directly dependent on the size and shape of this embayment (Fig. 5.12). In the Kambalda area the ultramafic-basalt contact is a planar undisturbed sediment covered surface in unmineralized areas (Gresham and Loftus-Hill, 1981). The embayments may be hundreds of metres long and up to tens of metres wide. Their margins are often the locus of strike-slip and moderate to high angle reverse or normal dip-slip faults. The shoots occupying the troughs are known as contact shoots and are

Table 5.2. Published premining resources, Ni/Cu ratios and metamorphic grades of some nickel sulphide deposits in Western Australia (after Lambert and Groves, 1981).

Deposit name	Million metric tons ore	% Ni	Ni/Cu	Metamorphic grade
Carnilya Hill	0.12	2.88	8	low amphibolite
Dordie Rocks North	1.0	1.23	12	mid-amphibolite
*East Scotia	0.09	2.0		low amphibolite
Kambalda-St. Ives	31.0	3.60	13	greenschist-amphibolite
Mt. Edwards 26N	1.70	2.49	11	mid-amphibolite
Nepean	0.92	3.5	16	upper amphibolite
Redross	1.0	3.43	14	mid-upper amphibolite
Scotia	0.82	2.14	16	low amphibolite
Spargoville 1	0.36	2.35		mid-amphibolite
Spargoville 2	0.12	2.32		mid-amphibolite
Spargoville 3	0.63	2.46	11	mid-amphibolite
Wannaway	4.5	1.22	14	mid-upper amphibolite
Widgie 3	1.0	1.23	10	mid-amphibolite
Windarra (Mt.)	7.2	1.94	11	mid-amphibolite
Windarra (South)	4.5	1.22	21	mid-amphibolite

Table 5.3. Combined production plus reserve figures for some Zimbabwean and Canadian deposits (after Groves and Hudson, 1981).

	Million tonnes (approx.)	Grade % Ni (approx.)
Canada		
Texmont	3.5	1.0
Langmuir (2)	1.5	1.8
McWatters	0.7	1.0
Sothman	0.6	1.0
Marbridge (3)	0.5	2.3
Alexo	0.1	4.1
Rhodesia		
Shangani (2)	20	0.9
Damba-Silwane (2)	7	0.9
Epoch	2.5	0.8

The figures are not intended to be authentic statements, but estimates based on most recent figures published by the respective companies. Due to government control, figures are unobtainable for most Rhodesian deposits. Deposits are listed in order of decreasing tonnage.

typically ribbon-like in form and highly irregular along strike (Figs. 5.13 and 5.12). Dimensions of the shoots varies from about 100 m in length and 50 m in width to 700 m in length and 150 m in width, with thickness of 1 m to 5 m in higher grade (> 2% Ni) shoots and 5 m to 20 m in lower grade (1-2% Ni) shoots (Marston et al., 1981). Some contact ore shoots are accompanied by one or more horizons of

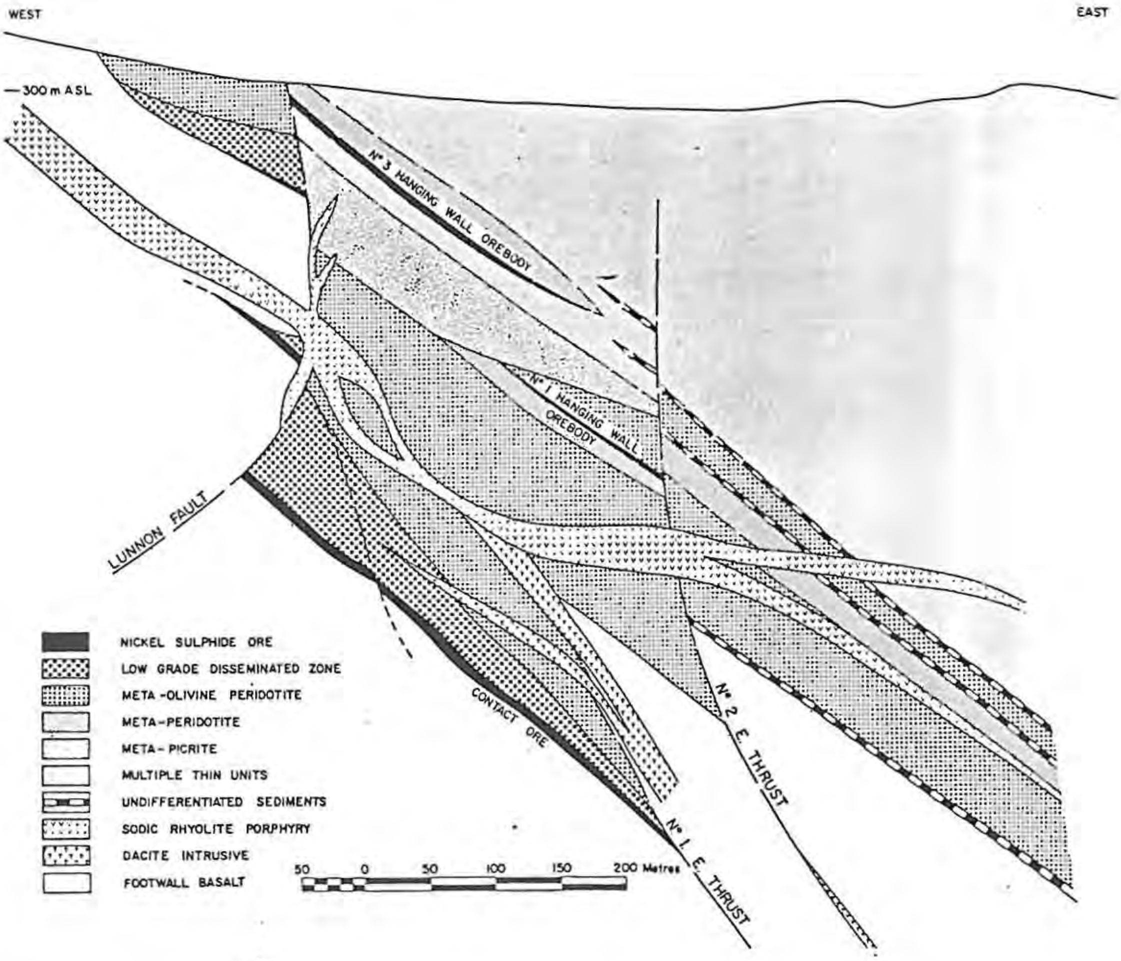


Fig. 5.12. Generalized east-west section of the Lunnon Shoot environment at 546 279N (after Ross and Hopkins, 1975)

hangingwall mineralization which occur within, and at the base of stratigraphically higher ultramafic units, or within the upper section of the basal ultramafic unit (Woodall and Travis, 1969). Some shoots are also accompanied by offset mineralization, which comprises ore located on fractures and faults within both the footwall and ultramafic host sequence (Woodall and Travis, 1969). Where contact, hangingwall and offset mineralization are present in any one environment, the contact ore usually contains the most sulphide. At Kambalda contact ore occurs for some 83% of the metal reserve, hangingwall ore 14%, and offset ore 3% (Gresham and Loftus Hills, 1981). Thus, the tonnage and grade of any one deposit is critically dependent on the amount of contact ore developed.

The alignment of these embayments parallel to the regional structure and the presence of bounding faults, all seem to indicate

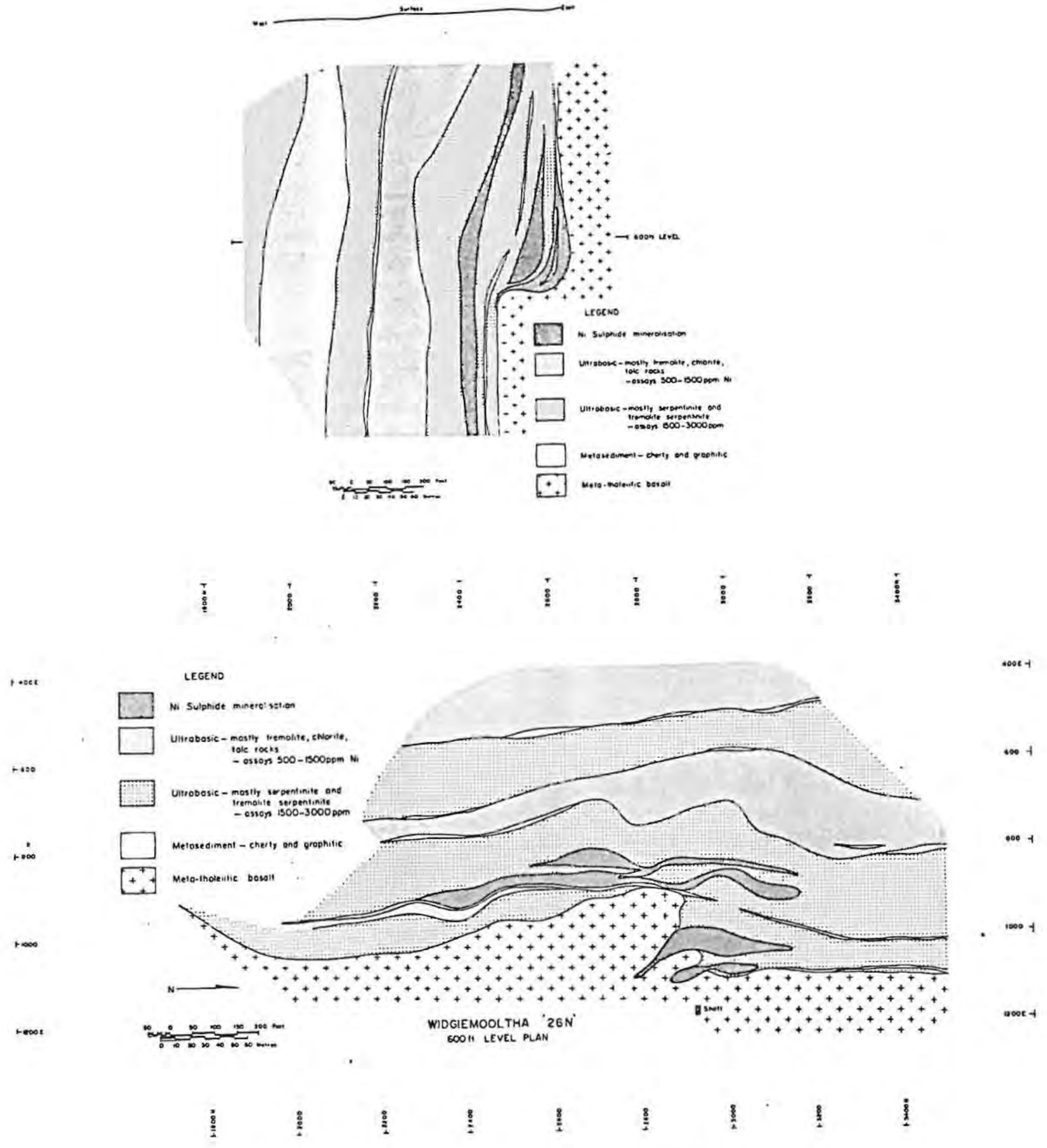


Fig. 5.13. Plan and section across Mt. Edwards "26N" deposit (after INAL Staff, 1975).

that structural deformation controlled the configuration of these footwall irregularities. There is a considerable amount of evidence indicating that these irregularities were present at the time of formation of the ultramafic pile (Ross and Hopkins, 1975; Marston et al., 1981; and Gresham and Loftus Hills, 1981): metasediments present on the basal ultramafic-metabasalt contact outside the embayment structure can be traced laterally into the general embayment area where they are found capping the ultramafic unit that is confined to the embayment, the presence of hangingwall ores above the basal ores, and finally, the thicker development of ultramafic within these troughs.

Many of the Zimbabwean deposits are directly located above vents and their size, shape and continuity is directly dependent on the configuration of the vent. The Shangani deposit is associated with an unusual mushroom shaped ultramafic complex (Fig. 5.14). The host peridotites are confined to the stem which has an average width of 120 m and is just over 300 m in length, while the width of the "mushroom" across the two lobes in the north-south direction is 500 m (Viljoen et al., 1979). A sulphide ore body is situated on the underside of each of the lobes. The eastern occurrence is far better developed and the western, which is not shown in the figure, consists of irregularly stacked lenses which pinch out rapidly and are not present continuously down plunge (Viljoen et al., 1976).

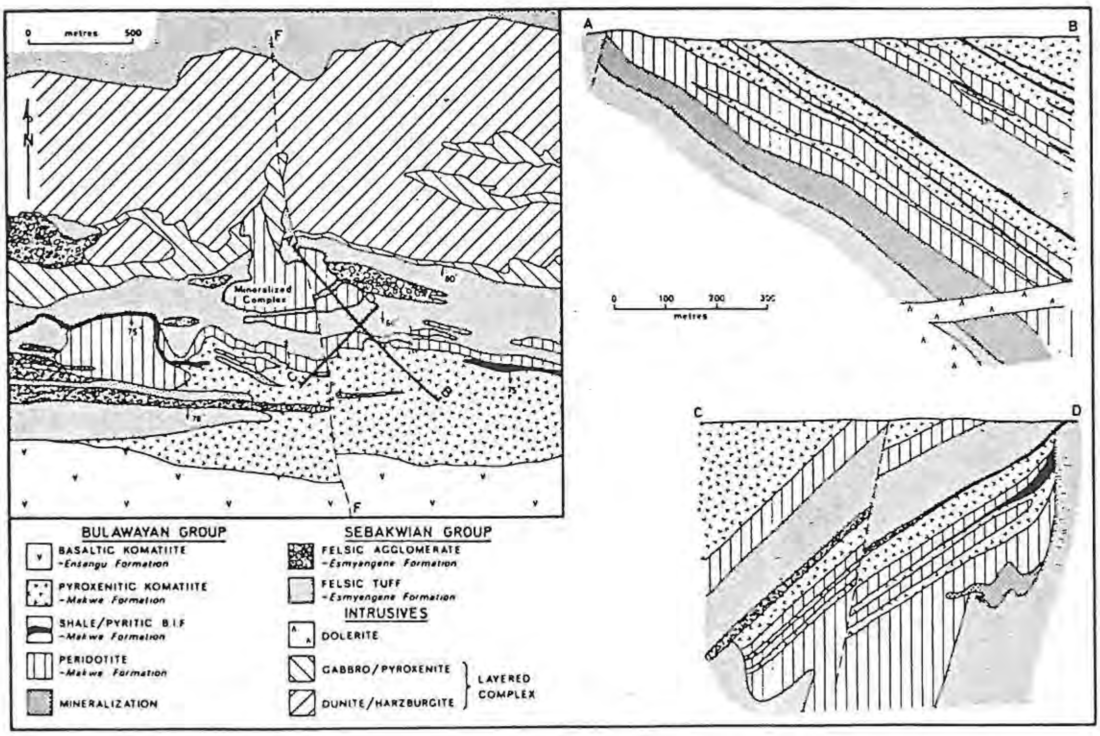


Fig. 5.14. Simplified plan and sections for Shangani (modified after Viljoen et al. (1976), from Williams, 1979).

In a typical section through an individual komatiitic volcanic-hosted orebody, a thin zone of massive sulphides is overlain by a thicker zone of matrix ore and then by more disseminated ores (Fig. 5.15). It should be noted that this sequential layering may not occur. At Kambalda for instance, individual ore types can occur without others, massive ores can overlie disseminated and matrix ores, and matrix ores may be separated from the basalt contact by up to a metre of barren ultramafic rock (Gresham and Loftus-Hills, 1981).

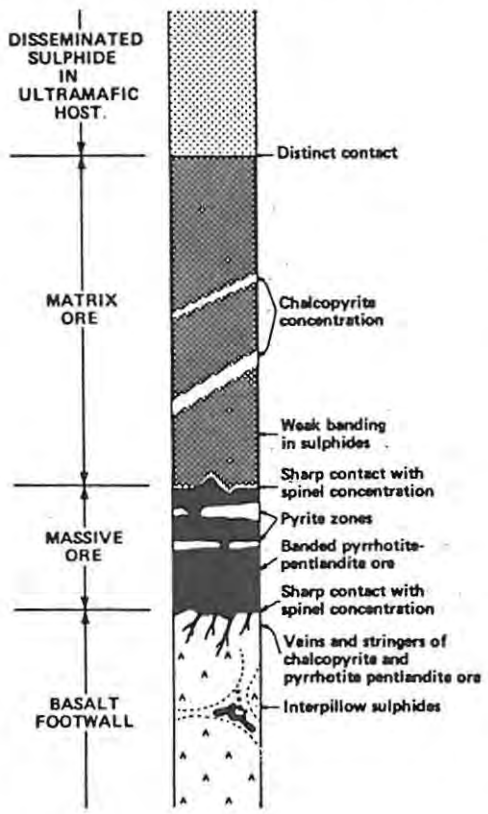


Fig. 5.15. Section through mineralization at the Lunnon shoot (after Seccombe et al., 1981).

The interface between the footwall rocks and the massive ore layer is a sharp geological cutoff, but is sometimes marked by the developments of a thin chrome-spinel band up to 3 mm thick (Ewers and Hudson, 1972). Veins of stringer ore comprising massive unfoliated sulphide often penetrate the footwall along fractures (Woodall and Travis, 1969). The massive ore is composed of 90 to 96% sulphides and invariably contains disseminated spinels (Ewers and Hudson, 1972). It may be a well banded pyrrhotite-pentlandite mixture as at the Lunnon shoot or a structureless massive layer as at Alexo mine (Ewers and Hudson, 1972; Naldrett, 1973). The banding generally parallels the footwall contact and individual bands are lenticular. The massive ore is irregularly distributed compared with the disseminated ore (Fig. 5.16) and at the Lunnon shoot for example, the disseminated ore is about 15% areally more extensive than the massive ore (Marston and Kay, 1980). Although some massive ore is normally present, the amount varies considerably, and it appears to increase its shoot size; notable exceptions occurring at Windara, where relatively large shoots lack massive sulphides (Marston et al., 1981). Generally however, the massive ore appears to range in thickness from 0,5 m to 2 m.

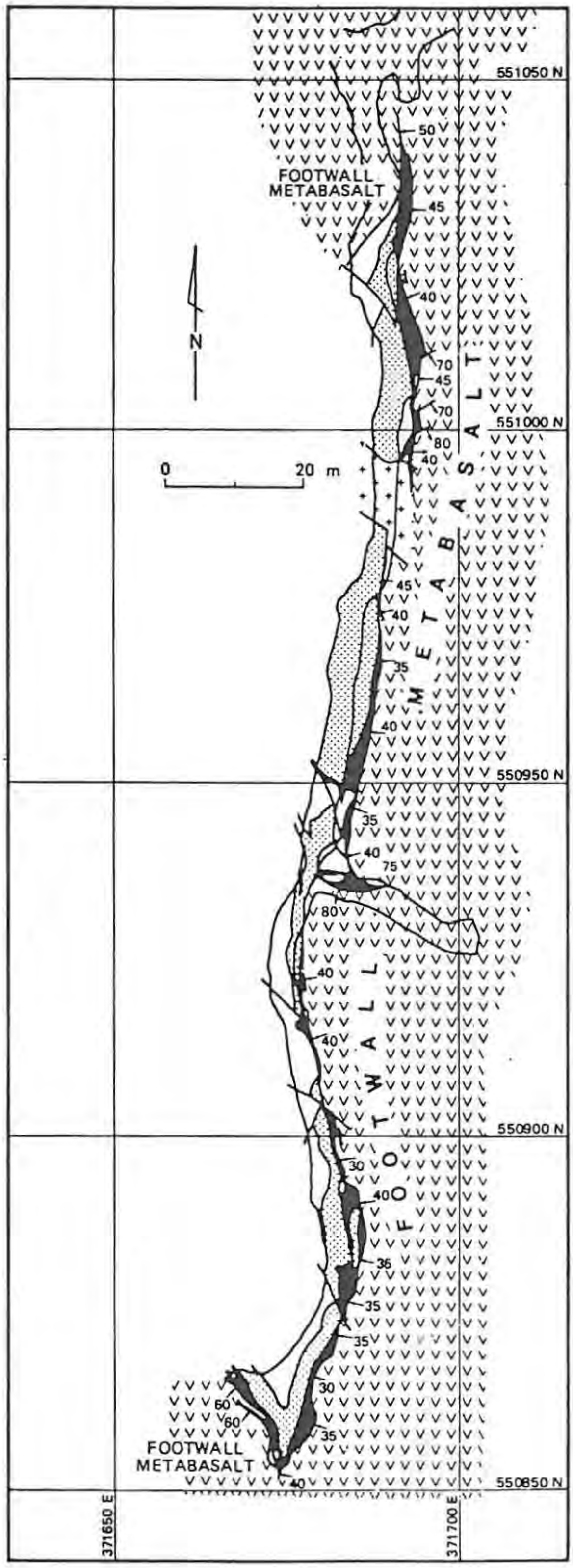


Fig. 5.16. Geological plan of the 5 sublevel, Juan Main shoot, showing the detailed structure of the basalt contact and overlying ore (after Marston and Key, 1980).

The upper part of the massive ore may be marked by a massive pyrite band (Ewers and Hudson, 1972). Pyritic bands often containing high concentrations of spinel may also be present along the basal contact, as scattered conformable lenses associated with lenses of spinel within the layered ore, and as irregular discordant pods cutting the layered ore (Marston and Kay, 1980). These non-economic oxide-rich layers may act as severe dilutents to the overall grade of the massive ore. The contact between the massive and matrix ore is often marked by a thin spinel-rich band.

An abrupt sharp contact separates the matrix (net-textured) ore from the underlying massive ore (Ewers and Hudson, 1972). This ore contains 50 to 60% sulphide which consists of a continuous network of sulphide filling the matrix of the host ultramafic (Ewers and Hudson, 1972). This zone is often non-economic and consequently, the grade and tonnage of many deposits is directly dependent on the continuity and thickness of the massive ore. The lower portions of this zone may be mineable and in these cases the upper limit of mining is an irregular surface defined by an assay cutoff.

Massive ore is rarely encountered in the Zimbabwean deposits (Williams, 1979) and this accounts for their low nickel tenor.

This continuous network of sulphides containing disseminated spinel, is itself in sharp contact with an overlying, very much weaker, usually less than 5% sulphide, discontinuous dissemination which grades upwards into an ultramafic with a very low sulphide content (Naldrett, 1973). The contact may be marked by a thin band of spinel. Blebby sulphides may occur with the weaker disseminations (Keele and Nickel, 1974).

In some deposits, for example Redross and Windarra, breccia ores make up a significant percentage of the ore. The breccia ores at Windarra have a varying, but usually high, sulphide content and occur at the ultramafic metasediment contact and within the metasediments themselves (Roberts, 1975). Breccia ore is characterized by deformed inclusions of gangue which compliment the sulphide phases. Included fragments at Windarra range up to several centimetres in size and may act as a severe dilutent to the overall grade.

The ores are primarily composed of, in decreasing order of abundance, pyrrhotite, pentlandite, pyrite, chalcopyrite and spinel. Pentlandite typically occurs as relatively coarse-grained discrete grains or discontinuous, lens-like grain-aggregates in a pyrrhotite matrix (Groves and Hudson, 1981). Less commonly, pentlandite occurs as small flame-like exsolutions along (001) or (0001) planes of the pyrrhotite. As in the Sudbury ores, very fine grinding is required to liberate this form of pentlandite, and in many cases it is never recovered, resulting in a drop of the overall nickel tenor. The overall nickel grade is directly dependent on the amount of pentlandite present and its nickel tenor. The composition of pentlandite varies in accorance with the nature of co-existing sulphide assemblages (Lambert and Groves, 1981). The most nickel-poor pentlandites (19-27 at.% Ni) coexist with hexagonal pyrrhotite ± troilite or pyrite, whereas pentlandite coexisting with dominantly monoclinic pyrrhotite + pyrite assemblages contains 28 ± 2 at.% Ni.

Chalcopyrite occurs as discrete grains within a pyrrhotite matrix and as an interstitial phase in pyritic ores (Groves and Hudson, 1981).

It may also occur as a symplectite-like intergrowth with pyrite from which it may be difficult to fully recover.

As would be expected from the composition of their host rocks, these ores are nickel-rich and copper-poor. Typical copper values range from 0,6% at Wannaway, 0,32% at Redross, 0,23% at Spargoville, to 0,1 at Widgie 3 (Andrews, 1975; Dalgarno, 1975) and Ni/Cu ratios are normally in the range 10 to 15 (Table 5.2). Consequently, the komatiitic volcanic-hosted deposits are critically dependent on current nickel prices and market trends. The Canadian deposits generally have significantly lower Ni/Cu ratios than the western Australian examples, and probably equilibriated with less magnesian melts than the latter (Groves and Hudson, 1981). Higher than normal Ni/Cu ratios occur at South Windara (22), Carnilya East (20-24), Mirian 23, and Bouchers (30) but may be partly due to the preferentially migration of Cu during metamorphism (Groves and Hudson, 1981). The Perserverance orebody in Zimbabwe has a Ni:Cu ratio which varies from 1:1 or 1:4 (Anderson, 1979). However, this deposit has not been proven definitely to be hosted by komatiitic volcanics and it may well represent a layered mafic-ultramafic sill. Within any one deposit the Ni/Cu ratio varies considerably and at Redross for example, the ratio varies from 6:1 to 50:1 (Dalgarno, 1975).

Lower S/Ni ratios are associated with millerite-bearing ores. The Otter ore shoot differs from many of the other shoots at Kambalda because of its extremely high grade : 400 000 tons at 35% Ni (Keele and Nickel, 1974). This is primarily because of the high primary millerite content of the ores. A similar situation exists in some of the Canadian deposits. The Marbridge No. 2 deposit is a small, but rich, orebody producing mill-head grades at well over 3% (Buchan and Blowes, 1968). This is primarily due to the massive sulphide pods and gash veins as well as the overlying disseminated ores carrying a high percentage of primary millerite which has a stoichiometric composition of 64,0% Ni, 12% Fe, and 34,7% S. The Marbridge No. 3 deposit also contains a significant percentage of primary millerite accompanying the pyrite and pentlandite and has an overall average grade of 2,28% (Graterol and Naldrett, 1971). This is significantly higher than most Canadian deposits. It should be noted that the pentlandite co-existing with millerite ores is typically very nickeliferous and also contributes to the higher grade obtained in ores of this type.

The total precious metal tenor of typical Western Australian nickel sulphide ore, is similar to that of the average Sudbury ore although gold, ruthenium, iridium, and osmium are higher and platinum contents are often lower (Keays and Davidson, 1976). Consequently, the sale of precious metals recovered as a byproduct may be an additional source of revenue for many mines. Both palladium and platinum are distinctly lower than the average ore from the Merensky Reef. Palladium ranges from 5,000 ppb in high grade ores with 20 wt% Ni to 0,2 ppb in unmineralized ultramafic rocks; iridium varies from 1000 to 3 ppb in the same rocks (Keayes and Davidson, 1976). In bulk ores (100% sulphides), the P.G.E. exhibits ranges of 1000-2500 ppb Pt, 500-3500 ppb Pd and 200-400 ppb lr (Groves and Hudson, 1981). Palladium and iridium (above 3-5 ppb) is exclusively associated with the Ni-Cu sulphide component in the ore zones (Keays and Davidson, 1976). At concentrations of less than 3 to 5 ppb, iridium is associated with silicates and oxides. Results from separates for several shoots in the Kambalda area indicate that pentlandite is the dominant host for Pd, lr is predominantly hosted in pyrite, and that chalcopyrite is the most important host for Au and Pt (Keayes et al, 1981). Taken as a whole, the precious metal content for the Langmuir group of deposits is similar to those of Western Australian deposits (Green and Naldrett, 1981). Cobalt is housed mainly in pyrite.

Accessory iron-nickel arsenides may occur in some deposits and high values are recorded in some of the Spargoville ores (Willmshurst, 1975). High arsenic concentrations are deleterious to the smelting process and may even result in a deposit being regarded as uneconomic.

The spinels within the ore zones in many of the Western Australian ores have a variable composition (Groves et al, 1977). Zoned spinels with ferrochromite cores and magnetic rims are present within the disseminated and massive ore but are rarely encountered within the matrix ore. Ragged to subhederal and euhederal magnetites are found within both the disseminated and matrix ore. In the massive ore the magnetite is euhederal to subhederal.

An important feature of the contact and hangingwall ore shoots is the variation in composition of the sulphide fraction. At Kambalda the sulphide fractions of the hangingwall ores are more nickel-rich than in the contact ores. The nickel content of the sulphide fraction varies from about 5 to 23% Ni and data presented by Ross and Keays (1979) indicates that increases in the Ni/Cu ratio from 10 to 16 and in Ni/Co from about 40 to 65 accompany the increasing nickel grade in the sulphide fraction. This could have resulted from the transfer of original S from the matrix to the massive layer (Keays et al., 1981).

Geochemical profiles through the ore zone are rare, although available data suggest that the maximum nickel and copper concentrations are offset. Most contact ore shoots exhibit an increase in the copper grade towards the footwall on a broad scale. On a more detailed scale, the distribution of copper is highly erratic (Groves and Hudson, 1981). Copper is preferentially concentrated at the footwall stringer zone and in the pyritic lenses within the massive zone. The basal portion of the massive layer and the zones immediately adjacent to the pyritic lenses are depeted in copper.

Keays et al. (1981) during a study of the precious metal content of the Lunnon shoot found that the palladium content of the sulphides increases upwards in the contact ores, but that there was considerable lateral variation in values. The footwall stringer ore is commonly enriched in Pd and Au and much of this may have been derived from the base of the massive layer which is depeted in these elements (Ross and Keayes, 1979). The distribution of Ir in the shoot is more uniform than Pd and suggests that the contact ores have experienced no major loss or gain (Keayes et al., 1981). The highest concentrations of Ir were found in the massive ores. Average Au values are higher in the matrix layer than in the contact ores and suggest loss from the contact ores (Keayes et al., 1981).

Apart from controlling the overall shape of individual ore deposits, structural deformation and metamorphism have played an important role in the textural relationships and zonation of the ores.

The disseminated ores exhibit little internal evidence of deformation (Barrett et al., 1977). The major modification in most cases appears to have been a retexturing and/or replacement of sulphides by metamorphic silicate and carbonate phases. The ores may also show evidence of intergrowth with metamorphically derived spinels. In high grade environments disseminated sulphides may be interstitial to metamorphic olivines producing a distinctive triangular-textured ore. Locally, concentrations of this ore type may reach the levels of the underlying matrix ore suggesting metamorphic upgrading of the original disseminated ores. In the very disseminated ores the sulphides are commonly more Ni (and Co)-rich and cobaltiferous pentlandite assemblages are commonly present. This is a direct result of nickel loss by silicates and uptake by sulphides during serpentinization and talc-carbonate alteration. The exact processes resulting in this nickel uptake is explained in more detail in section 5.2. The concentration of nickel in the sulphide fraction of the hangingwall ores as described above may therefore be a secondary metamorphic feature.

Matrix ores also show little direct evidence of significant modification during metamorphism (Barrett et al., 1977). The contact separating the matrix from the massive ores generally represents a tectonic boundary and it is evident that both behaved independently during deformation. In high grade metamorphic terranes, it is possible that some effective upgrading of the ores took place either by volume reductions in silicate phases during dehydration of earlier formed serpentinites or by local remobilization of sulphides to form patches of stringer ore (Groves and Hudson, 1981). The ragged magnetites which form the layer at the top of the massive layer appeared to have formed from iron release during the serpentinization process (Groves et al., 1977).

In marked contrast to the other ore types, the low strength massive ore layer represented a zone of concentrated strain and shows abundant evidence of ductile deformation (Barrett et al., 1977). In some cases it is evident that the remobilization of the massive ores relative to the more disseminated ores took place over tens of metres. The evidence for sulphide mobilization during deformation is well illustrated by the Redross deposit (McQueen, 1981). Massive and breccia ores have been mobilized off the footwall meta-basalt contact along shear zones and emplaced for up to 100 m into the metabasalt (Fig. 5.17). At other deposits around the Widgiemooltha Dome, the development of off-contact

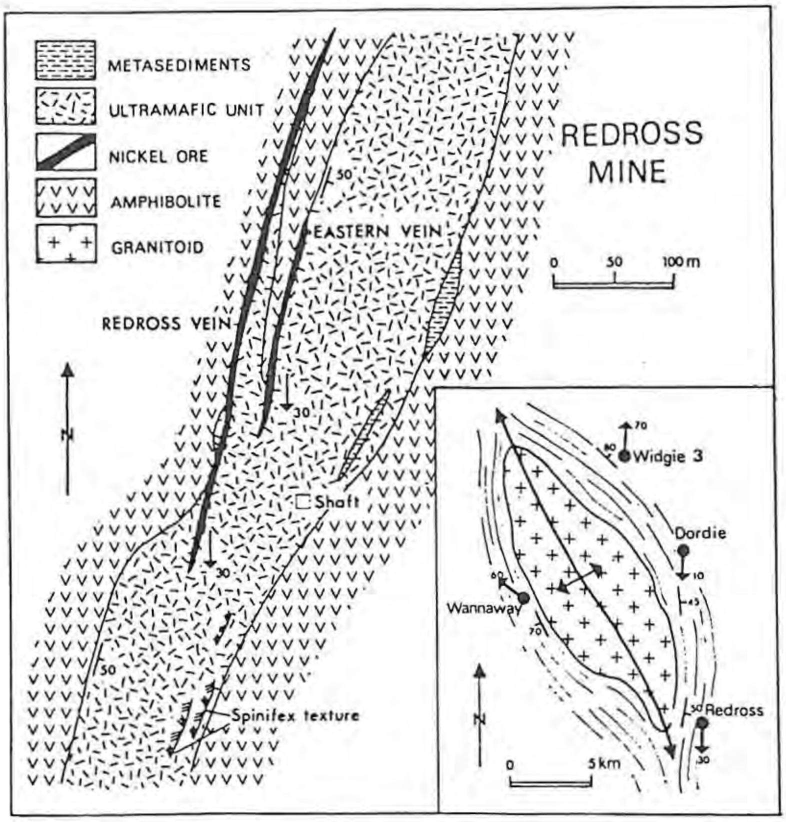


Fig. 5.17. Diagrammatic plan of the 3 Level of Redross mine showing position of main ore veins. Inset shows the position of other deposits around the Widgiemooltha Dome (after Barrett et al., 1977).

ores along deformed zones, the presence of massive sulphide stringers along footwall fractures, and the concentration of sulphides in other areas of low stress such as footwall embayments and fold hinges, all suggest sulphide mobilization (McQueen, 1981).

The temperatures of prograde metamorphic reactions are significantly higher than the temperatures of separation of pentlandite and pyrrhotite from a magmatic monosulphide solution and therefore, during high grade metamorphism the pre-existing sulphides revert to a monosulphide solution (Barrett et al., 1976). Ores that have suffered predominantly pre-metamorphic deformation show a wide spread in Fe/Ni ratios, presumably due to the segregation of the more ductile pyrrhotite from the pentlandite during the deformation of a "monosulphide solution-poor"ore (Barrett et a., 1977). On the other hand, massive ores that have been subjected to syn-metamorphic deformation show little evidence of the segregation of pyrrhotite from pentlandite and thus have very limited Fe+Ni ratios. However, banded ores could also form by the coalescence of exsolved pentlandite lamellae along the (0001) plane of of a cooling metamorphic monosulphide solution (McQueen, 1981).

The discordant and concordant pyrite pods in the massive ores of syn-metamorphically deformed deposits are heavily fractured and flattened and are thought to have formed by mechanical aggregation during deformation(Barrett et al., 1977). Many of the spinel layers appear to have formed in a similar way. During metamorphism and deformation, the more ductile chalcopyrite is remobilized and concentrated as stringer zones in the footwall, at the margins of the breccia ore/massive ore lens, as fracture fillings within pyrite crystals, and as concentrations within the more brittle pyrite lenses themselves. Therefore, in deformed and metamorphosed ores there is a sympathetic association of pyrite and chalcopyrite.

The distribution of many undeformed concordant and discordant pyrite layers and lenses in some massive ore shoots, the palimpest foliation in transgressive pyrite, the concentration of chalcopyrite and palladium in footwall stringer zones all point to significant sulphur diffusion during metamorphism. Seccombe et al. (1981) provides evidence for the late stage sulphur addition to the massive sulphides which resulted in the generation of pyritic layers. It appears that the controlling factor for sulphur addition was the high permeability of the massive ore as a result of thermal contraction during the cooling from metamorphic peak temperatures. Potential sources of excess sulphur include the breakdown of pyrite to pyrrhotite and/or magnetite in sulphidic metasediments in lower portions of the ultramafic pile and the loss of sulphur from the ultramafics during talc-carbonate alteration. These late stage solutions could have transported Pd, Au, and Cu from the matrix and massive layers to the footwall rocks and S from the matrix to the massive layer and, therefore, accounts for much of the zoned distribution these elements (Keays et al., 1981).

Retrogressive serpentinization in massive ores led to the formation of reducing conditions and the release of iron and nickel from relict olivine (McQueen, 1981a). This led to the formation of nickel-rich assemblages and the replacement of chromite by vallerite. In some cases this appears to have upgraded original ores but does not appear to be as marked as in intrusive dunite deposits (McQueen, 1981a).

Introduction of arsenic accompanied the carbonation of ultramafic rocks, as ores in talc-carbonate hosts at Redross and Spargoville, often tend to be enriched in aresenic without significant concentrations of nickel arsenides in the ore assemblages (Groves and Hudson, 1981).

It is evident in some rare cases that the massive ores themselves may have been derived from the reworking of disseminated ores, resulting in a marked upgrading of the original ore assemblage. At Nepean the matrix ore was upgraded during prograde metamorphic dehydration reactions and then acted as a zone of low strain throughout subsequent metamorphic and deformational events (Barrett et al., 1976). Matrix and triangular net-textured ore is commonly absent in the immediate vicinity of broad flexures in the basal contact. In these axial zones, more disseminated ores occur in well developed metamorphic reaction zones that preferentially developed along the basal contacts because of the marked contrast in composition between the host ultramafic and footwall amphibolite (Fig. 5.18). Massive sulphides however, do occur in the adjacent hangingwall or footwall of the matrix ore. These are interpreted as remobilized

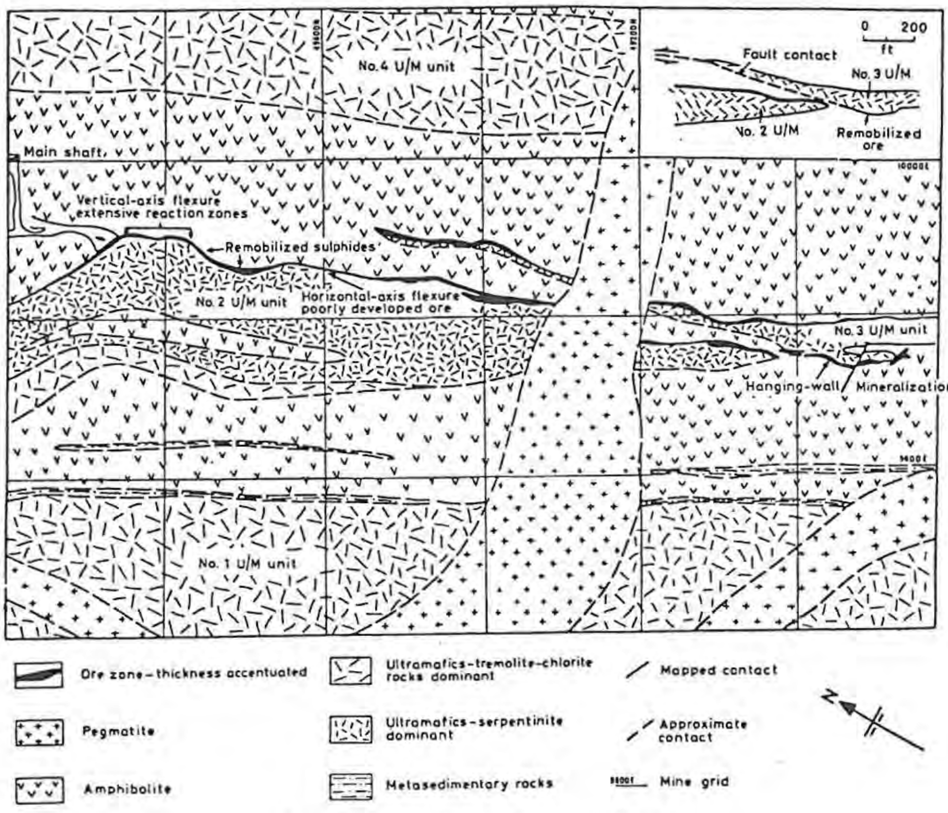


Fig. 5.18. Geological plan of Nepean mine area projected on to 530-t level (positions of vertical and horizontal flexures, and remobilized and hangingwall mineralizattion should be noted). Inset: interpreted relationship between ultramafic units 2 and 3 (after Barrett et al., 1974).

original matrix sulphide which moved off of the basal contact during the shearing that produced the flexures. Besides the basal contact being a zone of strong ductility contrast where shearing would preferentially develop, it is also a zone of high chemical potential gradients and would therefore be a site of diffusion during metamorphism. Strike-slip faulting subparallel to the basal contacts of units 2 and 3 resulted in the remobilization of ore to form pods of massive, matrix,and disseminated ore in the hangingwall portion of the ultramafic lenses as well as stringer zones in the footwall amphibolite rocks.

Sulphide ores may also develop in the metasomatic reaction zones that developed during metamorphism at the contacts between mineralized ultramafics and chemically contrasting rocks such as footwall metabasalts and/or metasedimentary rocks (Barrett et al., 1977). Sulphides here are intimately intergrown with chlorite, tremolite, anthophyllite, and biotite and are also characterized by the metamorphic growth of magnetite.

Most breccia ores appear to have formed during the latter stages of metamorphism and the sulphide matrix in some cases is remobilized massive sulphide.

Most of the metamorphosed deformed ores are coarser grained and show a characteristic polyonal texture. Chalcopyrite is often present as discrete segregations at the interface between pyrrhotite-rich and pentlandite-rich layers. The coarser grain and segregated nature of individual constituents makes the ores easy to benificate. However, chalcopyrite is also often found filling fractures in the more brittle pyrite and consequently only very fine grinding will liberate this "locked" chalcopyrite.

The supergene alteration profile over these ores can be subdivided into four zones (Nickel et al., 1974): the transition zone, the violarite-pyrite zone, the oxide zone (Fig. 5.19). The boundaries of these zones are commonly irregular, especially if the orebody is heavily faulted. The depth of the supergene profile is dependent on the geomorphological setting and climatic conditions prevailing. The transitional zone is commonly present over a vertical thickness of 90 m to 110 m, the

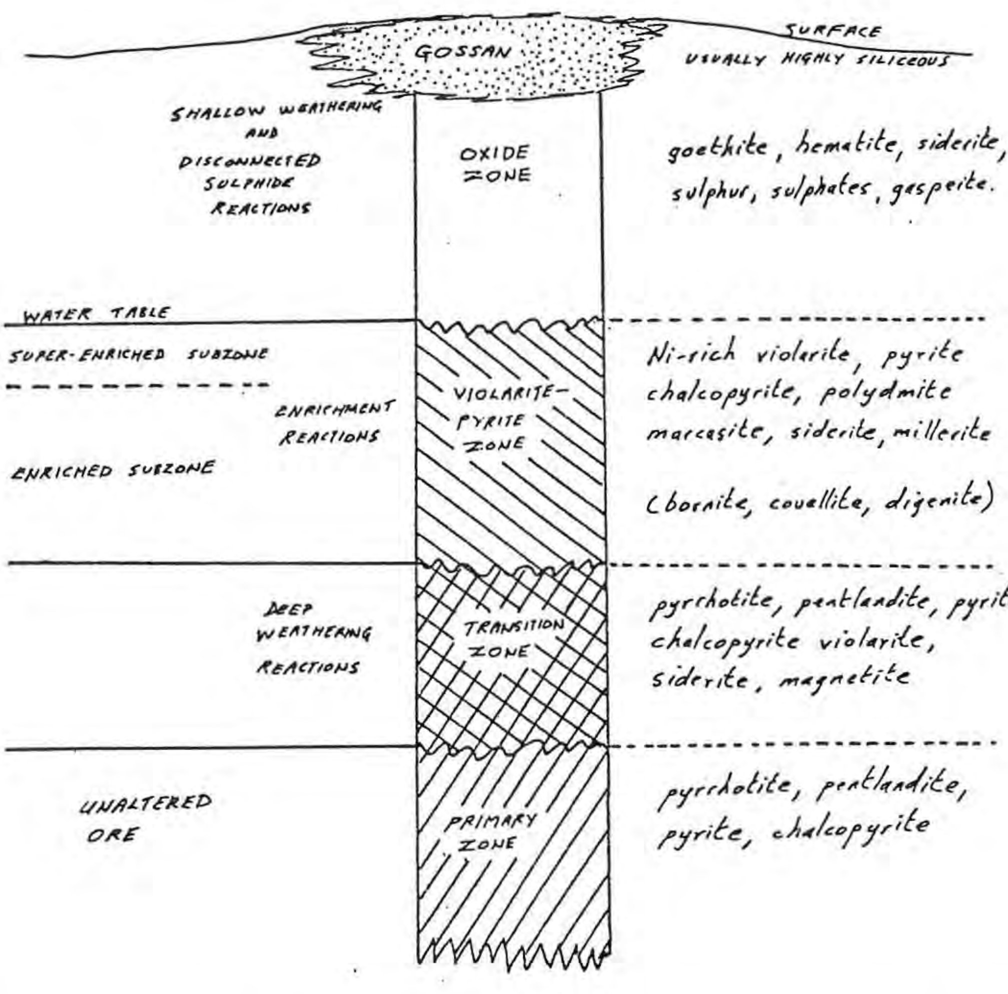


Fig. 5.19. A schematic diagram showing the supergene alteration of a nickel sulphide ore (after Reynolds, 1982a).

violarite-pyrite zone 35 m to 45 m, and the oxide zone 30 m (Blain and Andrew, 1977). The alteration sequence encountered in the Western Australian deposits is shown in Fig. 5.20 and summarized below.

In the transition zone pentlandite and pyrrhotite are partially converted to violarite (Nickel et al., 1977). In the monoclinic pyrrhotite-pentlandite assemblages, found mainly in the massive ores, pentlandite is psuedomorphically converted to violarite, while the excess nickel produced reacts with the monoclinic pyrrhotite to produce a serrated fringe of violarite around the pyrrhotite grains and along all fractures until all the pentlandite has been consumed. The development of violarite in pyrrhotite is commonly preceeded by an alteration front representing the conversion of pyrrhotite to smythite.

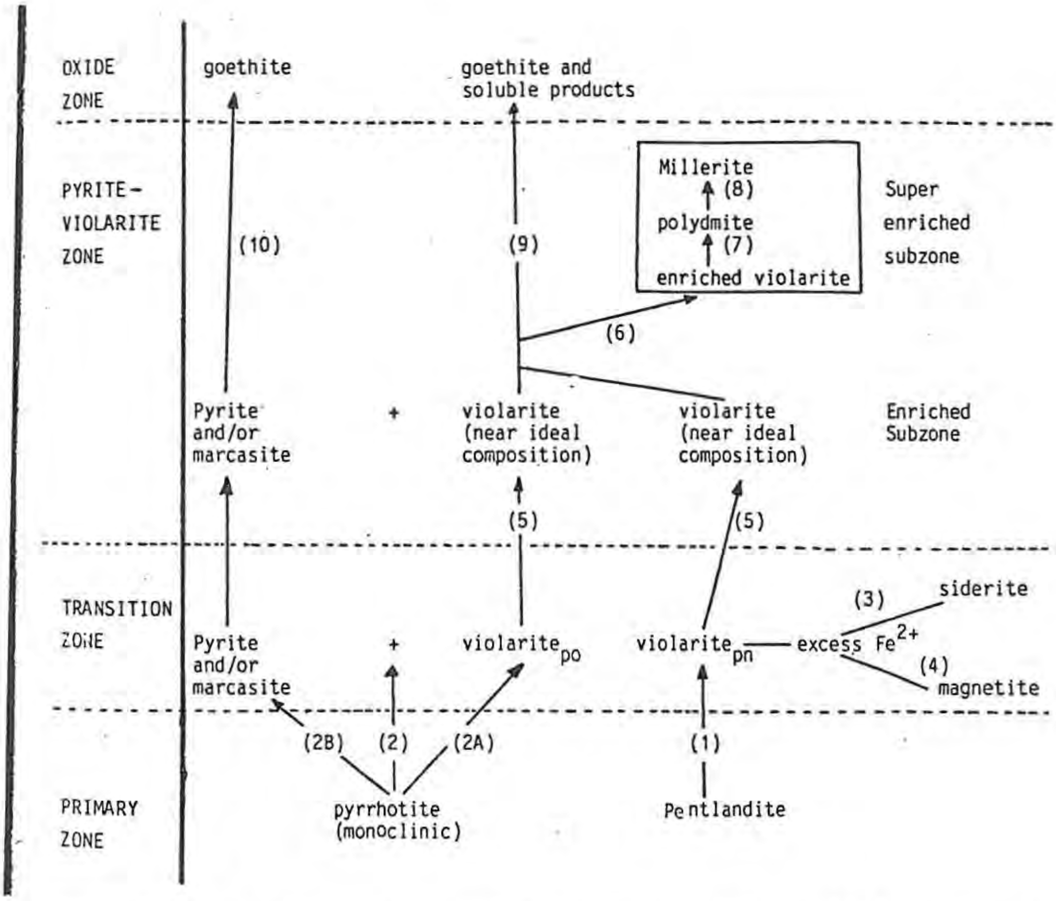


Fig. 5.20. Summary of the alteration sequence of komatiitic volcanic-hosted nickel sulphide deposits (after Reynolds, 1982).

In the hexagonal pyrrhotite-pentlandite assemblage, characteristic of disseminated sulphides, pentlandite is pseudomorphically converted to violarite, and the excess nickel released, reacts with the hexagonal pyrrhotite to produce nickeliferous monoclinic pyrrhotite along the grain boundaries and fractures (Nickel et al., 1977). The hexagonal pyrrhotite is particularly unstable under conditions of increasing oxidation and can be replaced by pyrite if there is still some unreacted pentlandite nearby. If all the hexagonal pyrrhotite is converted to pyrite before the pentlandite has been consumed, some of the secondary monoclinic pyrrhotite may react to form violarite. This reaction results in the release of considerable quantities of iron and leads to the formation of siderite and/or magnetite in this zone (Nickel et al., 1974). Primary chalcopyrite and pyrite remain unaffected by supergene processes in this zone.

The top of transitional zone is regarded as the level at which the last vestiges of pentlandite and pyrrhotite disappear (Nickel et al., 1977). The violarite-pyrite zone is composed of violarite, pyrite, and/or marcasite which tend to remain stable through a considerable portion of the supergene profile (Nickel et al., 1974). Supergene enrichment of violarite can take place in this zone, presumably through exchange with the nickel-rich solutions migrating downward from the overlying oxide zone (Nickel et al., 1974). Watmuff (1974) divided the violarite-pyrite zone into two sub-zones: the enriched sub-zone and super-enriched sub-zone. The former forms the lower portion of the violarite-pyrite zone and is characterized by a relatively small change in the composition of the violarite and the continued stability of chalcopyrite. The super-enriched sub-zone occupies the upper portion of the violarite-pyrite subzone and is characterized by a marked increase in the nickel and copper contents of violarite at the expense of iron, and the alteration of chalcopyrite to secondary copper sulphides. Podymite may form from highly enriched violarite and then may be oxidized to form supergene millerite (Reynolds, 1982). Local spectacular increases in the nickel grade are achieved with the development of this form of millerite (Nickel et al., 1977). However, this is no as pronounced as in many copper deposits and does not usually increase the ore grade significantly. Supergene silica is introduced into the violarite-pyrite zone as veins and zones of silicification and often enclose specks of primary sulphide. Carbonate veins derived from the weathering of ultramafic rocks are present at all levels within the zone (Nickel et al., 1974).

The base of the oxide zone coincides approximately with the water table and marks the point where atmospheric oxygen has access to the sulphides (Nickel et al., 1974). Here violarite becomes unstable and is replaced by nickel carbonates and iron oxides. Pyrite and marcasite are oxidized to goethite, although relict pyrite and marcasite may persist upwards, in decreasing abundance through much of the oxide zone.

The supergene process can be explained in terms of an electrochemical model (Nickel et al., 1974); Blain and Brotherton, 1975; Thornber, 1975a; Thornber, 1975b). In this model (Fig. 5.21), anodic reactions at depth liberate metal ions and electrons. Electrons are conducted through the sulphide ore to cathodic regions situated at, or near, the water table, where they take part in reactions of the

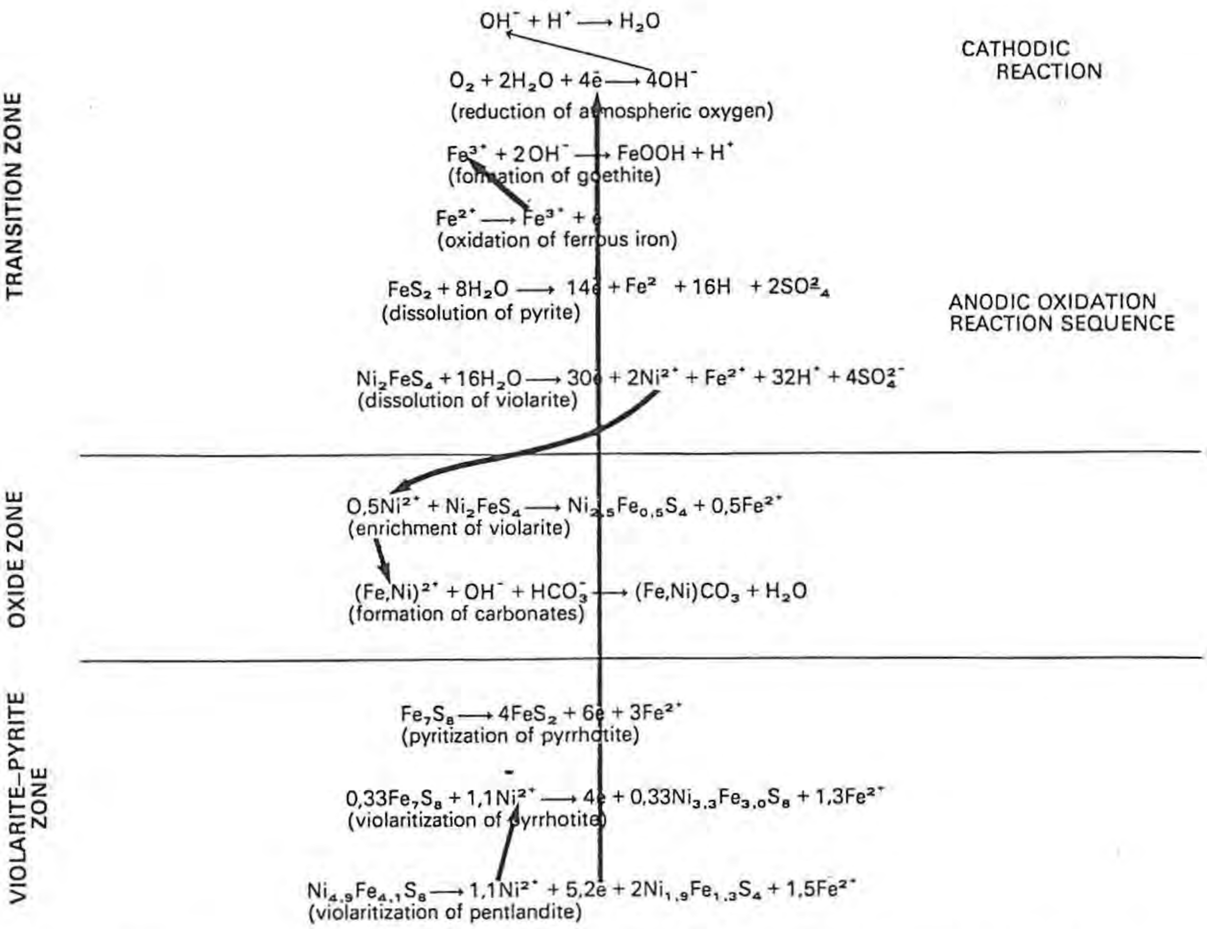


Fig. 5.21. Chemical reactions and their inter-relations during the electrochemical alteration of nickel sulphide bodies in the supergene environment (after Blain and Andrews, 1978).

general type: $O_2 + 2H_2O + 4e^- \rightarrow 4(OH)^-$. This consumption of free electrons creates a potential gradient and encourages anodic reactions at depth. Above the water table, where sulphides are no longer protected by cathodic reactions, they decompose, releasing nickel and ionic sulphur species that are transported downwards by aqueous solutions and redeposited resulting in secondary enrichment zone below.

The characteristic supergene profile developed over the komatiitic volcanic-hosted deposits is applicable in general to those developed over most nickel deposits. A great deal of caution must be exercised when mining in the supergene zone. When freshly exposed to the atmosphere or disturbed by blasting, marcasite-rich ore in the violarite-pyrite zone undergoes spontaneous combustion in an exothermic reaction with the emission of sulphur dioxide fumes and the formation of ferrous sulphate. This has an adverse effect on the handling of the ore, which is also aggravated by the cementing products in the crushed ore, and as at Selebi-Pikwe, can result in explosions being experienced in the drying plants (Lear, 1979).

The overall variability in thickness (0,3 m to 20, 0 m), variation in grade (zero to + 30% Ni) and erratic zonation of metals, suggest a very poor assay/thickness correlation between drill sections and a large standard deviation on both thickness and grade values. It is likely that any genuine correlation between sample points would be on a grid well under 5 m in dimensions and any raw data obtainable for ore reserve calculations is truely random (White, 1979). For these reasons all ore reserve estimations should be based on a calculation from sections both perpendicular and parallel to strike, as well as from accurate level plans. As the ores are largely mixtures of pyrrhotite and pentlandite, and more importantly, as the grades for the massive sulphide bodies are highly variable, ores of similar nickel contents may consist of vastly different sulphide contents (White, 1979). Therefore, all cored intersections should be measured for a tonnes per cubic metre (T.C.M.) factor and each individual assayed sample should be weighted by this factor in any ore reserve calculation.

The irregular size and shape of the orebodies, their variability in strike and dip, the presence of stacked orebodies, the narrow thickness of commercially exploitable ores, and the description of ore zones by late intrusive dykes, necessitate mining methods (up-dip room and pillar, and cut and fill) which employ hand held machines, are directionally mobile, are capable of taking the best grade over a minimum thickness, and which can leave narrow pillars between ore zones (White, 1979).

A series of diagrams showing the proposed modes of formation of these deposits is shown in Fig. 5.22.

The present consensus favours a magmatic origin for the nickel sulphides (Ewers and Hudson, 1972; Naldrett, 1973; Ross and Hopkins, 1975; Groves et al., 1979; Gresham and Loftus Hills, 1981; McQueen, 1981; and Lesher and Lee, 1981) and most features are consistent with derivation from oxy-sulphide liquid droplets carried by phenocryst-rich komatiitic flow units that were extruded on the sea floor and concentrated in depressions. Groves et al. (1979) and Barrett et al (1977)

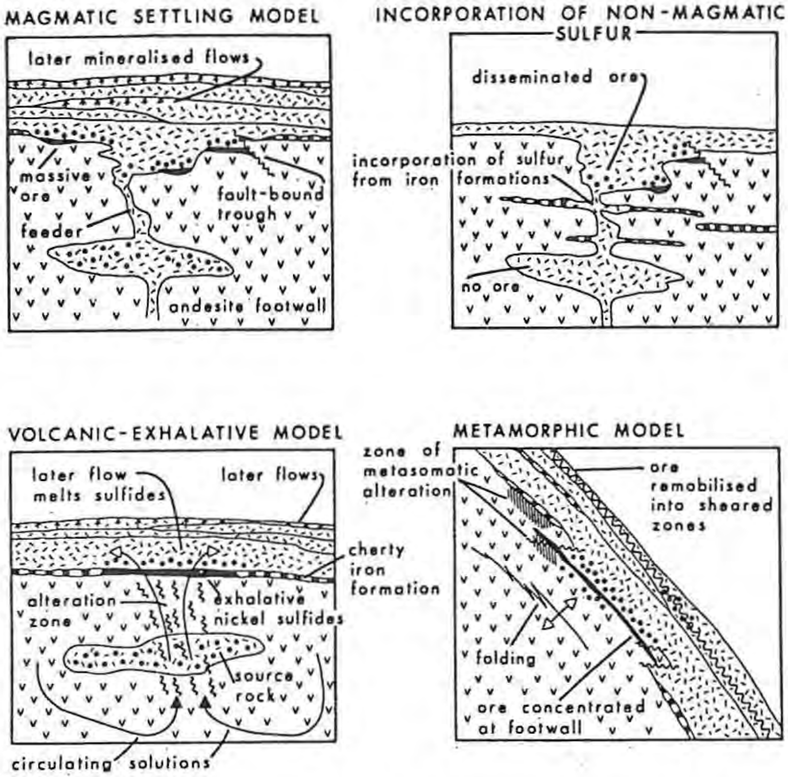


Fig. 5.22. Series of cartoon-type diagrams illustrating modes of formation of volcanic-komatiitic hosted deposits (after Green and Naldrett, 1981).

have argued against the single-stage settling model - the "billiard ball" model of Naldrett (1973). One of the main factors against a single stage settling model is the fact that chemical data indicate that the gangue material in the massive sulphide unit is very similar in composition to the immediately overlying basal unit. If the silicate liquid had been displaced by sulphides in the matrix ore, as suggested by the billard ball model, a composition approaching that of pure olivine would be expected (Gresham and Loftus Hills, 1981). These data imply that some of the segration of the sulphide-silicate phases took place during extrusion or emplacement of the flows. There are marked viscosity differences between the components of a mixure of molten sulphide, olivine crystals, and picritic liquid. Ross and Hopkins (1975) considered that segregation of these components took place during vertical flow in the volcanic conduit, with the result that the sulphide melt preceded a mixed section of sulphide and silicate melt, and that was followed by an olivine-rich section. Marston and Kay (1980), on the basis of the close spatial and chemical affinities of the massive and disseminated ores at the Juan shoot proposed that peridotitic magma and sulphide liquid were both erupted at the same time and that segregation took place during transport on the ocean floor, with the main mass of sulphide being emplaced slightly in advance of olivine-rich magma containing sulphide droplets. There is insufficient evidence to rule out either of these models, and it is probable that varying degrees of segration took place during both vertical and horizontal transport. The massive sulphide melt would disperse to form a discontinuous sheet of variable thickness, but would be concentrated in irregularities in the footwall contact and, because of the rapid cooling by seawater, it would be partly crystalline when the peridotitic magma came to settle on it (Marston et al., 1981). This magma would contain matrix and/or disseminated ore at its base as a result of the settling out of sulphides during flow.

Some workers (Naldrett, 1966; Naldrett, 1966; Naldrett and Gasparrinni, 1971; Hopwood, 1981 and Green and Naldrett, 1981) believe that ultramafic magmas did not carry enough sulphur in solution to allow the separation of an immiscible sulphide phase. They favour a model in which a large proportion of the sulphide was obtained by the assimilation of sulphur from sulphide-bearing exhalative sediments and graphitic metasediments. This was followed by mixing with mantle-derived sulphur and metal and the subsequent separation of an immiscible sulphide phase. Many of the Canadian ores have lower sulphur isotope ratios and higher S/Se ratios than other nickel sulphide deposits and the assimilation of country rock sulphides may have been important in the genesis of these deposits, as their low grade suggests that original magmas were deficient in both metal and sulphide. However, as Naldrett (1973) has suggested, many of the Archaean ultramafic magmas were saturated in sulphides as a result of sulphide melting in the Archaean upper mantle below 100 km depth (Fig. 5.23). This combined with the absence of interflow sediments in the immediate vicinity of the ores does not tend to support this model being operative on a major scale in the Archaean.

Consideration of the modifying effects of tectono-metamorphic processes suggests that these effects cannot really account for the generation of massive sulphide layers, as massive basal sulphide zones are known from many relatively undeformed and unmetamorphosed deposits.

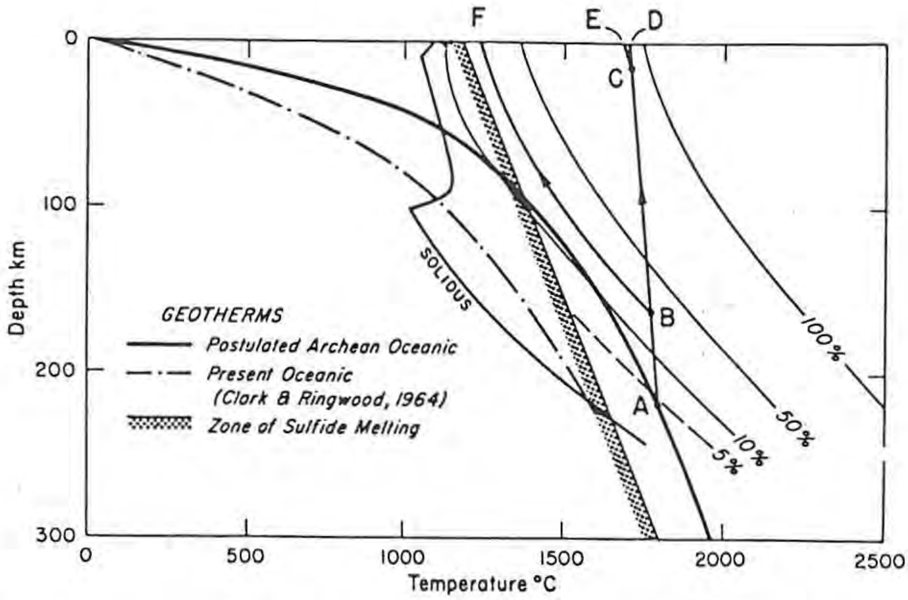


Fig. 5.23. A depth-temperature diagram showing the possible relationship between modern and Archaean oceanic geotherms, and melting of komatiitic magmas and mantle sulphides. A mantle diapir (S-rich) generated at A rises to B at which stage ca. 25% melting occurs, and basaltic liquid separates and rises along a non-adiabatic path BF. The residium of partial melting rises from B to C, resulting in ca. 30% further melting and separation of komatiitic magma that rises along path CE (after Naldrett and Cabri, 1976).

Lusk (1976) pointed out the similarity of many features of the volcanic-associated Ni-Cu ores with volcnogenic Cu-Zn deposits associated with felsic volcanics. Although there appears to be overwhelming evidence against this a general process in their formation (Groves et al., 1979; Bravinton, 1981), there are some deposits, for example Sherlock Bay and the Windarra F shoot, that are intimately associated with sulphidic interflow sediments and these may represent volcanic-exhalative Ni-Cu deposits (Lambert and Groves, 1981).

A summary genetic model is shown in Fig. 5.24.

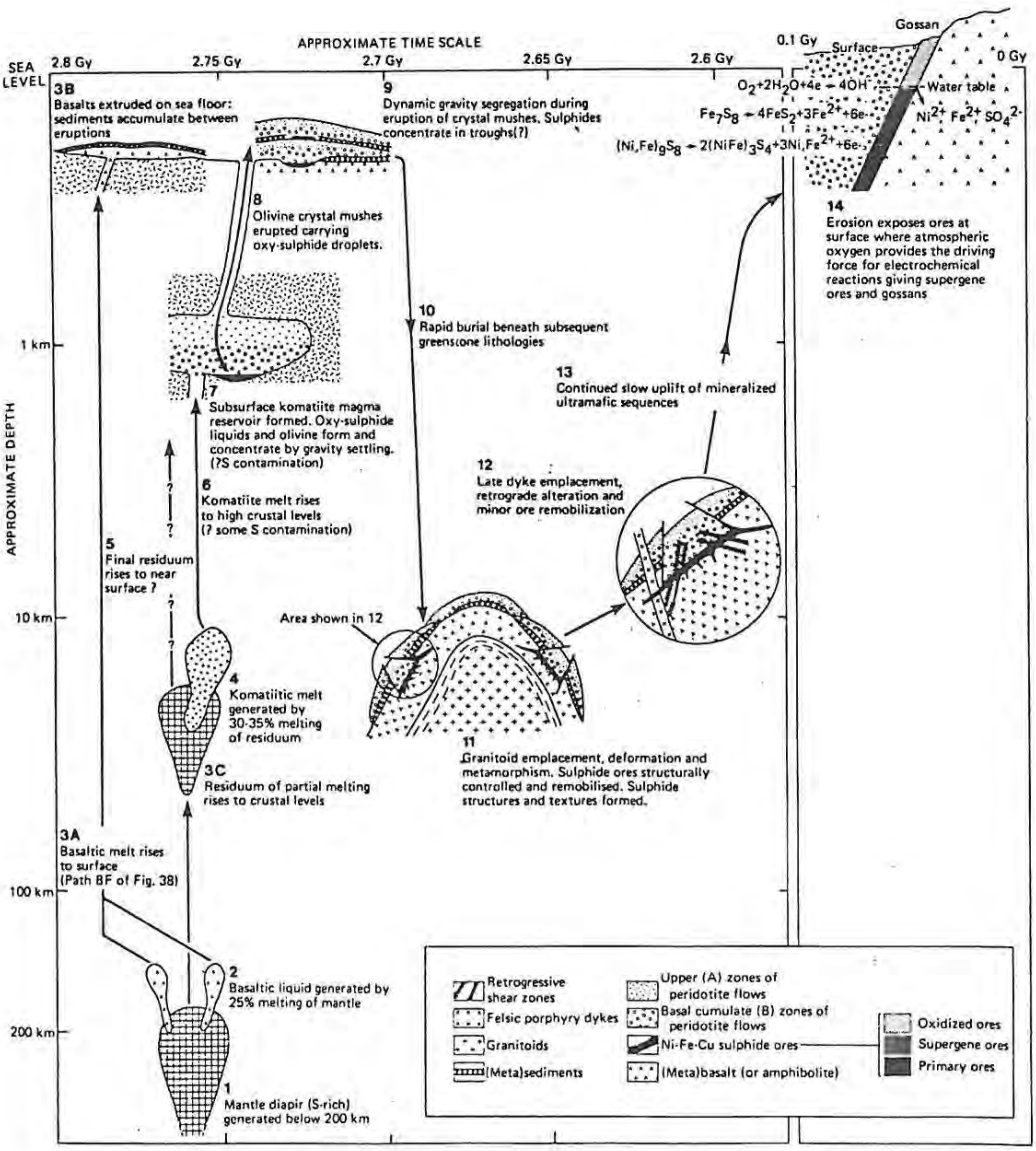


Fig. 5.24. Schematic diagram showing the possible evolution in depth and time of volcanic-associated Ni-Fe-Cu sulphide ores with particular relevance to Western Australian deposits (after Groves and Hudson, 1981).

5.2 Intrusive dunite-associated deposits within Archaean greenstone belts

Important deposits of this type are only known from the Yilgarn Block in Western Australia. The Dumont serpentinite in Canada appears to be the only published example in an Archaean greenstone belt outside Australia. The deposits are generally too low grade to mine econonically. A stunning exception is the Perserverance deposit, a major accumulation of 45 million tonnes at 2% Ni. The deposits are spatially separated from the volcanic-hosted types and are concentrated in the northern third of the Norseman-Wiluna belt (Fig. 5.25) and the southern part of the Southern Cross-Forrestania region (Fig. 5.26). Isolated, small deposits occur at Ravensthorpe, Lake Johnson, and Queen Victoria Rocks, Black Swan, and Acra.

The most striking feature of the distribution of the dunite-hosted deposits is their restriction to narrow curvilinear zones commonly several hundred kilometres in length, containing pod-like accumulations of dunite (Marston et al., 1981). This is in marked contrast to the cluster-like patterns exhibited by the volcanic-hosted deposits. These linear zones are the site of narrow fold belts containing persistent faults and ductile shear zones parallel to the strike of the supracrustals. Many deposits are related to large north-northwesterly striking faults which parallel the strike of the curvilinear zones. O'Driscoll (1981) has shown that the Perserverance deposit and the Mt. Keith deposit lie at the intersection of these strike faults and west-northwesterly tending lineaments which are thought to be related to the Kalgoorlie-Shark Bay lineament. Both sets of structures could have been sites of crustal weakness which allowed the upwelling of metalliferous magma from the mantle.

The host dunites are discontinuous, elongate, steeply dipping pods (Lambert and Groves, 1981). The dunitic bodies are normally concordant with the country rocks but are locally discordant. Marginal shearing and boudinage during subsequent tectonism has often obscured original contact relationships (Marston et al., 1981). Individual dunitic lenses vary widely in size and range from 15 km long by 1 km thick to 200 m long by 20 m thick (Porter and McKay, 1981). It appears that the higher grade deposits occur in the larger lenses. For example, the Agnew (Perseverance) deposit which has the highest grade of mineralization occurs in a lens 6000 m long, 700 m thick and at least 1100 m in vertical extent.

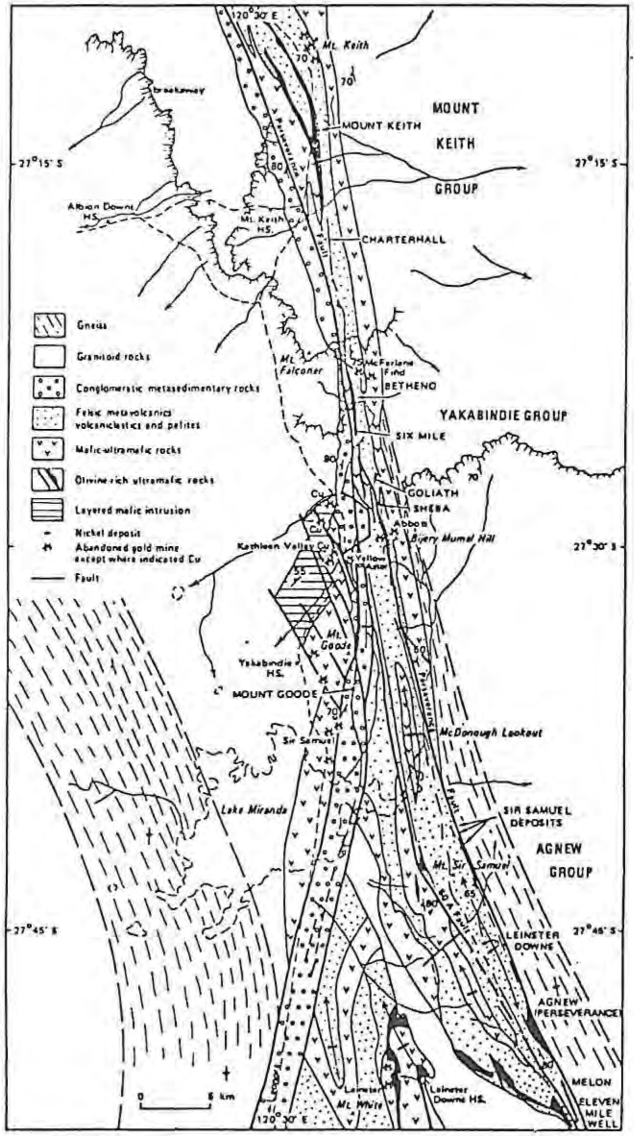


Fig. 5.25. Geologic map showing the setting of the Agnew, Mt. Keith, and Yakabindie groups of nickel deposits

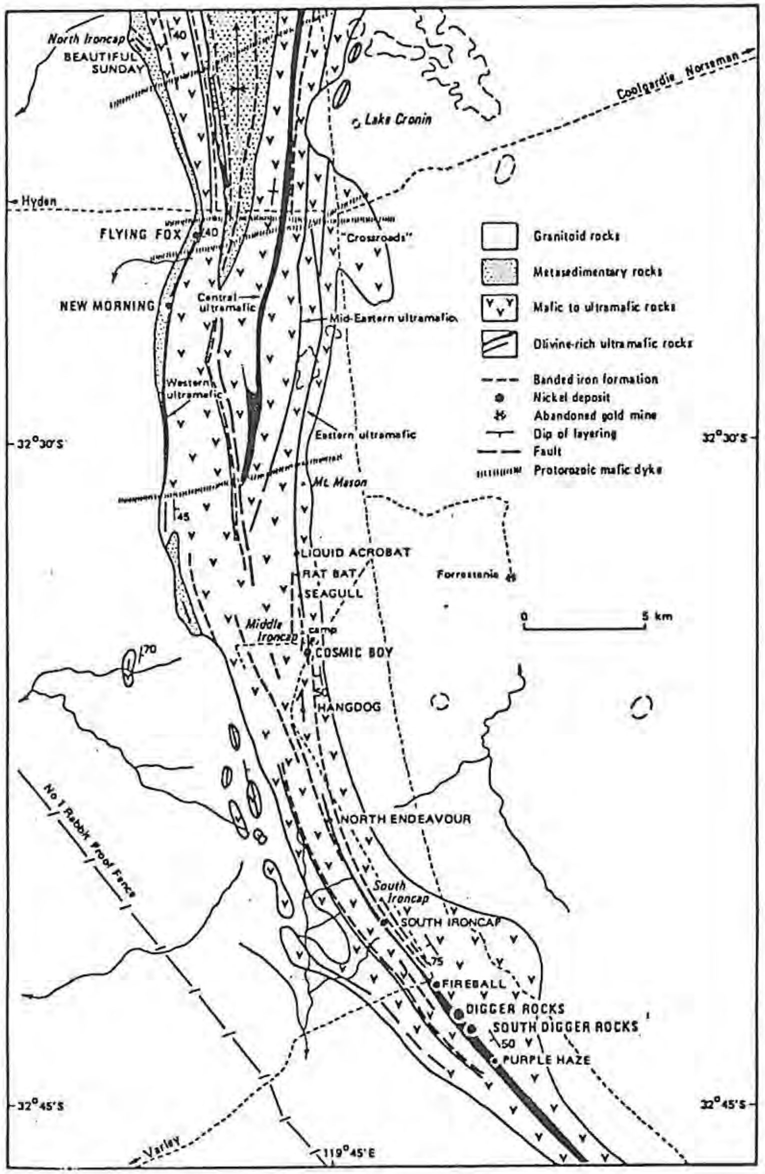


Fig. 5.26. Geologic map showing the setting of the Forrestania group of nickel deposits (after Marston et al.,

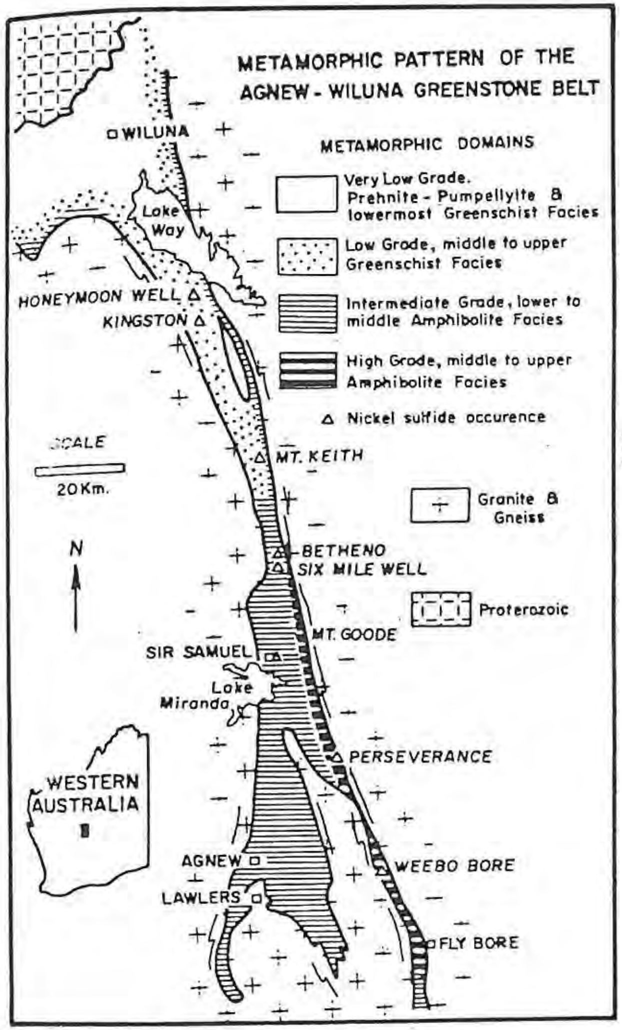


Fig. 5.27. Metamorphic pattern of the Agnew-Wiluna greenstone belt (after Donaldson and

In contrast to the volcanic-hosted deposits, the mineralized dunites are not specifically associated with ultramafic flow sequences. Country rocks include felsic metavolcanics, volcaniclastics, pelitic arenaceous metasediments, banded iron formation, as well as tholeittic and komatiitic volcanics (Marston et al., 1981).

The two lithologies that characterize the dunite deposits are olivinite and olivine peridotite, both characterized by their consistently high MgO contents (45% - 51%) and it is clear that olivine comprised 95% by volume (Fig. 5.7)(Donaldson, 1981). Some of the lenses are, like Webbo Bore (Legge, 1975), compositionally and texturally monotonous. Some lenses show an almost continuous variation between sago-textured olivine peridotite and mosaic-textured olivinite, with alterations being abrupt and on the scale of millimetres or broadly gradational across the lens. Subtle cryptic variation in the mineralogy of some large dunitic deposits has been noted. In a differentiated, partially serpentinized dunite body at Mt. Clifford, the Ni content varies with height between 0,1% to 0,35%, sympathetically with the forsterite content of relict olivine (Fo_{87} to Fo_{94}) (Donaldson, 1981). The Cr_3O_3 content shows similar variations and 300 m thick sections having contents of over 1% alternate with similar thickness containing about 0,2%. Donaldson and Bromley (1981) illustrate wide variations in Mg/Fe ratio, Ni sulphide content, Cr distribution, and the Ni/Cu ratio in a thick serpentinized dunite at Honeymoon Well. At Six Mile Well, Naldrett and Turner (1977) describe cryptic layering in the upper more peridotitic section of the ultramafic body.

The dunite deposits occur within rocks showing a wide range of metamorphic grade, ranging from prehnite-pumpellyite to amphibolite-granulite facies transition (Fig. 5.27)(Binns et al., 1976). Two contrasting styles of regional metamorphism are recognized (Barrett et al., 1977). The dominant style of low- to medium-grade domains is that of static recrystallization (static style) resulting in the preservation of primary structures and textures. In contrast, intense deformation has produced penetrative foliations and lineations throughout the high grade areas of dynamic-style metamorphism.

Former dunites have recrystallized to a predominantly lizardite + brucite + magnetite ± stichtite assemblage in low grade metamorphic terrains, or to antigorite + magnetite + magnesite in areas of low to medium amphibolite facies metamorphism (Donaldson, 1981). In the high amphibolite facies domains, such as those preserved at Perserverance, antigorite may be accompanied by a metamorphic forsterite-talc assemblage (Donaldson and Bromley, 1981). Many bodies, the Six Mile deposit (Turner and Randord, 1975) being a typical example, exhibit a strongly altered talcose envelope surrounding a much thicker serpentinized dunite core in which relict olivine may survive. As in the volcanic-type ores, the occurrence of talc and serpentinite are detrimental to the floatation of the ores. Chemical compositions are not greatly affected by serpentinization and talc-carbonate except for the addition of volatiles and loss of CaO and alkalies from some rocks (Marston et al., 1981). The generation of hydrogen gas during serpentinization is particularly dangerous and some drill rigs have ignited when drilling highly serpentinized lithologies.

There has been some controversy concerning the timing of emplacement of the dunitic bodies and their relationship to komatiitic flow sequences and associated mineralization. Burt and Sheppy (1975) and Binns et al. (1977) have suggested that the dunites were emplaced as stepply dipping subconcordant bodies along major fracture zones, presumably following initial deformation of the greenstone belt sequences. Naldrett and Turner (1977) have suggested that they have represent sill-like feeder chambers for overlying komatiitic volcanics. Many authors, consider the evidence for the emplacement of the dunites as subvolcanic sills is compelling. The metadunites are apparently conformable to the surrounding metavolcanics and metasediments at Perserverance, Six Mile Well, Mt. Keith, and Honeymoom Well; where stratigraphic relationships are clear, the thick dunitic bodies underlie komatiitic lava piles suggesting emplacement as subvolcanic sills which acted as feeders to the overlying komatiites; many of the dunitic bodies exhibit mineralogical and/or cryptic layering which is unlikely to have developed in a dyke; and finally, the textures observed in the dunites are well preserved adcumulate textures.

There is a broad geographic variation in the degree of fractionated of the dunitic lenses and in the nature and grade of contained mineralization that tends to parallel the variation in metamorphic grade and degree of internal strain in enclosing rock sequences (Lambert and

Groves, 1981). In the very low grade environments (e.g. Wiluna), the dunites show marginal fractionation to orthopyroxenite, norite, and possibly even sodic granophyre and generally contain no significant mineralization. In intermediate-grade environments of low strain, for example Mt. Keith, Six Mile, and Black Swan, the dunites exhibit a varied development of marginal orthopyroxenite and contain disseminated mineralization. In the high grade, high strain environments as at Agnew and most Forrestania orebodies, the dunites normally only show minor, if any, marginal fractionation and contain disseminated, matrix, breccia, and massive sulphides.

The dunitic-hosted deposits in the greenschist facies or amphibolite/greenschist transition environments are typically large low grade deposits. The Mt. Keith deposit contains approximately 290 million tonnes at 0,6% Ni (Burt and Sheppy, 1975). The sulphides are of a disseminated nature and occur as interstitial films or lobate to rounded aggregates (Marston et al., 1981). Veinlets and stringers of sulphide may also occur. The orebodies within the dunitic lenses may form a single centrally disposed body composed of uniformly distributed sulphides (Mt. Keith - Figs. 5.28 and 5.29), or a number of separate lenses which tend to be concentrated towards the base of the intrusion (Mt. Clifford - Fig. 5.30); they may form a number of converging linear zones (Six Mile - Fig. 5.31) or they may occur as discrete lenses along both contacts of the intrusion and are spatially related to footwall irregularities (Honeymoon Well) (Burt and Sheppy, 1975; Travis, 1975; Turner and Ranford, 1975; and Donaldson and Bromley, 1981). In all cases both the hangingwall and footwall contacts of the orebodies are ill-defined and outlined by assay cutoffs.

In the more strongly metamorphosed deposits, transitions from disseminated through high grade disseminated and matrix and/or triangular-textured ores to massive and breccia ores occur on one margin, as at Perserverance. The deposits are of a smaller tonnage but invariably contain a high grade of mineralization. Perserverance for example, contains 45 million tonnes at 2,05% Ni and the Forrestonia group of deposits collectively contain 14 million tonnes 1,3% Ni (Marston et al., 1981). The massive and breccia sulphides are found along the basal contact of the intrusion, along faults, and

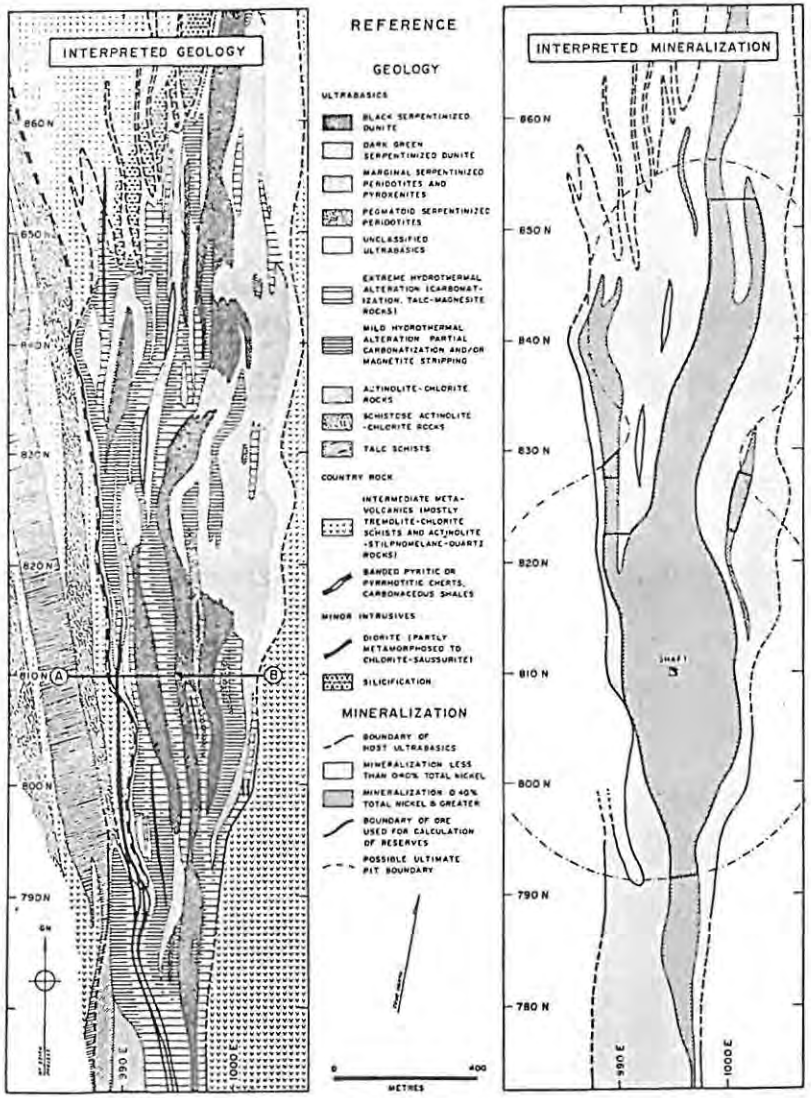


Fig. 5.28. Mt. Keith Nickel Deposit: Plans of geology and mineralization at 153 m Level (500 ft. deep). (after Burt and Sheppy, 1975).

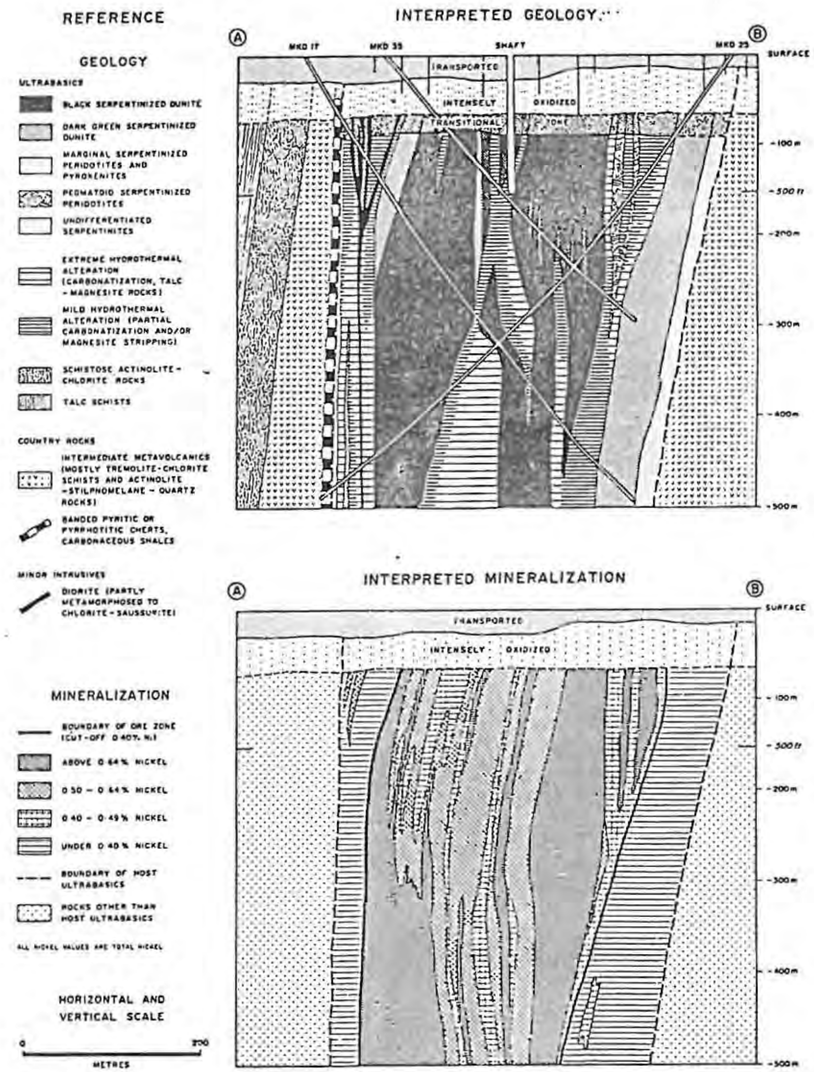


Fig. 5.29. Mt. Keith Nickel Deposit: Cross-section of geology and mineralization at prospect shaft (after Burt and Sheppy, 1975).

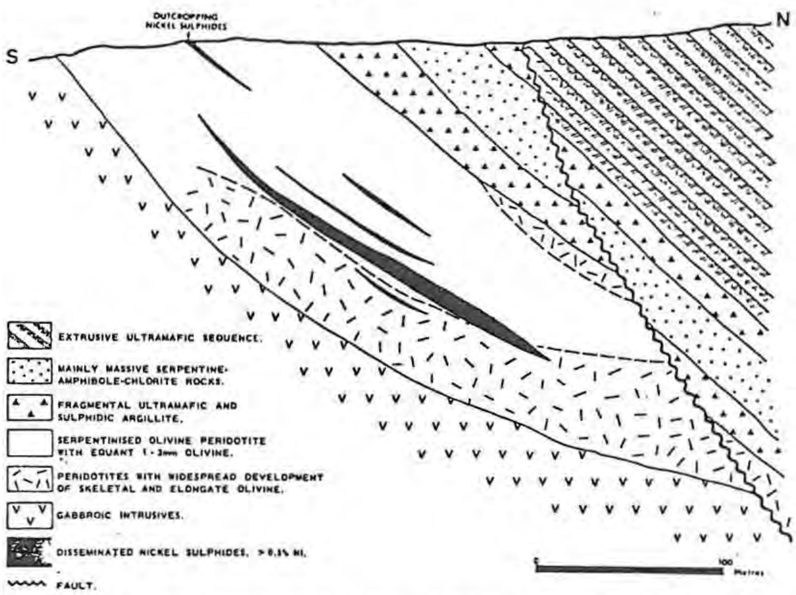
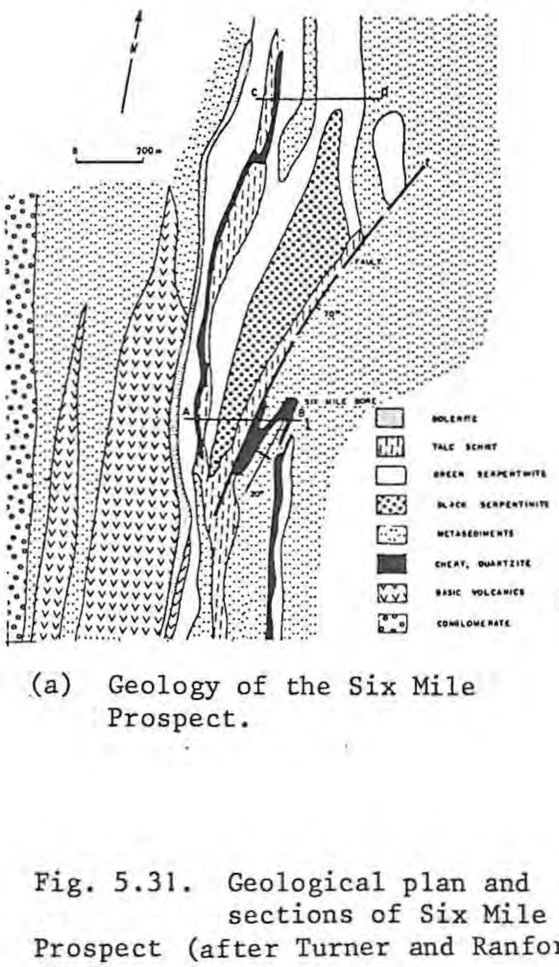
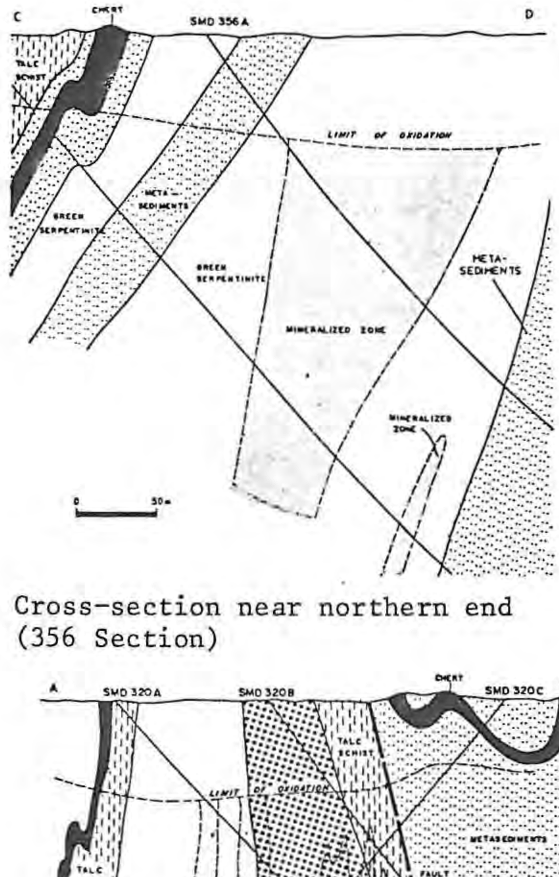


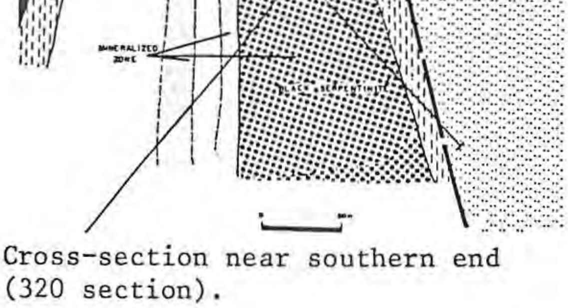
Fig. 5.30. Simplified cross-section through Mt. Clifford nickel deposit (after Travis, 1975).



(a) Geology of the Six Mile Prospect.



(b) Cross-section near northern end (356 Section)



(c) Cross-section near southern end (320 section).

Fig. 5.31. Geological plan and sections of Six Mile Prospect (after Turner and Ranford, 1975).

often as remobilized zones located entirely within the footwall metasediments (Fig. 5.32). The ores show a great variability in grade along strike and downdip and often form tabular and lensoid bodies or shoots defined by a specified assay-cutoff. At Perserverance three ore shoots, which may reach 600 m in length and a hundred metres in width individually, have been defined on the basis of a 1% Ni cutoff (Fig. 5.33) (Marston and Allchurch, 1975).

Many of the ores are spatially related to embayments in the footwall rocks and the largest zones of mineralization typically occur in the thickest portions of the lenses.

In some of the Forrestania ores,zones of sulphide mineralization are found in the internal and hangingwall portions of the dunites, but are of much less economic importance than the basal deposits, and generally consist of weak patchy disseminations (Porter and McKay, 1981) (Fig. 5.33). It should be noted that not all the deposits occurring in high grade metamorphic terranes contain massive mineralization. At Webbo Bore mineralization is disseminated throughout the intrusion and at Liquid Acrobat a broad zone of low grade disseminated mineralization is found in the central portion of the body (Legge, 1975; Porter and McKay, 1981).

It is apparent that there is a fundamental difference in the major sulphide minerals present between certain deposits and that this difference parallels the metamorphic grade. In unserpentinized dunites at Betheno and those at lower-most greenschist facies as at Honeymoon Well, the sulphide is predominantly pentlandite (with some rare alteration to heazelwoodite) and pyrrhotite is rare (Donaldson, 1981). The S/Ni ratio here varies between 0,7 and 0,8. Sulphides in serpentinites from higher metamorphic grades, that is upper greenschist, as at Mt. Keith and in large sections of the Six Mile deposit, are typically pentlandite and pyrrhotite (S/Ni = 1,8), and they are commonly associated with appreciable quantities of magnetite (Donaldson and Bromley, 1981). Chromite, pyrite and chalcopyrite occur as important accessories. The Perserverance deposit, which is at mid- to upper-amphibolite facies, has an estimated S/Ni of 4 and contains pyrrhotite and pentlandite in the ratio of 3:1.

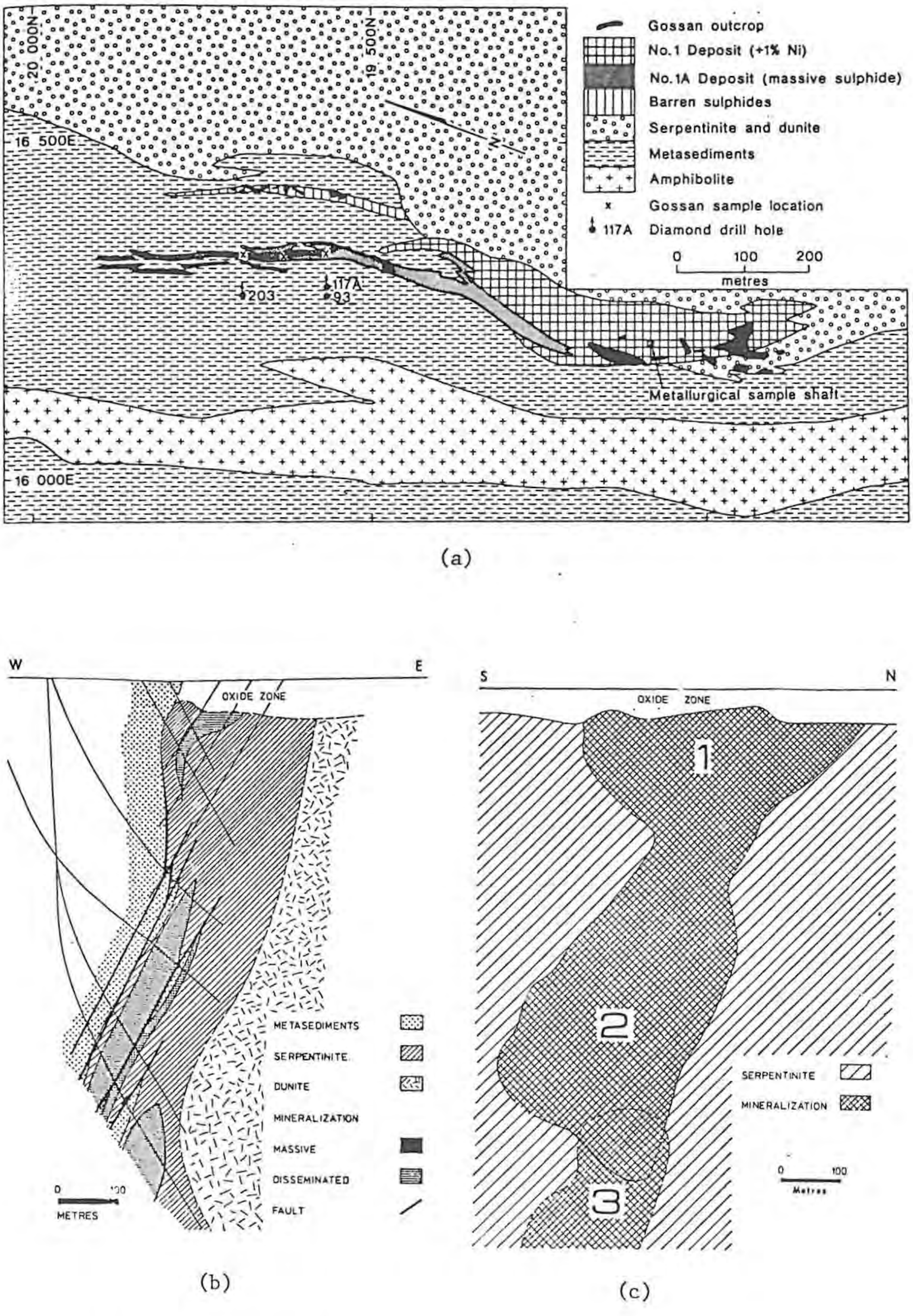
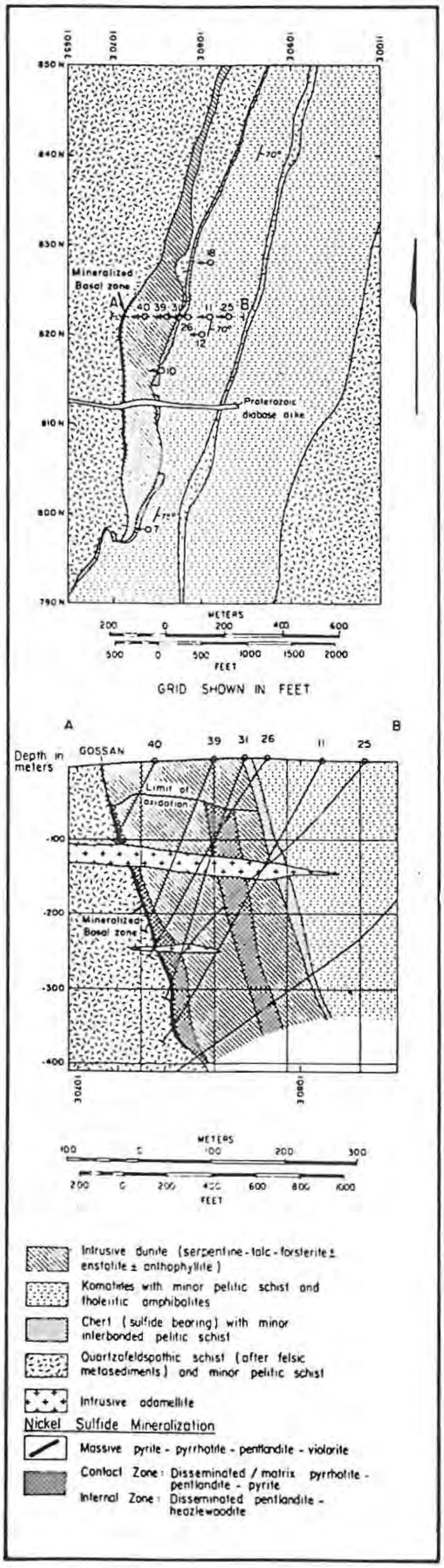
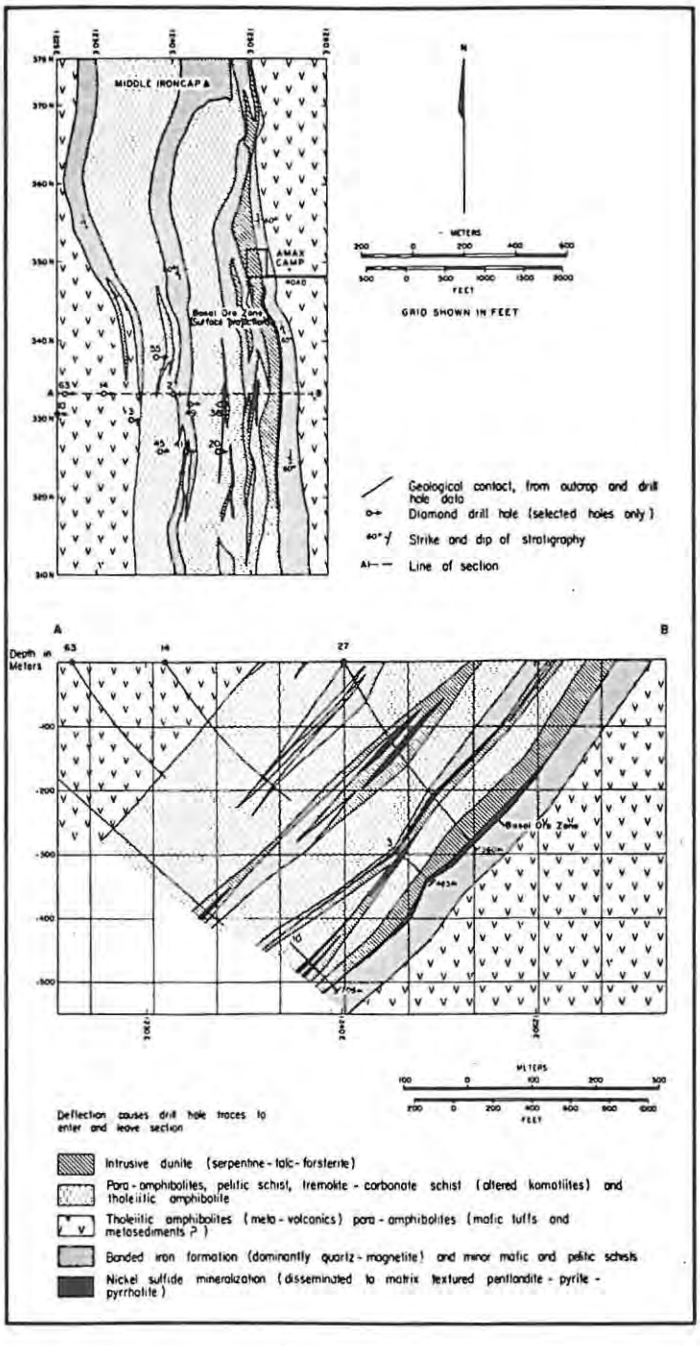


Fig. 5.32. Geological plan and cross-sections of the Perserverance deposit. Note (c) is a longitudinal projection showing the position of the ore shoots (after Martin and Allchurch, 1976; Thornber et al., 1981).



(a)



(b)

Fig. 5.33. Geological plans and cross-sections of some of the Forrestania orebodies; (a) New Morning and (b) Cosmic Boy (after Porter and MacKay, 1981).

The nickel-sulphide mineralogy of the low-grade disseminated ores hosted by the dunites is strongly controlled by Fe-related redox mechanisms coincidenct with serpentinization and talc-carbonation. The minerals vary from strongly reduced assemblages such as heazelwoodite-awaruite through pyrrhotite-pentlandite-magnetite to strongly oxidized pyrite-millerite-magnetite assemblages (Eckstrand, 1975). Other phases found include godlevskite, polydymite, vaesite, bravoite, cobaltite, nickeliferous linnaeite, and cubanite (Marston et al., 1981). This is because the very low abundance of sulphides in dunitic-hosted deposits allows them to be highly modified during metamoprhism; the sulphides are not self buffered, so silicate chemistry and altering solutions radically influence them. Massive sulphides are self buffered with respect to oxygen and sulphur and therefore, remain laregely unaffected by alteration reactions (Eckstrand, 1975).

Serpentinization and talc carbonate alteration of barren and weakly mineralized dunites in the Yilgarn block occurred without any apparent loss of major components (Si, Mg, Fe, Al, Cr, Ni) on a hand-specimen scale, although these elements were redistributed to new silicate, oxide, or sulphide phases over a distance of several metres (Donaldson, 1981). As well as the obvious introduction of H_2O during serpentinization, the bulk sulphur content of the unmineralized serpentinites (0,01% to 0,2% S), together with the common observation of fine-grained heazelwoodite with lizardite pseudomorphs after olivine, indicates a minor but significant introduction of sulphur with the serpentinizing fluid (Donaldson, 1981). Minor amounts of CO_2 and Cl were also added.

During the initial stages of serpentinization, olivine is converted to serpentine and magnetite (Eckstrand, 1975). H_2 is generated and reducing conditions (low fO_2) ensue. Opaque mineral assemblages characterized by awaruite or heazelwoodite are formed by the reactions : olivine + water = lizardite = brucite and lizardite + brucite + sulphur = lizardite + brucite + magnetite + heazelwoodite + water + H_2 (Donaldson, 1981). Sulphur addition during the early stages of serpentinization can result in about 60% of the original olivine-held nickel, that is 0,2%, being redistributed to original and newly-formed sulphides. Thus, in a typical disseminated dunitic-hosted ore containing 0,7% total nickel, perhaps 30% of the sulphide nickel (0,6%) is of metamorphic origin (Donaldson, 1981). Serpentinization at a higher temperature and increased CO_2 partial pressure, or metamorphism of the original lizardite-bearing assemblage, results in even more nickel being redistributed to the sulphide phase by the reactions : lizardite + brucite + magnetite + heazelwoodite + CO_2 + S = antigorite + magnesite + magnetite + Ni sulphide + water + H_2 (Donaldson, 1981).

During talc-carbonate alteration the serpentinite and magnetite are converted to talc and magnesite, which produce oxidizing conditions (high fO_2) that result in assemblages characterized by millerite (Eckstrand, 1975). If sulphur is added during talc-carbonate alteration, some of the silicate nickel may be redistributed to the sulphides by the reaction : antigorite + magnesite + magnetite + Ni sulphide + CO_2 + S = talc + magnesite + pentlandite + Fe sulphide ± magnetite + water + O_2 (Donaldson, 1981). Magnetite is largely consumed during talc carbonate alteration, and if the S activity is high, iron sulphides may form in addition to the nickel sulphides. Therefore, because of the additional Ni release some 40% of the total sulphide content of the disseminated talc-carbonate hosted ores is probably of metamorphic origin (Donaldson, 1981).

As outlined above low grade metamorphic reactions can upgrade the original low grade dunitic hosted ores. This has been shown to hold for the Black Swan deposit (Groves et al., 1974) and the Dumont deposit (Echstrand, 1975). It should be noted that this is not always the case. Nickel sulphide may be consumed during talc carbonate alteration (see reaction above) and thus, although a larger percentage of nickel occurs in the sulphide form, the sulphide fraction has a lower nickel tenor because of the additional sulphur added during the serpentinization and alteration. This has been shown to have occurred at the Mt. Keith-Betheno area by Groves and Keayes (1979).

The typical Honeymoon Well mineralization is extremely depleted in Cu when compared to other deposits and Ni/Cu ratios over 1000 are common. These ratios become lower as the metamorphic grade increases and average values for Mount Keith and Six Mile of 60 are much higher (Burt and Sheppy, 1975; Naldrett and Turner, 1977). The deposits at the highest metamorphic grade have very much lower ratios, for example at Perserverance the Ni/Cu ratio is approximately 25 and in the Forrestania ores it ranges from 21 to 44 (Martin and Allchurch, 1975; Porter and MacKay, 1981). It is possible therefore, that some Cu was introduced during both prograde and retrograde serpentinization (Donaldson and Bromley, 1981). Nevertheless, all deposits, as would be expected from their high MgO contents are strongly depleted in Cu and therefore would gain little in the way of additional income from the extraction of this element. Ni/Co ratios are as would be expected from the ultramfic character of the hosts, is large and range from 30 to 70.

The supergene alteration profile exhibited by the dunitic deposits is very similar to that observed in the volcanic type deposits. Supergene alteration profiles over the Perserverance and Mt. Keith deposits have been discussed in detail by Nickel et al., 1977 and by Butt and Nickel, 1981, respectively.

The low grade disseminated type of body is probably the easiest of all nickel sulphide deposits to evaluate. Many would have to be mined by large scale open pit methods because of their low grade. Estimations of tonnage and grade would be best evaluated on the basis of a set of oppositely inclined drillholes penetrating to a fixed depth corresponding to the final depth of the proposed pit floor.

The high grade "basal-hosted" deposits have many similarities to the volcanic komatiite-type of deposit in that their irregular shape and grade distribution make them exceedingly difficult to evaluate. As in the volcanic-type, ore reserve estimations are best calculated on the basis of accurate closely spaced section and level plans. Martin and Allchurch (1976) have discussed the sampling methods used in the evaluation of the Perserverance deposit. Three visually identifiable types of mineralization occurred : sparsely disseminated, heavily disseminated and massive ore. Frequency and log-probability diagrams of the assay data not only depicted the three fundamental classes of mineralization but also defined the nickel domains of each type. The sparse disseminations ranged from 0,4 to 1,0% Ni, heavy disseminations from 1,0% to 4,0% Ni, and massive ore exceeded 4% Ni. These classes where then used as basic controls in subsequent sampling and evaluation. The Perserverance deposit was evaluated by drilling inclined holes (60^{o}) so that intersections were made approximately every 60 m along strike and downdip. The spacing stemmed from experience gained on other projects, most notably the investigation of the Spargoville deposits. One-third of the BQ core was analysed, so that the remainder could be used for metallurgical testing. The sample limits depended both on the character of mineralization and lithology, but never exceeded 1,52 m. Specific gravities were determined on whole pieces of core, usually 0,2 m long, every 7 m intervals in mineralization and at 30 m intervals in unmineralized rock. The sample values were found to be log-normally distributed indicating that the distribution of grade was determined by structures larger than the size of the sample (Grant, 1981). This appears to be a characteristic of massive sulphide layers in any nickel deposit and the sampling spacing is more likely to be determined by external influences on the distribution of the massive ore, such as footwall embayments (Grant, 1981). A comparison between the values of core samples and the values of channel samples taken from the walls of development winzes suggest that this negative bias can be substantially reduced by taking larger samples (Grant, 1981). The large (19,2%) difference between diamond core sampling and channel sampling also reflects poor core recovery in the oxide zone with consequent poor representation. Although a large number of S.G. were measured, some difficulties were encountered in relating S.G. to grade, because samples, as stated in a previous section, containing similar S.G. values had widely differing grades. In nickel sulphide deposits where S.G. values are typically variable, it should be standard practice to measure the S.G. of each sample.

As in the case of the volcanic-hosted deposits there is abundant evidence for the early existence of magmatic sulphides in the dunitic pods (Lambert and Groves, 1981). It appears that both the grade and tonnage of these deposits is strongly dependent on the character of the original magmatic processes. Many of the deposits exhibiting high grade basal accumulations could have formed from static crystallization and fractionation of a peridotitic magma within a subvolcanic magma chamber. Those that are composed of centrally disposed low-grade disseminated mineralization may have formed from dyke-like bodies containing an olivine-rich crystal mush. The closely packed olivine crystals in this mush would have only contained a small amount of trapped intercumulus liquid and sulphide melt and furthermore, would have allowed little gravitational settling of the sulphides to form a major concentation of sulphide.

5.3 Proterozoic intrusive dunite-hosted deposits

5.3.1 Thompson (Manitoba) nickel belt

Nickel-copper sulphide mineralization spatially associated with ultramafic intrusions occurs in a complex elongate tectonic zone, known as the Thompson Mobile Belt, along the contact of the Churchill and Superior Provinces of northern Canada (Fig. 5.34). The deposits show many similarities to the smaller high grade type dunite associated deposits of Western Australia and are good examples of those developed in Setting III Group II (see Chapter 1).

The Thompson belt is underlain by variably migmatized gneisses comprising migmatitic gneisses, paragneisses, amphibolitic gneisses, and orthogneisses (Brooks and Theyer, 1981) (Fig. 5.34). These constitute a basement to a supracrustal assemblage comprising deformed and highly metamorphosed metasediments, lower grade (greenschist to lower amphibolite facies) basaltic to picritic metavolcanics, and ultramafic intrusions (Cranstone and Turek, 1976). The metasediments have been sub-divided into two groups: the Thompson and Pipe Groups. The stratigraphic succession in each passes upwards from sileceous rocks (felspathic quartzites and quartz-rich arkoses), through carbonates, to pelites, and finally metamorphosed iron formation The supracrustal assemblage which is found as linear belts on the western margin of the mobile belt, was infolded and down-faulted into the basement during the Hudsonian Orogeny. Elongate bodies of porphyritic diorite and granodiorite also outcrop within the belt.

To the north-west the Thompson belt is separated from the Churchill Province by a discontinuous cataclastic fault zone, the Setting Lake lineament (Cranstone and Turek, 1976) (Fig. 5.34). Numerous subparallel faults occur to the west of this lineament, which is up to 150 km long by 15 km wide. The Churchill province is composed of an east-west trending sequence of paragneisses derived from arkoses and greywackes, locally developed siliceous, calcareous and ferruginous metasediments, and bodies of granite, agmatite, and porphyroblastic gneiss (Brooks and Theyer, 1981; Cranstone and Turek, 1976).

The boundary between the Thompson belt and the Pikwitonei region is partially faulted (Fig. 5.34) and marks the limit of retrogressive amphibolite facies overprinting during the Hudsonian Orogeny (Russel, 1981; Brooks and Theyer, 1981). The lithotypes in the Pikwitonei region comprise hornblende- and pyroxene-granulites, crudely layered mafic granulites, and their retrograded equivalents (Cranstone and Turek, 1976). Numerous ultramafic and mafic dykes intrude these rocks.

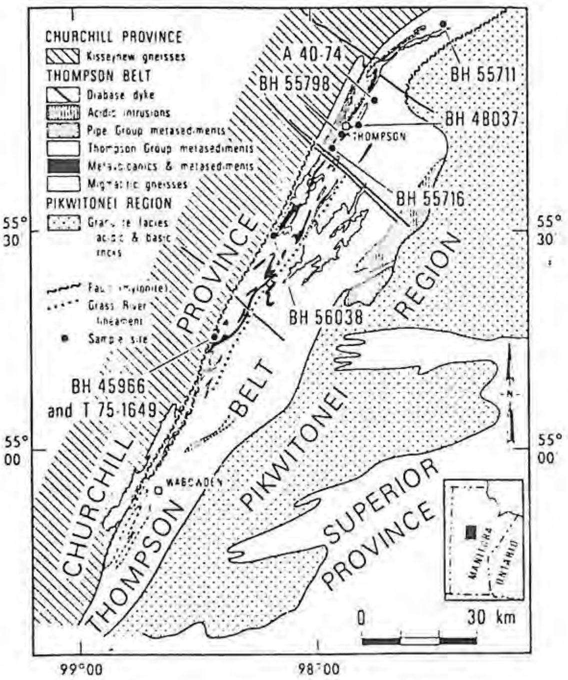


Fig. 5.34. Regional setting of the Thompson belt showing geological relationships and sample locations (after Brooks and Theyer, 1981).

The Pikwitonei region (Fig. 5.34) grades into the lower grade east-west trending sequence of granodiorites and tonalitic gneisses of the Superior Province. The metamorphic grade exhibits a constant decrease from the Pikwitonei towards the Superior Province.

The Thompson belt has a distinct geophysical expression. The setting Lake lineament is marked by a distinct gravity low, while gravity highs are present over the dense Pikwitonei granulites and the gneisses of the Superior Province. The Thompson belt is thought to mark the site of a major intracontinental rift zone because of the preponderance of large-scale bounding faults.

The supracrustals exhibit a complex deformational history (Brooks and Theyer, 1981). The earliest phase of deformation (1875-1825 My) is characterized by the development of sub-horizontal plunging folds and shearing. During the Hudsonian event (1775-2650 My) these early folds were crossfolded, resulting in the development of northeast-southwest trending elliptical structures, and earlier formed granulite facies assemblages were overprinted by amphibolite facies assemblages. The last period of deformation (1625-1550 My) was characterized by the development of shear zones and associated retrograde metamorphism. The Setting Lake lineament started forming between 2100 and 1800 My ago.

The nickel-copper sulphide deposits occur in,or in the immediate vicinity of, lenticular pods of ultramafic amphibolite and serpentinite (Peredery, 1979). The ultramafic amphibolites contain actinolite, olivine, orthopyroxene and spinel in varying proportions. The ultramafic amphibolites tend to occur only on one side of the serpentinites and exhibit gradational contacts with the latter. The amphibolitic rocks are commonly mineralogically layered, with the layering more or less parallel to the serpentinite contact. The layering is defined by varying amounts of amphibole, olivine, orthopyroxene and spinel. The ultramafic amphibolite-serpentinite bodies are strongly differentiated with the MgO content decreasing and the FeO content increasing towards the ultramafic amphibolite side of the bodies. In general the Al_2O_3, CaO, Cr_2O_3 and TiO_2 trends are in agreement with the iron-magnesia trends and nickel also shows a slight decrease towards the amphibolitic side. The rapid alteration of chromium and nickel values in the central portions of some bodies are indicative of cryptic layering. The rapid alternation of high MgO and high FeO within some ultramafic amphibolites are reflective of emplacement in a series of pulses. The relationships described above clearly indicate that both are derived from a common magma source. Both portions of the intrusions plot in the area of Al_2O_3 vs FeO/(FeO + MgO) diagram characteristic of komatiites. Some bodies are entirely ultramafic amphibolite and others entirely serpentinite.

The ultramafic amphibolite-serpentinite bodies may be concordant or discordant to the country rocks but are invariably highly deformed and characterized by a metamorphic texture overprinting an igneous texture (Peredery, 1979). The host intrusions show a strong regional structural control in that all are preferentially located along the Setting Lake lineament and many, including Moak, Mystery, Birchtree, Bowden and Manibridge, occur within or are enclosed by cataclastic fault zones (Fig. 5.35). Many of the mineralized intrusions are found in the vicinity of large domal structures and many are also preferentially located within metasediments.

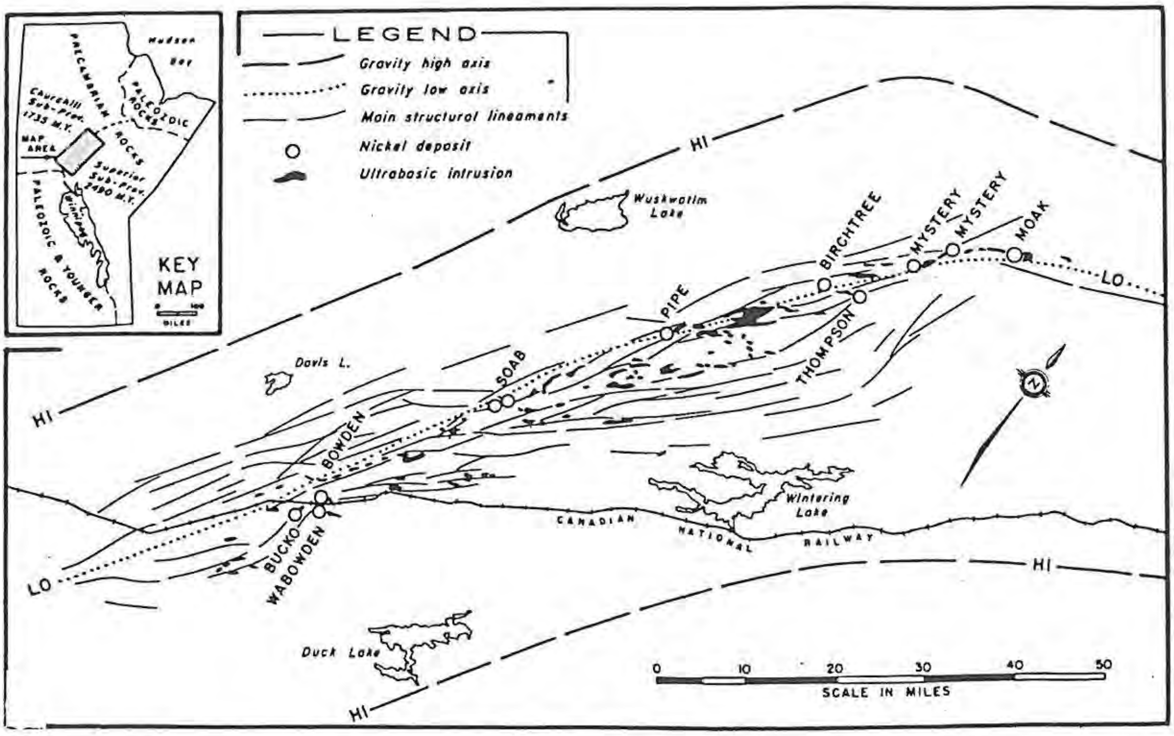


Fig. 5.35. Distribution of ultrabasic intrusions, nickel sulphide deposits, main structural lineaments and main gravity axes, Thompson Belt, Manitoba (after Kilburn et al., 1969).

Mafic sills and dykes, layered mafic complexes, high Mg (komatiitic) basalts with spinifex textures, pillowed metabasalts, and komatiitic flows are found associated with the intrusions but are barren of mineralization (Peredery, 1979).

Radiometric dating has indicated that the ultramafic intrusions and their associated mineralization were emplaced during the interval between the deposition of the Thompson belt supracrustals and the main phase of Hudsonian deformation, that is, between 2100 My and 1800 My and are therefore early Proterozoic in age. The intrusions are thought to have originally formed part of a flow or shallow intrusive sheet which formed an integral part of the sedimentary and volcanic accumulation in the rift. During later deformation the ultramafics were squeezed up and tectonically emplaced along major strike faults.

The Thompson belt holds some 67 313 000 tons of ore at an average grade of 1,89% Ni and 0,18% Cu. During 1980 some 12 700 tons of ore at an average grade of 0,13% Cu, 1,76% Ni, 0,10 g/t Au and 2,74 g/t Ag were recovered from the Pipe and Thompson mines, the only two producing mines (C.M.J. Staff, 1982). Several established mines are maintained on a standby basis following the cutback during 1971 and 1977 and include Soab South, Soab North, Pipe 2, and Birchtree.

Many of the Thompson orebodies show evidence of tectonic reworking and metamorphic remobilization. Four distinct classes of orebody are found within the belt and include those composed of disseminated ore confined to the ultramafic intrusions, those composed of disseminated and vein/stringer ores within the ultramafic, those consisting of massive and disseminated ores within the ultramafic, and finally, those composed of disseminated ore within ultramafic intrusions and massive or breccia ore within the adjacent metasedimentary and gneissic country rocks.

The Bowden and Bucko Lake deposits are examples of those orebodies primarily composed of disseminated ores within the serpentinised intrusions. The Bowden ore is hosted by a concordant sill-like series of ultramafic units intrusive into a steeply dipping zone of paragneiss (Kilburn et al., 1969). The Bucko Lake deposit is found within a discordant intrusion emplaced along a strike fault (Kilburn et al., 1969)(Fig. 5.36). The Bucko Lake intrusion has a marginal alteration envelope, consisting of anthophyllite-cummingtonite-biotite schist, formed as a result of later ganite intrusion. The sulphides are disseminated irregularly throughout the intrusion and in certain zones disseminated sulphides may be found a few centimeters away from the intrusive contact within the adjacent wall rocks or in fractures cross-cutting pegmatites. Therefore, although the mineralization is disseminated throughout the intrusion, its irregular distribution makes the deposits exceedingly difficult to evaluate. The deposits are of large tonnage and low grade with reserves of 30 million tons at 0,78% Ni and 80 million tons at 0,6% Ni being quoted for Bucko Lake and Bowden respectively (Coats et al., 1971). The low grade of the deposits is directly

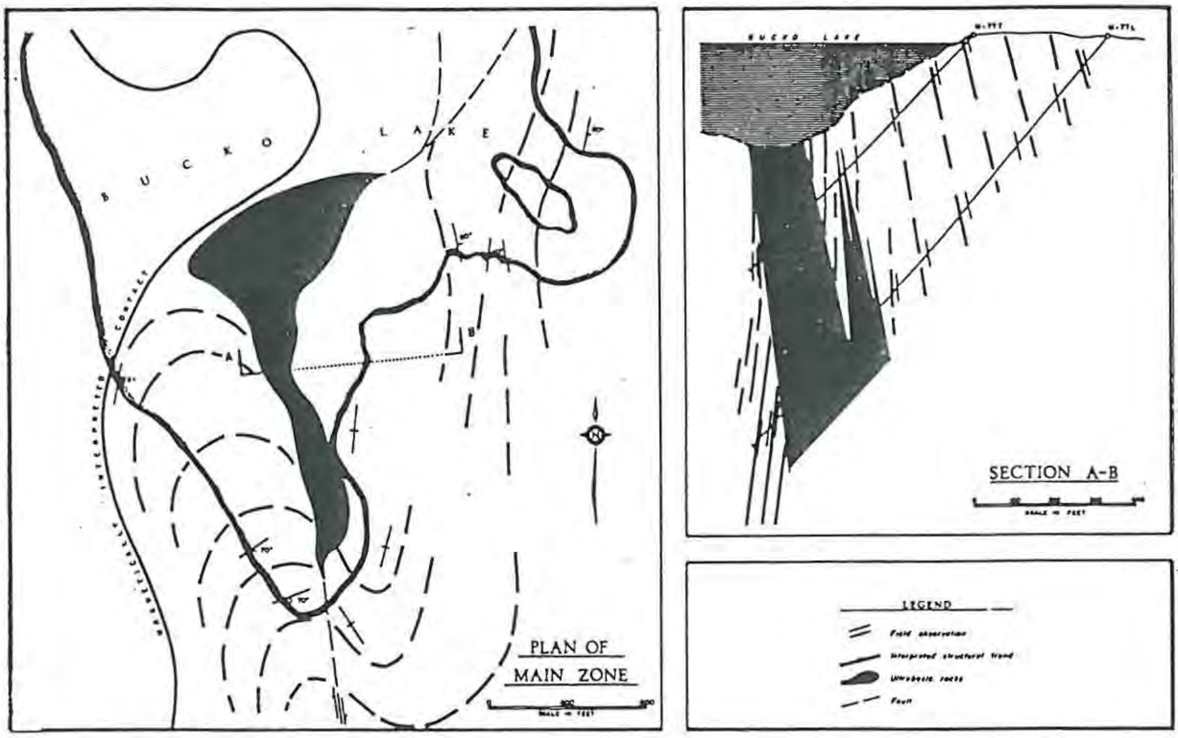


Fig. 5.36. Geological plan and section of the Bucko Lake deposit (after Kilburn et al., 1969).

attributable to the nature of the magma at the time of emplacement. The magma from both deposits is interpreted to have been composed largely of closely packed olivine crystals with a relatively small amount of interstitial liquid, part of which contained immiscible sulphide (Wilson et al., 1969). The near vertical attitude of these intrusions combined with the high solid content provided less opportunity for sulphide segration during either flow or after emplacement. These deposits bear a striking resemblance to the low grade-high tonnage dunitic-hosted deposits. The remaining classes however, are good examples of the high grade-low tonnage dunitic deposits (Setting III, Group II).

The Pipe No. 2 deposit belongs to the second-class of orebody - those composed of disseminated and vein/stringer ores within the ultramafic. The orebody occurs on a limb of a major refolded fold and is confined to a serpentinized peridotite (Fig. 5.37). Some

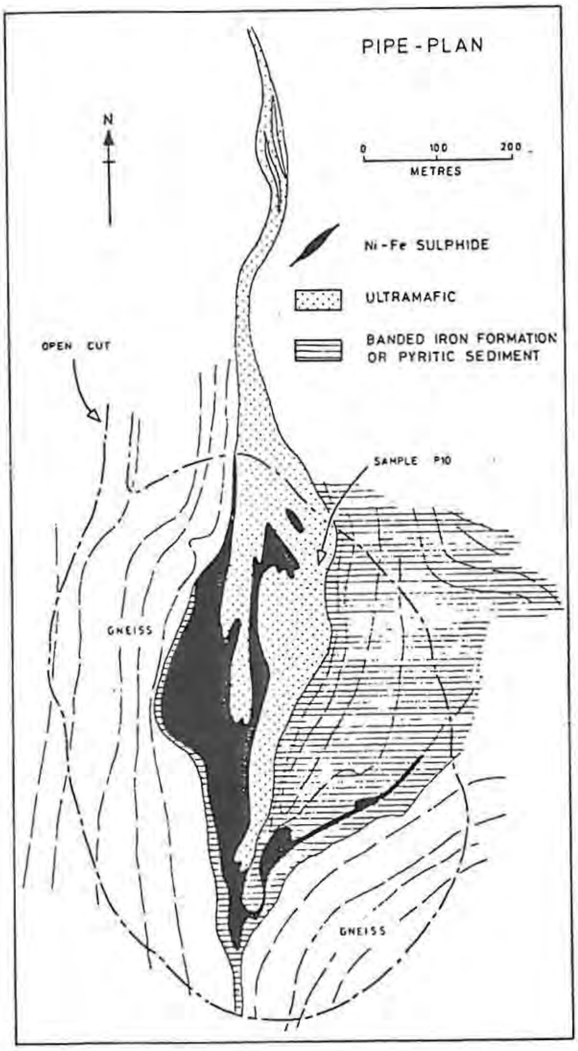


Fig. 5.37. Relationship between pyritic metasediment, host ultramafic and mineralization, Pipe Mine (after Hopwood, 1981).

14 million tonnes averaging between 0,5% Ni and 1% Ni occur over a strike length of 730 m and a width of 30 m to 200 m (C.M.J. Staff, 1980). The most widespread ore type comprises disseminated sulphide which shows a considerable variation in grade (Coats et al., 1972). The second major form of sulphide is a stringer-type whose distribution is controlled by a number of sub-parallel shear zones. These contain massive sulphide and are concentrated in the western half of the intrusion. The stringers range in size from microscopic to a few metres in width and locally penetrate the country rocks.

The Ospwagen deposit is quite similar to the Pipe deposit in that it contains a vein-network of sulphides within a serpentinised peridotite body (Lambert and Groves, 1981). The grade and tonnage in both deposits is directly dependent on the proportion of stringer ore to disseminated ore. As the whole ultramafic body is generally mineralized, the shape and size of the orebody is greatly dependent on the size and shape of the host intrusion.

The Manibridge deposit which is located at the south-western edge of the Thompson mobile belt is an example of those deposits which contain both massive and disseminated mineralization within the ultramafic host. The deposit is small, 1,409,000 tons, but contains a high average grade, 2,55% Ni and 0,27% Cu. The strongly serpentinized dunite or olivine peridotite host rock is an irregularly shaped, steeply dipping, conformable body which pinches out to the south-west along a fault zone (Coats and Brummer, 1971). The mineralization is concentrated in the hangingwall portion of the orebody and may be subdivided into a higher grade zone (> 3% Ni) and a lower grade zone (1% to 3% Ni) (Fig. 5.38). The high grade zone is a lens shaped body, some 100 m long, extending to a depth of some 415 m. The ore is preferentially located in the vicinity of a gentle bulge in the contact of the ultramafic. Subparallel lenses of lower grade ore occur adjacent to the higher grade zone and in a similar bulge to the south of the main mineralization. Two additional zones of lower grade occupy a more central position in the ultramfic body on the western side of an included segment of country rock. Granite pegmatite, varying in width from a few centimetres up to 17 m, has intruded the orebody.

Structural deformation and metamorphism, and granite intrusion have disrupted the continuity of the ores, and have produced structural and mineralogical changes that have caused difficulties in both evaluation and mining. The ore types are broadly classed as primary or secondary remobilized (Coats et al., 1976). The former includes disseminated, disseminated to net-textured, net-textured, and massive ores, while the latter includes net textured to mobilized, blotchy, massive mobilized and shear mobilized. Fig. 5.39 and Fig. 5.40

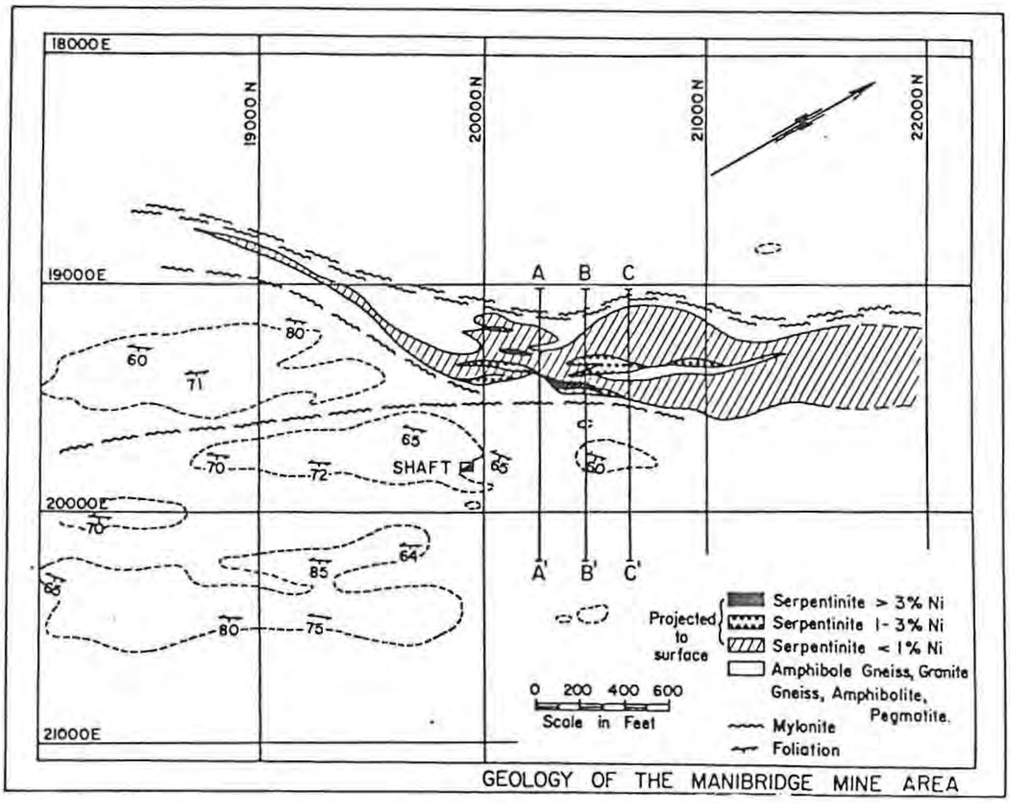


Fig. 5.38. Geology of the Manibridge Mine area (after Coats and Brummer, 1971).

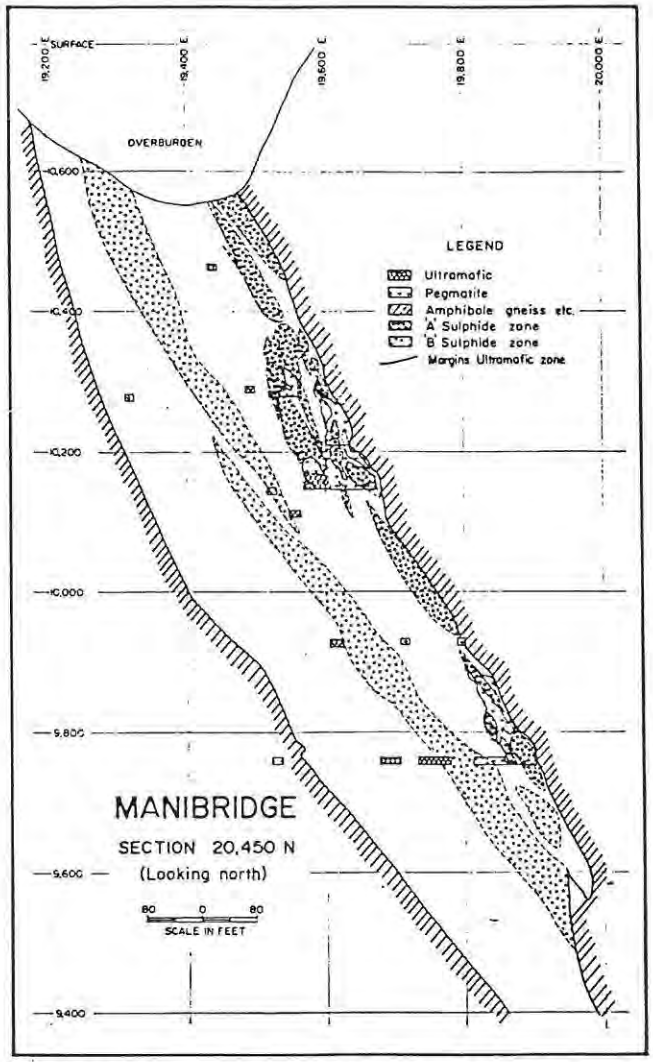


Fig. 5.39. Geological section 20,450N, Manibridge. The A zone is the high grade (1-3% Ni) zone while the B zone is the low grade zone (after Coats et al, 1976).

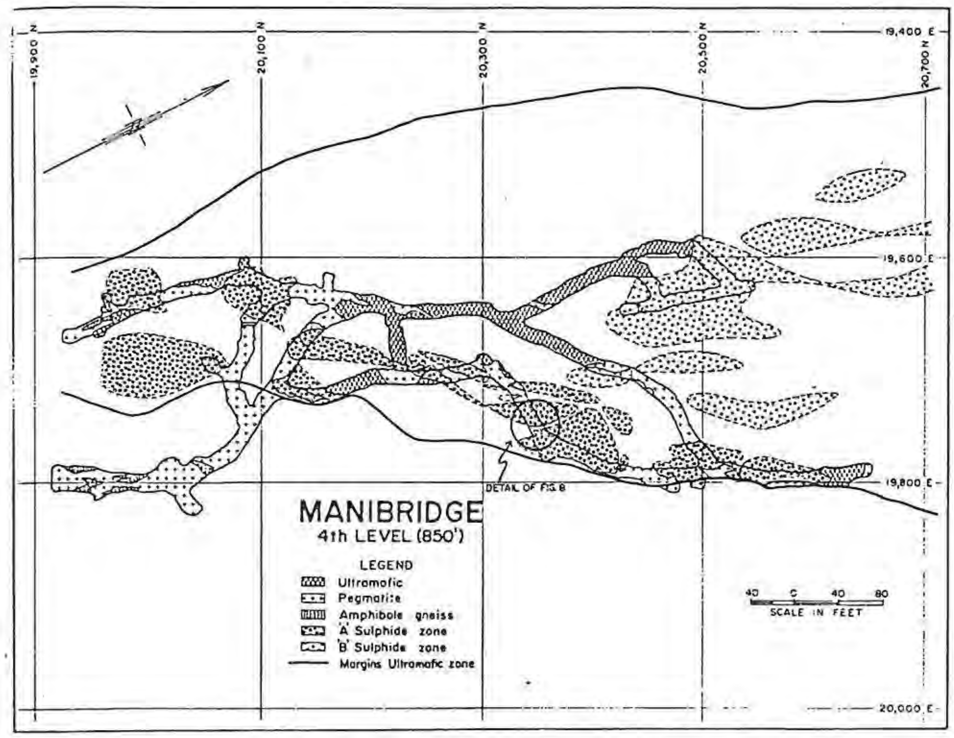


Fig. 5.40. Geological plan of the fourth level at Manibridge (after Coats et al., 1976).

are a section and level plan respectively through the main mineralized area in Fig. 5.38 and aptly illustrate the complexity of the ore zone. Incipient mobilization of the ore is recognized in the net to mobilized group where amalgamation of the sulphides has produced small patchy areas. Localized sulphide movement over distances measureable in millimetres culminated in the formation of strongly orientated blebs of ore up to 7 mm in diameter which are interconnected by sulphide veinlets. This is known as blebby ore and the host serpentinite matrix is recrystallized to a matte of subparallel serpentinite veinlets with no textural evidence of an original cumulate origin. Massive remobilized sulphides occur as veins, ranging in size from minute stringers to 30 cm wide seams filling fractures a few metres in length, or more commonly as diffuse patches. The massive ores are consistently coarser grained and their distribution within the general limits of the A zone suggests sulphide movement over distances not greater than a few metres. Although they contain a high nickel grade, they are quantitatively small in tonnage and occur in sheared and fractured pegmatite as well as ultramafite. The shear mobilized type is located with the sheared matrix to ultramafic and pegmatite blocks. All the primary ores are low in copper and consist primarily of pyrrhotite and pentlandite, but a lower Cu/Ni ratio in the blotchy and massive remobilized ore confirms the generally recognized higher mobility of chalcopyrite under the metamorphic and deformational conditions in the Thompson belt. Fig. 5.41 is a sketch map of part of a stope at Manibridge showing the complex distribution of high grade ore, low grade ore, and barren inclusions. The figure clearly illustrates the day to day problems in obtaining a good grade control as well as the difficulty in delineating accurate ore reserves.

At Moak the serpentinite body hosting the nickel sulphide mineralization has a synformal shape and is concordant with the enclosing sediments (Coats et al., 1972). The sulphide content of this orebody, as at Manibridge, is extremely variable ranging from scattered disseminations with only background nickel values to massive sulphide zones a few metres thick.

The Thompson orebody occurs within a downward facing steeply plunging antiform-synform (Hopwood, 1981) (Fig. 5.42). The deposit is the largest within the mobile belt and contains 25 million tons

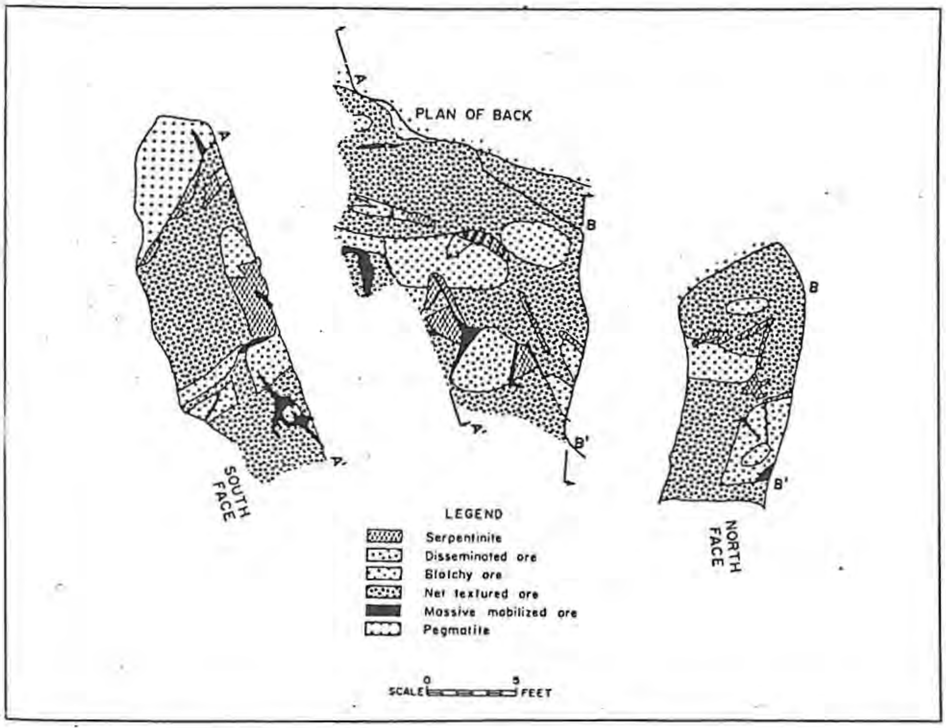


Fig. 5.41. Sketch map of part of 3A stope, Manibridge, illustrating the distribution of textural ore types (after Coats et al., 1976).

at 2,5% Ni and 0,2% Cu (E.M.J. Staff, 1981). The locus of the ore is a "schist" zone which is continuous over the length of the structure and is conformable to both the overlying and underlying formations (Zurbrigg, 1963). The "schist" zone consists of biotite schist, graphite schist, sulphide-bearing iron formation; and phlogopitic skarn. The Thompson orebody is a fine example of the control of nickel sulphide mineralization by structure. The main concentration of ore occurs along the southern portion of the eastern limb of the fold, around the nose of the fold and within associated parasitic folds (Fig, 5.42). The ore pinches and swells along strike and downdip, with the result that mining widths vary from 2,5 m to a maximum of 45 m (Fig. 5.43). As a result stope outlines are highly irregular and may include a considerable amount of dilution from barren wall rock. The sulphides occur as fine grained masses, lenses and veinlets in the schist, as coarse grained masses and stringers where the host rock is less schistose and as stringers, veinlets and disseminations in the peridotite. Both the coarse- and fine-grained masses are termed breccia sulphides in recognition of the numerous barren wall rock inclusions contained in them. The remnants range in size from mere specks to several inches in diameter, and often have extremely ragged

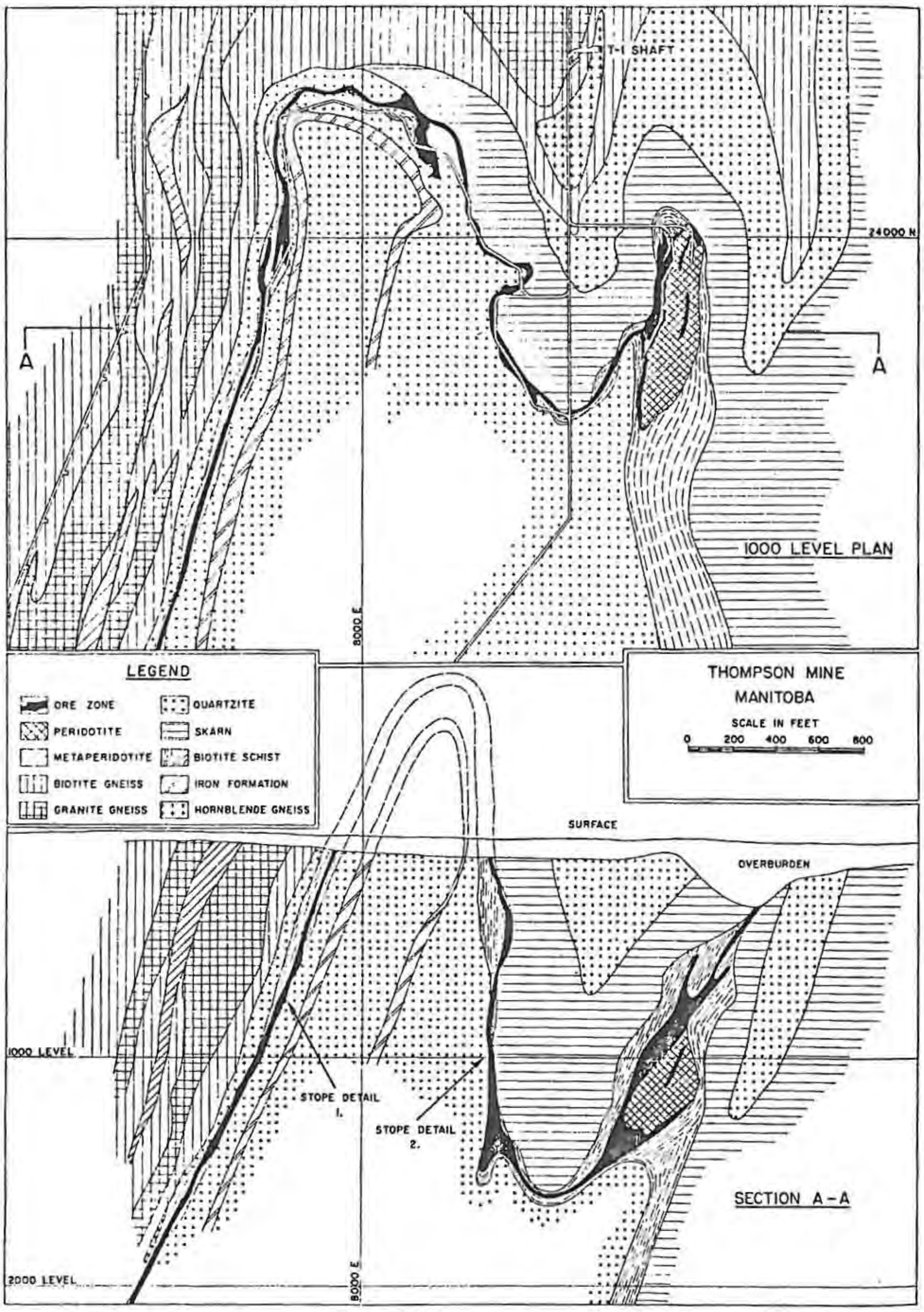
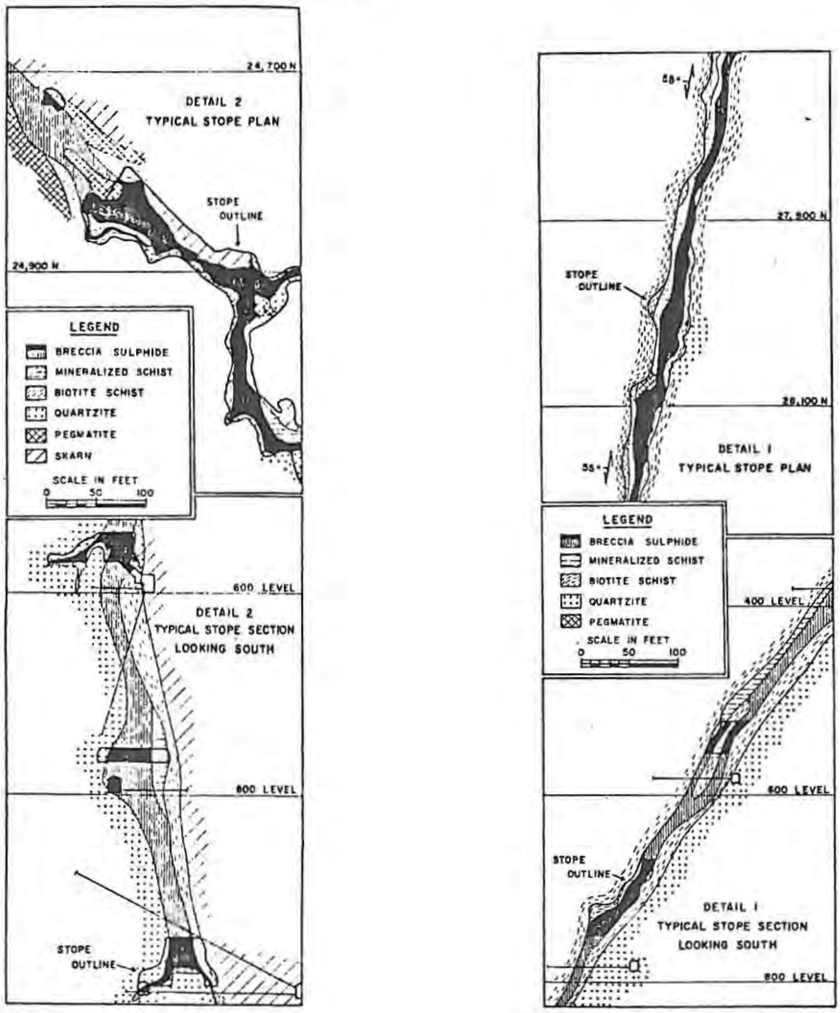


Fig. 5.42. Section and level plan of the Thompson mine (after Zurbrigg, 1963).

contacts with the country rock. The fragments are composed of folded graphitic schist, graphitic quartzite and siliceous black schist and act as a serious dilutent to the grade of the ore in certain zones. The host peridotite is thought to have been emplaced along a shear zone now marked by the "schist" zone (Hopwood, 1981). Subsequent folding allowed migration of sulphides along schistosity planes, and concentration of sulphide in dilational fractures as well as in the hinge zones of folds.



(a) (b)

Fig. 5.43. Typical stope plans in the Thompson Mine. See Fig. 5.42 for location (after Zurbrigg, 1963).

The Birchtree and Soab South mines are similar to Thompson in that they contain quite a large amount of sulphide in the gneissen and/or sediments (Coats et al., 1972). The irregular shape and size of this class makes them the most difficult of all the Thompson orebodies to evaluate, but the preponderance of massive ores makes them a much more viable economic proposition.

The ores of the Thompson group of deposits are typically composed of pyrrhotite and pentlandite with lesser amounts of chalcopyrite, cubanite, pyrite, magnetite and violarite. As would be expected from the composition of their hosts, Ni/Cu ratios are high and range from 10:1 or 15:1 at Thompson to 20:1 at Bucko Lake. Very little copper is reported in some deposits and therefore, copper is not a major contributor to the revenue obtained from mining.

The ultramafic rocks are almost completely altered to lizardite and/or antigorite, talc, amphibole, chlorite, and/or carbonate. Consequently as in other komatiitic hosted deposits the high talc content of the ore may result in losses during benificiation. This is particularly true where fibrous serpentinite or talc has penetrated the interstitial sulphide ores. Ore from the Pipe Mine is characterized by a serpentinite gangue content which can vary from 25 to 90% of the ore weight. Even though marked improvements have been made, nickel losses in the tailings still amount to 0,25% (Joe, 1976). Unlike the Archaean dunitic-hosted deposit little upgrading of the nickel sulphides has occurred during serpentinization.

The Thompson ores also contain a fair amount of pentlandite as exsolution bodies within the pyrrhotite and rougher tailings are reground and scavenged to recover this residual pentlandite (C.M.J. Staff, 1980). By rejecting more pyrrhotite in the milling process, the SO_2 emissions at the smelter have been lowered, but as a result more nickel is lost in the form of pentlandite exsolution lamallae present within the pyrrhotite.

As in most nickel sulphide deposits alteration as a result of the mineralization is absent and this hampers both exploration and underground developments.

Underground mining at the Thompson mine has been dominated by cut-and-fill stopes, with crown pillars removed by undercut and fill (E.M.J. Staff, 1981). Some of the lower grade deposits, for example Pipe, have been mined mainly by open pit. Many of the deposits are overlain by a thick cover of muskeg which greatly hampers initial development. At the Pipe open pit it took two years to drain an area containing approximately 13 million cubic metres of muskeg and after this an additional 13 million cubic meters of cover had to be removed (C.M.J. Staff, 1980). The strongly sheared walls of many of the deposits create poor ground conditions and at the Pipe open pit, sediments along the east wall tend to break off along shear planes (C.M.J. Staff, 1980). The walls have to be supported by grouted cable anchors and screening, resulting in a considerable amount of additional expenditure.

The ores are generally regarded as metamorphosed magmatic ores derived from the gravity settling of immiscible oxy-sulphide liquids from ultramafic magmas (Lambert and Groves, 1981). However, in many cases, the volume of sulphide is high when compared to the volume of peridotite, and it is felt by authors that the peridotite could not have been the sole source of sulphur (Coats et al., 1972). Many of the larger and higher grade deposits are spatially associated with graphitic metasediments and/or sulphide-bearing iron formations. The assimilation of sulphur from these sediments could have provided an additional source of sulphur. Detailed studies by Naldrett et al. (1979) on the Pipe deposit indicate that these magmas were depleted in Ni, Cu, Pt, and Pd relative to most komatiitic deposits and they suggest an origin involving localized assimilation of barren country rock sulphides.

5.3.2 The Ungava (Cape Smith-Wakeman Bay) nickel belt

The nickel deposits of the Cape Smith-Wakeman Bay fold belt provide another example of nickel sulphides associated with Proterozoic rocks of komatiitic affinity. The deposits exhibit strong similarities to the high grade-lower tonnage dunitic hosted ores of western Australia and are good examples of the Setting III, Group 2 deposits.

The fold belt is situated along the Churchill-Superior boundary and is consequently, in structural setting, identical to that of the Thompson nickel belt (Fig. 5.3). The belt comprises a sinuous folded volcano-sedimentary sequence which overlies the Archaean craton of the Superior Province unconformably. Essentially the belt is composed of a basal sequence of red beds, phyllites, siltstones, and dolomites, overlain by an upper unit comprising volcanics and intrusive sills of tholeiitic and komatiitic composition (Schwartz and Fujiwara, 1977; Moore, 1977). The entire succession is some 6000 m thick. Thomas and Gibb (1977) regard the fold belt as being a vestigal suture zone between collided protocontinents. Other workers feel that the sediments and volcanics fill ensialic basins in an incipient rift zone (Lambert and Groves, 1981).

Three rich deposits, as yet unmined, Raglan, Katinig, and Cross-Lake occur in discontinuous lensoid-shaped peridotitic sills (Naldrett et al., 1980a). The bodies were preferentially emplaced along a single stratigraphic zone, some 64 km in length, near the contact between the lavas and underlying sediments (Naldrett et al. 1980a). The largest deposit so far defined is Katiniq, with reserves estimated at 10,2 million tonnes at an average grade of 2,4% Ni.

The magmas hosting the ores are much less magnesian (19 wt% MgO) than typical Archaean peridotitic komatitiites. High magnesian basalts overlie the ore-bearing intrusions and contain lenticular bodies of pyroxenite which are thought to represent shallow-level sills or ultramafic flows. Irregular stock-like bodies of pyroxenite are also present and are thought to represent feeders to surface volcanism. Whole rock analyses and major element plots of data from the Katiniq sill suggest a comagmatic origin for the main sill, the pyroxenites and basalts through fractional crystallization of olivine followed by clinopyroxene (Naldrett et al. 1980a). Whole rock geochemistry, textural evidence, including the occurrence of clinopyroxene micro-spinifex and unsettled peridotitic textures, support the classification of the ore-bearing series as komatiitic. It is probable that the ore-bearing sills acted as 'holding chambers' from which the magmas, depleted of much of their olivine and sulphide, then continued closer to the surface (Naldrett, 1980).

The sills hosting the ore deposits are characteristically strongly differentiated. The Katiniq sill is dominantly composed of serpentinized peridotite (Naldrett et al., 1980a). There is however, a continuous gradation in rock types from serpentinized dunites through wherlites, to metapyroxenites (Fig. 5.44). The serpentinized rocks contain variable amounts of serpentinite, chlorite and talc; while the metapyroxenites contain tremolite after augite in a chloritic matrix. As in the other types of dunitic ores, these fibrous and platy minerals may act as deleterious constituents in the floatation of sulphides. The spatial relationship between these rock types indicates that the sill is in fact composed of three to four separate symmetrically zoned units each consisting of a clinopyroxene-poor core and a pyroxene rich margin. These units probably represent three discrete pulses of intrusion (Naldrett et al., 1980a).

The ores at Katiniq are localized by topographic lows in the footwall, and there is a tendency for the sulphides to be banked up on one side of these lows (Fig. 5.44). At Cross Lake the sill has been preferentially

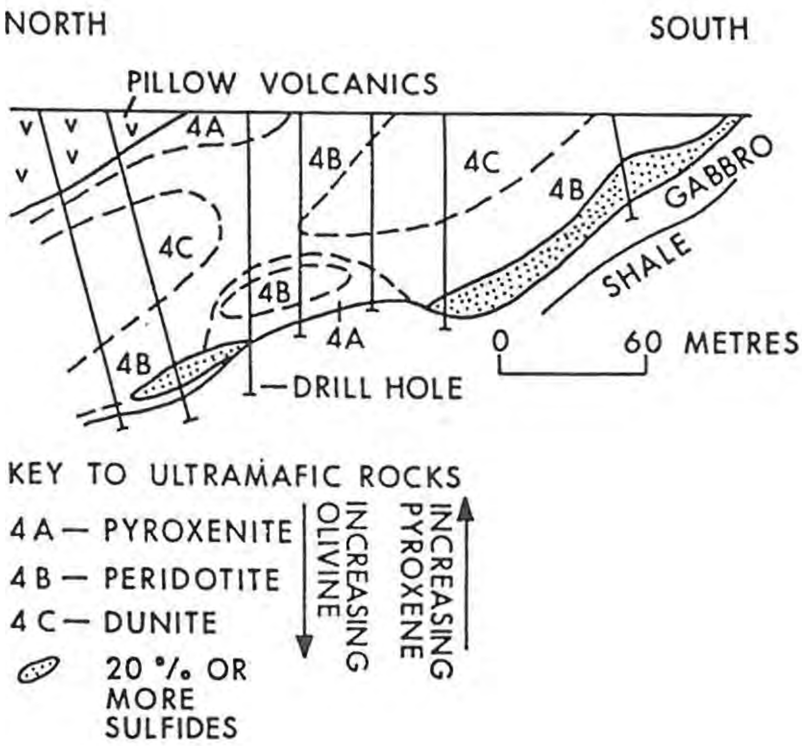


Fig. 5.44. Cross-section through the Katiniq mineralized ultramafic intrusion illustrating the basal control of the nickel sulphide ore and the zonal distribution of olivine and clinopyroxene (after Barnes, 1979, from Naldrett, 1980a).

emplaced into a pre-existing synform within the country rocks (Kilburn et al., 1969). Nickel sulphide is concentrated at the base of the sill within prominent subsidiary flexures in the fold surface (Fig. 5.45).

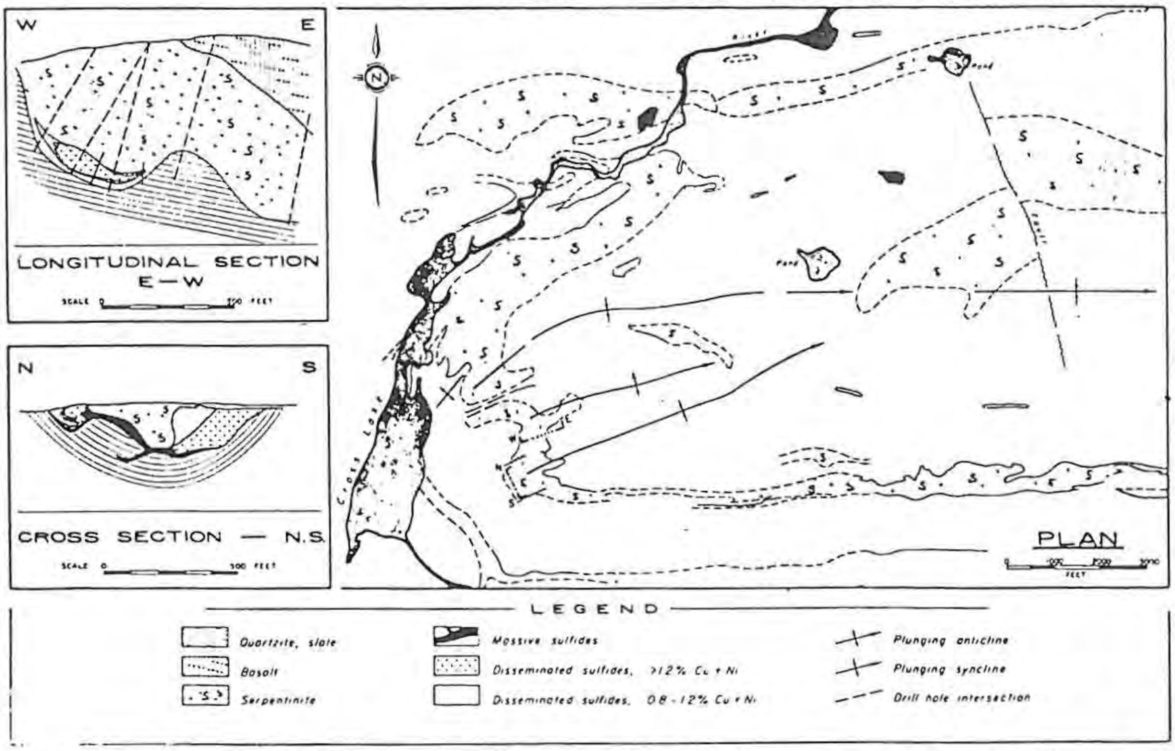


Fig. 5.45. The Cross Lake deposit (after Kilburn et al., 1969).

The shape, size and continuity of the deposits are therefore controlled by the configuration of these footwall depressions. As in many other nickel sulphide deposits, the orebodies are irregular lenticular-shaped masses and are consequently difficult to evaluate and mine.

The orebodies show a characteristic downward gradation from massive to disseminated. Three distinct textural types are present in the Katiniq sill (Naldrett et al., 1980): a fine dusting of disseminated grains and small blebs interstitial to silicate minerals; net-textured ore, consisting of a continuous network of sulphides enclosing 30% to 60% of the serpentinised olivine grains; and massive sulphides. The net-textured ore accounts for approximately 80% of the economically recoverable ores at Katiniq. The massive ores are located immediately above or close to the footwall of the sill and show a sharp contact against the overlying disseminated ore. The textural relationship of the ores is very similar at Cross Lake (Kilburn et al., 1969). Here, massive sulphide sheets at the base of the sill are overlain by disseminated sulphides which then show a progressive decrease in concentration towards the upper portions of the sill. However, frequent modifications to this pattern do occur. At Katiniq, bodies of massive sulphide are found within the net ore, massive sulphide zones may have no overlying net zone, and frequently, massive sulphides may be absent beneath major intersections of net-textured ore (Naldrett et al., 1980a). As a result of these textural relationships, the Ungava deposits show a strong resemblance to many other nickel sulphide deposits in that they have a sharp geological footwall cutoff and an irregular assay cut-off in the hangingwall. Furthermore, they also have another characteristic shared by many nickel sulphide deposits, in that the grade is dependent on the proportion of massive to disseminated ore.

The mineralogy of the ore is simple, consisting entirely of hexagonal pyrrhotite, pentlandite, chalcopyrite and magnetite, the latter being rare but more abundant in the massive sulphides. Pentlandite occurs in all stages of exsolution from pyrrhotite and is found as lamallae and flames along the basal parting, grain boundary segregations, and coarse eyes (Naldrett et al., 1980). Consequently, because of this complex intergrowth, major losses in nickel recovered may be incurred if the ore is not ground fine enough.

The average Ni/Cu ratios are commonly between 3 and 5 (Naldrett, 1973). The Katiniq sill shows a Ni/Cu ratio of 3,5 and a Ni/Co ratio of 48 (Wilson et al., 1969). The Ungava deposits are thus enriched in copper and cobalt when compared with ultramafic hosted deposits (Lambert and Groves, 1981). This combined with their high nickel values makes them very attractive economic propositions.

The Ungava deposits have (Pt + Pd)/(Ru + lr + Os) ratios of nearly 6 and substantially-higher-than-chondritic levels of Pt and, in particular, Pd (Naldrett, 1981). This is in marked contrast to the generally low values of Archaean komatiitic-hosted deposits and is an added 'sweetner' to the overall grade of the ores. A possible explanation for the high P.G.E. and Cu content of the Ungava ores lies in the fact that they contain much lower MgO contents than typical Archaean komatiites.

Low grade metamorphic modifications of the primary ore textures is common (Kilburn et al., 1980). Sulphides often replace original olivine grains along fractures. Fibrous serpentinite may also penetrate interstitial sulphide areas. Such changes often result in an increase in sulphide content of the rock to 70% or 80% (Naldrett et al., 1980).

The deposits may exhibit fairly strong mineralogical and compositional zoning. At Katiniq the Ni/Cu ratio is much lower in the massive sulphide ores than in either the net-textured or disseminated ores, which generally have similar ratios. This data, together with evidence of textural modifications and the occurrence of massive ore even in the disseminated zones, is taken to support the contention that much of the massive sulphide is the product of metamorphic concentration and remobilization of sulphides over short distances (Naldrett et al., 1980).

The ores are again generally regarded as magmatic ores formed by the gravity settling of immiscible oxy-sulphide liquids from ultramafic magmas. The textural relationship of the ores is consistent with the billiard ball model of Naldrett (1973) for gravity settling of an immiscible sulphide liquid phase. The concentration of sulphides in topographic depressions is interpreted as indicating that settling and segregation of sulphides occurred during flowage of the host magma, and that the sulphide concentrations owe their position to flow separation and riffling of the sulphide liquid during emplacement (Naldrett et al., 1980a). Wilson et al. (1969) drew attention to the concentration of olivine towards the centre of a single unit and attributed the variation to flowage differentiation of an olivine phenocryst-charged magma, with migration of suspended particles to the centre of the flow channel. This process would have aided the separation of a low viscosity sulphide melt from the more viscous olivine-rich magma.

5.4 Deposits associated with tholeiitic intrusions

Certain nickle-copper sulphide deposits are found in layered differentiated ultramafic-mafic complexes of Archaean age which are intrusive into the surrounding granite-greenstone country rocks. Host intrusions are small and generally less than 100 sq. km. Although many intrusions have a kmomatiitic affinity (e.g. Mt. Sholl, Empress), others have been derived from tholeiitic magmas (e.g. Lynn Lake, Carr Boyd, and the Pechenga group of deposits).

5.4.1 The pipe-like deposits

The most characteristic feature of these deposits is their form. The orebodies and host intrusions are typically pipe-like in shape, and are generally irregular, both laterally and vertically.

At Carr Boyd the deposits are found in sulphide-bearing noritic pegmatoids (bronzitite-sulphide-pegmatoids) intrusive into a cyclically layered ultramafic-mafic complex (Schultz, 1975; Purvis et al.,1972). The sulphide-bearing bodies are pipe-like breccia intrusions 20 m to 60 m across and 300 m deep. They are restricted to a dunite-trocholite-olivine anorthosite sequence and are thought to represent residual liquids derived from the fractional crystallization of these rocks. Not all the pegmatoids are mineralized, but three separate shoots of ore have been located within the east-northeast striking zone of pegmatoids (Fig. 5.46 and Fig. 4.47). The No. 1 shoot has average plan dimensions of 70 m by 10 m and a depth extent of 200 m. The No. 2 shoot which lies some

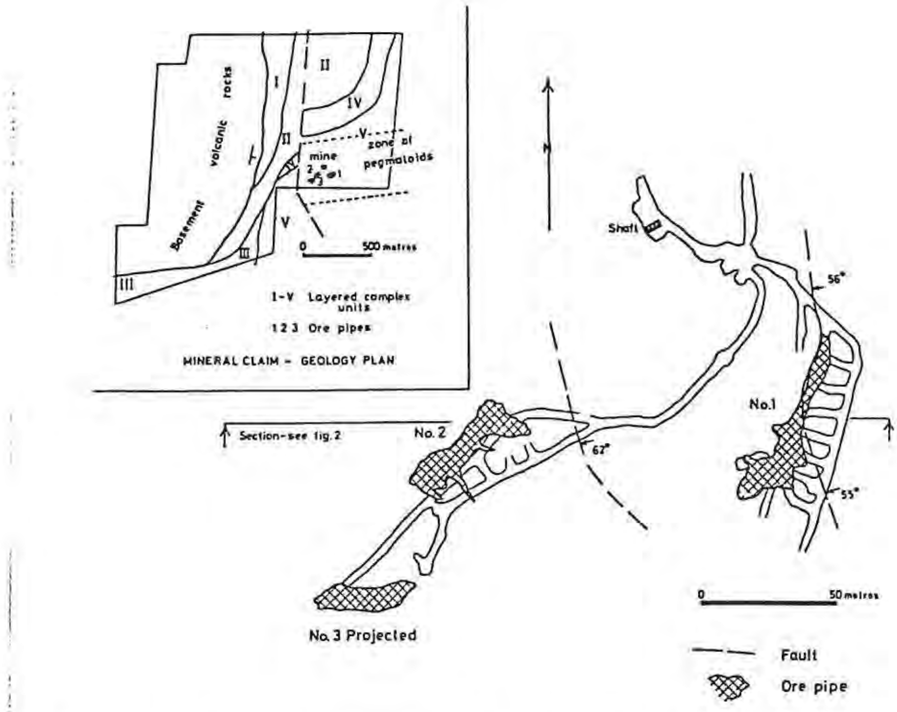


Fig. 5.46. Carr Boyd : 106 m level plan (after Schultz, 1975).

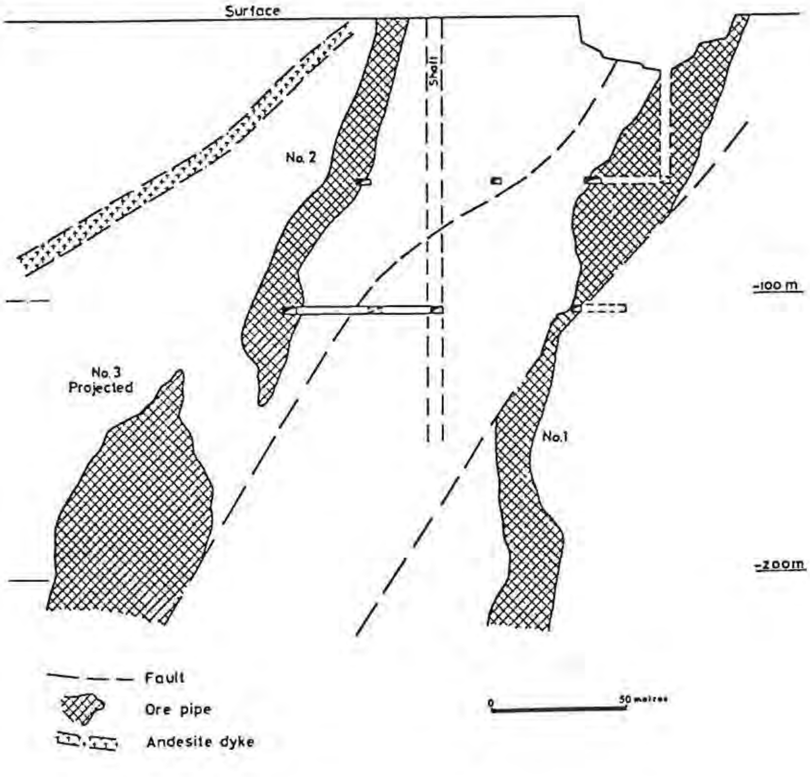


Fig. 5.47. Longitudinal section through the Carr-Boyd deposit (after Schultz, 1975).

120 m to the west, has average plan dimensions of 50 m by 10 m and a depth extent of 120 m. The No. 3 shoot is located down plunge from the No. 2 shoot and extends from 140 m below surface to just below 200 m. The plan dimensions are some 70 m by 12 m.

The Empress deposit lies on the south-western margin of the Empress Complex, a diorite-tonalite stock rimmed by mafic rocks on it's western side (Sutton, 1979; Sharpe, 1974; and Eales, 1974). The rock types are thought to be consanguineous and are intrusive into Archaean andesitic lavas. A wedge-shaped plug consisting of a peridotite-pyroxenite core and an amphibolite (meta-gabbro) envelope is the host to the mineralization (Fig. 5.48). The plug has an average width of 45 m and a variable dip of between 60° and 80°

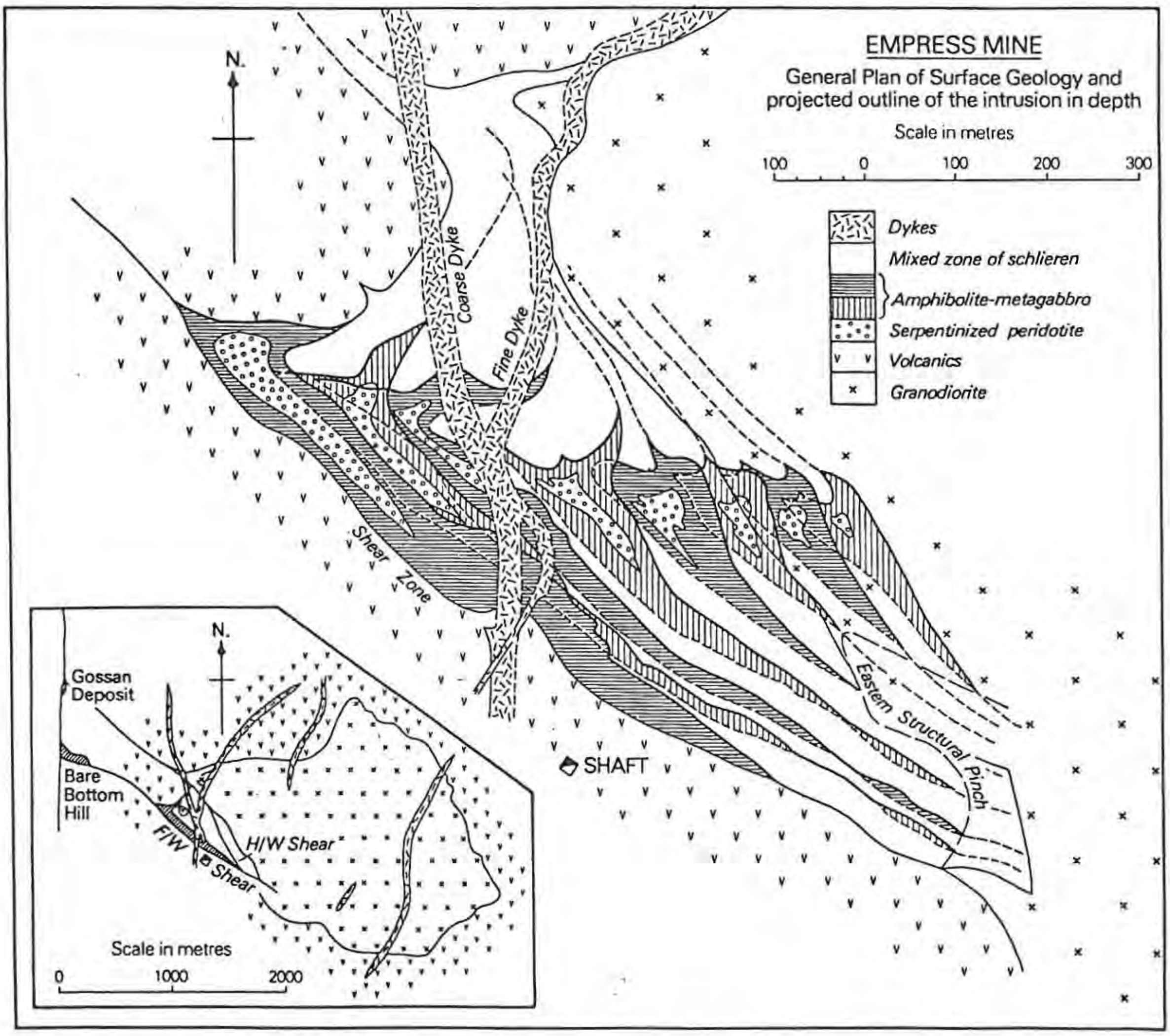


Fig. 5.48. General plan of surface geology and projected outline of the intrusion at depth (after Sutton, 1979).

north-east. Between the amphibolite and the stock is a 90m thick heterogeneous zone consisting of innumerable lenticular alteration of leucocratic and melanocratic bands, similar in compositon to the diorite of the stock and the meta-gabbro respectively. Although much of the plug is mineralized to some extent, the ore, whose limits are determined by a combined Ni-Cu cutoff of 1%, lies mainly in the central part of the body within both the meta-gabbro and peridotite. The orebody averages 15 m wide, but may reach a maximum of 27 m, and extends along strike for a distance of 600 m on surface reducing to some 150 m at a depth of 600m.

The "Lynn Lake gabbro" and the "EL gabbro" host 11 nickel-copper orebodies (Sherritt Gordon Staff, 1972; Rutton, 1957; Rutton et al., 1968). These mafic plugs are mainly composed of diorite and gabbro which grade abruptly into amphibolite and lesser amounts of norite. Lenses and irregular masses of serpentinized peridotite are found in the vicinity of the orebodies and these appear to be younger than all the other members of the igneous suite except the quartz-hornblende diorite. The latter occurs as large irregular masses and as long persistent dykes. The "Lynn Lake gabbro" is an elliptical pipe-like body some 3600 m long by 1500 m wide and contains seven significant concentrations of ore, the A, B, C, D, E, F, and G bodies (Fig. 5.49). The "El gabbro" is a small pipe-like body 360 m in diameter and hosts only one orebody, the EL orebody (Fig. 5.50). Most of the orebodies at Lynn Lake are pipe-like in form and are irregular in both the horizontal and vertical dimension. Two of the orebodies have a more regular lenticular shape. They dip from 75^{o} to vertical. The orebodies range in length from 65 m to 145 m and from about 330 m to 660 m in height. In vertical section the orebodies consist of a series of blocks of mineralized mafic rock offset between steep-dipping thrust faults (Fig. 5.51). The EL body is an exception in that no major offsets occur down plunge (Fig. 5.52). The orebodies often bulge as they approach a fault and the greatest width of ore is generally found in the vicinity of these faults. Although the ore-bodies are preferentially hosted by the amphibolite, orebodies are found in the gabbro, norite, and quartz-hornblende diorite and extend from one lithotype to another. The bodies need not necessarily outcrop at surface and consequently they are not easy exploration targets.

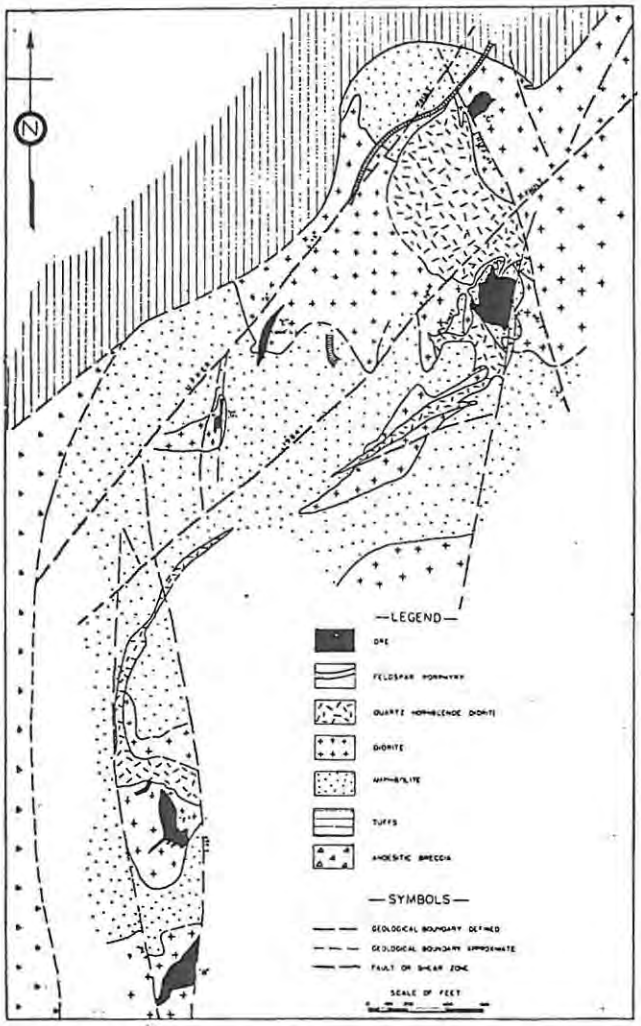


Fig. 5.49. Geological plan, 'A. shaft area 1000-foot level, Lynn Lake mine (after Ruttan, 1957).

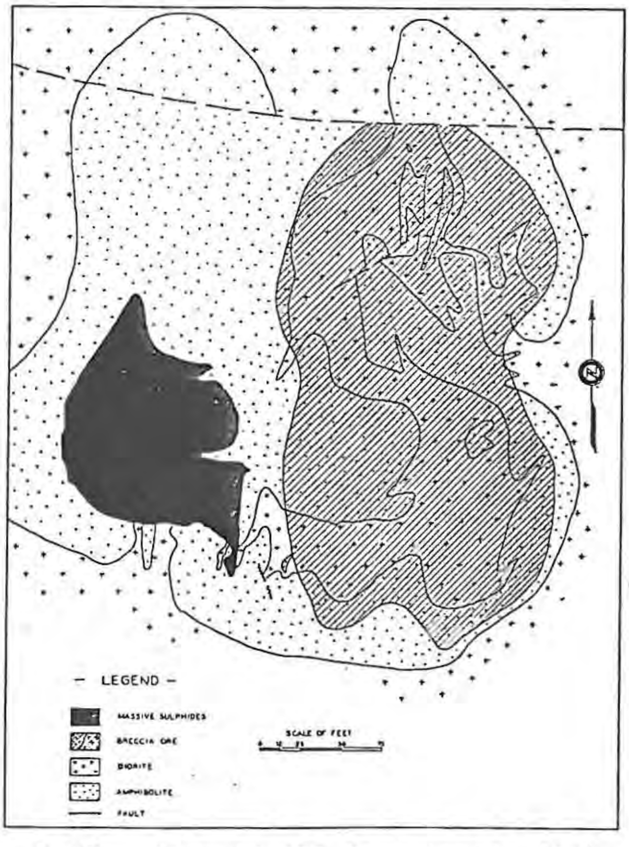


Fig. 5.50. Plan of 575-foot level, 'EL' orebody, Lynn Lake mine (after Ruttan, 1957).

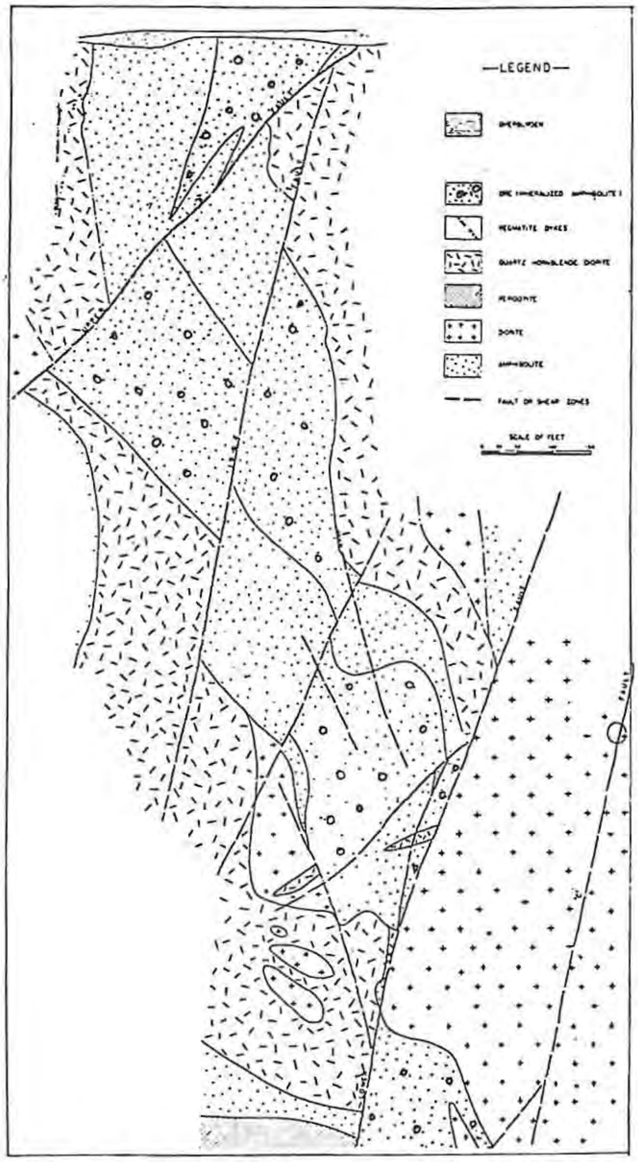


Fig. 5.51. West-east vertical section 'A' orebody, Lynn Lake mine (after Ruttan, 1959).

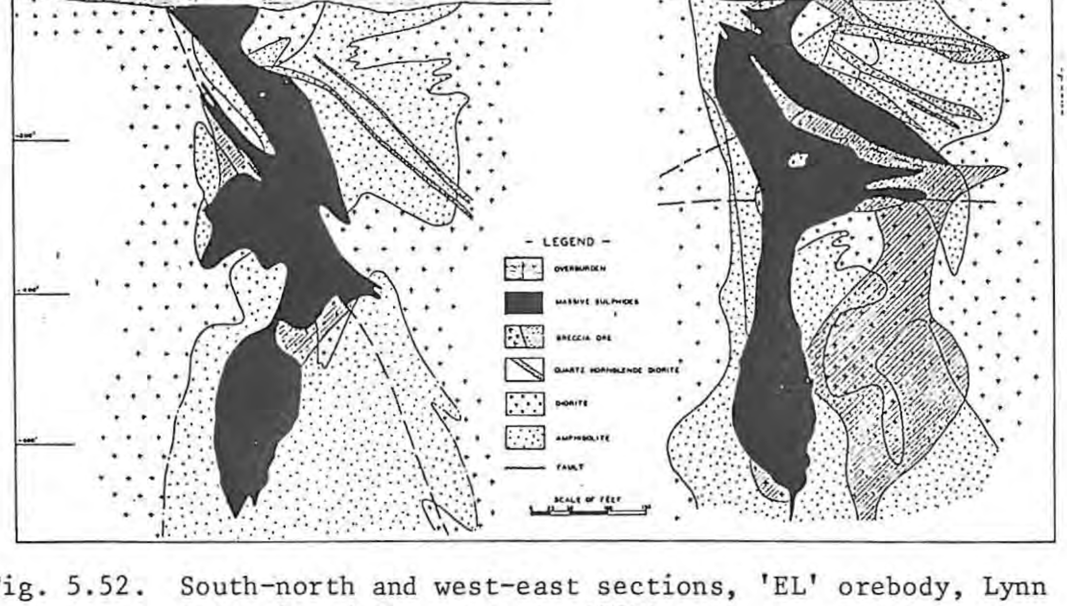


Fig. 5.52. South-north and west-east sections, 'EL' orebody, Lynn Lake mine (after Ruttan, 1957).

The tonnage and grade of the deposits vary considerably, but they are generally of a medium size and moderately high grade. Diamond drill indicated reserves at Carr-Boyd average 1,3 million tonnes at 1,65% Ni and 0,57% Cu (Schultz, 1975). Empress is a much larger deposit, 18 million tonnes, but of lower grade 0,7% Ni, 0,6% Cu, and 0,03% Co (Sharpe, 1979). Ore reserves at Lynn Lake total some 14,055,000 tons at an average grade of 1,22% Ni and 0,62% copper (Tuttan et al., 1968). The size of individual pipes within any one district varies considerably and generally averages between 1 and 5 million tons, but bares no direct relationship with the size of the pipe (Table 5.4). To make mining a feasible operation, these high grade ores have to be located and the discovery of the high grade EL pipe in 1947 was the turning point in the establishment of a mine at Lynn Lake (Ruttan, 1957).

Table 5.4. Tonnage and grade figures for pipe-type deposits.

DEPOSIT		TONNAGE	GRADE (%)	
			Ni	Cu
Carr-Boyd	No. 1	-	1,47	0,60
	No. 2	-	1,47	0,60
	No. 3	-	1,97	0,49
Lynn Lake	'EL'	2 445 000	2,50	0,93
	A	4 975 000	1,22	0,64
	B	4 275 000	0,74	0,50
	C	760 000	0,77	0,50
Combined E F G		1 600 000	0,79	0,43

In many of the deposits, for example Lynn Lake and Empress, irregular spatial distribution of rock types does not favour emplacement with differentiation taking place in situ. Evidence favours emplacement of a partly differentiated mass in several heaves into folded and deformed greenstones (Eales, 1974; Ruttan, 1957).

The deposits of this class show a strong spatial ralationship to fault zones and in many cases, these are thought to have provided favourable loci for the intrusion of the host mafic-ultramafic bodies and for ore deposition. The Empress body and its associated satellites are thought to have been emplaced along cymoidal shear zones which sheath and transect it (Sutton, 1979). At Carr-Boyd the pitch of the line of intersection of north-northwest and east-northeast trending shears approximates the plunge of the ore pipes and are thought to have provided favourable loci for the emplacement of the ore-bearing intrusions (Schultz, 1973). The relationship is not as clear cut in the Lynn Lake deposit. Two steeply dipping thrust faults, the Lynn Lake and Eldon Lake faults, occur on either side of the ore zone. In the immediate vicinity of Lynn Lake the movement on the faults resulted in an intricate system of shears and breccia zones forming in the plugs. These are considered by Ruttan (1957) to have been favourable loci for ore deposition. as the ores occur preferentially in areas of intensely fractured and brecciated intrusives. Furthermore, ore is often concentrated along a major zone of ductility contrast - the contacts between component quartz-hornblende-diorite or diorite and the incompetent amphibolite. It would appear that these ores have been remobilized as a result of post-ore faulting or by the reactivation of pre-ore faults which acted as feeders to the mineralization. Alternatively, the sulphides could have separated as an immiscible melt at depth and were then emplaced into the already brecciated mafic rocks during one of the later magmatic pulses/heaves.

The majority of ore found in these deposits is of a disseminated nature in which blebbs and wisp-like intergrowths are found interstitial to olivine and/or orthopyroxene crystals. Massive and breccia stringer stockwork sulphides are found in the higher grade deposits at Carr-Boyd and Lynn Lake. These pipe-like orebodies generally carry abundant unmineralized xenoliths. At Carr-Boyd the xenoliths of troctolite-anorthsite may reach 3 m in diameter and make up 30% of the pipe material. These xenoliths act as severe dilutants to the grade and when small result in overgrinding of the ore and production of slimes. In individual pipes any type of sulphide type may dominate. At Lynn Lake each orebody is essentially of one type, although combinations of two or more physical types may be present (Ruttan, 1957). At the EL body the ore is of two types: massive sulphides with a variable number of mineralized rock fragments (2,5 cm to 17,5 cm) grading at 4,5% Ni, 1,5% Cu, and 0,20% Co; and secondly, as sulphide filling finely spaced irregular small breccia zones. The A, B, E, F, and G deposits consist of disseminated sulphides in amphibolite and diorite between faults. The grade of the ore is directly proportional to the intensity of brecciation, with the highest grade material found in the vicinity of these faults. Low grade stringer stockwork ore occurs in the C orebody where the faults are relatively widely spaced and the ore dies out where these faults become widely spaced.

The mineralogy of the ores of this class are relatively simple and consist of, in decreasing order of abundance, pyrrhotite, generally monoclinic, pentlandite, chalcopyrite, pyrite, and (chrome-titano)-magnetite. Traces of sphalerite may also occur. Cobalt is extractable from the nickel ores and is a valuable by-product. Traces of Au and Ag occur with the deposits, but amounts are not given. A peculiar feature of the ores is that although exsolution flames of pyrrhotite do occur in the pentlandite, this is not common, and the bulk of the pyrrhotite occurs as equant grains 0,5 mm to 1 mm in size (Empress) or as late stage veinets (Lynn Lake). The pentlandite, in strong contrast to many other nickel sulphide deposits, is separable mechanically and major losses during benificiation are not encountered. The pentlandite is usually much finer grained than pyrrhotite. Chalcopyrite occurs as discrete particles or as complex intergrowths with other sulphides, and in many cases, is finer grained than both the pyrrhotite and chalcopyrite. The deposits, as would be expected from their mafic character, are characterized by low Cu:Ni ratios varying from 1:1 to 3:1 with an average of 2:1. Empress in particular has a low Cu:Ni ratio which averages 1:1 to 1:1,4. No prominent compositional zoning appears to be present in these deposits and the Cu/Ni ratio in any one pipe appears to remain consistent.

As the deposits occur in greenstone belts, low-grade metamorphism alteration of their hosts may be present. Dunites and harzburgites are converted to serpentine-tremolite-(talc-chlorite) rocks and pyroxenites into tremolite-actinolite-(chlorite) rocks. Both talc and amphibole are detrimental to the floatation process and their distribution must be carefully monitored.

Alteration as a result of the mineralizing processes is not common and its absence hampers both exploration and mine development. The

Empress deposit is a glaring anomaly in this regard. Intense alteration is associated with the ore and includes albitization of feldspars, development of clinozoisite and zoisite, and mineralization of the pyroxenes (Eales, 1974). The Mixed Zone adjacent to the Empress mafic complex appears to be a zone along which the mafic magmas reacted with the country rock and assimilated silica. The alteration could merely represent the product of this reaction. The contamination may have instigated sulphide separation. Sulphurization does not appear to have played a major role in the genesis of other members of this class and they all show evidence of the segregation of an immiscible sulphide liquid within the host magma, followed by intrusion.

The deposits may show a well developed supergene weathering profile similar to many Archaean volcanic-hosted komatiitic deposits.

Longhole open-stope methods are ideal for the mining of these deposits because of the relatively small lateral dimensions of the orebodies and the strong gabbroic wall rocks which enclose them (Ruttan and Staff, 1957). The pipe-like shape of the orebodies and the strong wall rocks permit continuous mining of a high-ore column without serious ground problems. The low over-all grade of the deposits rules out the more selective mining methods.

The irregular shape of the orebodies necessitates the use of detailed closely spaced exploratory drilling prior to the evaluation of the deposits. Vertical holes are the most effective and efficient for sampling the steeply dipping, pipe-like orebodies. These holes are excellent for establishing vertical continuity as well as the position of faults or other major irregularities. All the Lynn Lake bodies were drilled out in this manner on sections 33 m apart, with holes 17 m apart of each section (Rutton et al., 1968).

Any mining of these bodies requires detailed geologic information provided by closely spaced diamond drillholes to permit full recovery of the ore, and at the same time to keep dilution to a minimum. At Lynn Lake detailed underground ore-outline drilling is done on parallel cross-sections 17 m to 8 m apart (Ruttan et al., 1968). The drilling is done from drifts at vertical intervals 100 m to 130 m apart. Holes are drilled horizontally, and up or down to give data on ore limits and grade at approximately 17 m intervals. Stoping at Lynn Lake has been accompanied by a 12,5% dilution. This dilution, due in large part to the irregularity of the bodies mined is of two types: that included with the ore when smoothing irregular ore boundaries, and slough from the walls of the stope. Detailed diamond drilling of the ore limits decreases the amount of the former and regular stope walls help to limit the slough.

The calculation of any ore reserve within any of these pipe-like orebodies, because of its irregular shape and grade distribution (i.e. disseminated versus massive ore breccia ore), entails a considerable knowledge of the orebody, it's geological relations and peculiarities of composition. At Lynn Lake both tonnage and grade are calculated from cross-sections and the system of medians between holes is used (Ruttan et al., 1968). At Lynn Lake as in many of these plug-like deposits, the Ni to Cu and pentlandite to pyrrhotite ratios are relatively constant in each orebody, but varied from orebody to orebody. Specific gravities were determined for samples of differing sulphide content from each orebody, and cubic feet per ton (ton factors) calculated for each. The samples were assayed, and the per cent nickel was plotted graphically, with the corresponding ton factor for each orebody. This ton factor, based upon the nickel grade, is applied in the calculation of each block of ore and one is able to achieve good correlations between the tonnage mined and that reported at the mill. Experience has shown at Lynn Lake that in this type of ore deposit tonnages and grades calculated on the basis of a regular pattern of closely spaced diamond drillholes provide a tonnage/grade estimate nearer to that milled. By the end of 1966, 13,7 million tons at a grade of 1,16% Ni and 0,56% Cu has been milled. Calculations based on exploration diamond drilling had indicated a grade of 1,19% Ni and 0,60% Cu for this ore; calculations based on ore-outline drilling had indicated a grade of 1,17% Ni and 0,57% Cu.

5.4.2 Sill-type intrusions

The orebodies of this class are generally continuous sheet-like accumulations concentrated near or along the bases of sill-like intrusions.

The Maskwa West nickel deposit forms portion of a 30 km long differentiated mafic-ultramafic sill emplaced within the Bird River greenstone belt, Manitoba (Coats et al., 1979). The 180 m thick lower portion contains cyclic repetitions of serpentinized peridotite and chromitite and is capped by a pyroxenite layer (Fig. 5.53). The upper portion consists of some 365 m of gabbro, anorthositic gabbro,

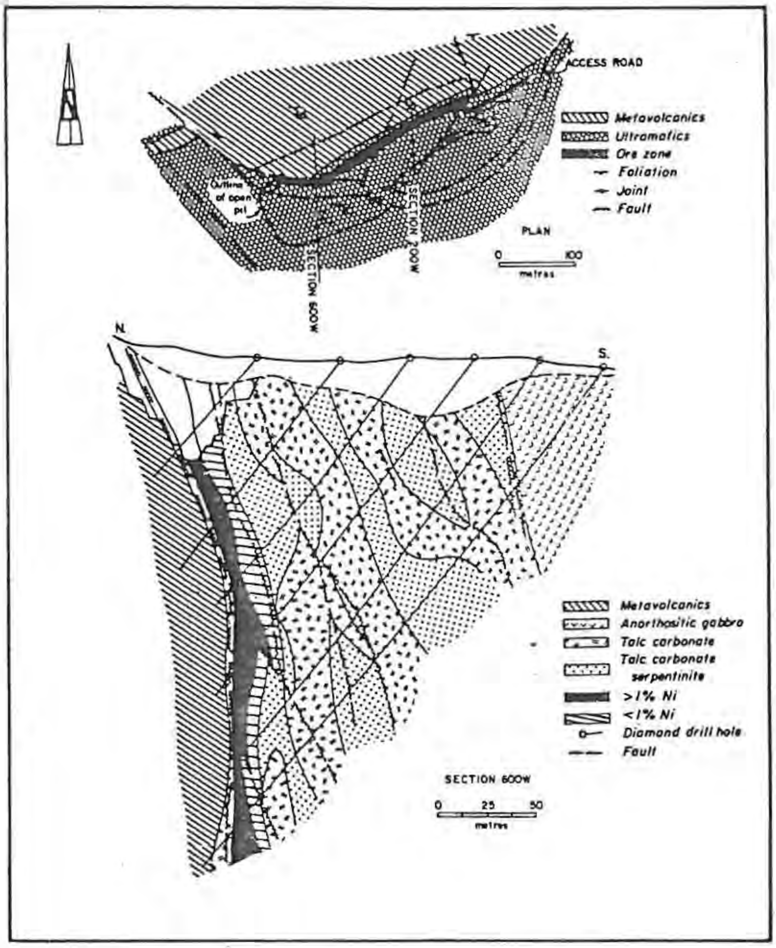


Fig. 5.53. Geology of the Maskwa West open pit area and geological cross-section 600W (after Coats et al., 1979).

and anorthosite. The sill dips at some 60^{o} to 80^{o} to the south. Sulphide mineralization occurs at the base of the ultramafic unit and has a strike length of 1280 m (Fig. 5.53). Only 300 m of this is of sufficient grade to be economically viable. In this zone the mineralization has an average thickness of 12 m, but varies between 3 m and 20 m.

The Mt. Sholl body is intrusive into greenstones in the Pilbara block, Western Australia (Mathison and Marshall, 1981). The intrusion forms an irregular sheet with tapered sheet-like extensions, 30 m to 150 m thick, along the layering of the surrounding volcanic rocks (Fig. 5.54). The rocks within the intrusion comprise recrystallized tremolitic meta-gabbros, gabbros, feldspathic-pyroxenites, with smaller

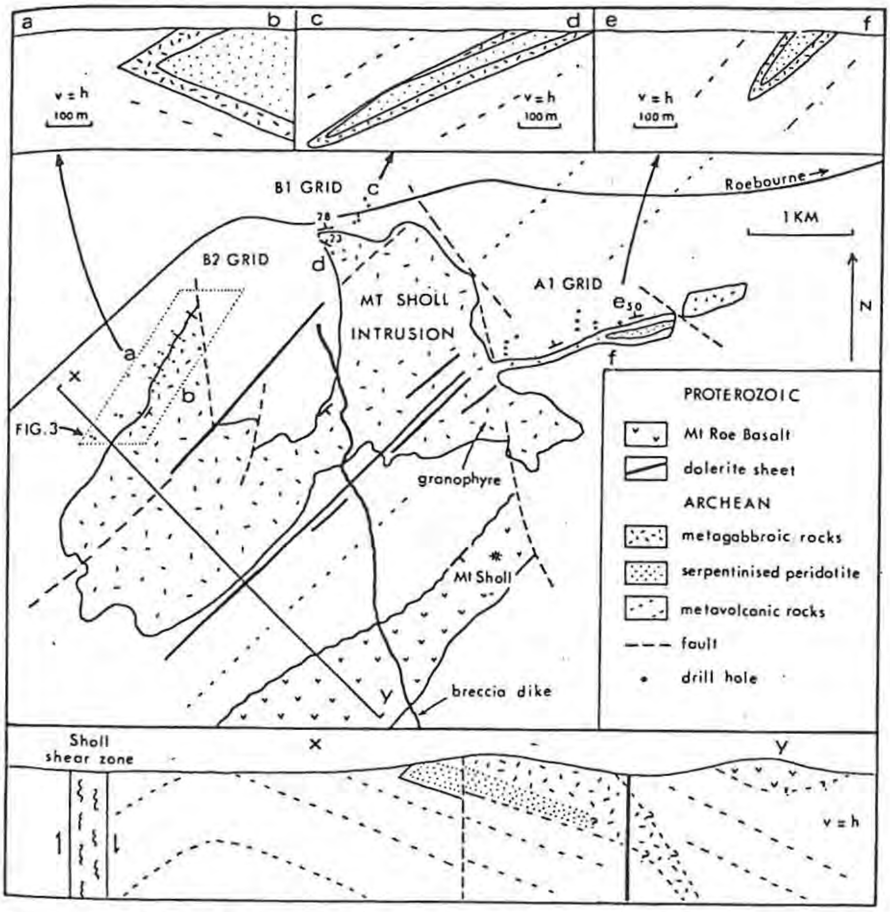


Fig. 5.54. Simplified geologic map and interpretive cross-section of the Mt. Sholl intrusion (after Mathison and Marshall, 1981).

amounts of serpentinized peridotite and granophyre. The mineralization is found in the tapered extensions of the intrusion which consists of a central core of peridotite within a gabbro envelope containing a chilled margin (Fig. 5.54). The sulphides are hosted mainly by the gabbros, but some are also encountered within the peridotite. The ore is found within 100 m of the basal contact and the main concentrations occur within 20 m of this contact. The sulphides thicken laterally towards the margins of these sheets.

The deposits are of low grade and low tonnage and generally do not form economically viable deposits. At Maskwa West deposit consists of 1,065,700 tons at 1,16% Ni and 0,20% Cu. The largest concentration at the Mt Sholl is 4 million tons at 0,5% Ni and 0,6% Cu.

Disseminated sulphides filling the interstices between olivine and orthopyroxene grains are by far the most dominant textural type present and usually comprise 10% to 20% by volume of the ore zone. Thin massive sulphide zones up to 1 m thick, but averaging 10 cm, are found at Mt Sholl (Mathison and Marshall, 1981). Massive sulphide gash veins (6-9% Ni) occur at sporadic intervals within the footwall volcanics at Maskwa West (Coats et al., 1979). These are sulphides which have been remobilized during metamorphism and deformation. Where the deposits are deformed, chaclcopyrite often forms thin cross-cutting veinlets and blebs along shear zones.

The main minerals in order of abundance are pyrrhotite, pentlandite, chalcopyrite and pyrite (Marston et al., 1981). Ni/Cu ratios range from 7 to less than unity and Ni/Co ratios average around 25. Much of the pyrrhotite in these ores is coarse to medium-grained and lacks deformational or annealing-recrystallization textures. Pentlandite occurs mainly as separate grains and is easily beneficiated, but in some deposits important amounts are found as flame-like exsolution bodies in the pyrrhotite. Zonation of the nickel and copper sulphides are not a common feature.

As in many Archaean deposits, the mafic and ultramafic rocks have been altered by low-grade metamorphism and the metamorphic assemblages now consist of varying amounts of talc, serpentinite, tremolite, and actinolite.

The copper- and cobalt-rich nature of the sulphides, the less magnesian nature of the host rocks, and the intercumulus sulphide textures are consistent with the formation of the deposits from immiscible sulphide liquids within the host magma.

6. A SUMMARY OF THE FACTORS AFFECTING THE TONNAGE AND GRADE OF NICKEL SULPHIDE DEPOSITS

Although the nickel sulphide deposits described above differ in detail, they are strikingly similar in many respects because: all are associated with prominent fault zones or sites of intracontinental rifting, all have a similar mechanism of formation as they have formed from an immiscible sulphide melt, they commonly form in topographic or structural depressions at the base of the flow/intrusion, they commonly comprise a zone of massive sulphides overlain by zones of disseminated sulphides, and finally, they have strikingly similar mineralogies. Therefore, a number of fixed factors control the tonnage and grade of nickel sulphide deposits.

The tonnage of nickel sulphide deposits is dependent on:

(a) The size of the host complex. As the size of the intrusive or flow hosting the mineralization increases, the potential for forming larger deposits increases. The largest deposits form in Archaean dunitic intrusions which invariably contain the greatest volume of magma. Furthermore, the largest komatiitic volcanic-hosted deposits occur within the thickest flows.

(b) The nickel and sulphur content of the magma. The potential for forming large deposits increases as the nickel and sulphur content of the magma increases. Sulphurization, that is the assimilation by the magma of sulphur from the country rocks, appears to have played a prominent role in the upgrading of the sulphide content of many magmas. This appears to have only been important in Proterozoic or later times, as most Archaean magmas appear to have been saturated in sulphide at the time of emplacement.

(c) The size and regularity of the footwall trap. Obviously, the largest deposits are encountered in those footwall embayments having the largest dimensions. It is critical that these embayments have an highly irregular form, so as to cause a riffling out of the higher density immiscible sulphide liquid from its host magma.

(d) The number of "stacked" lenses. In some deposits, ore lenses, each consisting of massive ores overlain by more disseminated ores, occur as separate entities separated vertically by a zone of barren host rock. The overall tonnage of a deposit is directly dependent on the extent to which this "stacking" occurs.

The grade of nickel sulphide deposits is dependent on:

(a) The magmas primary nickel and sulphur content. If a magma is initially saturated in sulphide a high grade immiscible sulphide melt can form. If saturation occurs at a later stage, the immiscible sulphide melt separating has a lower nickel grade. If the magma is not saturated in sulphur prior to the onset of major olivine crystallization, a significant amount of nickel may enter the silicate lattice and consequently, a low nickel tenor is to be expected.

(b) Circulation within the magma chamber. Ultramafic or mafic bodies which exhibit little gravity differentiation are unlikely hosts for high grade deposits because their initially high solid content would allow little chance for the complete settling of sulphides to form a high grade massive sulphide zone.

(c) Magma composition. Ultramafic rocks tend to be nickel-rich, while mafic rocks tend to be more copper-rich.

(d) The proportion of massive to disseminated ore. Naturally, the massive ore layers have a much higher grade than the more disseminated ores.

(e) The mineralogy of the sulphide assemblage. The nickel grade is primarily dependent on the proportion of pentlandite to pyrrhotite present. It is also a function of the amount of pentlandite which is present in the pyrrhotite as non-recoverable exsolution lamellae. The presence of millerite considerably upgrades nickel ores.

(f) Serpentinization and talc-carbonate alteration can upgrade nickeliferous ores by forming a nickel-rich sulphide assemblage. However, serious losses may be incurred during the beneficiation of these ores as a result of the floatation and grinding properties of the soft platy minerals.

(g) Metamorphism and deformation. Massive ores can be generated from more disseminated ores during metamorphism. Low grade ores can be concentrated in the hinge zones of folds to form relatively high grade deposits. Metamorphism and deformation can also modify the original distribution of the sulphides on a more local scale to form a distinct zonal sequence, whose characteristics greatly influence the distribution of grade on a mine scale or even on a handspecimen scale.

(h) Supergene enrichment. Some nickel and copper enrichment is found at the top of the violarite-pyrite zone, but is rarely of any economic significance.

(i) The amount of barren wallrock inclusions in the massive ore. In some breccia ores at Sudbury and in the pipe-like tholeiitic/komatiitic intrusions in greenstone belts, these inclusions may considerably lower the overall tenor of a particular portion of the orebody.

(j) Zoning. Most nickel-copper sulphide deposits have copper-enriched/nickel-poor bases and/or footwall stringer zones. This zonation, whether metamorphically induced or as a result of primary crystallization from a monosulphide solution, has a great influence on grade distribution within any one deposit.

Within most nickel sulphide deposits the average grade and tonnage appears to be lognormally distributed (Froose et al., 1980). However, the relationship between tonnage and grade between the different classes of deposit is quite variable.

For deposits associated with komatiitic rocks (Setting IIIB), deposit grade correlates inversely with tonnage (Fig. 6.1). However, it should be noted that regional differences exist for the average tonnage/grade relationships of the komatiitic association (Fig. 6.2).

Within deposits hosted by small to medium sized intrusions, which are predominantly of a mafic character, including both tholeiitic intrusions in greenstone belts (Setting IIIA) and layered tholeiitic intrusions in Phanerozoic orogenic belts (Setting IV), grade varies independently of tonnage (Fig. 6.3).

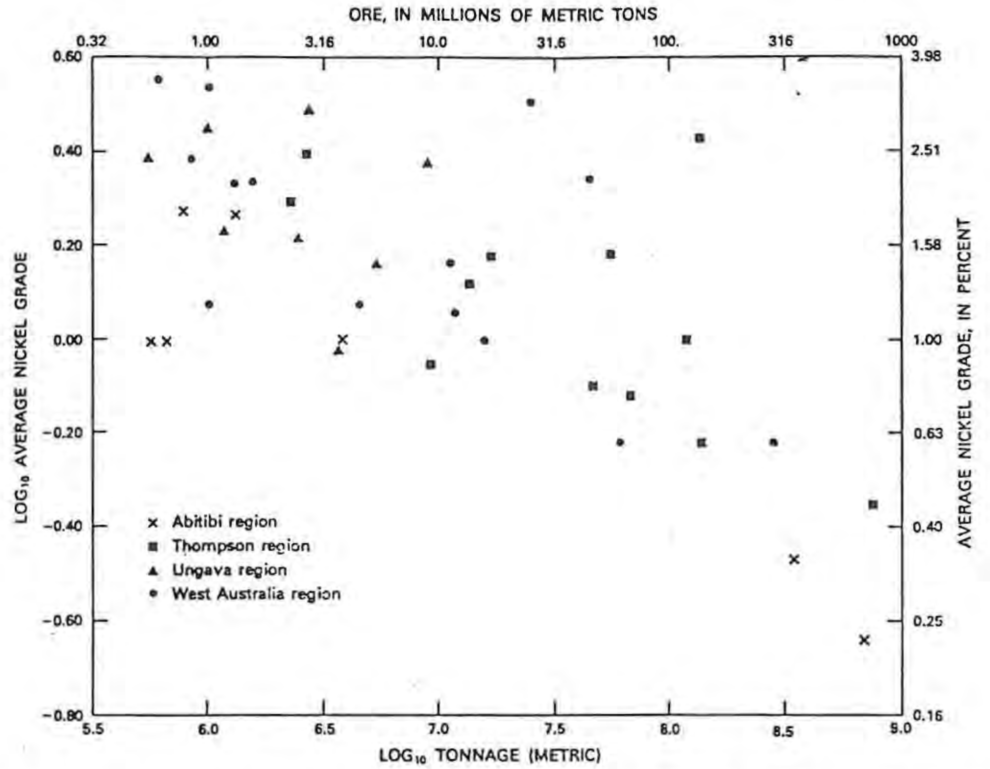


Fig. 6.1. Grade and tonnage of nickel sulphide deposits in komatiitic rocks from four regions (after Froose et al., 1980).

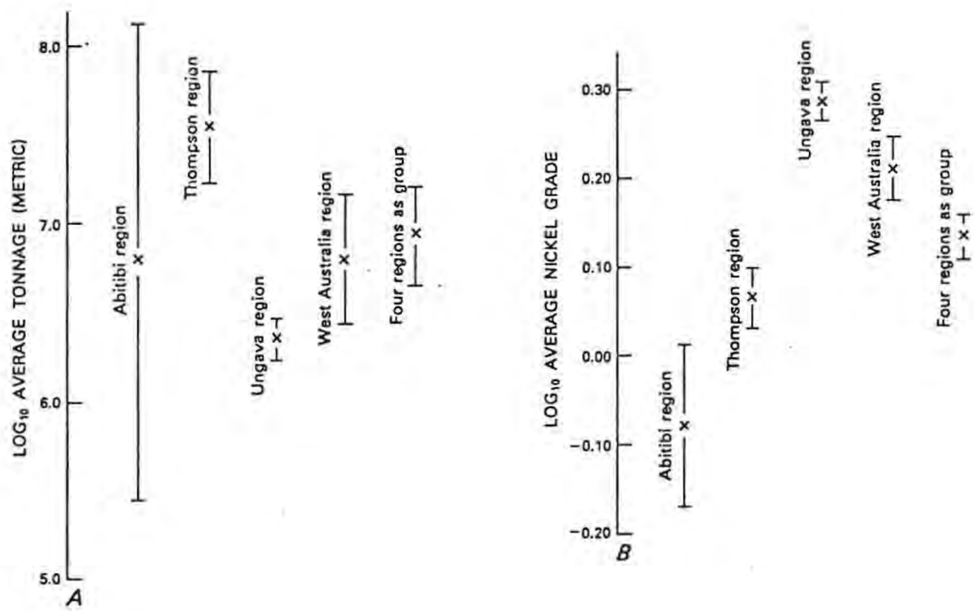


Fig. 6.2. Quality-control chart (a plot of means and standard errors) of tonnage and grade for nickel sulphide deposits in komatiitic rocks. Data are from four regions, plotted both as a group and as separate areas. X represents the means; bar extensions indicate plus and minus 2 standard erros, A, for tonnage, B, for grade (after Froose et al., 1980).

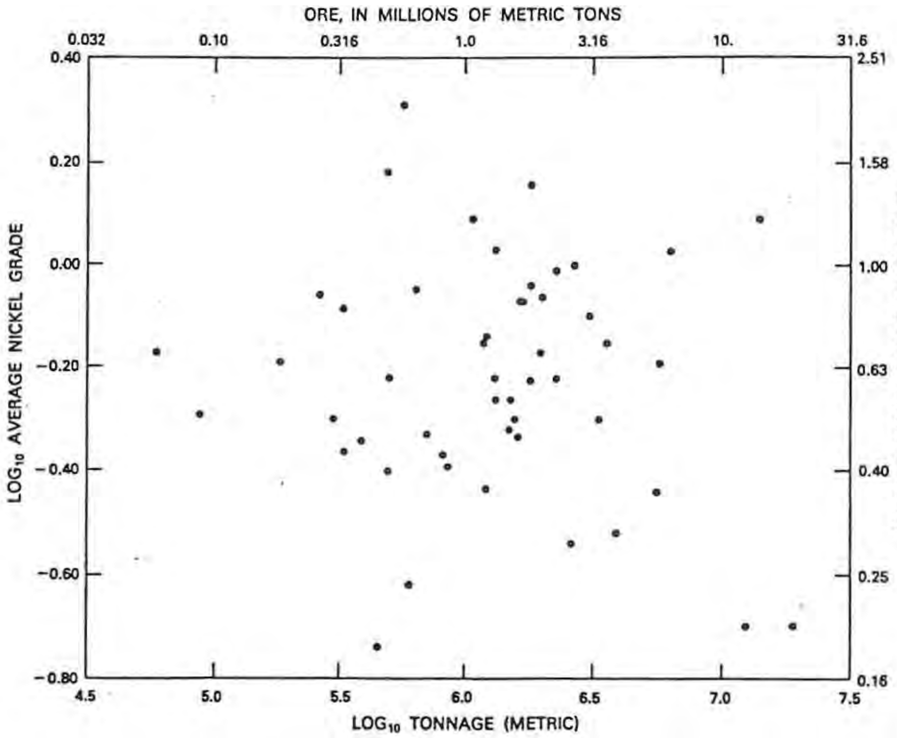


Fig. 6.3. Grade and tonnage of nickel sulphide deposits associated with small intrusions (after Froose et al., 1980).

7. GEOPHYSICAL AND GEOCHEMICAL TECHNIQUES USED IN THE EXPLORATION FOR NICKEL SULPHIDE DEPOSITS

7.1 Geophysical techniques

As the mafic and ultramafic host rocks characteristically have enhanced magnetic susceptibilities, airborne magnetic surveys 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 terranes. The results of an airborne survey over the Pioneer Dome in Western Australia is shown in Fig. 7.1. The magnetic survey which was flown in the early stages of exploration, clearly indicates the value of airborne magnetics as a regional

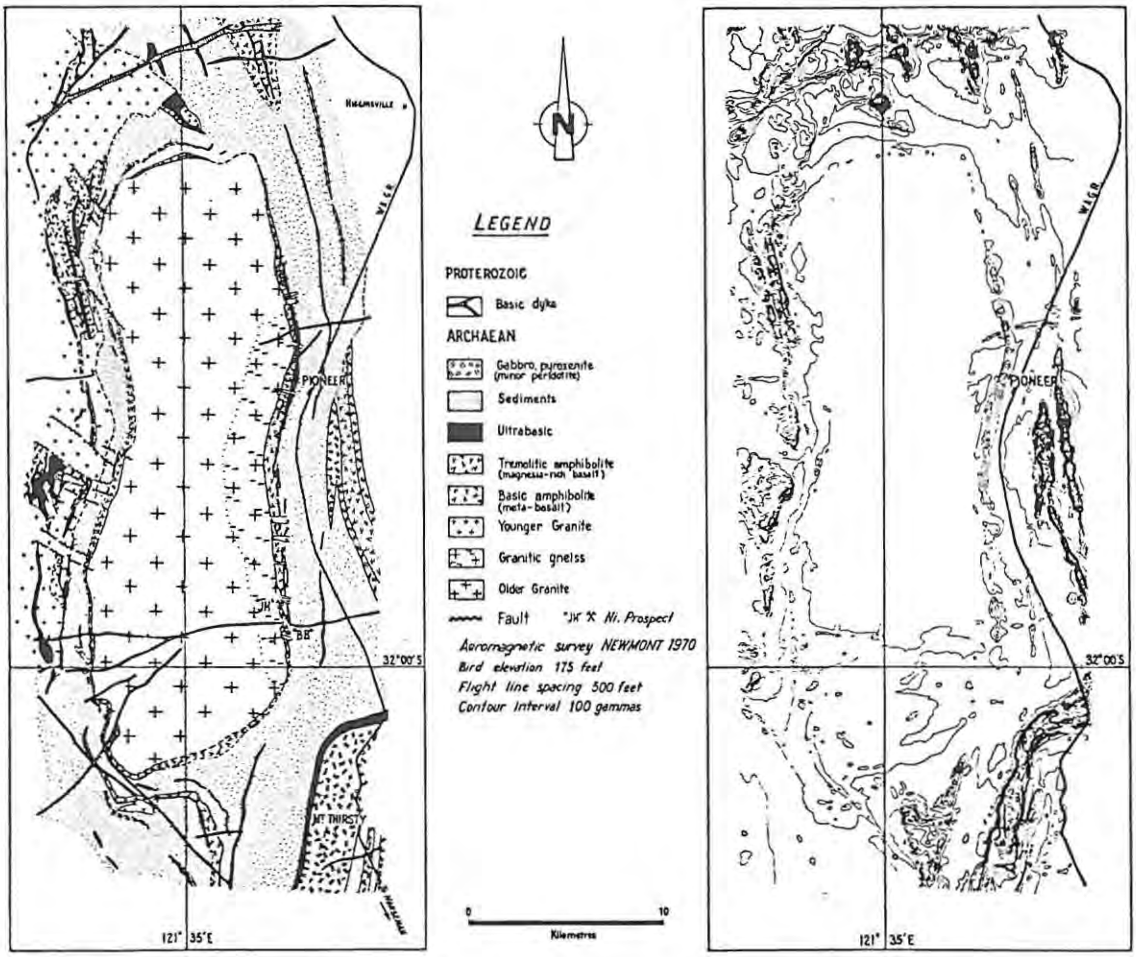


Fig. 7.1. Pioneer Dome, Norseman - A, geology, B. aeromagnetic map (after Cox and Tyrwhitt, 1975).

mapping tool (Cox and Tyrwhitt, 1975). The airborne magnetic data indicates that, despite its limited thickness, the greenstone units can be traced almost continuously around the domal structure. The strongest magnetic anomalies are found over differentiated pyroxenite-gabbro complexes in the south-eastern and eastern portions of the area. These tholeiitic rocks tend to be more magnetically susceptable than the other rock types because of the characteristic iron-enrichment trend they follow upon fractional crystallization. The differentiated sills do not host significant concentrations of nickel sulphides but the basal portions of the ultramafic flows overlying tremolitic amphibolite (high magnesium basalt) and basic amphibolite (meta-basalt) do. These units appear as anomalous linear zones on the aeromagnetic map and detailed ground magnetics could differentiate the ultramafic portions because of their higher magnetic susceptibility.

Magnetic surveys have been used extensively in the Sudbury district where they have proved to be the most cost-effective means of mapping out the various units of the Irruptive and of locating off-set deposits (Furnell, 1981).

Detailed ground magnetics can also be used to delineate the occurrence and shape of footwall irregularities in which the nickel sulphide bodies are most commonly encountered. The Windarra South deposits in Western Australia were found under 30 m of alluvial cover by using detailed magnetic surveys to establish the position and geometry of the potentially mineralized ultramafic volcanic/banded iron formation contact which had been located at surface further to the north (Roberts, 1975).

On a regional scale, there is a common association between many nickel camps and major fault zones. The Sudbury camp and Manitoba nickel belt are spatially related to rift zones along the boundary between the Grenville-Superior and Churchill-Superior structural provinces respectively. The Noril'sk camp is directly associated with the Noril'sk-Kharaelakh fault and the low grade dunitic-hosted deposits in Western Australia all fall along a braided fault zone. These crustal sutures are not very apparent on the ground but are easily picked up as strong linear features on airborne magnetic surveys (Furnell, 1981).

Accurate calculations of shapes, dips and depths of magnetic sources can be made from magnetic profiles (Furnell, 1981). This information will assist in the subsequent evaluation of these target areas by diamond drilling.

As magnetite and pyrrhotite are common constituents of nickel sulphide ores, the orebodies themselves may be directly detectable by magnetic methods. Magnetic surveys resulted in the direct detection of a number of orebodies in the Sudbury camp. These include Garson, Hardy and Falconbridge. Fig. 7.2 shows the results of a magnetic survey over the Maclennan mine. The magnetic contours clearly outline the ore zone. The follow up of airborne magnetic anomalies has also been successful in detecting nickel sulphide mineralization in Western Australia and resulted in the discovery of the Carr Boyd and Windarra deposits (Roberts, 1975; Schultz, 1975). Detailed ground magnetics were the mainstay of exploration in the southern extensions of the Manitoba nickel belt (Roth, 1975). Here a thick cover of glacial overburden and Palaeozoic sediments masks the ultramafic host rocks. Detailed magnetic surveys disclosed a linear magnetic anomaly over serpentinized ultramafics. The anomaly, which was of moderate amplitude, terminated at its southern end with the suggestion of a fold closure (Fig. 7-3a). Vertical-loop E.M. coverage indicated a weak anomaly associated with this magnetic feature and I.P. surveys confirmed that the magnetic source was weakly polarizable (Fig. 7.3b). Gravity surveys indicated that a weak low was associated with the magnetic anomaly. The initial drillhole (DDH MXB-69-27) intersected substantial sections of sub-economic nickel sulphide mineralization under 60 m of overburden. Subsequent drilling within the nose area delineated 7,3 million tonnes of disseminated ore to a depth of 400 m grading at 1.33% Ni.

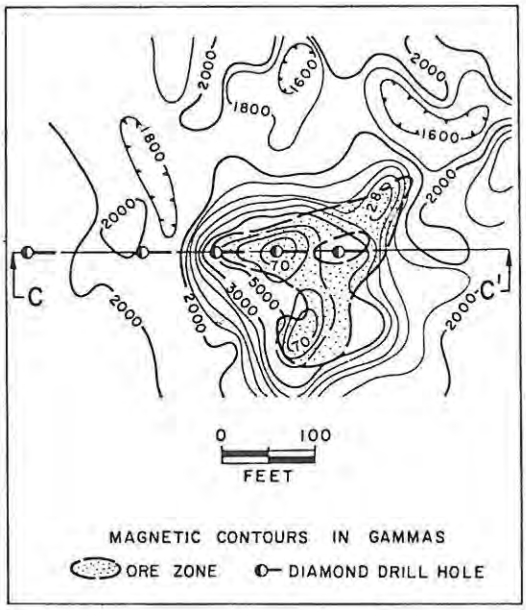


Fig. 7.2. Detail ground magnetic survey, Maclennan mine (after Dowsett, 1967).

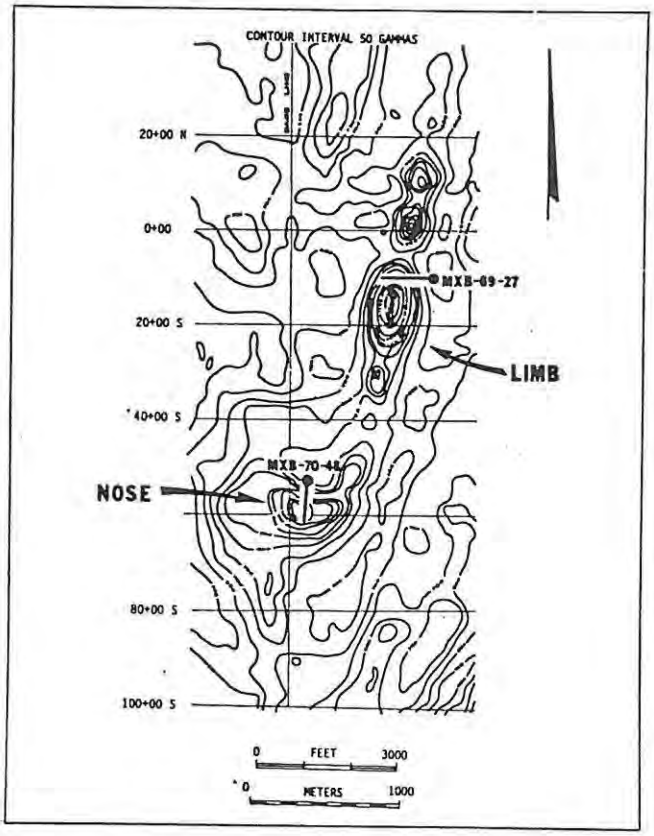


Fig. 7.3a. Detailed Magnetics: Area 1.

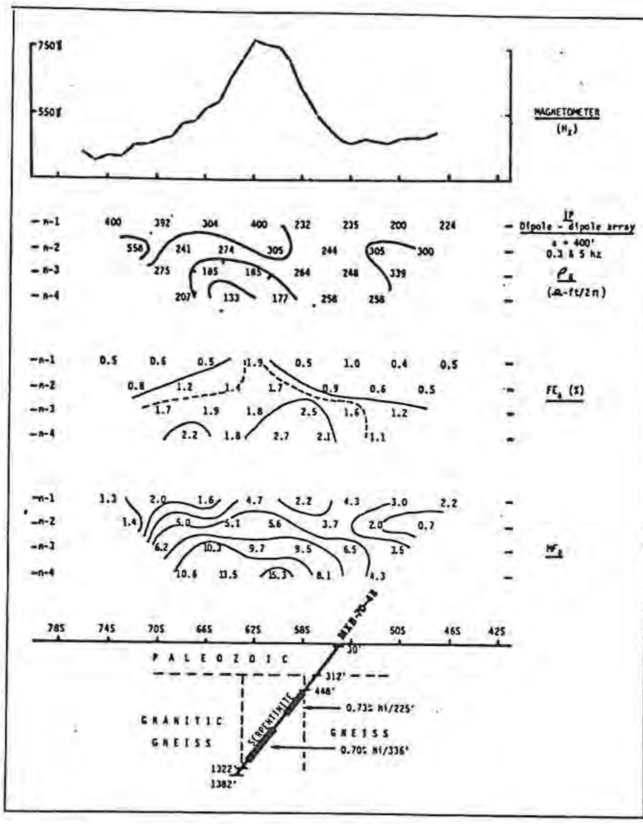


Fig. 7.3b. Composite Geophysics and MXB-70-48 (nose).

Ground magnetic and I.P. surveys over a portion of the southern extension of the Manitoba Nickel belt (after Roth, 1975).

Airborne and ground E.M. surveys have proved particularly effective in the detection of nickel sulphide deposits because pyrrhotite, which is invariably the dominant sulphide present, is characterized by its high electrical conductivity. Extremely high conductivities are observed over many nickeliferous sulphide deposits and conductivities may be as much as a thousand times better than their surrounding host rocks (Dowsett, 1967). However, good E.M. responses are only found over deposits with massive mineralization and therefore, many of the disseminated ores in intrusive dunitic rocks and gabbroic intrusives constitute poor E.M. targets.

The strength of an electromagnetic response from a conductor is, to a large extent, dependent on the area of the conductor (Furnell, 1981). Consequently, E.M. systems usually respond well to fault zones, shear zones and conductive overburden. Although these responses may be undesirable in some surveys, in others the detection of fault zones may tend indirectly to the discovery of an orebody.

Airborne AFMAG methods have been used fairly extensively in the mapping of shallow geologic structure and are consequently of value in locating large fault zones spatially associated with many nickel sulphide deposits. AFMAG is essentially a dip angle technique which uses naturally occurring fluctuations in the earth's field due to distant thunderstorm activity (located at infinity) as a power source (Furnell, 1981). AFMAG surveys can detect sizable tilt angles at distances up to 250 m from conductive fault and shear zones. The value of airborne AFMAG surveys in locating these fundamental zones of crustal weakness is illustrated by exploration in the southern portions of the Manitoba nickel belt (Roth, 1975). As thick glacial overburden and/or Paleozoic sediments conceal the bedrock geology of the southern portions of the belt, exploration was forced to rely heavily upon geophysical techniques. Airborne AFMAG was chosen as a primary reconnaissance technique because faulting was regarded as the primary control on the occurrence of nickel mineralization. Sifting of the anomalies on the basis of anomaly character and amplitude revealed a number of long semi-continuous features. These indicate the southerly continuation of the major fault trends delineated in the better exposed northern portion of the belt (Fig. 7.4).

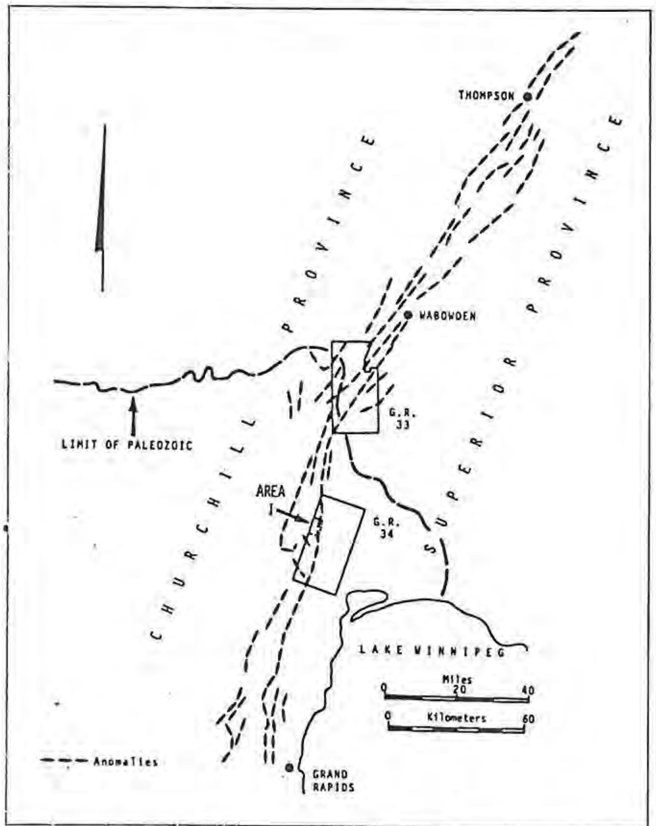


Fig. 7.4. Principal AFMAG Anomalies: southern portion of Manitoba nickel belt (after Roth, 1975).

Airborne V.L.F.-E.M. methods have also been used in conjunction with magnetic data for the mapping of shallow geologic structure. The V.L.F. method makes use of powerful radio transmitters set up for military communications in different parts of the world. The transmitters are capable of inducing electric currents in conductive bodies thousands of kilometers away (Lewis, 1982). These currents produce secondary magnetic fields that can be detected at the surface through deviations of the normal V.L.F.

field. The successful use of this relatively inexpensive prospecting tool requires that the strike of the conductor be in the direction of the V.L.F. station, so that the lines of magnetic field from the V.L.F. transmitter cut the conductor. The major disadvantages of V.L.F. are that a multitude of anomalies result from unwanted sources such as swamp edges, creeks, and topographic highs, and at times it is impossible to get a powerful enough V.L.F. station near to the strike direction of the expected conductor. The V.L.F. technique may be used to establish conducting rock units (Telford et al., 1976). The V.L.F. profiles across the Atlantic Nickel property near St. Stephan in Southern New Brunswick are shown in Fig. 7.5. The deposit is hosted by a stock-

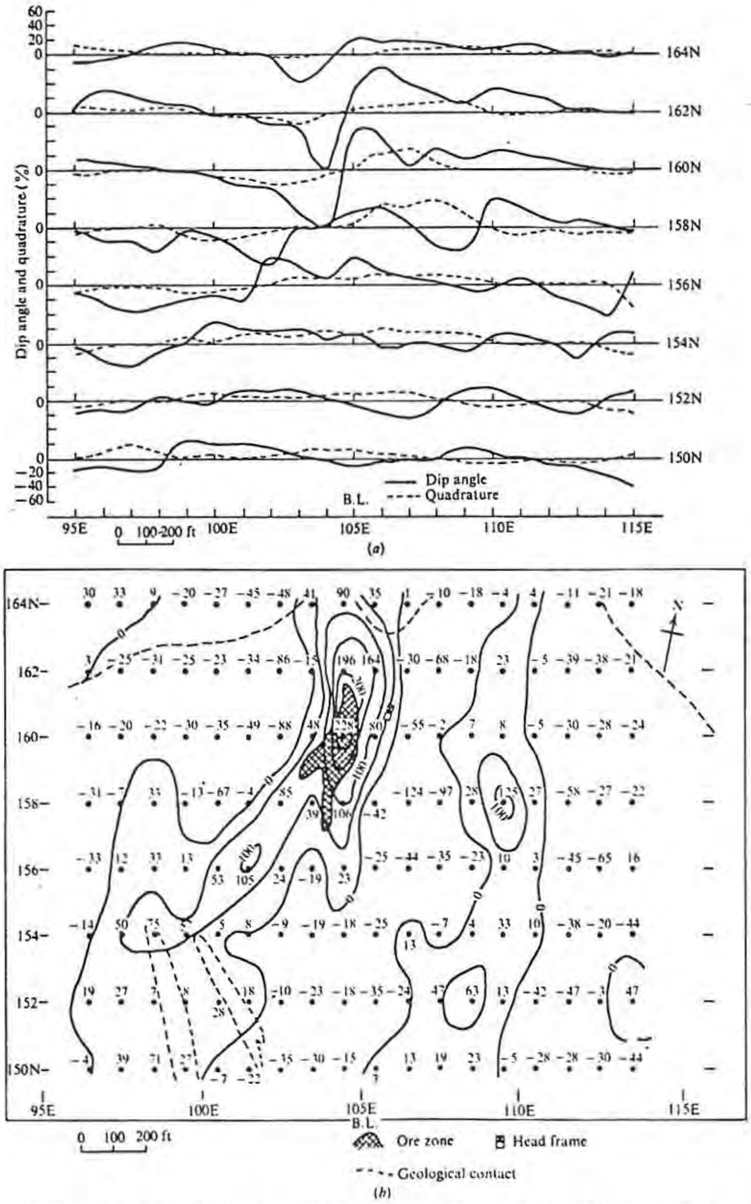


Fig. 7.5. Results of V.L.F. survey, Atlantic Nickel property, Southern New Brunswick. Transmitter station: Cutler, Maine (17-8 kHz). (a) V.L.F. profiles; (b) V.L.F. contours (after Telford et al., 1976).

like ultramafic intrusive. Chalcopyrite, pyrrhotite, and pentlandite mineralization occurs close to the contact of the intrusive with metamorphosed and altered sediments. The V.L.F. source was a transmitter at Cutler, Maine, located some 110 km to the south. Huge dip angles and steep crossovers on lines 160N and 162N are caused by a good conductor outcropping on line 160.

The Thierry Orebody, a medium-sized copper-nickel sulphide deposit located near Pickle Lake, Ontario, occurs partly in gabbroic and ultramafic intrusives of Archaean age, and partly as remobilized bodies within a shear zone (biotite-chlorite-hornblende schist) which transects the intrusives (Fig. 7.6). Mineralization of ore grade and width is known over a strike length of 1070 m and has been followed down to a

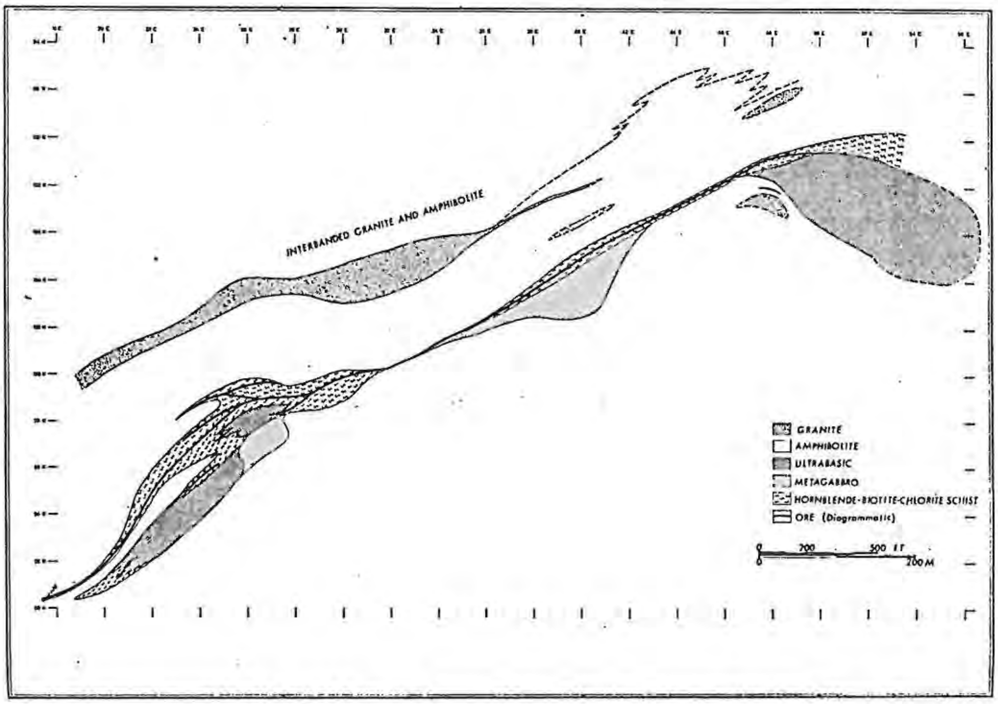


Fig. 7.6. Geological plan of the 500 ft. level. Thierry Deposit, as inferred from surface diamond drilling (after Verbeek et al., 1972).

vertical depth of 500 m (Verbeek et al., 1972). The average Cu and Ni grades are 1,68% and 0,18% respectively. The primary sulphide minerals in order of abundance, are pyrrhotite, chalcopyrite, pyrite and pentlandite. Magnetite and minor ilmenite are also present. There is no outcrop in the area. The mineralized zone is well outlined by the V.L.F. survey (Fig. 7.7). The V.L.F. survey also

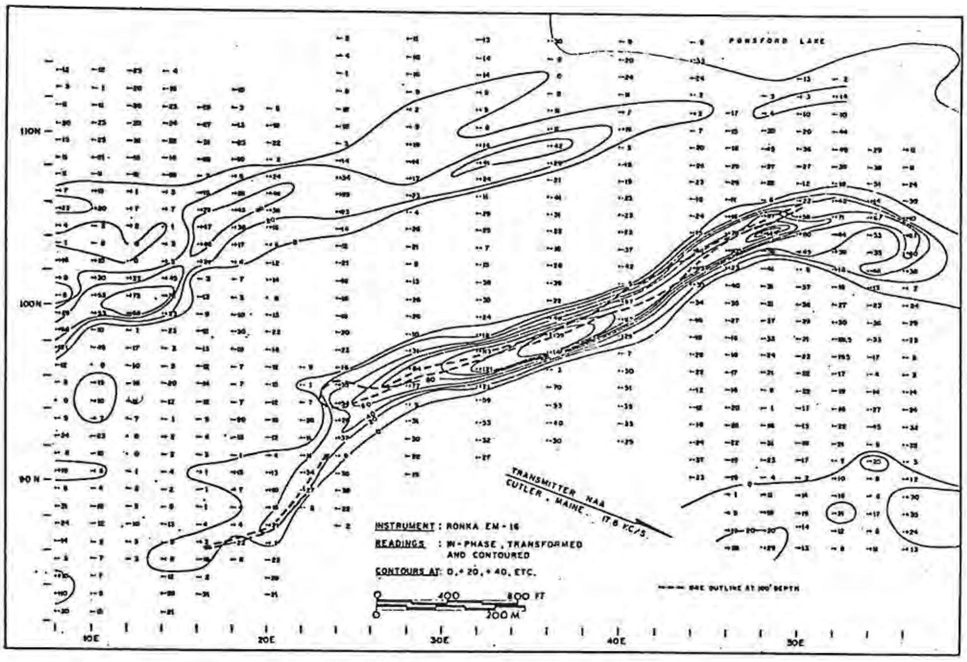


Fig. 7.7. V.L.F. electromagnetic survey over the Thierry Deposit, the results numerically filtered and contoured (after Fraser, 1969, from Verbeek et al., 1972).

detected a thin barren deeply buried sulphide zone to the north of the main ore zone (Fig. 7.7). However, suprious V.L.F. anomalies are developed over the ultramafic, especially its contacts, and a swamp. Therefore, its use as a prospecting tool is limited. The contoured V.L.F. data show different patterns for conductive overburden and sulphide zones and therefore, the method may be of value in locating relatively deeply buried deposits.

The majority of the Sudbury ore bodies respond to E.M. surveys. For example, the Strathcona deposit was found by drilling a weak E.M. anomaly (Cowan, 1968). An assortment of profiles from several airborne E.M. systems from a single traverse over the Whistle offset are shown in Fig. 7.8. The profiles include responses from V.L.F., E.M., magnetics and AFMAG. All four readily detect the presence of a shallow moderately good conductor.

Integrated airborne E.M., ground E.M., and magnetic surveys have been widely used in the exploration for nickel sulphide ores. An interesting case study of the use of integrated E.M. and magnetic surveys in the discovery of nickel sulphide mineralization is presented by the Manitoba nickel belt. International Nickel Corporation's (Inco)

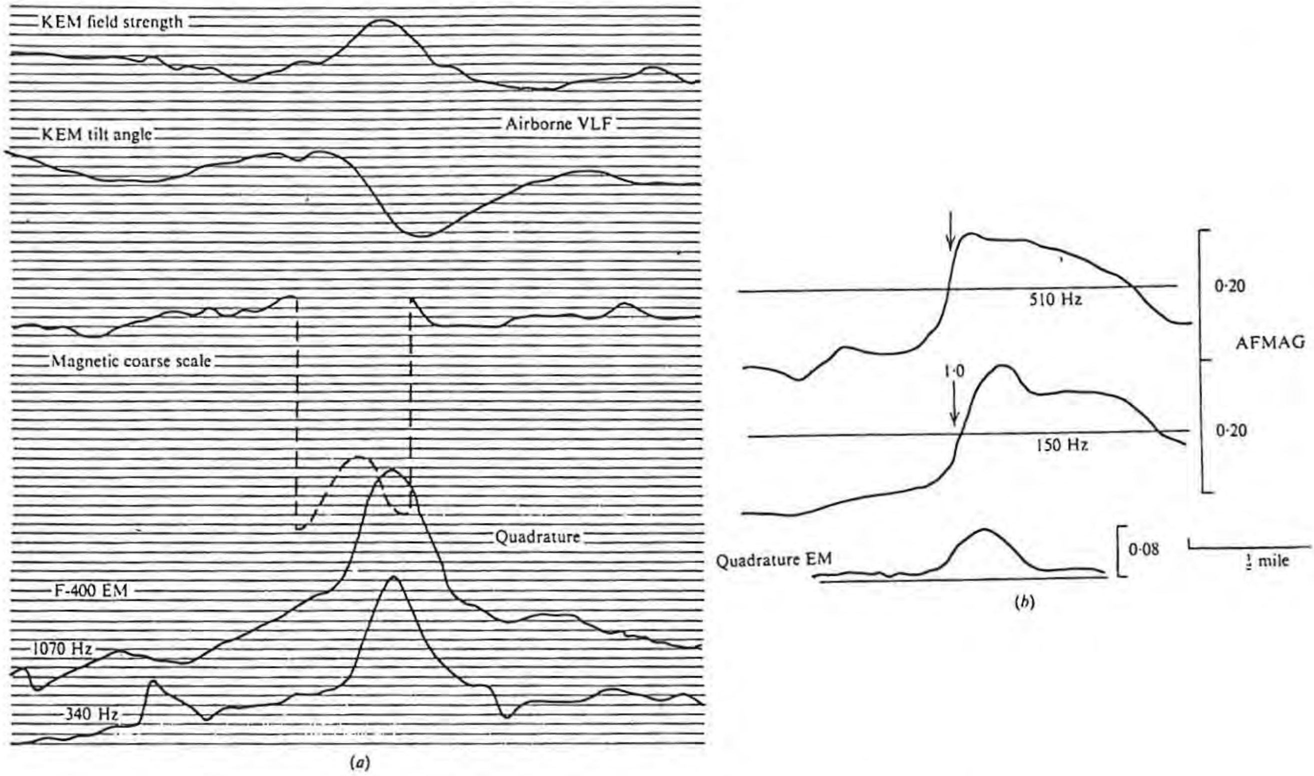


Fig. 7.8. Comparison of various airborne E.M. systems and aeromagnetics, Whistle Mine, Sudbury, Ontario. (a) Comparison of V.L.F., quadrature E.M., and aeromagnetics; (b) AFMAG quadrature E.M., (after Ward, 1959b, from Telford et al., 1976).

search centred on a 160 m long by 24 m wide belt of ultramafics along the boundary of the Churchill and Superior provinces. The overburden in the area may reach some 100 m in depth and outcrops average one per 1,5 sq. km. The exploration programme which began in 1946, was therefore, geophysically orientated and dominated by ground and airborne E.M. and magnetic surveys. However, by 1956, when the first drillhole intersected a major orebody (the Thompson orebody), Inco had sampled some 720 km of drillcore and spent some $10 million on exploration (E.M.J. staff, 1981). This high failure rate is attributable to a number of factors. In the early days of exploration no E.M. equipment was available and consequently, it was impossible to tell whether there was a possibility of any sulphides being associated with the magnetic anomalies. Therefore, Inco's policy of drilling magnetic highs was not very successful. Even when E.M. equipment became available in the early fifties, drilling of coincident magnetic/E.M. anomalies had a high failure rate because it was found that many of the E.M. anomalies were developed over graphitic horizons or barren pyrrhotite bodies. Care must be exercised when interpreting E.M. surveys over greenstone belts as graphitic and pyritic schists can produce significant E.M. responses. Fig. 7.9 shows a portion of the original

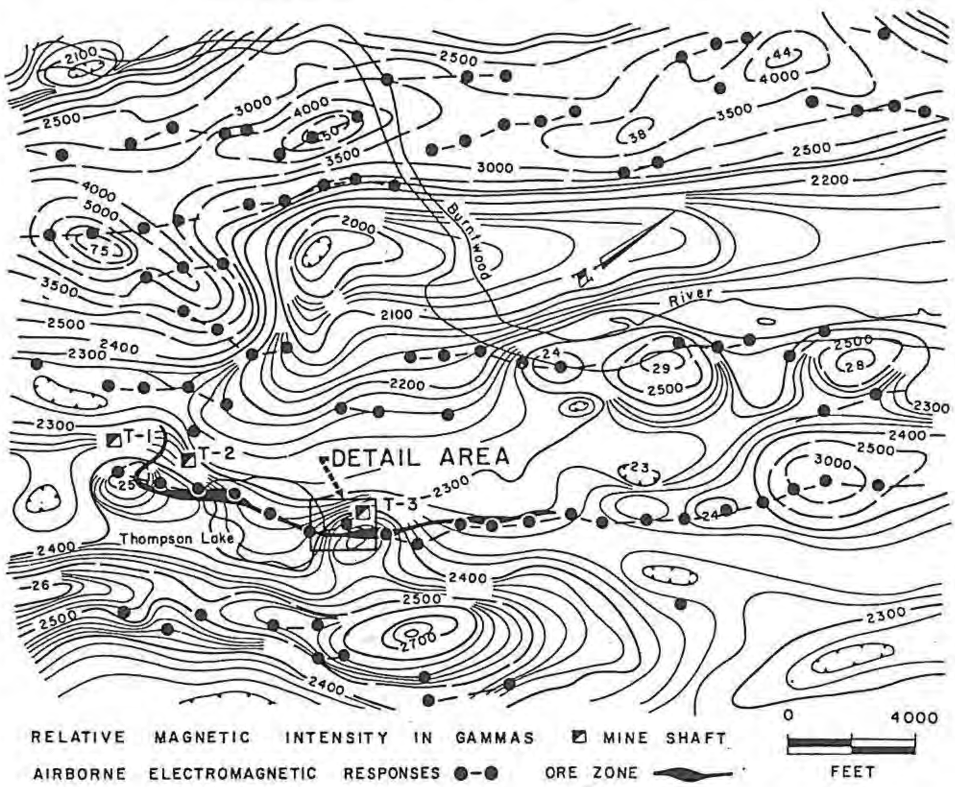


Fig. 7.9. Airborne electromagnetic and magnetic survey. Thompson area (after Zurbrigg, 1963, from Dowsett, 1967).

airborne E.M.-magnetic survey over the Thompson area. Numerous coincident electromagnetic and magnetic anomalies are visible in the figure. Fig. 7.10 shows the corresponding follow-up ground E.M. and magnetic data for the area. The ground E.M. conductor over the Thompson body is long and strong and coincides with a string of magnetic anomalies which peak in the 2000γ to 3000γ range. The detailed ground and airborne magnetics and E.M. over the actual mine area is shown in Fig. 7.11. The E.M. anomaly coincides with the position of the ore zone and is caused by the conductive sulphides within the orebody. The pyrrhotite within the orebody is the major cause of the magnetic anomaly, although the iron formation adjacent to the ore zone, because it contains disseminated

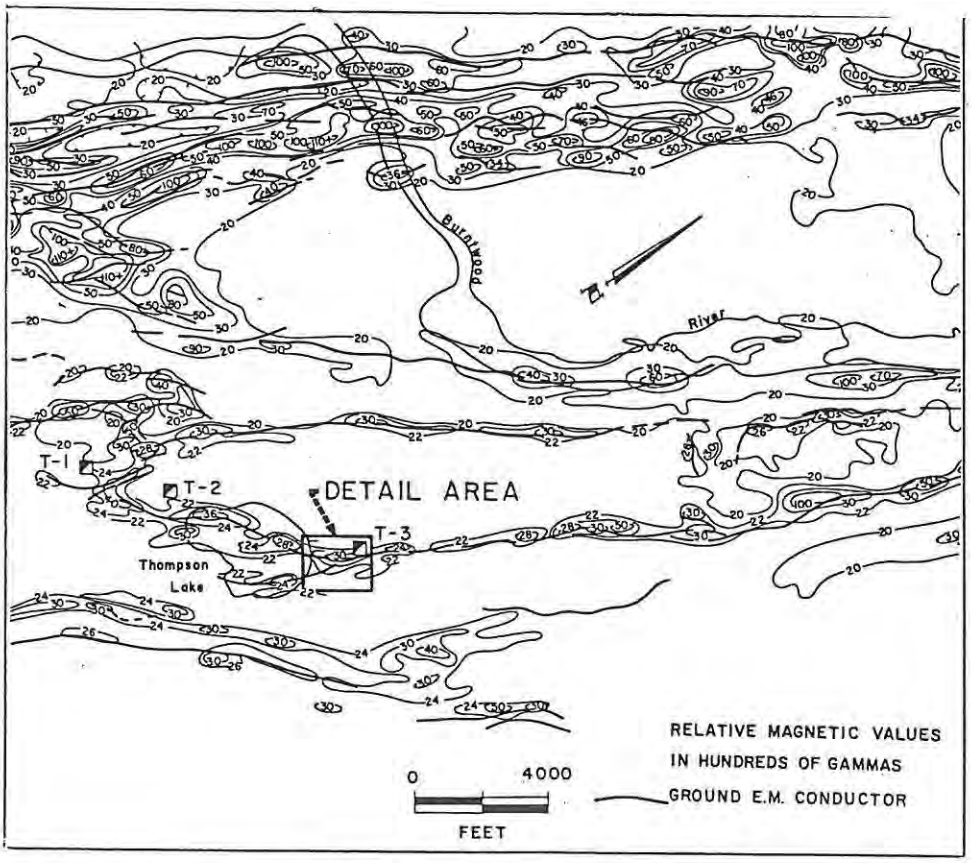
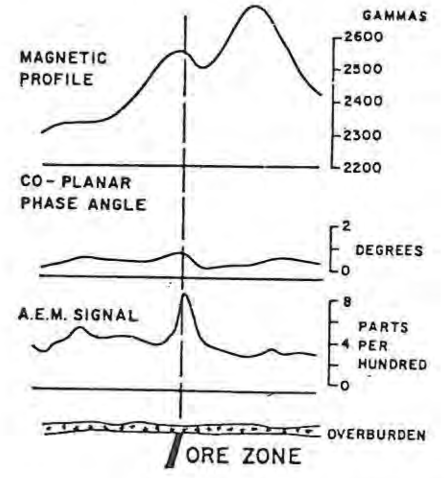


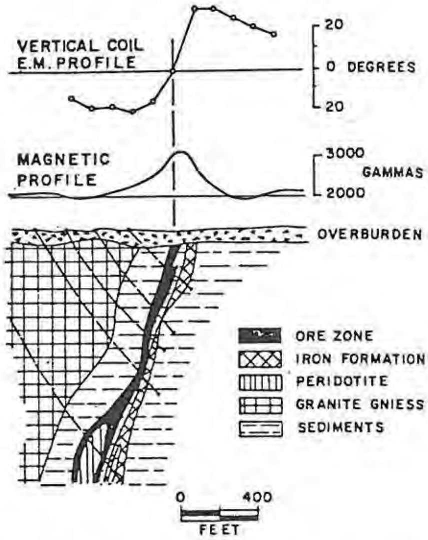
Fig. 7.10. Ground electromagnetic and magnetic surveys. Thompson area (after Zurbrigg, 1963, from Dowsett, 1967).

pyrite and pyrrhotite, contributes to a minor extent. The peridotite body is quite deep and consequently, contributes little to the amplitude of the magnetic anomaly. Prior to the discovery of the Thompson orebody, Inco were only following up magnetic anomalies in the 3000γ to 4000γ range. After the intersection of significant mineralization on this weaker magnetic anomaly, crews were sent out to investigate all the ground falling within contours above 2000γ (E.M.J. staff, 1981). The exploration sequence resulting in the discovery of the Pipe deposit was identical to that of the Thompson orebody and similar results were obtained (Figs. 7.12 and 7.14).

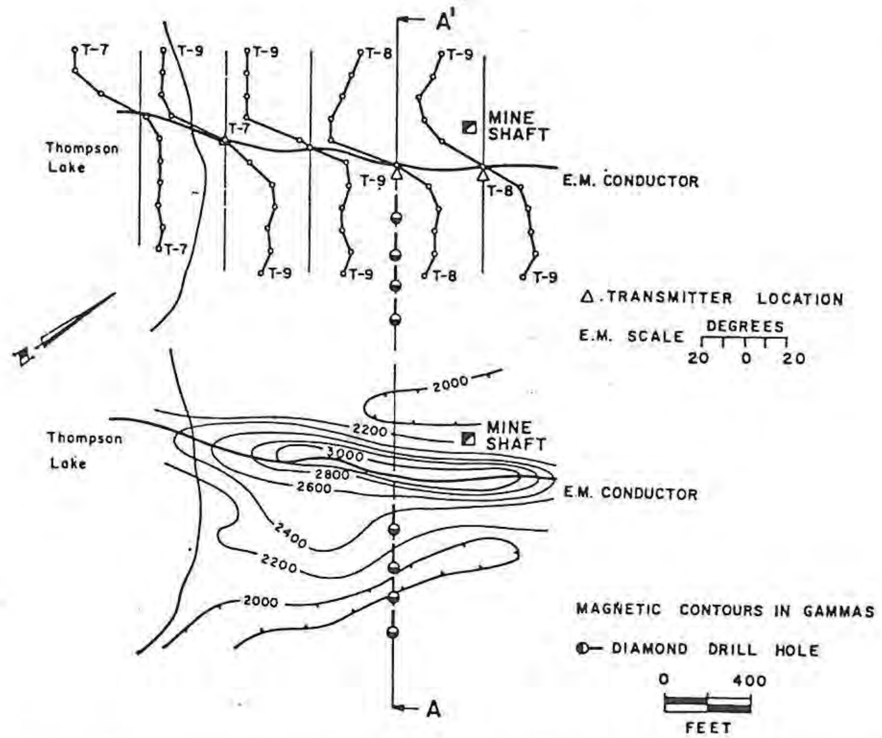
Fixed transmitter vertical loop E.M. surveys were used to screen the various AFMAG anomalies located by AMAX during exploration of the southern portions of the Manitoba nickel belt in the early seventies (Roth, 1975). A multitude of conductors, generally of considerable length, were tested by drilling. Most were found to be caused by variations in the thickness of the glacial overburden (which may reach



(a) Airborne electromagnetic profiles, Thompson mine.



(b) Geophysical and geological section through Thompson mine.



(c) Ground electromagnetic and magnetic surveys in discovery area, Thompson mine.

Fig. 7.11. Airborne and ground E.M. magnetic data over the Thompson mine (detail area in Fig. 7.10). (After Dowsett, 1967).

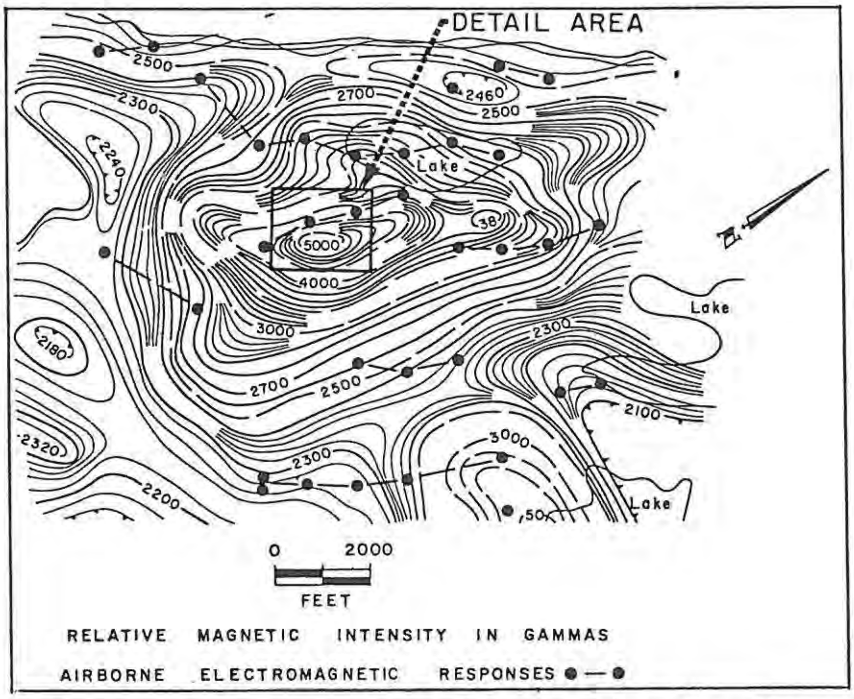


Fig. 7.12. Airborne electromagnetic and magnetic survey, Pipe area.

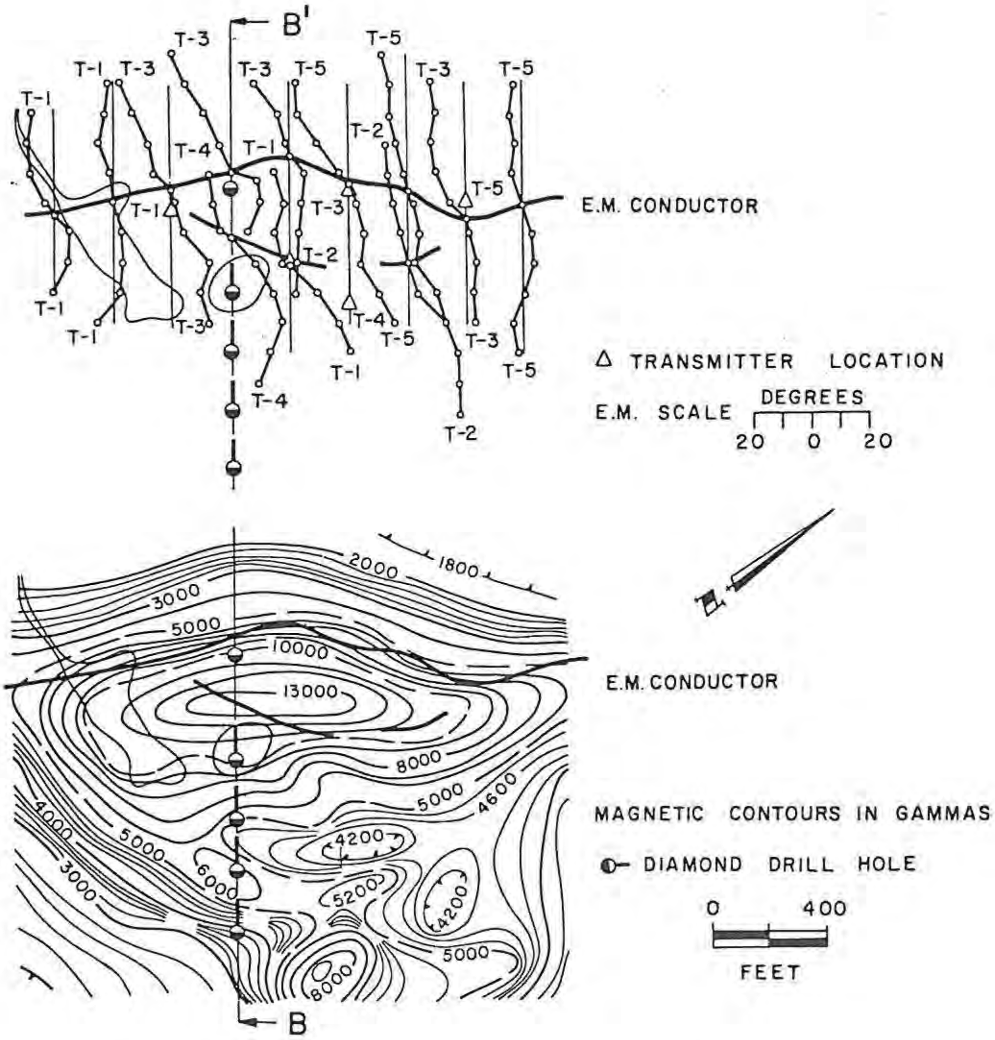


Fig. 7.13. Ground electromagnetic and magnetic surveys in detail area, Pipe mine (after Dowsett, 1967).

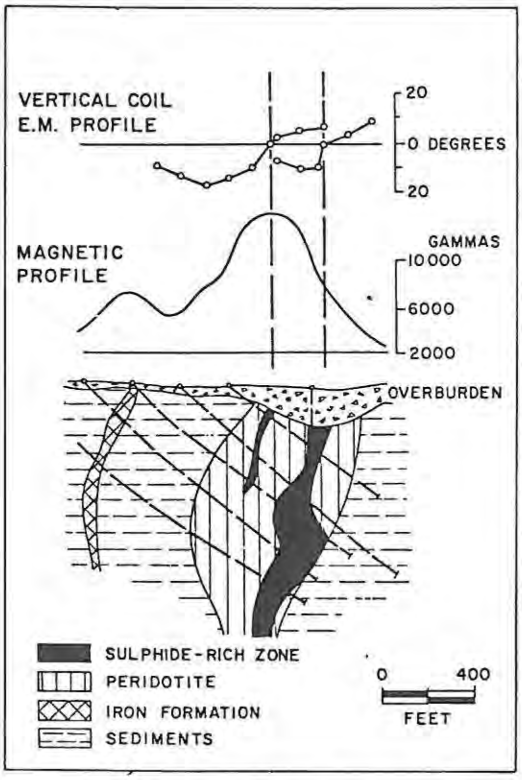


Fig. 7.14. Section B-B[1], Pipe mine (Dowsett, 1967).

60 m in thickness), weak shear zones, and barren zones of graphite-pyrite-pyrrhotite-magnetite mineralization. Another reason for the high failure rate of the E.M. surveys is that, in marked contrast to the more northerly sections of the belt, most of the mineralization is of a disseminated nature. Careful attention must be paid to the interpretation of E.M. surveys in strongly sheared and deformed terrains because significant E.M. response may be obtained over shear and fault zones containing circulating saline groundwaters. Furthermore, as indicated above, variations in overburden thickness and the presence of conductive overburden result in spurious E.M. anomalies, and care must be taken in the interpretation of E.M. surveys over deeply weathered terrains. This clearly limits the use of E.M. surveys in locating nickel sulphides in areas of excessive alluvial cover.

Not all shear zones are barren of mineralization, an example being the Thierry deposit. The orebody was discovered by ground magnetic and E.M. (vertical-loop tilt-angle method) surveys. The results of the detailed follow-up magnetometer and vertical-loop electromagnetic surveys are shown in Figs. 7.15 and 7.16. The E.M. results show that the ore zone, because of its low sulphide content, is only a moderate conductor. Strong magnetic responses are developed over the ore zone and related ultramafics. At a later stage an airborne E.M. and magnetic survey was flown and the orebody was delineated as a distinct anomaly.

The Montcalm copper-nickel deposit in Ontario is hosted by a gabbroic intrusive which has been emplaced into Archaean greenstones.

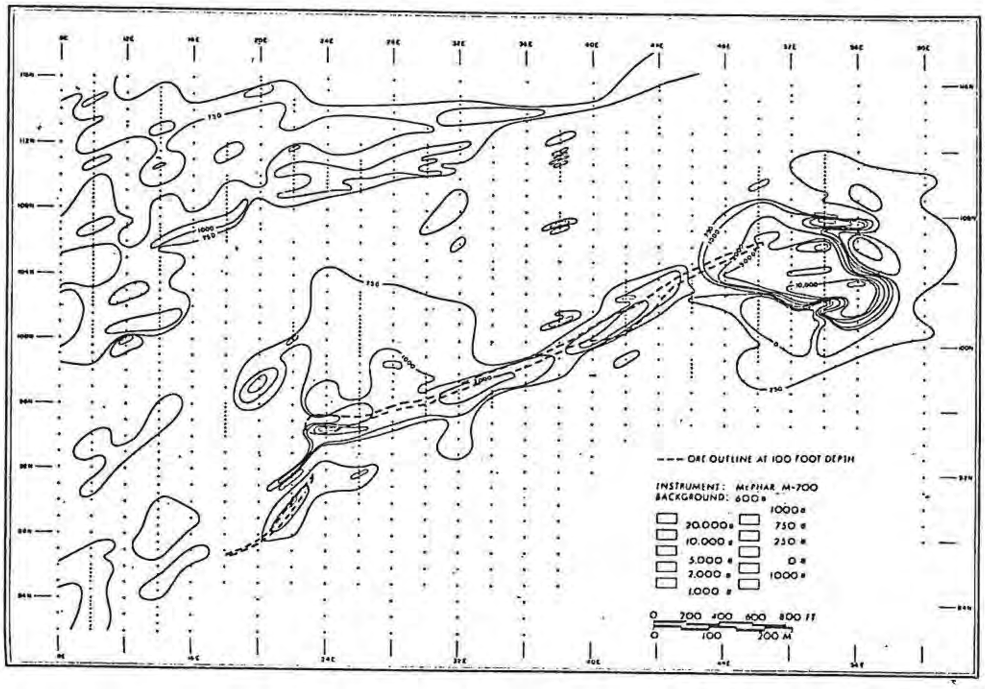


Fig. 7.15. Detailed magnetometer survey over the Thierry Deposit (after Verbeek et al., 1972).

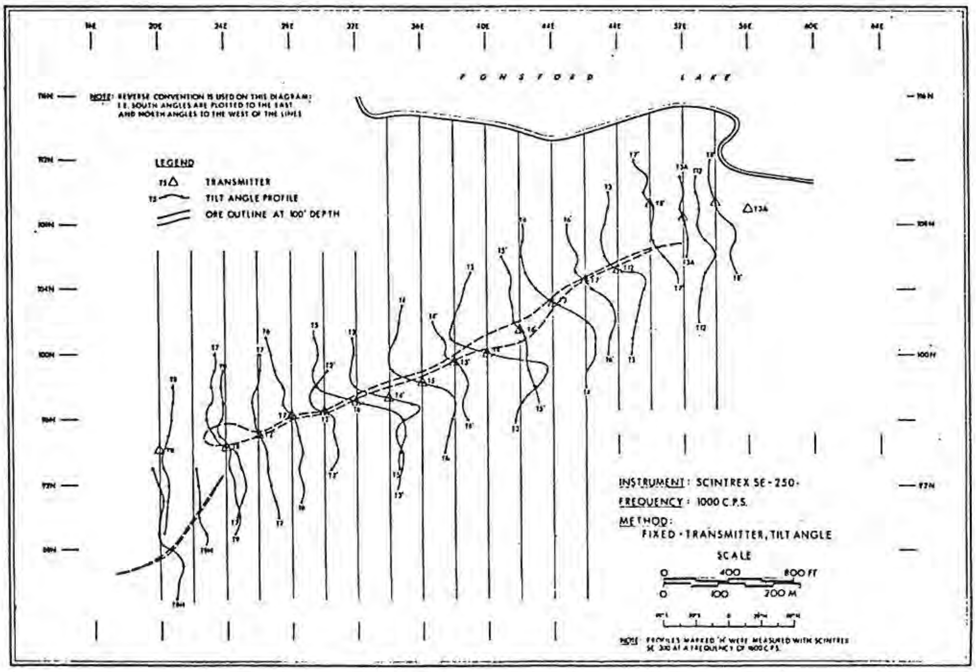
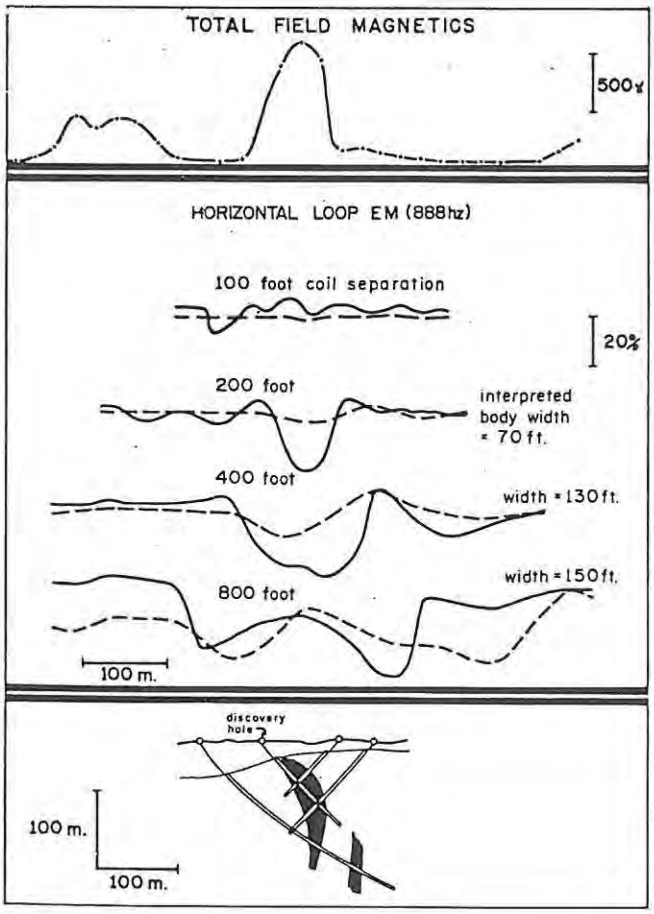
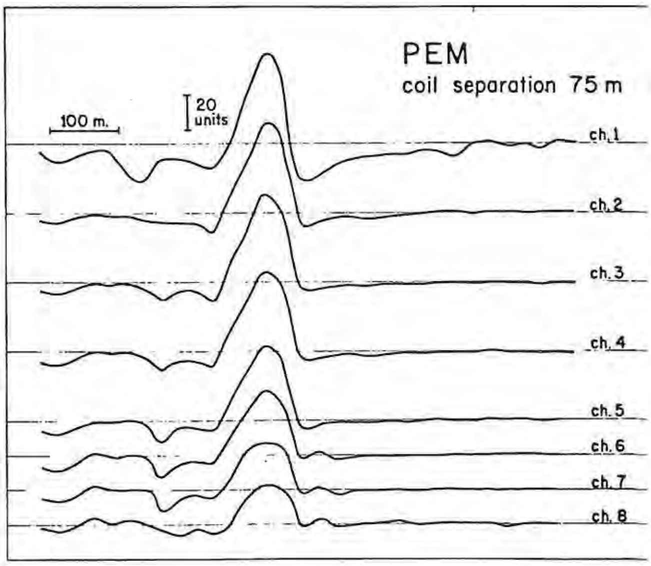


Fig. 7.16. Vertical-loop electromagnetic survey over the Thierry Deposit (after Verbeek et al., 1972).

The mineralization consists of massive pyrrhotite with lesser amounts of pentlandite, chalcopyrite, and pyrite. The deposit was discovered in 1976, when the first drillhole testing a DIGHEM airborne E.M. anomaly intersected 81 m of sulphides assaying 0,36% Cu and 0,81% Ni (Fraser, 1978). The E.M. anomaly was highly visible as a result of three factors: it had the highest conductance in the area (154 mhos). it correlated with a 175Y thumbprint-shaped magnetic anomaly, and it was isolated from conductive bands (its nearest neighbour was more than 800 m away). Ground E.M. and magnetic surveys were used to test the anomaly on the ground. A strong magnetic anomaly is present over the orebody. The horizontal-loop E.M. results over the orebody is shown in Fig. 7.17a. The best resolution of the ore zone, which occurs at a depth of 75 ft (25 m), is obtained at the 200 foot coil separation. The increase in the estimated width of the deposit with increasing coil separation reflects an increase in thickness of the orebody with depth. The results for a pulse-E.M. survey using a coil separation of 246 ft (75 m) is shown in Fig. 7.17b. The eight channels represent increasing time delays





(a) (b)

Fig. 7.17. (a) Max Min-II horizontal-loop E.M. at 888 hz for four coil separations Magnetics and geological section are also shown. (b) Crone pulse E.M. using a 75-m coil separation. Ground E.M. surveys over the Montcalm deposit (after Fraser, 1978).

from top to bottom and the slow decrease of anomaly size with channel number is a characteristic of a highly conductive body.

SIROTEM is an outgrowth of research into electromagnetic prospecting techniques by the Division of Mineral Physics of the Australian Research Organization, CSIRO, from 1972 to 1977 (Smith, 1980). SIROTEM is essentially a transient E.M. technique. It is based on the principle that current flowing in a transmitter loop sets up a magnetic field, which induces eddy currents to flow in any good electrical conductor in the ground. These eddy currents set up a secondary magnetic field which can be detected by a receiver loop. The main advantages of the SIROTEM method is its ability to penetrate thick (up to 100 m) layers of conductive oxidation and to operate in areas of high noise interference. The SIROTEM profile over a conductive horizon in the Yilgarn block of Western Australia is shown in Fig. 7.18. The double peak profile in later channels

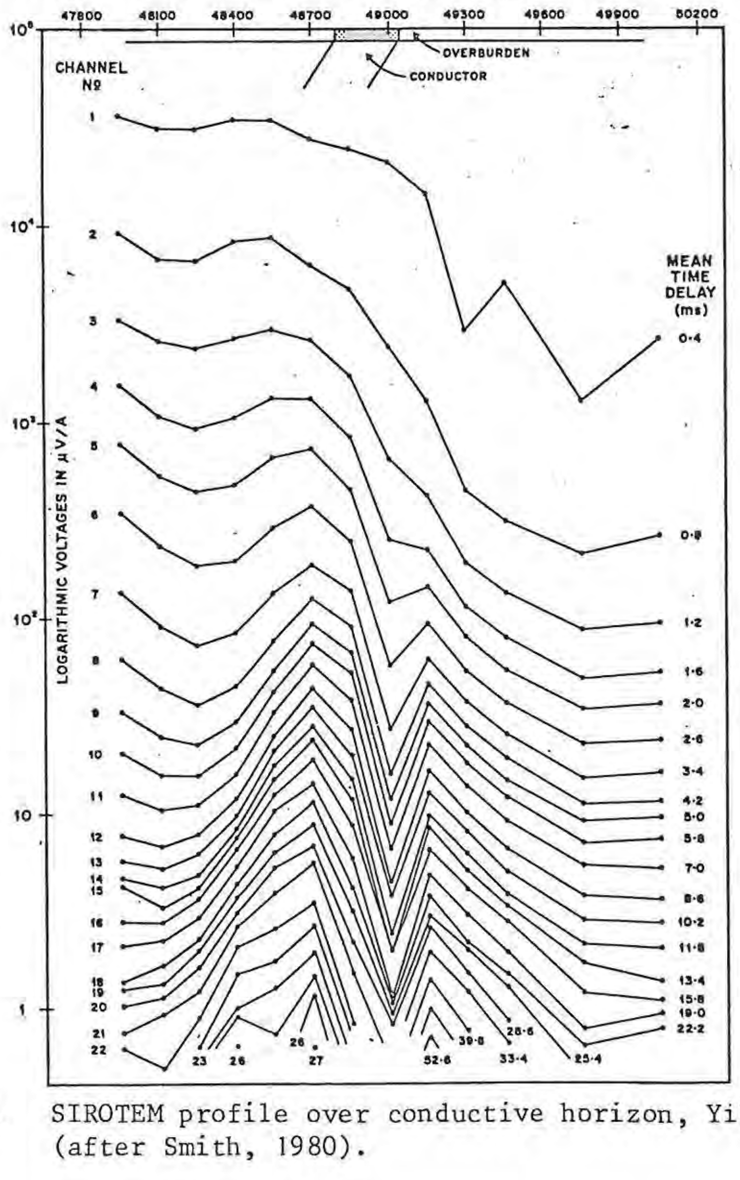


Fig. 7.18. SIROTEM profile over conductive horizon, Yilgarn block (after Smith, 1980).

is indicative of a conductor at 49000 ± 150. The higher amplitude of the south peak suggests a dip in that direction. The lack of expression of this feature in early channels suggests masking by conductive overburden. A SIROTEM profile over a massive pyrite-pyrrhotite zone under 25 m thick zone of oxidation in the Yilgarn block is shown in Fig. 7.19. A peak in the values at 500-5505 is

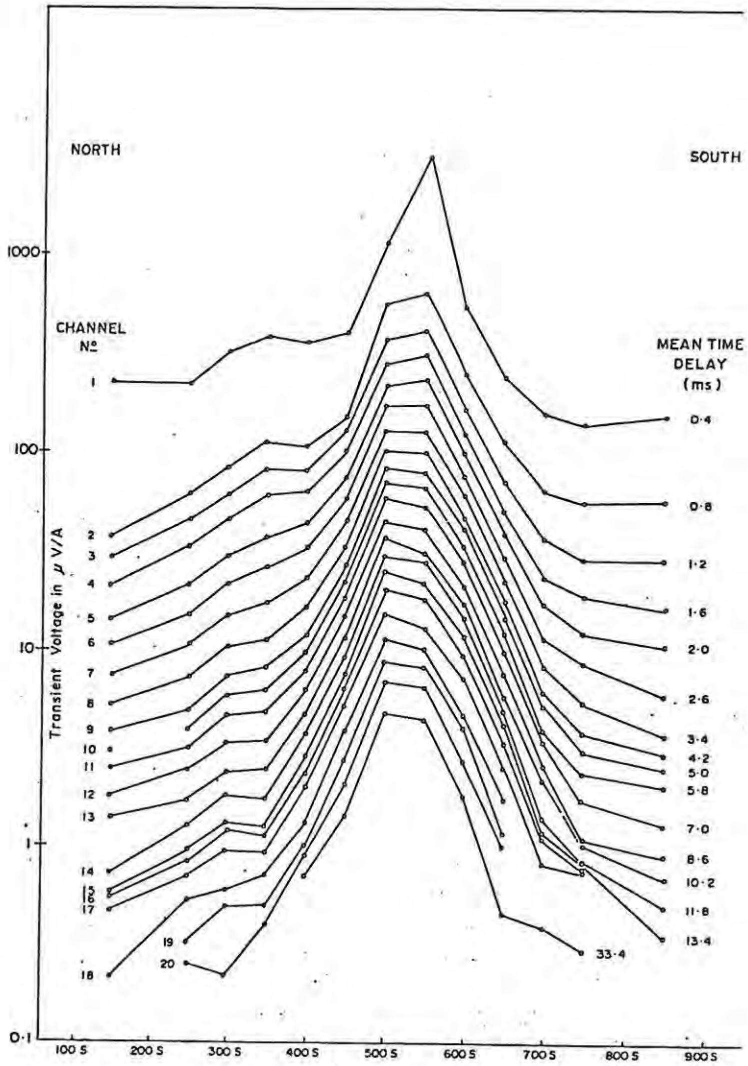


Fig. 7.19. SIROTEM profile over pyrite-pyrrhotite mineralization, Yilgarn block (after Smith, 1980).

evident on all channels and the asymmetry suggests a steep dip to the north. The great depth of oxidation has little effect on the quality of resolution.

The induced polarization (I.P)-resistivity method was primarily designed to detect disseminated sulphide mineralization, and its effectiveness in this regard is firmly estalished (Furnell, 1981).

An important advantage of the I.P. method stems from its ability to distinguish between metallic and ionic conductors (Furnell, 1981). Water-filled faults and shears and conductive overburden commonly produce spurious E.M. anomalies that are often interpreted as being due to metallic conductors. The I.P. and E.M. results from a deposit in the Lynn Lake area are shown in Fig. 7.20. The E.M. data clearly outlines the position of two conductors. Both of these were tested by drilling prior to the advent of the I.P. survey. The western conductor is associated with a massive sulphide zone at depth, while the

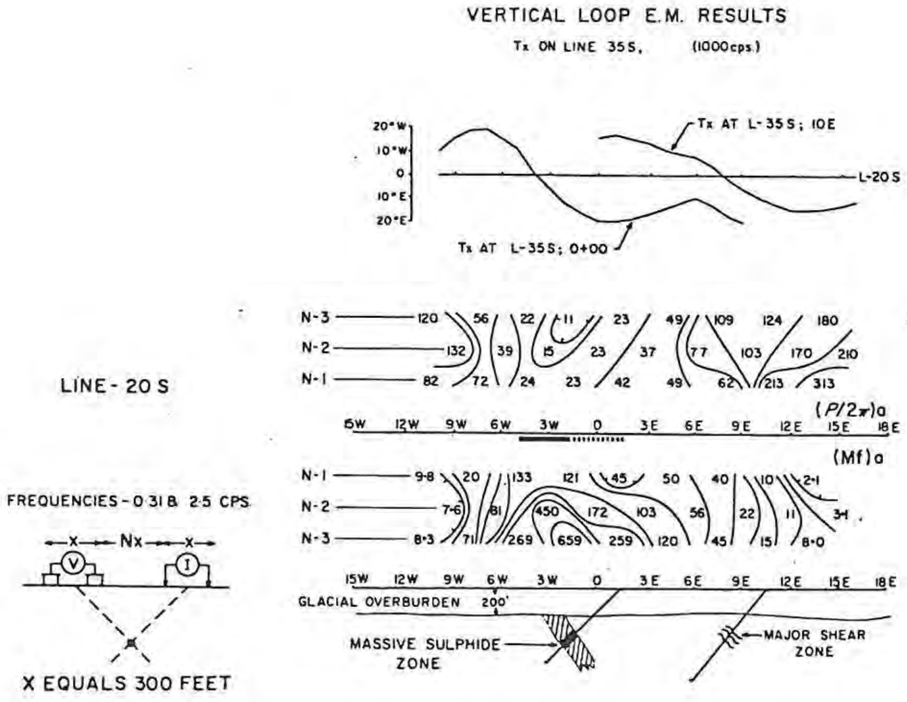


Fig. 7.20. Comparison of E.M. methods and I.P. results from Lynn Lake area, Manitoba, Canada (after Hallof, 1967).

eastern conductor is associated with a fault zone within the ultramafic rocks. A strong I.P. anomaly is centered over the eastern conductor but no anomalous I.P. effects are encountered over the E.M. conductor at 8400E. Geological evidence suggests that the zone of low resistivity reflects a broad zone of shearing adjacent to the fault. Although the E.M. responses from the two sources are similar, the I.P. measurement clearly indicates the importance of the zone of massive sulphide mineralization.

The high background effects in the Lynn Lake data are common of most ultramafic terranes and are due to metallic magnetite. Caution should be exercised when using I.P. methods in prospecting for nickel-copper sulphides because magnetite can produce a significant I.P. response (Furnell, 1981). The interpretation of the results of an I.P. survey over prospective nickel targets should be guided by the results of geological and magnetic surveys.

Pyritic tuffs, shales, and volcaniclastic sediments as well as graphitic horizons may also produce spurious I.P. anomalies. Considerable caution should therefore be exercised when interpreting I.P. surveys over ultramafic rocks in Archaean greenstone belts. Spurious anomalies from these horizons can generally be recognized by their more persistent character (Furnell, 1981). The low magnetite content of these horizons also provides an effective means of screening.

Ultramafic rocks that have either been partially or completely serpentinized and strongly sheared are capable of causing I.P. anomalies of a similar magnitude to those originating over sulphide mineralization. This has been demonstrated by Moeskops and his co-workers during a study of the Bulong serpentinite in the Kalgoorlie district of Western Australia. The serpentinite originally formed a sheet of cumulus-textured and crytic layered dunite and wherlite. Local alteration to a talc-carbonate-chlorite assemblage is visible in some areas. A typical I.P. anomaly caused by disseminated sulphide mineralization in the serpentinite is shown in Fig. 7.21a. The sulphides occur as fracture fillings and form 20% by volume of the mineralized zone. Similar I.P. responses can be obtained over shear zones in unweathered serpentinites (Fig. 7.21b) and over partially serpentinized zones containing relict olivine grains in a thoroughly serpentinized ultramafic rock (Figs. 7.21c and d). These spurious I.P. anomalies cannot be easily distinguished from anomalies due to sulphide mineralization. The process of polarization in the former is apparently similar to membrane polarization displayed by certain lithologies containing clay minerals. Only those samples displaying I.P. transient decay curves with very short time constants may be positively distinguished as non-metallic polarizers.

The depth penetration of the I.P. method is considerably greater than that obtained by E.M. techniques. In regions of conductive overburden, most E.M. surveys are adversely affected and their depth

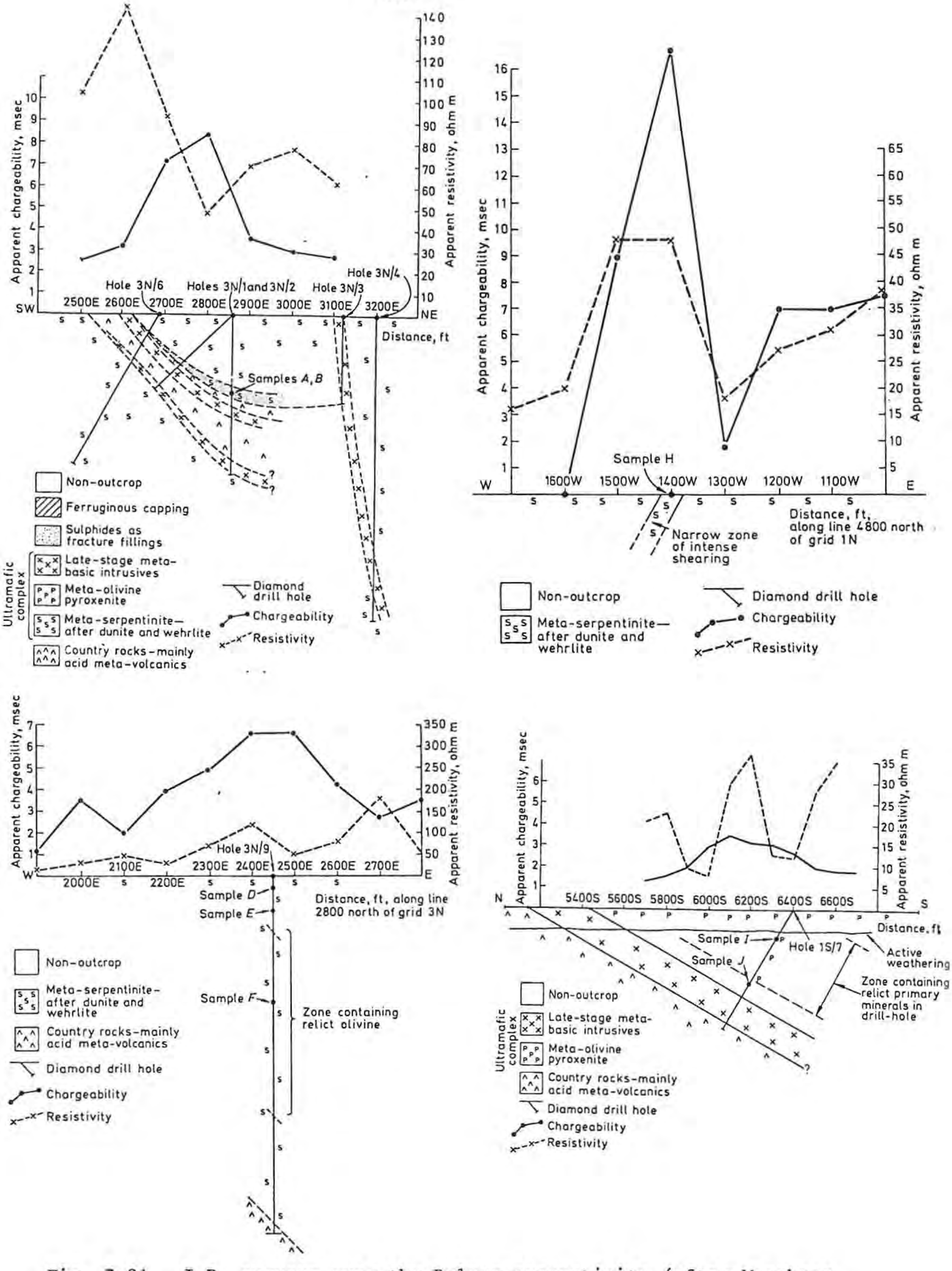


Fig. 7.21. I.P. surveys over the Bulong serpentinite (after Moeskops et al., 1971); (a) illustrates a typical field I.P. anomaly caused by sulphide mineralization; (b) the indicated I.P. anomaly, in well exposed unweathered serpentinite, correlated with a shear zone; (c) situation where drilling indicated the apparent source of the I,P. anomaly to be a zone containing relict primary minerals, 20-80 per cent serpentinized, surrounded by fully serpentinized ultramafic rock; (d) similar to (c). I.P. anomaly correlates with a zone in which the primary mineral grains had been partially preserved.

penetration is severely limited. I.P.-resistivity methods have been widely used in the search for nickel sulphide mineralization in the deeply weathered Vilgarn block in Western Australia where the depth of conductive overburden precludes the use of E.M. surveys. The surveys have met with considerable success. There were no gossans developed over the Nepean orebody and the successful diamond drillhole was located over a coincident ground magnetic-I.P. anomaly (Sheppy et al., 1975). The Six Mile deposit was discovered through the testing by diamond drilling of geologic targets associated with I.P. anomalies (Turner et al., 1975). The results of dipole-dipole, pole-dipole and gradient array over two narrow zones of nickel sulphide mineralization are shown in Fig.7.22. None of the three resistivity

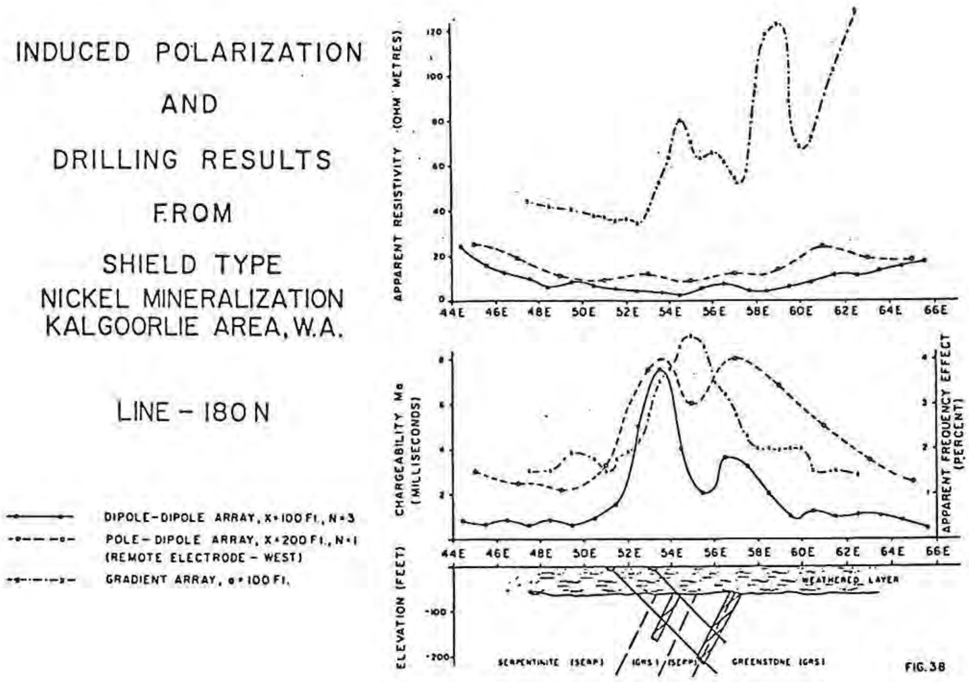


Fig. 7.22. Results of an induced polarization survey, over narrow zones of nickel sulphide mineralization in Western Australia (after Smith, 1980).

profiles show a distinct low over the mineralized zones and the gradient array detects a much higher resistivity level than the other two (Smith, 1980). The pole-dipole and dipole-dipole, show very low apparent resistivities reflecting the presence of a highly porous, conductive, weathered surface layer. The gradient array resistivity profile shows an indistinct double high over the two zones of mineralization. The gradient array chargeability profile shows a single anomalous peak centred between the two zones of mineralization and fails to discriminate between the two mineralized zones. This suggests that the gradient array technique has the least sensitivity in the separation of anomalies from closely spaced sources. The pole-dipole and dipole-dipole arrays would therefore be preferable in locating diamond drillhole sites where more than one mineralized zone is likely to be encountered (Furnell, 1981). This is particularly applicable to volcanic-hosted komatiitic deposits where the ore bodies form stacked lenses within the stratigraphy.

The Poseidon orebody at Windarra, Western Australia, is located within serpentinized peridotite, which lies just to the east of a broad band of siliceous banded iron formation containing pyrite and metallic magnetite (Smith, 1980). The latter gives rise to strong wide I.P. anomalies (Fig. 7.23). The gradient array resistivity results

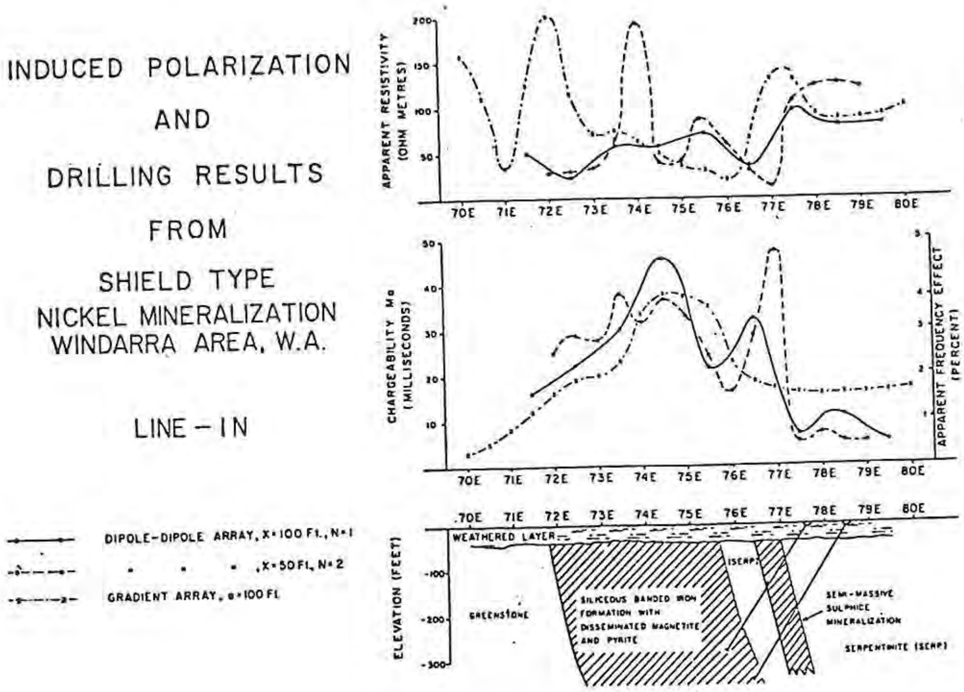


Fig. 7.23. Results of an induced polarization survey over the Posiedon nickel sulphide orebody, Windarra, Western Australia (after Smith, 1980).

give irregular values, with a local resistivity high over the narrow zone of mineralization. The dipole-dipole resistivity data shows a modest low over the mineralization. The wide variation in the resistivity profiles is reflective of the changeable porosity within the overburden. The gradient array chargeability results show a single broad peak which includes both the banded iron formation and the narrow zone of mineralization. The dipole-dipole chargeability data however, exhibits a discrete anomaly over the sulphidic zone. The broad I.P. anomaly to the west is due to metallic minerals within the iron formation.

During the mid-seventies a major breakthrough in the refinement of I.P. methods was obtained with the development of magnetic induced polarization (M.I.P.). The technique measures magnetic fields associated with the polarization current flow by a sensitive magnetometer (Siegel, 1979). This method can detect an induced polarization source through a conductive overburden layer which would normally seriously reduce the electric field I.P. effects of the source. In addition, it permits I.P. measurements to be made in areas of loose sand or permafrost, where electric contact with the ground is difficult or even impossible. The M.I.P. method has mostly been used to date in Australia. The results of a M.I.P. survey over the ore shoots of the Juan Complex at Kambalda are shown in Fig. 7.24. These clearly show the high quality of resolution obtainable through the conductive overburden, and clearly delineate the stacked orebodies within the stratigraphy - a characteristic feature of volcanic-hosted komatiitic deposits.

In areas where small copper-nickel sulphide deposits are thought to be near the surface, I.P. or S.P. methods should be used in preference to E.M. surveys. Fig. 7.25 shows a geologic section through the Maclennan orebody, Sudbury, with the corresponding magnetic E.M., S.P., and I.P. profiles. The vertical coil E.M. results were extremely weak over this orebody, but distinct anomalies were obtained using I.P., S.P., and magnetics.

Even where the mineralization is massive, I.P. surveys may produce meaningful results. The results of a frequency domain I.P. survey using a dipole-dipole array with an electrode spacing of 50 m over the Montcalm deposit is shown in Fig. 7.26 (Fraser, 1978). The

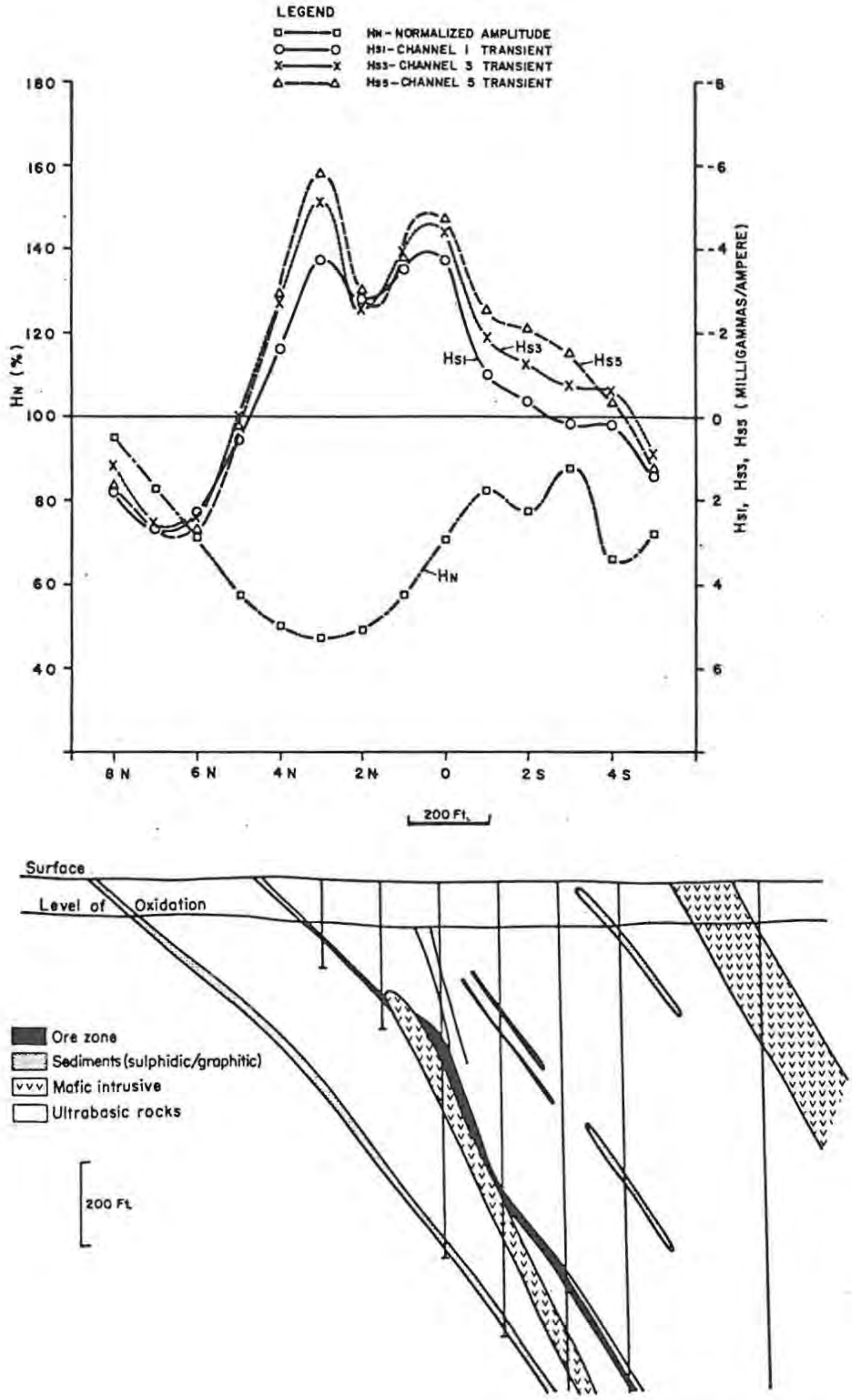


Fig. 7.24. Multichannel time domain M.I.P. response over Jan Shoot using Scintrex I.P.-8 receiver. Kambalda area, Western Australia (after Siegel, 1979).

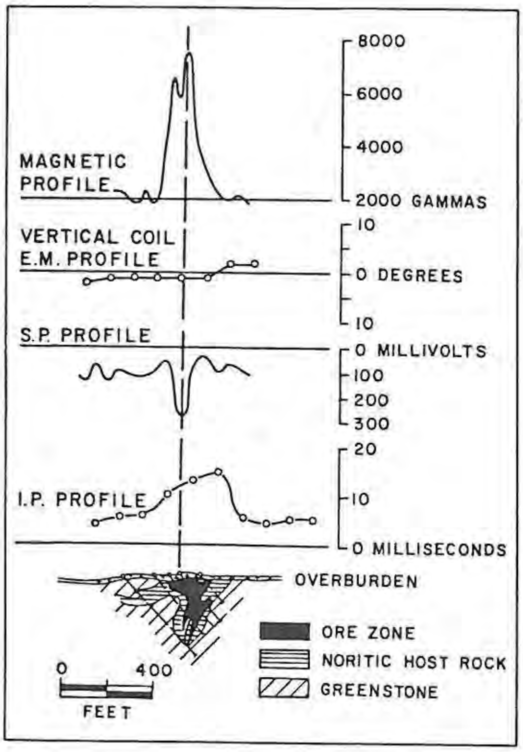


Fig. 7.25. Section C-C[1], Maclennan mine (after Dowsett, 1967).

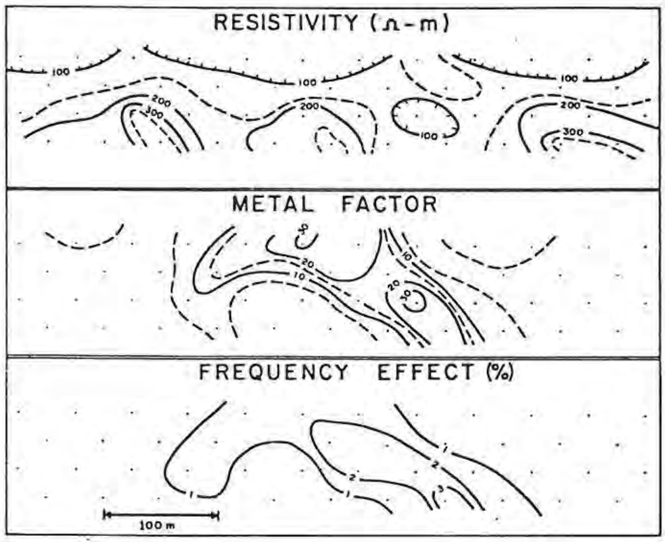


Fig. 7.26. Phoenix induced polarization survey, using frequencies of 5 and 0.3 hz (after Frazer, 1978)

existence of the deposit is not obvious on the resistivity data, but is more clearly defined on the frequency effect and metal factor.

Copper-nickel sulphide mineralization in the Temagami area, Ontario, is spatially associated with a large mass of peridotite (Hallöf, 1966). The distribution of the peridotite was known from outcrop and detailed magnetic surveys (Fig. 7.27). The known zone of copper-nickel mineralization is also outlined on Fig. 7.27. An electromagnetic survey was commissioned to delineate possible strike extensions to the known ore zone. The Turam E.M. method was chosen because the survey would be cheaper than an I.P. survey and also the known mineralization was of a massive nature. The best anomalies were located on the south-western part of the grid (Fig. 7.27). Three drillholes tested these anomalies, but little or no mineralization was intersected. At this stage the company commissioned an I.P. survey to indicate if any metallic mineralization was associated with the conductors. No I.P. response was found over the E.M. conductors in the south-western part of the grid. Definite I.P. anomalies were associated with the peridotite body because of its high content of metallic magnetite. Strong I.P. anomalies were located over the known mineralization and in

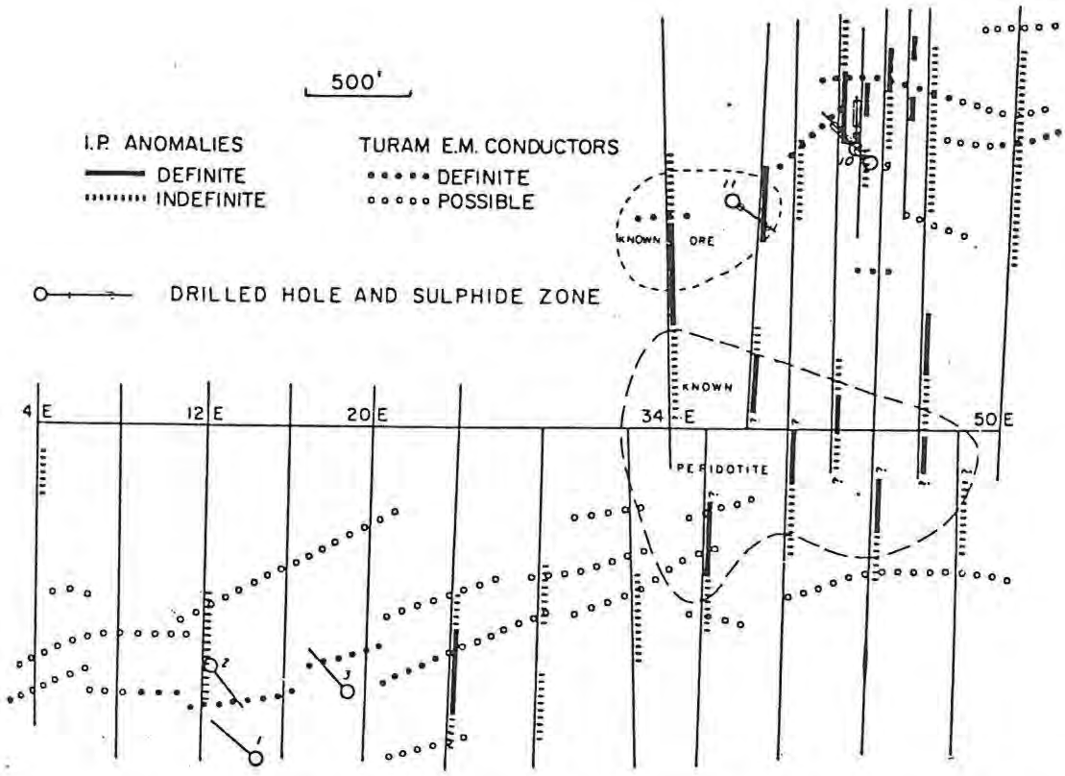


Fig. 7.27. Grid used for induced-polarization and Turam E.M. surveys (after Hallof, 1966).

an area to the north-east of the known ore. The latter anomalies were coincident with weak E.M. conductors. These were drilled and found to contain substantial amounts of massive and disseminated sulphide mineralization. The case history clearly illustrates some important characteristics of the I.P. method: its inability to distinguish between ionic conduction from sulphide and magnetite, as well as its enhanced ability to distinguish between narrow zones of ionic conduction and broad zones of disseminated mineralization. The limitations of the Turam E.M. system and the potential value of detailed magnetic surveys in this environment are also apparent.

Self-potential surveys have been effectively applied in the exploration for massive-type copper-nickel sulphides. The technique is really only effective over small bodies present at a shallow depth (Ward, 1966). If the overburden is deeper than 35 m, the method should be disregarded. Spurious S.P. anomalies are often caused by rapid changes in topographic relief. The results of a successful S.P. survey over a Sudbury-type orebody are shown in Fig. 7.25. The copper-nickel orebodies at Temagami mine, Ontario, are localized along the footwall of a large intrusive gabbro. The orebodies contain some 2,25 million tonnes of ore assaying 1,6% Cu + Ni and over 50 000 tons of massive chalcopyrite. Self-potential anomalies of over 500 milli-volts were recorded over the more massive copper-nickel sulphide ore and values of over 300 milli-volts were obtained over the massive chalcopyrite mineralization (Fig. 7.28).

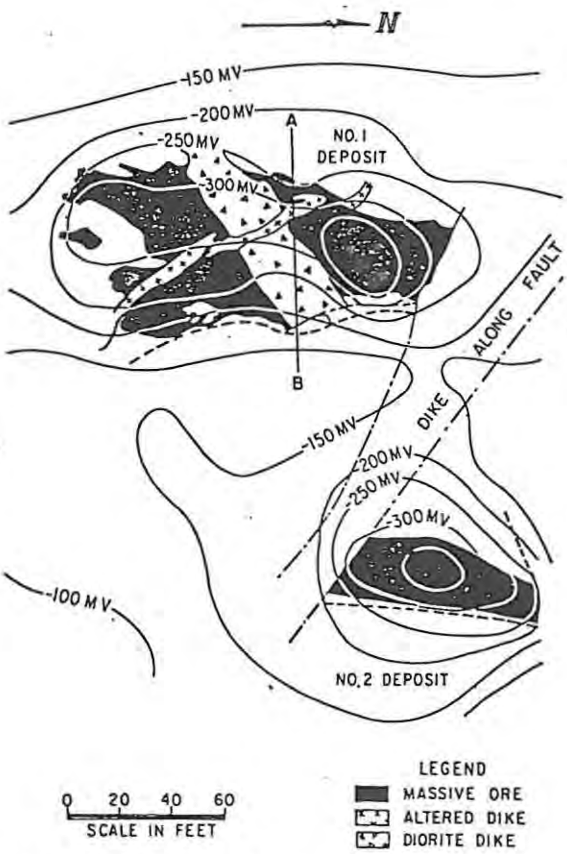


Fig. 7.28. Self-potential anomalies, no. 1 and no. 2 deposits, Temagami Mine, Ontario (after Bergey et al., 1958, from Ward, 1966).

Gravity methods are not commonly used in the exploration for nickel sulphide deposits because they are slow, expensive, require a high level of precision, and are sensitive to variations in overburden thickness and topography (Furnell, 1981). The density of sulphide minerals decreases upon weathering and the method is of limited use in exploring for heavily weathered or deeply buried deposits.

Gravity surveys may be utilized to locate major structural trends of metallogenic significance. In Canada the boundaries between the

Superior, Churchill, and Grenville provinces are defined by major gravity features which are broadly coincident with the Sudbury nickel deposits and the Manitoba nickel belt. The boundary between the Churchill and Superior provinces in northern Manitoba is marked by a strong gravity low along the Setting Lake lineament. This is bounded to the south-east by the Nelson River gravity high and to the north-west by the Burntwood gravity high (Fig. 7.29) (Innes, 1967). In some parts of the area there is an excellent correlation between surface rocks, their densities, and the Bouger anomalies (Gibbs, 1965). The Nelson gravity high outlines a belt of dense granulites over the Pikwitonei Region. To the northwest the three gravity lows are interpreted as the gravity effects of granitic intrusions. The Nelson River gravity high is separated from these lows by a steep gravity

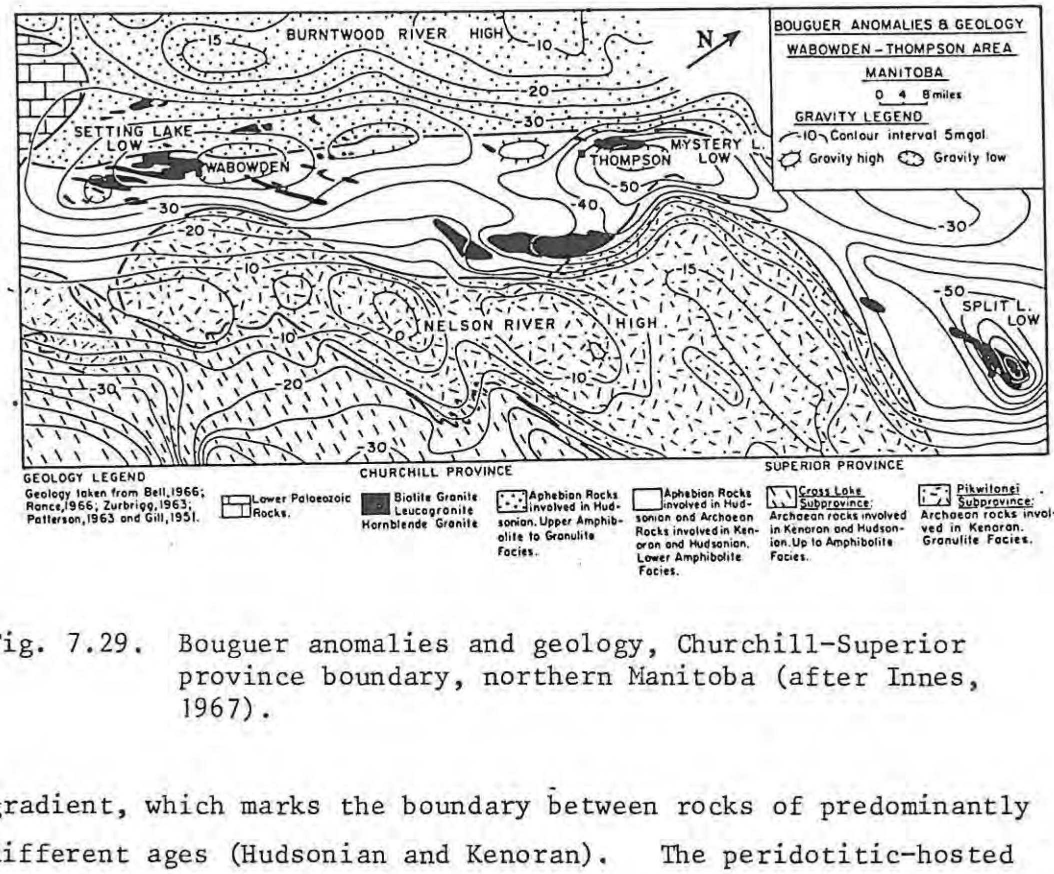


Fig. 7.29. Bouguer anomalies and geology, Churchill-Superior province boundary, northern Manitoba (after Innes, 1967).

gradient, which marks the boundary between rocks of predominantly different ages (Hudsonian and Kenoran). The peridotitic-hosted nickel sulphide ores of the Manitoba nickel belt lie scattered along the axis of the belt of gravity lows from south of Wabowden to north of Thompson (Fig. 7.29). The regional gravity survey thus provided a valuable guide for exploration within the area.

Massive chalcopyrite-pyrrhotite-pentlandite orebodies have a much higher density (15% to 80% higher) than their surrounding rocks

(Dowsett, 1967). If the overburden is shallow and of uniform thickness, gravity surveys can produce meaningful results. The Garson offset deposit in the Sudbury district is a pseudo-tabular body occurring under approximately 12 m of overburden. A geologic section through the deposit with the correponding gravity profiles, both before and after the removal of the regional trend, is shown in Fig. 7.30. The results clearly show that gravity can be a valuable tool in exploration for ores of this type.

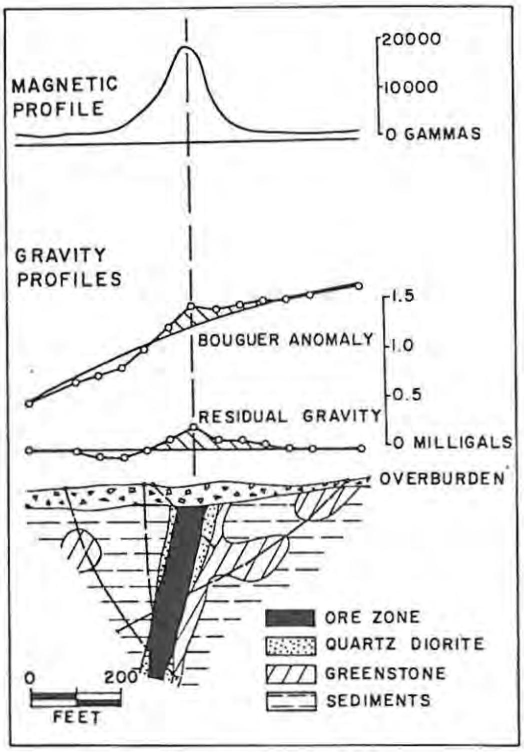


Fig. 7.30. Gravity and magnetic profiles, Garson offset sulphide deposit (from Dowsett, 1967).

7.2 Geochemical techniques

When planning any geochemical survey over ultramafic rocks, it must be borne in mind that ultramafic rocks (the major host for nickel suphide ore deposits), are a typical example of a high background source rock and are enriched in Cr, Ni, Co, and Mg (Table 7.1).

Lithogeochemical techniques have been applied in the exploration for nickel-copper sulphide ores. Most methods have attempted to ascertain whether the magma was originally saturated in sulphide or not. If the sulphur content of the magma was high at a relatively

	Ionic radii, Å	World averages Ultramafic rocks	Mafic rocks	Intermediate rocks	Felsic rocks
Si^{4+}	0.42	19.0	24.0	26.0	32.3
Al^{3+}	0.51	0.5	8.8	8.9	7.7
Fe^{3+}, Fe^{2+}	0.64, 0.74	9.9	8.6	5.9	2.7
Mg^{++}	0.66	25.9	4.5	2.2	0.6
Ca^{++}	0.99	0.7	6.7	4.7	1.6
Na^{+}	0.97	0.6	1.9	3.0	2.8
K^{+}	1.33	0.03	0.8	2.3	3.3
P^{5+}	0.35	170	1,400	1,600	700
Ga^{3+}	0.62	2	18	20	20
Cr^{3+}	0.63	2,000	200	50	25
Li^{+}	0.68	<1	15	20	40
Ni^{++}	0.69	2,000	160	55	8
Co^{++}	0.72	200	45	10	5
V^{3+}	0.74	40	200	100	40
Ti^{3+}†	0.76	300	9,000	8,000	2,300
Zr^{4+}	0.79	30	100	260	200
Mn^{++}	0.80	1,500	2,000	1,200	600
Sc^{3+}	0.81	5	24	3	3
Cu^{+}†	0.96	20	100	35	20
Sr^{++}	1.12	10	440	800	300
Pb^{++}	1.20	<1	8	15	20
Ba^{++}	1.34	1	300	650	830
Rb^{+}	1.47	2	45	100	200

Table 7.1. Average content of major and minor elements in four rock series. Major elements in weight percent, minor elements in p.p.m. (after Kavskopf, 1979).

early stage in its crystallization history, both nickel and copper would selectively partition into the sulphide phase to form immiscible sulphide droplets prior to the onset of heavy olivine crystallization.

Cameron and his co-workers (1971) collected 1079 samples of ultramafic rocks from 61 widely scattered localities across the Canadian Shield and Eastern Townships of Quebec. 372 of these samples came from ultramfic bodies associated with moderate to large deposits of nickel sulphides, 91 were from bodies associated with small deposits or significant sulphide showings, and the remaining 616 came from barren ultramafics or those containing only minor quantities of sulphides. The ore zones themselves were strictly avoided during sampling. Sulphide-bound copper, nickel, and cobalt were determined by atomic absorption spectrometry following cold leaching with a mixture of ascorbic acid and hydrogen peroxide. Sulphur was determined by the combustion method. It is apparent that there is a distinct enrichment of copper and nickel, and to a lesser extent cobalt, in the ultramafic rocks associated with the ore deposits, than those developed over barren areas (Table 7.2). Furthermore, it appears that the majority of bodies classed as barren may have been too low in sulphur to allow early separation and segregation of a sulphide-rich melt. For most of the rocks classed as ore, the reverse is true (Table 7.2). The authors derived a number of discriminant equations to distinguish ore-bearing ultramafics from barren ultramafics and the interested reader should refer to this article for more information.

Log-log plots of total nickel, that is both sulphide- and silicate-nickel, versus sulphur, from known orebodies, suggests that a favourable ratio lies within the range 1:2 to 2:1, and generally approaches 1:1 (Fig. 7.31).

Group	No. of Intrusions	Cu (ppm)	Ni (ppm)	Co (ppm)	S(%)
"Ore Group" (deposits with more than 5000 tons Ni-Cu)	16	67.8	715	57.4	0.166
"Minore Group" (deposits with less than 5000 tons Ni-Cu)	5	6.8	560	25.2	0.036
"Barren Group"	40	6.9	354	31.3	0.031

Table 7.2. Average contents of sulphur and sulphide-held Cu, Ni and Co in mineralized and barren ultramafic intrusives of the Canadian Shield, based on data from 1079 samples. (Based on data from Cameron et al. (1971), from Levinson, 1980).

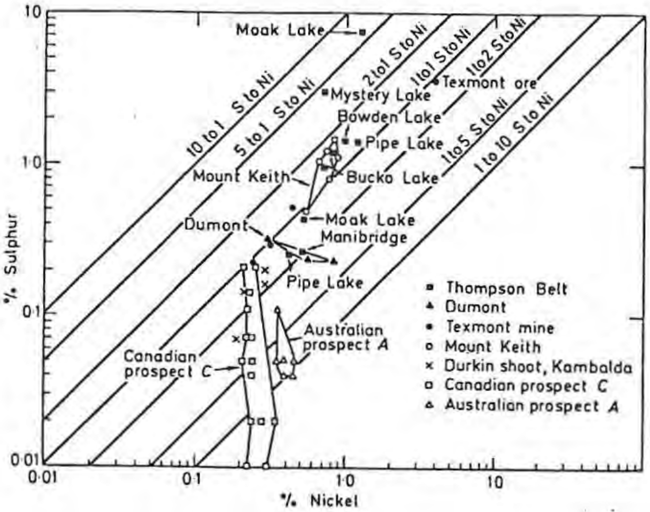


Fig. 7.31. Sulphur-nickel plots of serpentinized ultramafics (after Hausen et al., 1972).

If the ratios are significantly less, an unfavourable sulphur-poor environment is indicated, and suggests that the nickel is bound up in the olivine lattice. If larger ratios occur, a sulphur-rich environment is indicated, and this is especially favourable when high nickel values are encountered. There is a tendency for the S/Ni ratios from any one locality to cluster around a fixed ratio (Fig. 7.31). This ratio may be used as an index of favourability when prospecting in areas adjacent to known ore. Thus in the Penchenga nickel camp, a low Ni/S ratio in mafic rocks is a favourable indicator of mineralization, whereas in the Noril'sk region this ratio will approximate 1:9 (Table 7.3).

A method to establish whether ultramafic rocks have crystallized from a sulphide-saturated silicate magma is outlined by Duke and Naldrett (1978). The chemical trends of silicate liquids produced

Region	Type of rock	Character of mineralization	Ni(‰)	Co(‰)	Cu(‰)	Cr(‰)	Ti(‰)	S(‰)	Ni/S
Kola Peninsula	Basic	Absent	0.8	0.6	0.8	1.2	0.05	0.05	16.0
		Sulfide	2.1	1.3	0.8	1.2	0.3	1.1	1.1
	Ultrabasic	Absent	1.0	0.6	1.7	1.3	0.05	0.06	16.0
		Sulfide	2.3	1.0	5.1	0.9	0.3	0.8	2.9
Northern Baikal	Ultrabasic	Absent	0.6	0.5	1.1	1.4	0.15	0.01	60.0
		Sulfide	1.4	0.7	2.1	0.6	0.08	0.06	23.4
Norilsk	Basic	Absent	1.2	1.2	0.9	1.3	1.4	0.3	4.0
		Sulfide	1.9	1.1	2.7	3.9	0.8	1.0	1.9
Central Russia	Strongly metamorphosed ultrabasic rocks	Absent	0.12	0.57	2.31	0.84	0.02	2.30	0.05
		Sulfide	0.43	0.50	1.89	0.80	0.06	0.76	0.56
Northern Baikal	Strongly metamorphosed ultrabasic rocks	Absent	0.40	0.10	0.07	0.30	0.007	0.02	20
		Sulfide	0.95	0.46	1.60	0.60	0.064	0.06	16

Note:
At this time, only deposits in the Kola Peninsula and Norilsk regions are economic. The examples from the Northern Baikal region are not typical, nor are they likely to become economic deposits, because they only contain small quantities of sulfides (S = 0.06%) in the "mineralized" rocks.

Table 7.3. Data on selected trace elements in ore-bearing and barren (for Ni and Cu) basic and ultrabasic rocks. (Modified after Beus and Grigorian (1977), from Levinson, 1980).

during the fractionation of a komatiite magma are different depending upon whether or not sulphide as well as olivine is removed. These differences are particularly noticeable in the trends of Ni, Cu, and Co (Fig. 7.32). Numerical modelling by the authors indicate that

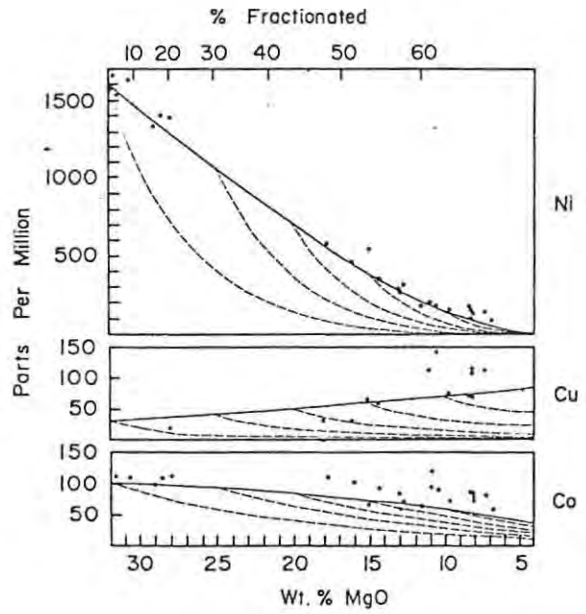


Fig. 7.32. Concentrations of Ni, Cu, and Co in derivative silicate liquids as a function of the concentration of MgO in the liquid for a model komatiite system for sulphide-free fractionation (solid lines) and olivine/sulphide ratios of 1000 (dotted line), 100 (short dashed lines) and 10 (long dashed lines) (after Duke and Naldrett, 1978).

analogous differences exist in the chemical trends of the fractionated olivine and in the bulk composition of the fractionated material (Fig. 7.33). The existence of differences in the chemical trends between sulphide-undersaturated and sulphide-saturated systems has far reaching applications in the exploration for nickel sulphide deposits. If a given suite of volcanic rocks are thought to have been derived from a common parent magma, a plot of the behaviour of the chalcophile elements with variation in the MgO content on Fig. 7.32, should indicate whether or not the parent magma was sulphide-saturated or not. Alternatively, in layered intrusions or other situations where it may not be possible to select a rock sample which represents a liquid composition, the nickel and forsterite contents of the olivine can be plotted on Fig. 7.33 and compared with the model sulphide-undersaturated and sulphide-saturated trends. The diagrams presented here have been derived for a specific initial magma compsition, but the distinction between the two types of trends should be generally applicable to the ultramafic magma series. However, for the analyses to be meaningful, the olivine in the rocks must be fresh and therefore, this technique has limited application in highly weathered terrains.

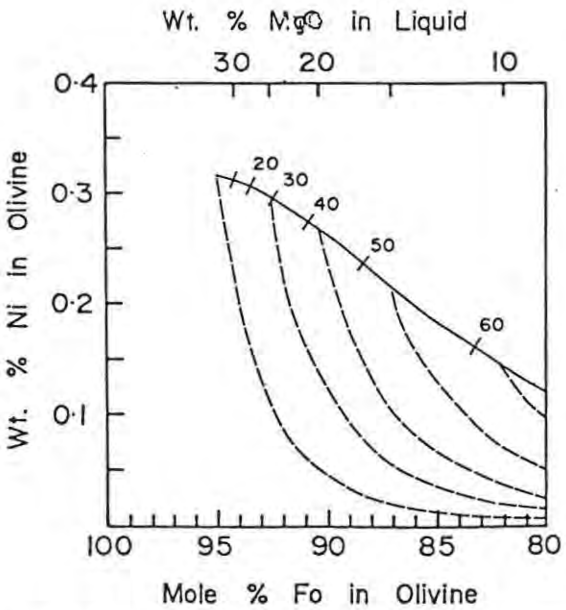


Fig. 7.33. Compositions of fractionating olivine for sulphide-undersaturated case (solid curve) and for sulphide-saturated case (dashed curves) where silicate liquid becomes saturated at various MgO concentrations. Numbers on solid curve indicate mol.% olivine fractionation (after Duke and Naldrett, 1978).

Chromites in the volcanic-type komatiitic deposits in the Yilgarn block of western Australia contain anomalously high zinc values (Groves et al., 1977). Similar high zinc contents occur in chromites from ultramafic rocks along strike from, or stratigraphically higher than the ore-bearing ultramafic unit, but chromites from areas where no mineralization has been discovered contain much less zinc. It is apparent that the anomalously high zinc contents (> 0,5% Zn) in chromites are a useful indicator of mineralized ultramafic sequences but are not specific indicators of the mineralized unit itself (Fig. 7.34). The majority of chromites within the massive sulphide fraction

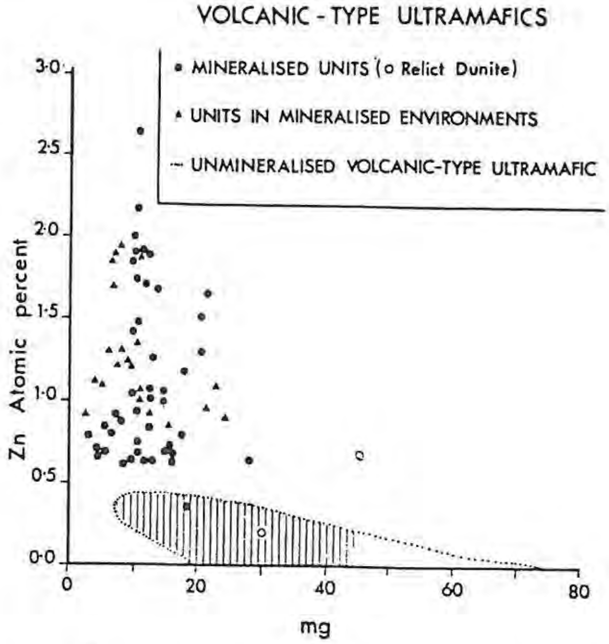


Fig. 7.34. Zinc content of chromites mineralized and unmineralized ultramafic rocks. Shaded area in lower right-hand plot includes all chromites from unmineralized volcanic-type ultramafic units in amphibolite facies metamorphic domains. Not all chromites were analysed for Ti.

Chromites from the following localities are included in the compositional plots: Mineralized units: Lunnon Shoot, Kambalda; Scotia. Units in mineralized environments: Windarra; Windarra-South Windarra; Munda. Unmineralized volcanic-type units: Mt. Clifford; Fly Bore; Mt. Margaret; Hannan Lake; St. Ives; Cranium; Hayes Hill; Forrestania (after Groves et al., 1977).

mg = 100 Mg/(Mg + Fe^{2+} + Mn + Zn = Ni).

in many Australian deposits are composite spinels with a magnetite-rich rim and ferrochromite cores, which have very low magnesium and aluminium contents (Fig. 7.35). These are thought to have crystallized directly from the sulphide-oxide liquid (Groves et al., 1977). The ferrochromites contrast sharply with the chromites in the disseminated ore and in the barren ultramafics, characteristically having lower magnesium and aluminium contents and higher manganese and titanium than the latter.

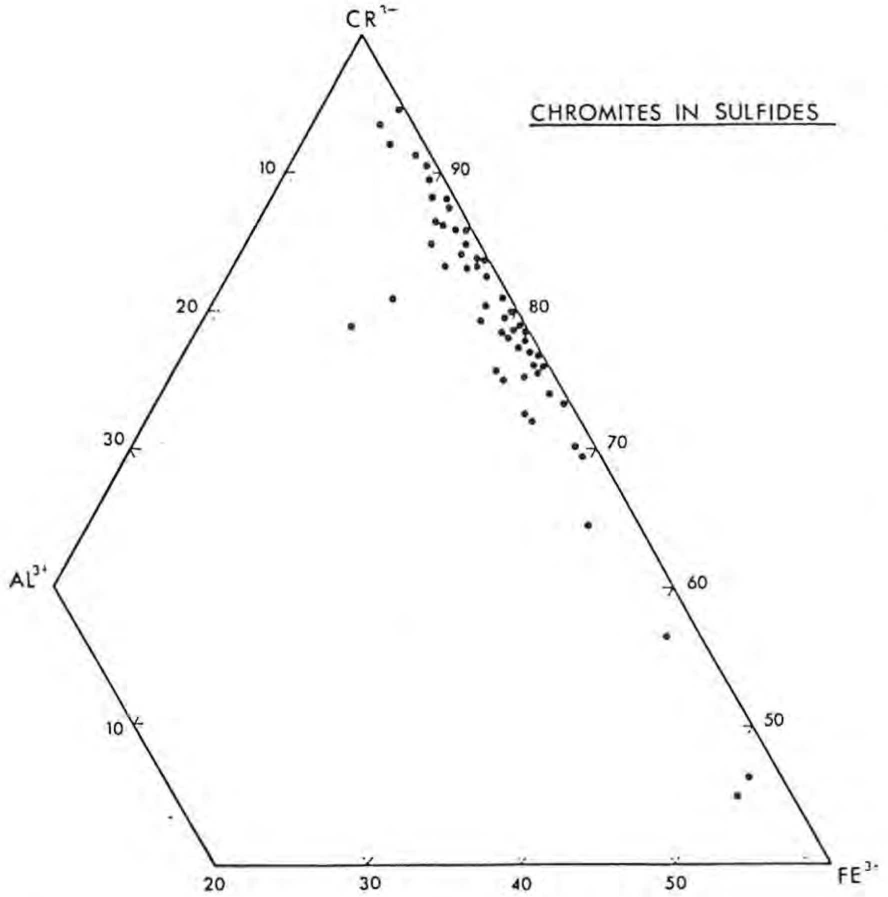


Fig. 7.35. Compositions of chromites from massive volcanic-type Fe-Ni sulphide ores. Chromites from the following localities are included in the compositional plots: Lunnon Shoot, Kambalda; Windarra, Redross, Wannaway, Scotia (after Groves et al., 1977).

The discovery of the Kambalda nickel sulphide deposits in 1966 initiated a period of intense exploration activity throughout the Eastern Goldfields regions of Western Australia. Because of the limited applicability of conventional prospecting techniques in this deeply weathered terrain, the evaluation of gossans was soon recognised as an important exploration tool in the search for massive nickel sulphides (Blain and Andrew, 1977). Ferruginous cappings are not only derived from base metal sulphide ores, but also from barren pyrite-pyrrhotite bodies, ferruginous exhalites, sedimentary cherts, iron formation, laterites and silcretes, and any iron-bearing igneous and metamorphic rock (Andrew, 1978). It is often difficult to ascertain whether a gossan developed over ultramafic or mafic rocks is in fact a true base metal sulphide gossan or whether it is one of the unmineralized variants mentioned above.

Identification of accessory resistate minerals in ironstones may help in ascertaining whether they represent true base metal sulphide gossans (Blain and Andrew, 1977). Residual quartz encountered in many base metal sulphide gossans may contain traces of residual sulphides. Spinels commonly encountered in the ore zones in nickel sulphide deposits are often preserved in the gossans overlying the fresh ores. The composition of the spinels may help delinate the host lithotype, as chrome spinels are preferentially found in gossans developed over ultramafic rocks, while ilmenite and magnetite are mainly found in gossans developed over mafic lithotypes.

Macroscopic recognition of the oxidate assemblage in ironstones overlying possible nickel sulphide mineralization may lead to the immediate recognition of its true character (Blain and Andrew, 1977). Gossans overlying nickel-copper sulphide mineralization may contain light green crystalline aggregates of gaspelite together with nickeloan magnesite. Bright yellow reevesite, the pale to emerald-green minerals morenosite, retgersite, and annabergite, as well as basic nickel oxides and silicates may be preserved in nickel-copper gossans. Copper carbonates and sulphates may accompany the nickel oxides in trace to minor amounts.

A study of the textural features, particularly the shape of the cellular pseudomorphs (boxworks), of gossan is perhaps the single-most important method aiding their true recognition (Reynolds, 1982a). This study can also provide a considerable amount of information on the nature of the ore at depth, both with respect to the minerals present, their mutual relationships, relative proportions, grain size, and gangue mineralogy.

The shape of the cellular pseudomorphs encountered in nickel-copper gossans had been described by Reynolds (1982a) and the following description is taken from this article.

Pyrrhotite may oxidise directly to goethite or hematite. Incipient oxidation tends to open up the basal cleavage planes in both hexagonal and monoclinic pyrrhotite and goethite is commonly precipitated in situ along these cleavage planes. The basal cleavage exerts a strong influence on the development of the resulting cellular pseudomorphs (Fig. 7.36a). The gain boundaries and cleavage traces in recrystallized polycrystalline pyrrhotite

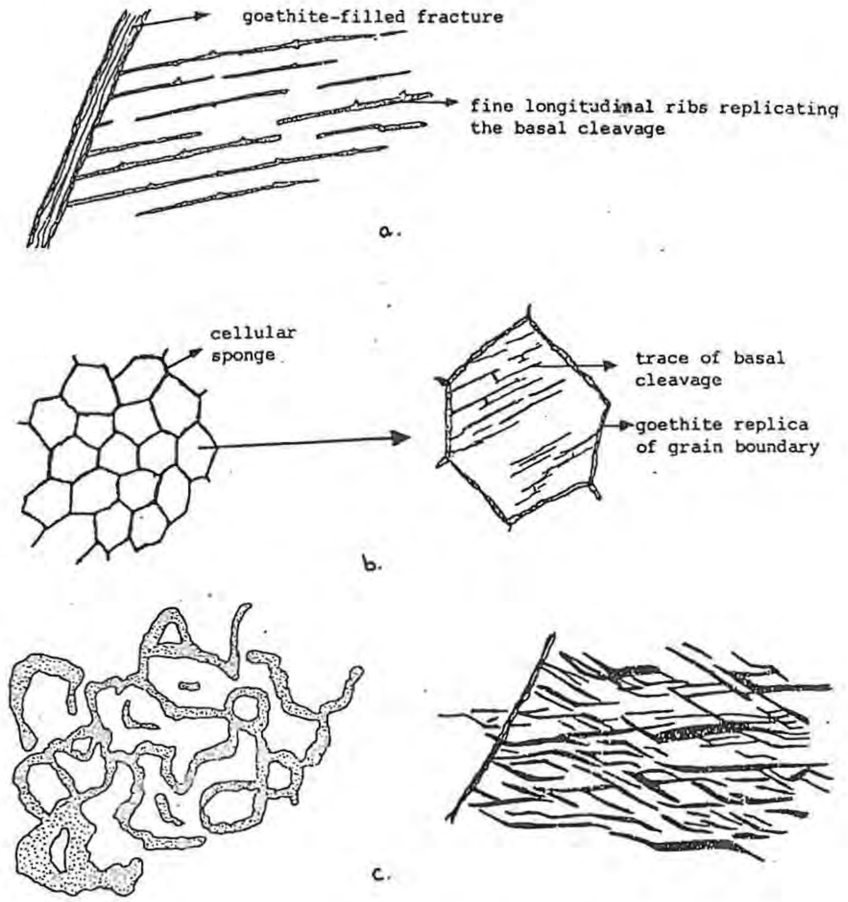


Fig. 7.36. Cellular pseudomorphs after pyrrhotite (after Reynolds, 1982a).

aggregates are often pseudomorphously replaced by goethite. This leads to the development of a cellular sponge with a distinct hexagonal structure (Fig. 7.36b). In certain cases the basal cleavage is not replicated and a complex hieroglyphic texture is formed whose orientation may in part be controlled by the basal cleavage direction (Fig. 7.36c). In complex intergrowths of monoclinic and hexagonal pyrrhotite, one of the phases may preferentially be replaced by goethite during weathering and the other component may be leached out. This results in a characteristic reticulate cellular pseudomorph (Fig. 7.36d). Pyrrhotite may also convert directly to marcasite and/or pyrite during the weathering process and may be more or less pseudomorphously replaced by these two minerals. The conversion is accompanied by a sharp reduction in volume and opening up of cleavage planes. The reduction in volume is more marked when the pyrrhotite is replaced by marcasite and therefore, the fractures are more robust and are accompanied by some bending. Both these types of textures may be pseudomorphously replaced by goethite and preserved in gossans (Fig. 7.37a). Alternatively, iron and sulphide ions may be taken

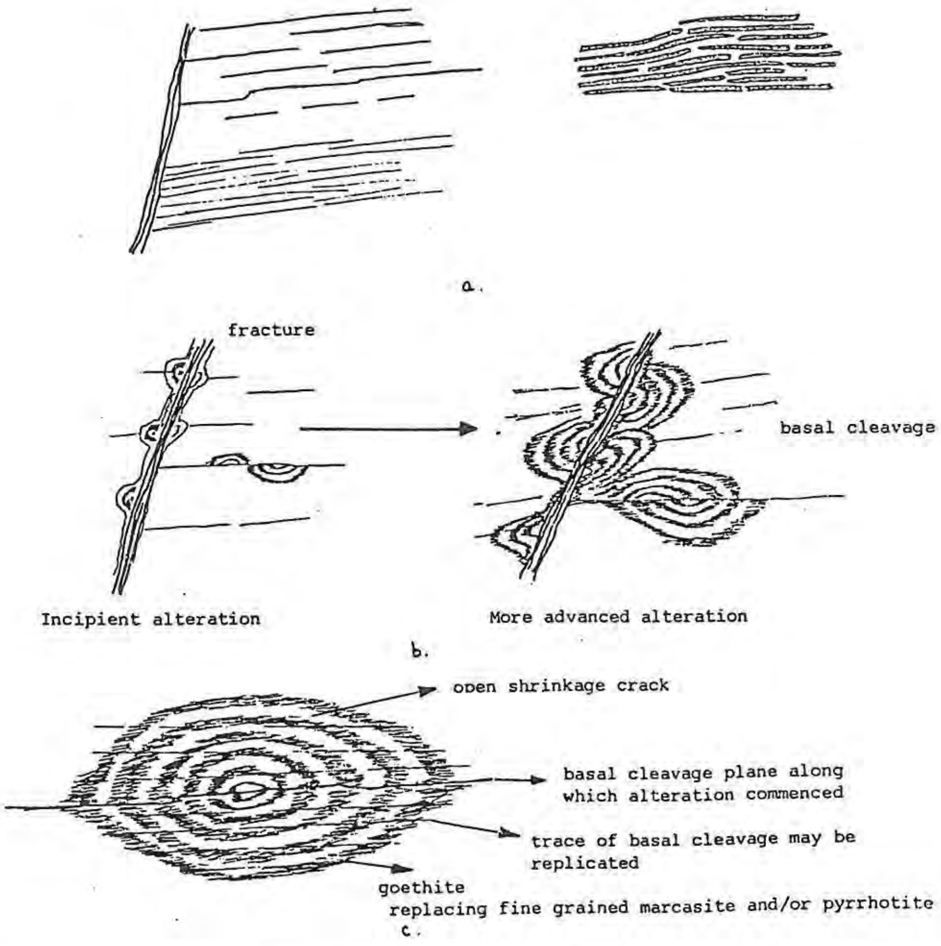


Fig. 7.37. Cellular pseudomorphs after pyrrhotite (after Reynolds, 1982a).

into solution and then reprecipitated as colloform pyrite or marcasite to form "birds eye" structures. These structures are characterized by the presence of well defined semi-circular shrinkage cracks. The alteration generally commences along fractures and the permeable basal cleavage and gradually eats its way into the pyrite (Fig. 7.37b). The "birds eye" structures are highly ammenable to pseudomorphous replacement by goethite and represent one of the few pyrrhotite replicas that can be readily identified in hand specimens (Fig. 7.37c).

Pendlandite is replaced by violarite during the early stages of weathering of nickel sulphide ores. This process is accompanied by a volume loss which results in the opening up of the octahedral cleavage planes. These cleavage planes then become filled in with siderite, silica, or magnetite. Subsequent oxidation of the violarite produces a structureless porous goethite that tends to remain in situ to form a pseudomorphous replacement. The presence of former pentlandite is easily recognizable from the well preserved octahedral cleavage that encloses blocks of fairly uniform and structureless goethite (Fig. 7.38).

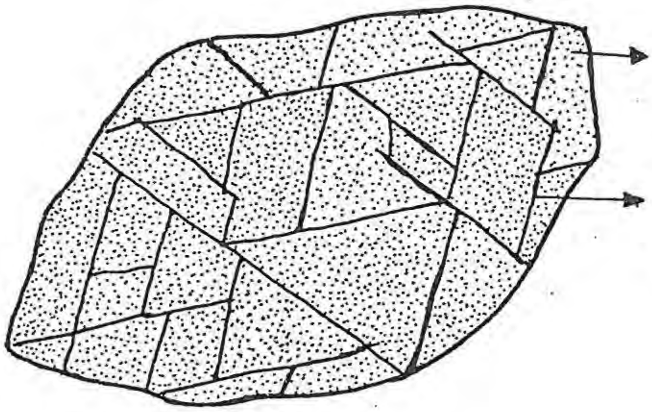


Fig. 7.38. Typical appearance of a goethite pseudomorph after pentlandite (after Reynolds 1982a).

Typically, nickel sulphide ores contain exsolution bodies of pentlandite, and larger grains of pentlandite are often located interstitially between the pyrrhotite crystals. The violaritization of the pentlandite releases Ni^{2+} ions that react with the adjacent monoclinic pyrrhotite to form violarite. This violarite usually develops parallel to the basal cleavage of the pyrrhotite and results in the formation of feather-like fringes of violarite at places where the pyrrhotite is in contact with violaritizing pentlandite (Fig. 7.39a). These feather-like bodies are directly oxidized to goethite which tends to remain in situ thus resulting in good pseudomorphous replacement. The violarite after pentlandite tends to produce replicas similar to those shown in Fig. 7.38. The remaining pyrrhotite that is not altered to violarite will weather to produce replicas shown in Fig. 7.36. Because the amount of violarite that replaces pyrrhotite is

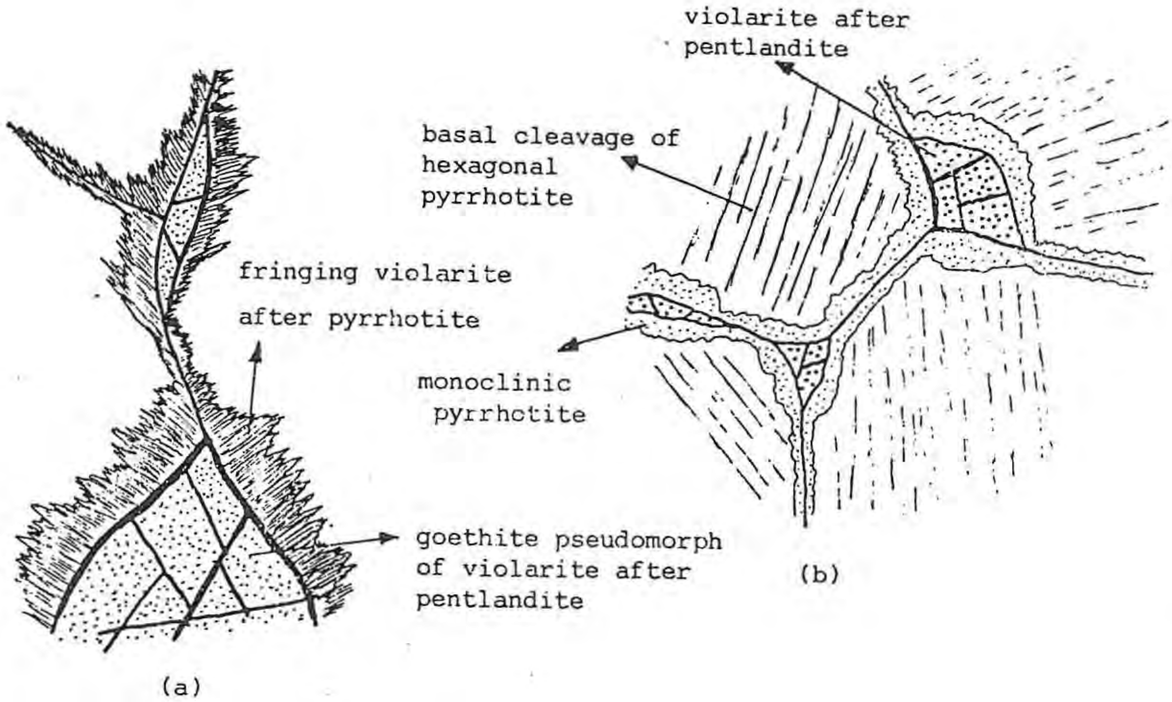


Fig. 7.39. (a) Typical-feathery fringing violarite developed around grain boundaries of monoclinic pyrrhotite.
(b) Situation hexagonal pyrrhotite. Ni-bearing monoclinic pyrrhotite forms around grain boundaries and remaining hexagonal pyrrhotite alters to pyrite (after Reynolds, 1982a).

genetically controlled by the amount of nickel released during violaritization of pentlandite, the proportions of the two texturally distinct violarite types are a measure of the original pyrrhotite: pentlandite ratio in the primary ore (Blain and Andrews, 1977). Large feathery violarite margins are indicative of pentlandite-rich ores, whereas small margins are indicative of pentlandite-poor ores. In many fine-grained nickel sulphide ores the pentlandite is often too fine grained to form discernable boxworks. In these cases the presence of the feather-like bodies is a valuable indicator of the presence of pentlandite in the primary ore.

Hexagonal pyrrhotite is not converted directly to violarite during the violaritization of pentlandite, but may form a rim of Ni-bearing monoclinic pyrrhotite along the contact zone. The remaining hexagonal pyrrhotite is then converted directly to pyrite which often contains a good replication of the basal cleavage of the pyrrhotite.

The monoclinic pyrrhotite can then alter to violarite if all the hexagonal pyrrhotite has been converted to pyrite before the complete violaritization of the pentlandite. The resulting texture may be pseudomorphously replaced by goethite to form replicas shown in Fig. 7.39b.

Chalcopyrite may oxidize directly to goethite. During the oxidation of chalcopyrite, goethite precipitates along grain boundaries and other permeable features. The shape of the cellular pseudomorphs is controlled to a large extent by the (11$\bar{1}$) cleavage of the tetragonal chalcopyrite. A set of long, robust ribs is intersected by less robust cross-septa at 70^{o} (Fig. 7.40a). This produces a roughly rectangular structure in which finer sets of ribs corresponding to (110) may be developed (Fig. 7.40a). The latter intersect the longitudinal ribs at 57^{o}. Sketches showing characteristic boxworks derived from chalcopyrite are shown in Fig. 7.40b and c.

Pyrite replicas are dominated by the crystallographic elements of this mineral. Pyrite may be pseudomorphously replaced by goethite to form "limonite dice". This situation if particularly favoured

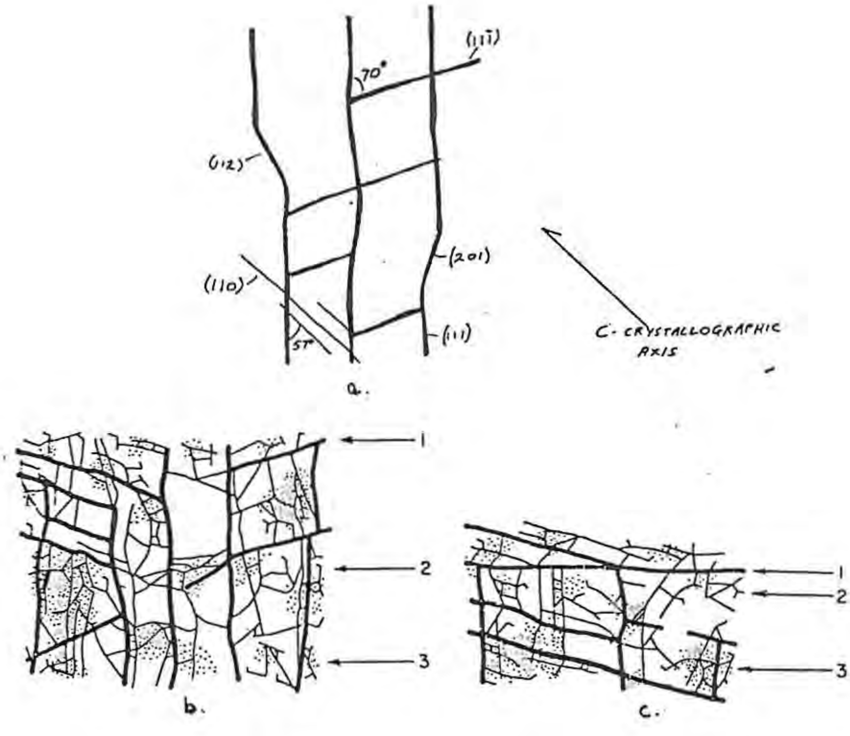


Fig. 7.40. Cellular pseudomorphs after chalcopyrite (after Reynolds, 1982a).

where the pyrite is disseminated in a silicate or carbonate gangue, and also where it is present in relatively minor amounts in an otherwise non-iron-bearing sulphide assemblage. The goethite is commonly arranged in a concentric pattern parallel to the crystal faces of the minerals (Fig. 7.41a) or parallel to the fracture pattern in the pyrite along which alteration was initiated (Fig. 7.41b). The presence

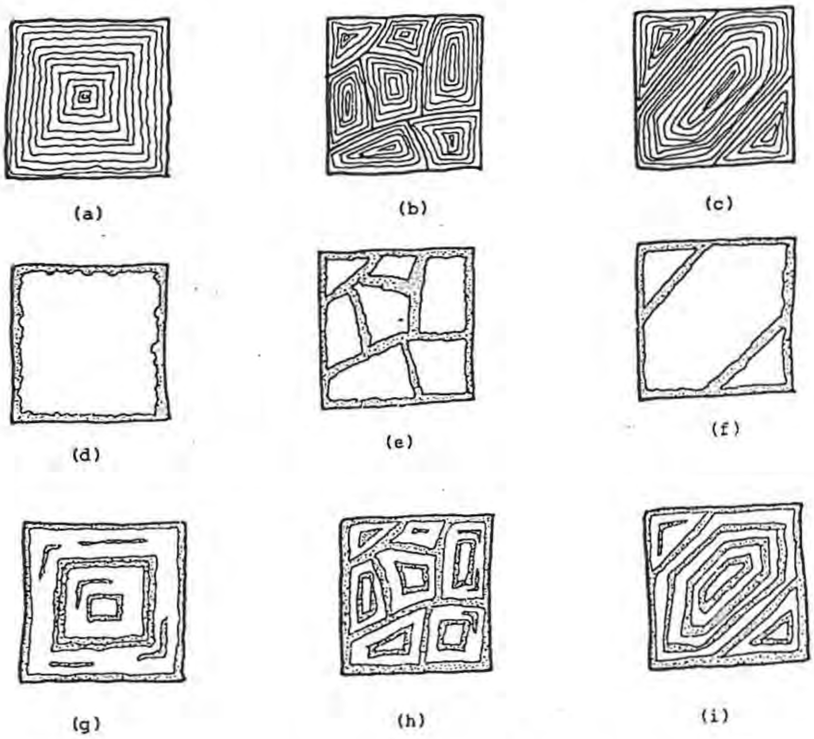


Fig. 7.41. Cellular pseudomorphs after chalcopyrite (after Reynolds, 1982a).

of a parting parallel (111) may sometimes be evident (Fig. 7.41c). Under highly acidic conditions and in the presence of abundant pyrite, the iron may be completely removed in solution, thus leaving cubic shaped cavities. Small amounts of goethite may precipitate on these cavity walls at a later stage, thus producing recognizable cellular boxworks (Fig. 7.41d). In other cases, the ferric hydroxide that forms during the initial stages of oxidation is precipitated in situ around the crystal margins, fractures, and partings as they are progressively opened up. The resultant increase in acidity on further oxidation may result in the leaching out and removal of the bulk of the weathering products to form voids. This produces cellular pseudomorphs of the type shown in Fig. 7.41e and f. Commonly however, the conditions governing the in situ precipitation of goethite fluctuate so that certain elements are replicated at different times. This gives rise to the various nested forms shown in Fig. 7.41 g, h, and i.

Cubanite, a common accessory of nickel-copper ores, commonly breaks down to chalcopyrite and pyrrhotite on weathering and therefore is not commonly replicated (Reynolds, 1982, pers. comm.).

Unfortunately, good replication of the original textures of the sulphides are not always encountered and in general only 10% of gossan samples will yield diagnostic textural features (Reynolds, 1982a). Supergene silicification, calcretization and laterization can destroy the original cellular boxwork structures within the gossan. Most of the gossans overlying the nickel sulphide deposits in Western Australia are massive and jasperoidal, consequently, the study of textural features in the gossan found little application in exploration (Blain and Andrew, 1977). The problem was compounded by a lack of outcrop and by the presence of a number of different types of false gossan. These included lateritic and ferruginous silcrete duricrusts, as well as those produced from the weathering of non-economic pyrite-chalcopyrite-filled shears, pyritic felsic and ultramafic tuffs, pyritic carbonaceous sediment, and pyritic laminated sediment now represented by albite-quartz-amphibole-chlorite rocks (Fig. 7.42). The potential base metal sulphide gossans were therefore identified primarily from their trace element signature.

The major elements in nickel-copper sulphide gossans include Fe, S, Si, Mg, Ni, while the minor include Cu, Cr, Mn, Al, Ti and Co (Blain and Andrew, 1977). Trace quantities of Se, Te, As, Ag, Au, Pd, Pt, and Ir are found.

Recently a number of major studies have been carried out on the geochemistry of gossans in the Yilgarn block. Cochrane (1973) determined the Cu, Pb, Zn, Ni, Co, $Cr^{(S)}$ (i.e. perchloric nitric acid-soluble chromium), Mn, Ag, Mo, and Fe contents of 73 true gossans and 10 false gossans from 23 localities in the Yilgarn Block. Clema and Stevens-Hoare (1973) assayed 430 gossan samples following an acid digestion, generally nitric-perchloric, for Ni, Cu, Zn, Pb, Mn and Cr, using conventional atomic absorption methods (Table 7.4). 250 of the samples were from 22 known massive nickel sulphide deposits and the remainder were from 58 localities containing other varieties of ironstone. Moeskops (1977) studied the data from 103 true gossans

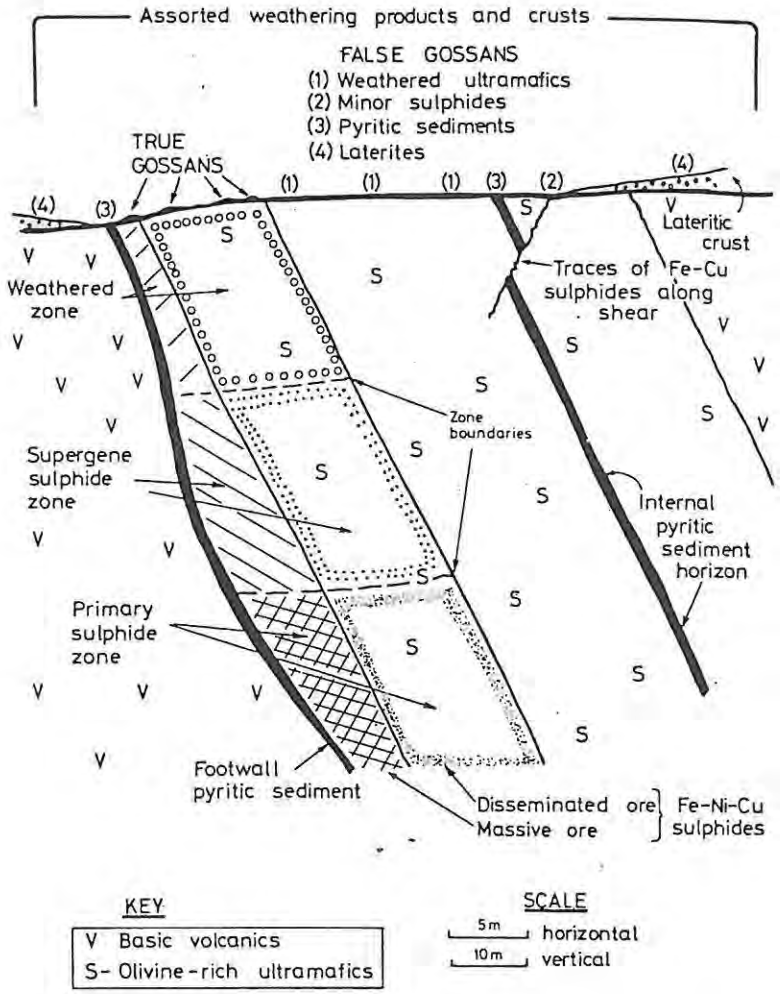


Fig. 7.42. Schematic vertical section through typical Yilgarn nickel sulphide deposit showing mineralized zones and relationships between true and false gossans (after Moeskops, 1977).

and 69 false gossans from 43 localities (Table 7.5). Their data suggests that gossans were generally, but not always, less ferruginous than false gossans, and that true gossans were characterized by high Ni (1000-5000+ p.p.m.), high Cu (500-5000+ p.p.m.), low Zn (100 p.p.m.), very low Pb, low Mn (500 p.p.m.), and low Mo values as well as being strongly depleted in Cr^{S} (500 p.p.m.) when compared to false gossans. Furthermore, the data suggests that gossans are somewhat enriched in Bi and invariably enriched in Se, Pt, and Pd when compared to false gossans. Bull and Mazzucchelli (1975) noted Te to be a useful confirmatory element. Willmshurst (1975) found in geochemical investigations over the Spargoville and Perserverance deposits, that fresh sulphide ore generally possessed Ni/Cu ratios of about 15, while on the other

Ironstone	Ni	Cu	Zn	Pb	Mn	Cr
Ni gossan	1900	1000	85	30	150	170
"	7600	3000	90	80	340	360
"	520	380	10	<20	60	<100
"	10,500	3000	105	<20	70	1000
Fe chert/shale	1975	40	590	<20	1850	350
"	140	100	325	85	415	135
"	3550	360	2125	<20	700	650
Laterite	2045	80	130	50	910	2000
"	1200	20	20	20	1200	3400
"	600	50	30	<20	350	1400
Wad	1350	880	110	<20	10,000	<100
"	3870	1270	375	45	12,500	100
"	225	320	410	<20	3100	<100
Vein/fault	260	1200	40	170	210	40
"	300	2800	580	410	200	50

Table 7.4. Summary of geochemical data from various ironstones in Western Australia (after Clema and Stevens-Hoare, 1973).

hand,true gossans and weathered and/or ferruginized ultramfics with disseminated sulphides contained lower ratios. In marked contrast, in the unmineralized weathered and/or ferruginized ultramafics, the ratios were commonly higher because of the low copper content of the rock. Moeskops (1977) obtained similar results in his study and concluded that the Ni/Cu ratios in true gossans ranged from 2 to 6 and in false gossans from 5 to 20. Willmshurst (1975) recorded high As values (6900 p.p.m.) commonly associated with high Au and Zn, in some of the gossan zones at the Spargoville deposit. These values cannot be treated as characteristic of nickel gossans in general, because they may have been derived from metasediments or intrusive porphyry mineralization and hence,may have not been associated with mineralization. On the other hand, they may have come from porphyry contaminated ultramafic and hence from arsenical nickel-copper sulphide. Cobalt has a very similar chemistry to nickel and therefore, the Ni/Co ratio remains fairly constant, both in fresh ultramafic rocks and weathered material. Smith (1977) found that this ratio

Table 7.5. Summary of geochemical data on nickel sulphide ores, true gossans and false gossans (after Moeskops, 1977).

Element (ppm) or oxide (wt.%)		Fresh nickel sulphide ores N	V	NR	M	True gossans N	V	NR	M	False gossans N	V	NR	M
SiO_2			n.d.	—	—	26	5—70	50—60	52	26	4—70	40—50	42
ΣFe_2O_3			n.d.	—	—	26	9—60	40—50	44	26	12—78	50—60	56
MgO			n.d.	—	—	26	0—12	1—3	1.5	26	0—15	1—4	2
Al_2O_3			n.d.	—	—	26	0—2	0.5—1	0.8	26	0—5	0.5—2	0.8
Cu	(5)	40	200—9500	2000—5000	2100	103	110—13,000	800—3000	1000	69	30—1200	80—150	90
Ni	(5)	40	12,000—85,000	25,000—40,000	31,000	103	950—25,000	1500—5000	3000	69	50—10,000	800—2500	1500
Zn	(5)	40	20—300	60—120	80	103	20—1100	50—200	140	69	50—2200	200—1500	800
Pb	(5)	40	20—70	30—60	40	34	20—80	30—40	35	28	5—40	10—20	30
Co	(5)	40	150—3500	400—1800	1200	103	40—1200	200—400	280	28	10—800	200—800	480
$Cr^{(s)}$	(5)	40	80—3000	300—700	600	103	10—11,000	200—2000	750	69	40—10,000	100—1800	600
Mn	(5)	40	50—1400	250—600	450	103	100—400	200—400	600	28	200—5000	800—2000	1400
Mo	(5)	40	<5	<5	<5	103	<5—120	<5	—	20	<5—20	∿10	10
Pt	(0.02)	20	0.07—2.2	0.08—0.80	0.45	20	0.05—0.28	0.1—0.2	0.15	20	⩽0.02	—	—
Pd	(0.02)	20	0.15—1.7	0.5—1.2	0.70	20	0.08—0.48	0.1—0.3	0.15	20	⩽0.02	—	—
Au	(0.02)	20	<0.02—0.52	∿0.02	0.02	20	0.0—1.7	⩽0.15	—	20	⩽0.02	—	—
Ag	(2)	20	<2—15	∿3.0	3.0	50	<3—11	⩽3	2	20	⩽0.02	—	—
As	(5)	20	<5—1500	<5—10	8	20	5—60	20—30	25	20	10—15	20—30	25
Bi	(5)	20	25—65	30—50	40	20	15—180	20—60	45	20	0—30	∿15	15
Se	(2)	20	5—100	10—40	25	20	10—200	20—40	35	20	0—2	⩽2	—
Sb	(4)	20	<4—25	<4	<4	20	<4—410	20—40	30	—	n.d.	—	—
Ni/Cu		40	1.6—57.4	8—20	14.8	103	0.4—11.9	2—6	3.7	69	1.5—31.7	5—20	14.9

$Cr^{(s)}$ refers to acid-soluble ($HClO_4$-HNO_3) chromium; figure in parentheses following elements represents detection limit.
Analytical techniques (initial sample weights 500—1000 g): Si, Fe, Mg, Al, As, Bi, Se, Sb — X-ray fluorescence (±2%); Cu, Ni, Zn, Pb, Co, $Cr^{(s)}$, Mn, Mo, Ag — atomic absorption spectrometry (±5%); Pt, Pd, Au — fire assay/atomic absorption spectrometry (±5%).
Symbols: *N* = number of samples analyzed, *V* = variation, *NR* = normal range (i.e. 15—85 percentiles) values rounded, *M* = median value.
n.d. = not determined.

varies between 10:1 and 30:1 in barren situations but in mineralized situations the ratio is often higher, with values of between 20:1 and 50:1. Because of the high affinity of cobalt for manganese, this ratio may be low even in a mineralized environment, and consequently the results must be treated with caution in manganiferous gossans.

False gossans derived from non-lateritic weathering of unmineralised ultramafics yielded similar, or lower, Ni values to those observed in true gossans but are strongly depleted in Cu (100 p.p.m.) (Cochrane, 1972)(Table 7.4). Laterites are characterized by relatively high Ni and Cr; medium to low Mn; and low Cu, Pb, and Zn (Clema and Stevens-Hoare, 1973). Their values for Zn are very suspicious as both Willmhurst (1975) and Cochrane (1973) report high zinc values (250+ p.p.m.) as being typical of unmineralized laterites. Laterized ultramafics are generally enriched in $Cr^{(S)}$ (2000-10000+ p.p.m.) (Cochrane, 1973). False gossans over shales and cherts are generally characterized by relatively high to medium Ni, Zn, and manganese; with medium to low Cu; medium Cr, and low Pb (Table 7.4). Wads were found to be characterized by very high Mn; medium Ni, Cu, and Zn; and by very low Pb and Cr values. Veins and rocks from fault zones may have high Cu (if sulphides are present); medium Pb, Mn, and Zn; and medium to low Ni and Cr values (Table 7.4).

Clema and Stevens-Hoare (1973) devised empirical scattergrams to delineate true from false gossans. They found that a plot of Cu + Ni/M, where M is the sum of Ni, Cu, Zn, Pb, Mn expressed as a percentage of the rock, against M, successfully delineated true gossans from false gossans (Fig. 7.43). Similar results were obtained by plotting Mn + $Cr^{(S)}$/M against M (Fig. 7.43).

Joyce and Clema (1974) applied the statistical technique of principle component analysis to derive a simple scattergram based only on Cu, Ni, and $Cr^{(S)}$ values (Fig. 7.44). It can be seen from the figure that a considerable amount of overlap exists between the true and false gossan field. Many of the true gossans that plotted in the false gossan field were from gossans developed over disseminated mineralization.

Moeskops (1977) stated that these scattergrams and a triangular plot of Cu-Ni-Zn (Fig. 7.45) have a 80%-90% success rate.

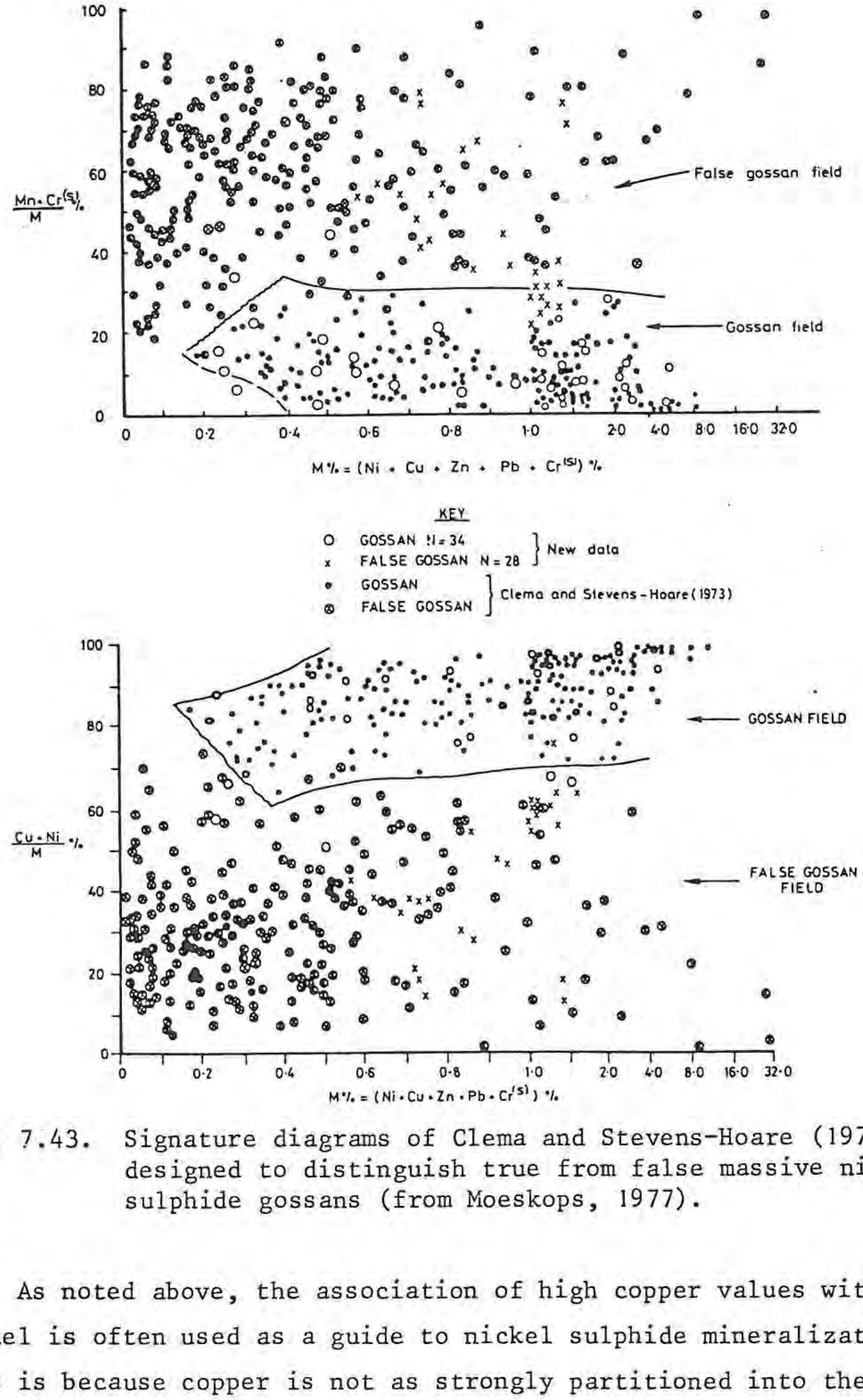


Fig. 7.43. Signature diagrams of Clema and Stevens-Hoare (1973) designed to distinguish true from false massive nickel sulphide gossans (from Moeskops, 1977).

As noted above, the association of high copper values with nickel is often used as a guide to nickel sulphide mineralization. This is because copper is not as strongly partitioned into the silicate phase as nickel is. Thus, if high copper values are present with nickel in the gossans, the chances of the gossan representing sulphide mineralization are very much greater. However, in many of the disseminated ores hosted by intrusive dunites in greenstone belts, as at Mt. Keith, chalcopyrite is rare. The extreme depth (up to 20 m) of overburden at the Mt. Keith deposit precluded

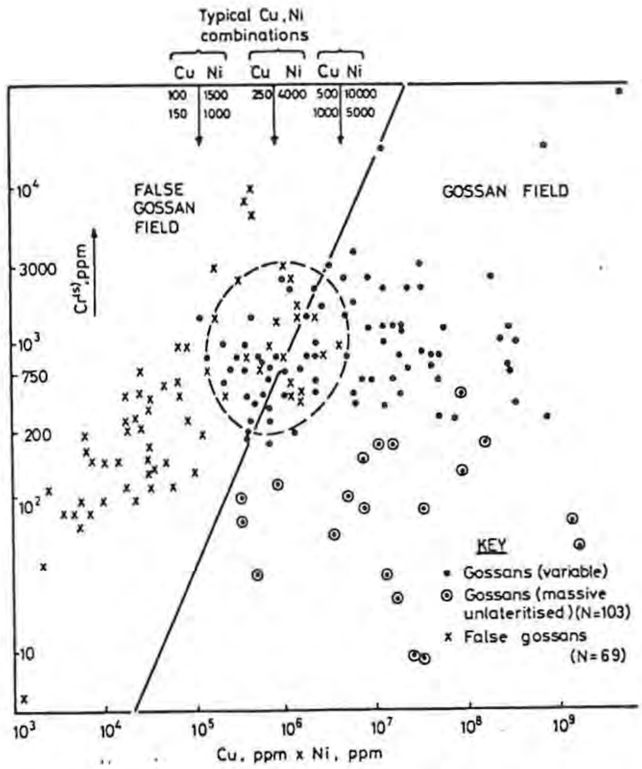


Fig. 7.44. Data of Moeskops (1977) plotted onto the simplified gossan scattergram of Joyce and Clema (1974). The main area of overlap (i.e. uncertainty) is indicated. (Note: four coincident gossan points in gossan field; two coincident false gossan points in false gossan field) (from Moeskops, 1977).

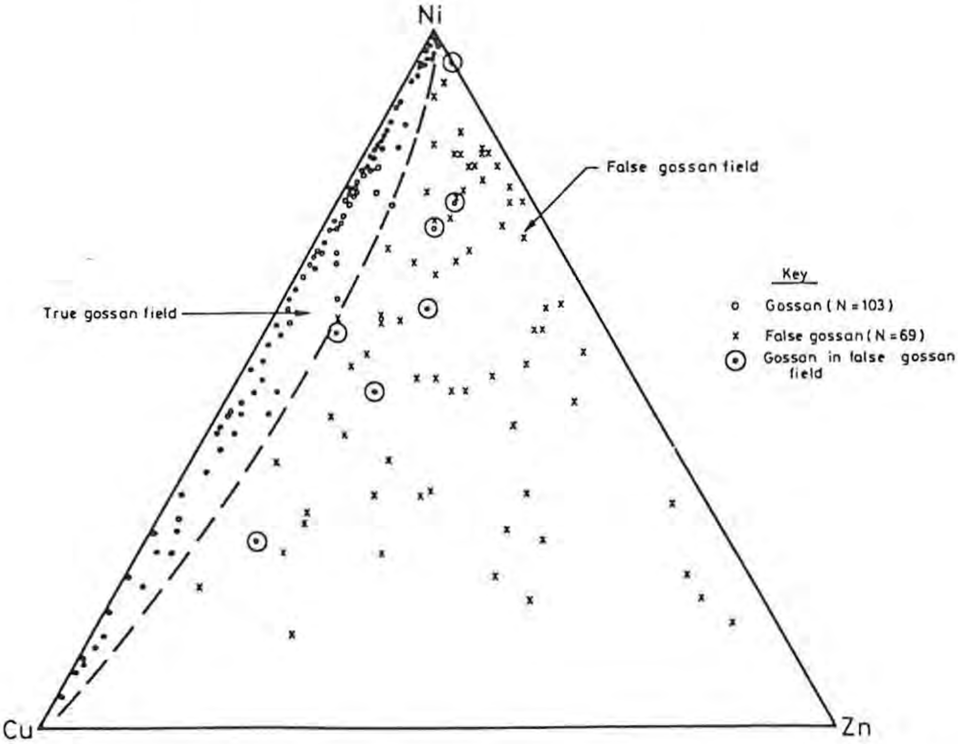


Fig. 7.45. Triangular diagram based on weight percent Ni, Zn and Cu, showing subjectively assigned true and false gossan fields. The indicated field boundary successfully classifies 93% of true gossans and all false gossans studied (after Moeskops, 1977).

the use of soil surveys as an initial exploration tool. Instead samples were obtained from the lateritic capping some 30 m below the surface through drilling. Although coincident Cu-Ni anomalies were obtained over the main orebodies (Fig. 7.46), because of the low Cu content of the ores the presence of coincident Cu, Ni anomalies were often not an indicator of sulphide (Butt and Sheppy, 1975). For example, the strong

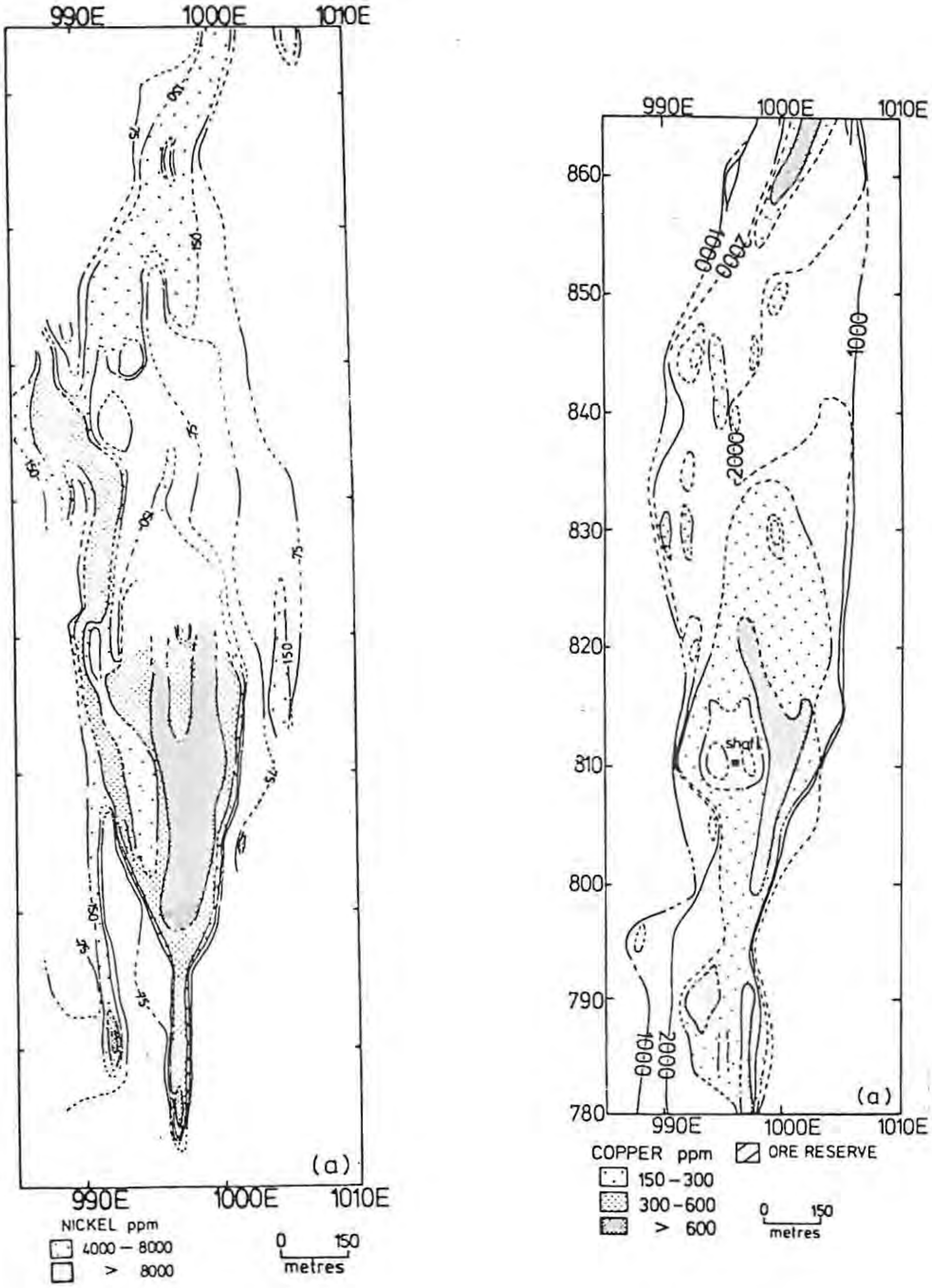


Fig. 7.46. Copper and nickel distribution in weathered rock over the main mineralized body at Mt. Keith. Samples obtained by drilling from a depth of 30 m (after Cox, 1975).

Cu-Ni anomaly located on the ultramafic/metavolcanic contact illustrated in Fig. 7.47 had no related sulphide accumulation.

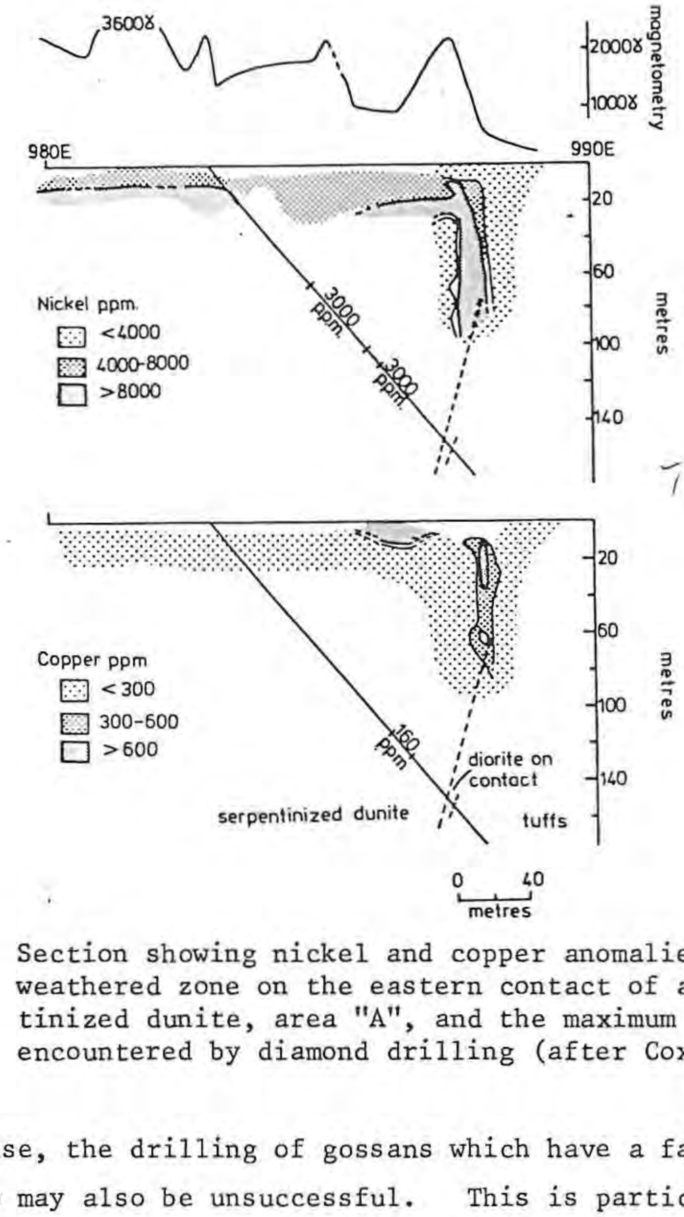


Fig. 7.47. Section showing nickel and copper anomalies in the weathered zone on the eastern contact of a serpentinized dunite, area "A", and the maximum intersection encountered by diamond drilling (after Cox, 1975).

Likewise, the drilling of gossans which have a favourable low Ni:Cu ratio may also be unsuccessful. This is particularly apparent in areas showing strong supergene silicification (Smith, 1977). During the silicification nickel is readily removed, perhaps more so than copper, resulting in the movement of the Ni:Cu ratio to lower values. Therefore, there may be little distinction left between mineralized and unmineralized rock based on either absolute or relative nickel and copper values.

High nickel values in a gossan need not necessarily reflect the presence of mineralization at depth. The two gossans developed over separate ore shoots at the Perserverance nickel sulphide deposit are notable for their different textures and compositions (Thornber et al., 1981). The gossan developed over the matrix sulphides (No. 1 shoot) in serpentinized untramafics has high Ni and Cu contents and exhibits a good retention of sulphide textures (Fig. 5.32). The second gossan developed over massive sulphides (No. 1A shoot) enclosed in metasediments, has high Cu but low Ni contents, and the cellular pseudomorphs have been largely destroyed. The striking differences in the geochemistry of the gossans can be attributed to differences in their geological environments, and thus to differences in the pH of the solutions generated during weathering of the sulphides. The pH was strongly influenced by the wall rock composition and non-sulphide components of the ore. In particular, serpentinite minerals and carbonates in the No. 1 shoot probably buffered the solutions, keeping the pH high, thus allowing the Ni to be retained on the goethite. In the 1A shoot this buffering did not take place and the low pH solutions leached the Ni completely. However, the 1A gossans can be distinguished from barren iron-sulphide gossans by their anomalous Cu, As, and Cr contents. Therefore, the low Ni values of the 1A shoot clearly emphasize that high nickel values in a gossan may, in certain cases, not be a reliable indicator of mineralization.

Both Willmshurst (1975) and Moeskops (1977) noted that Se and in particular Pd and Ir are excellent discriminators of true gossans. The application of Pd and Ir in gossan discrimination has been outlined by Travis et al. (1976). There is a marked Ir enrichment in gossans compared to their precursor sulphides and retention of Pd at comparable or perhaps slightly enhanced levels. It is clear that even in leached gossans, Pd and Ir are maintained at anomalous levels. For example, a gossan from Mt. Clifford in Western Australia that originally contained about 3% Ni, now contains only 200 p.p.m. Ni, but still has 1630 p.p.b. and 166 p.p.b Ir. An example of the contribution of Pd-Ir to the discrimination of nickel gossans is given in Figs. 7.48 and 7.49. The samples in these two scattergrams represent occurrences of 34 nickel gossans, 12 laterized ultramafic rocks, and 4 barren gossans from sulphidic sediments. The terms sedimentary and vein in the key to the two figues may be somewhat misleading. The term sedimentary is used to denote that group of samples taken from deposits where the nickel sulphide forms an intrinsic part of volcanogenic sediments genetically linked to the ultramafic extrusives. The term arsenides is used to denote those gossans derived from narrow sulphide-carbonate stringers carrying Ni-Fe arsenites and chalcopyrite in ultramafic fragmental rocks. The wide scatter of Ni-Cu values from both nickel gossans and barren laterites and sediments in Fig. 7.48 illustrates that little discrimination is achieved by these two elements. However, Fig. 7.49 shows that the Pd-Ir content clearly separates most nickel sulphide gossans from their barren equivalents. The six nickel gossan samples below the 5 p.p.b Ir/10 p.p.b Pd indicator line all reflect very low grade sulphides. Four are from the mafic association which reflect pyrrhotite-rich assemblages containing less than 0,3% Ni. The other two samples are from vein-type arsenical ores containing very little nickel sulphide mineralization. The field bounded by the indicator lines 5 p.p.b Ir/10 p.p.b. Pd and 10 p.p.b Ir/30 p.p.b Pd contains three gossans from low grade disseminated ores in dunitic intrusives. The fourth sample represents low grade disseminated sulphide in a silicified peridotite. The barren laterites in this field are thought to have gained their elevated Pd-Ir values through enrichment of background values. The remaining sample is from a pyrrhotite-bearing tuff within an ultramafic sequence. The results demonstrate that Pd and Ir are sensitive indicators of the former presence of nickel sulphides. By plotting the absolute Pd and Ir levels encountered in a gossan, after due allowance for the Ir enrichment is made, onto Fig. 7.50 and Fig. 7.51, a fairly reliable guide to the nickel grade of the precursor sulphide assemblage is obtained.

The presence of anomalous selenium values in any gossan generally indicates that it has been derived from the weathering of sulphide mineralization and Se is quantitavely preserved in the oxidized section of sulphide deposits. The S/Se ratios of magmatic sulphides are generally much lower than those obtained from sedimentary sulphides (Stanton, 1972). As the gossans derived from the latter are often confused with the former, the Se content of a gossan sample affords a means of discriminating the type of sulphide from which it is derived (McGoldrick and Keays, 1981). Most nickel sulphide deposits for which S/Se ratios have been determined have ratios of less than 12 000 (Green and Naldrett, 1981). These are in marked contrast to sedimentary sulphides which have ratios in excess of 20 000. Exceptions

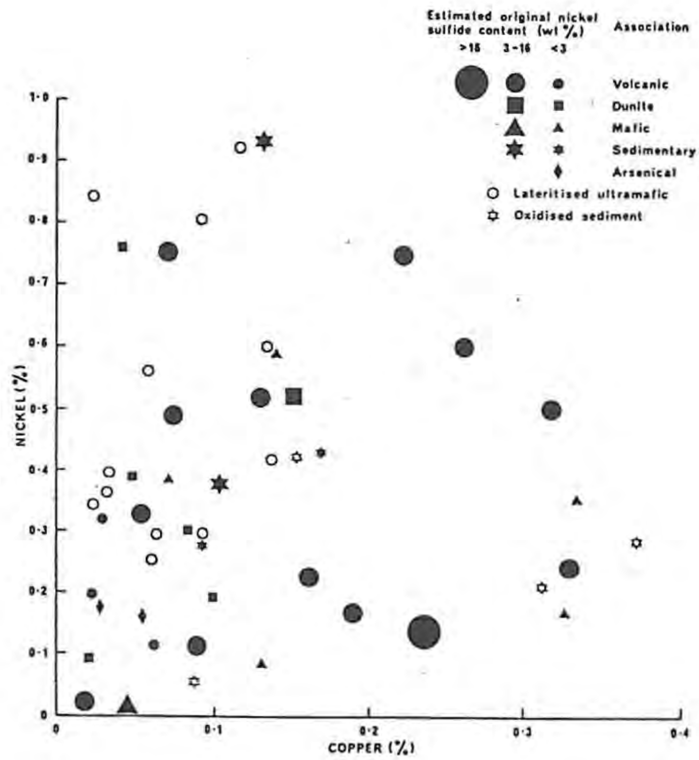


Fig. 7.48. Ni-Cu scattergram showing overlap in values between 34 nickel gossans, 12 laterized ultramafic rocks, and 4 oxidized sediments. Each sample is from a separate occurrence (from Travis et al., 1976).

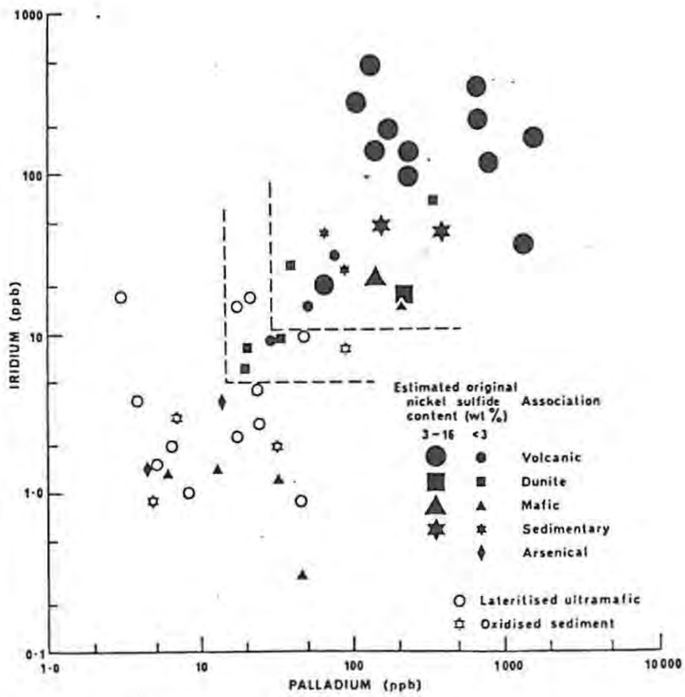


Fig. 7.49. Pd-Ir scattergram of the same samples as Fig. 7.48 showing separation of most nickel gossans from the barren samples; three of the nickel gossans have values outside the diagram (after Travis et al., 1976).

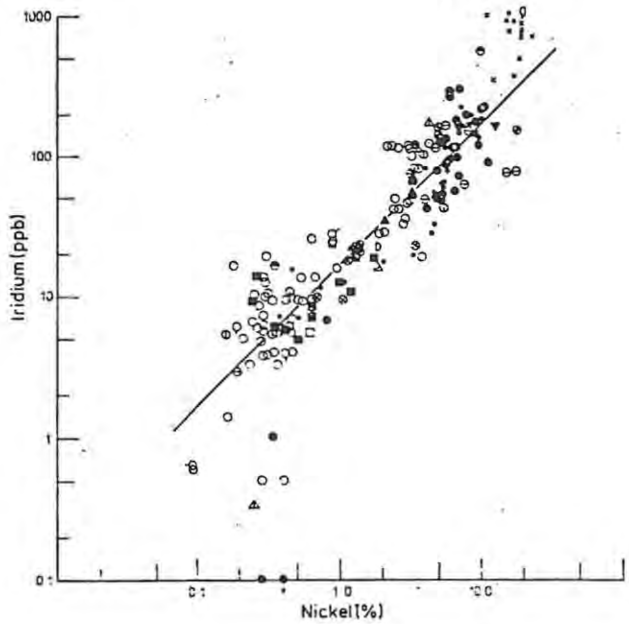


Fig. 7.50. Variation of iridium as a function of the whole-rock nickel content of nickeliferous sulphides and their ultramafic host rocks. The 45° line is for reference only. Each symbol represents a different mineral deposit. Small solid circles = diamond-drill hole KA-4.12, Lunnon Shoot, Kambalda, large solid circles = unpublished data for other Lunnon Shoot samples, crosses = oxide and supergene samples, Otter Shoot, Kambalda (after Keays and Davidson, 1976).

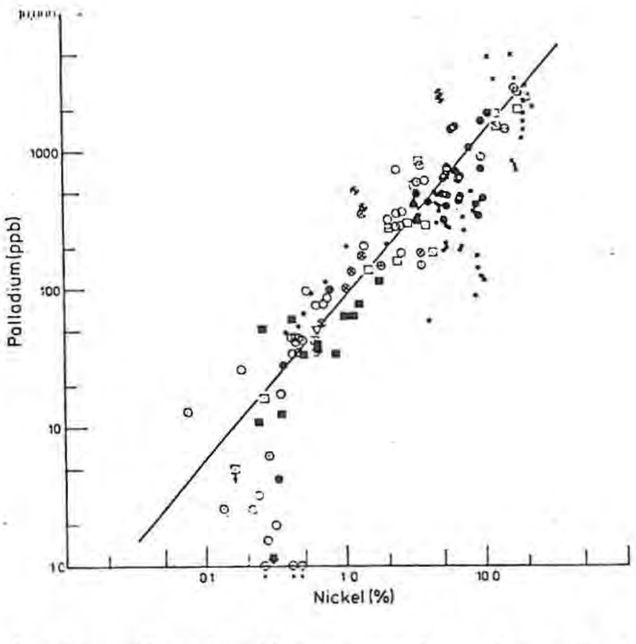


Fig. 7.51. Variation of palladium as a function of the whole-rock nickel content of nickeliferous sulphides and their ultramafic host rocks. Refer to Fig. 7.50 for further explanation (after Keays and Davidson, 1976).

to the rule do occur. Examples include the Windarra deposit which has ratios of between 19 000 and 25 000 and the Perserverance deposit which has ratios of 47 000. The ratio can provide a direct measure of the original magmatic sulphide content of the weathered samples in areas where the S/Se ratio is known, and may be helpful in delineating in evaluation extensions to known deposits (McGoldrick and Keays, 1981).

Although some Tl may be leached from gossans, the observed levels in Tl in the oxide zone at the Perserverance deposit are much higher than Tl levels in barren ultramafic rocks (the average content of nine ocean floor ultramafics is 2,92 p.p.b.) (McGoldrick and Keays, 1981) If this trend is proved to hold for other deposits, it may be a valuable discriminator of true nickel sulphide gossans.

Nickel is mobile in oxidizing acid or reducing gley environments but is immobile in alkaline or reducing hydrogen sulphide-rich environments (Levinson, 1980). Therefore, because of its mobility in such diverse conditions, the sampling of soils above potentially mineralized bedrock has met with considerable success in the exploration for nickel sulphides.

Soil surveys may indirectly lead to the detection of nickel-copper sulphide mineralization in areas of thick overburden. Because of their inherently high content of Ni, Mg, and Cr, poorly exposed ultramafic bodies can be mapped out quite accurately from a study of the soil sampling results. Mafic rocks have a lower content of Ni and Mg but a higher content of copper than ultramafic rocks and a plot of the Ni/Cu ratio for each sample may be very effective in distinguishing the mafic and ultramafic members of any particular magmatic suite. The use of soil sampling as an aid in the mapping of ultramafic and mafic rocks is discussed in some detail by Callahan et al., 1978; Ayräs, 1976; and Tonskanen, 1976.

As outlined above, Cu is often regarded as a sulphide indicator and the drilling of soil anomalies with coincident high Cu and moderate to high Ni values has met with considerable success in exploration. The following two case histories serve to illustrate this point.

The Shangani nickel deposit was discovered during a regional soil sampling programme. The deposit lies within a typical sub-tropical savannah grassland region characterized by a varying rainfall of between 600 mm and 1600 mm. Red, slightly acid (pH 5,5 - 6,0) soils characterize the serpentinite and black clayey neutral soils characterize the low-lying areas comprised of basalt. The results of a regional reconnaissance soil survey within the area are shown in Fig. 7.52. Samples were collected from a depth of 25-30 cm at at 60 m intervals along traverse lines 300 m apart (Philpotts, 1974). The -80 mesh fraction was assayed by atomic absorption subsequent to a total acid attack using a mixture of concentrated perchloric acid and 5% nitric acid followed by dilution to 10 ml with 5% hydrochloric acid. The results show a strong dependance on rock type, with the serpentinized ultramafic rocks being characterized by high Ni values and low copper values compared to the lower nickel values and higher copper values obtained in soils over the pyroxenites. The survey resulted in the location of a particularly strong and extensive coincident Cu-Ni anomaly over the Shangani deposit (Fig. 7.52). The maximum values recorded within the anomaly were 250 p.p.m. Cu (5 x background) and 4000 Ni (8 x background). It should be noted that although, the nickel value is not low, it is not the highest in the area, whilst the copper value is extremely high.

The Jimberlana dyke is a strongly differentiated mafic-ultramafic dyke consisting of dunites, peridotites, bronzitites, feldspathic bronzitites, noritic gabbros, and dolerites. The flat dipping layered sequences occur in canoe-shaped complexes. The dyke has a strike length of some 160 km. The climate is semi arid with hot summers and cool winters. The annual average precipitation is some 286 mm. The soils of the area, which may reach 2 mm in thickness, are desert loams and calcareous solonised brown soils. Reconnaissance lines 533 m apart were sampled at 8.3 m intervals (Mazzucchelli and Robbins, 1973). Where anomalous values were located the line spacing was progressively reduced to 33 m. 0.2 g of the minus 80 mesh fraction was analysed for Ni, Cu, Co, and Cr by atomic absorption spectophotometry following a 3:1 nitric/perchloric acid digestion. The Ni results showed most fluctuation, much of which could be attributed to variations in Ni concentrations in different bedrock lithologies.

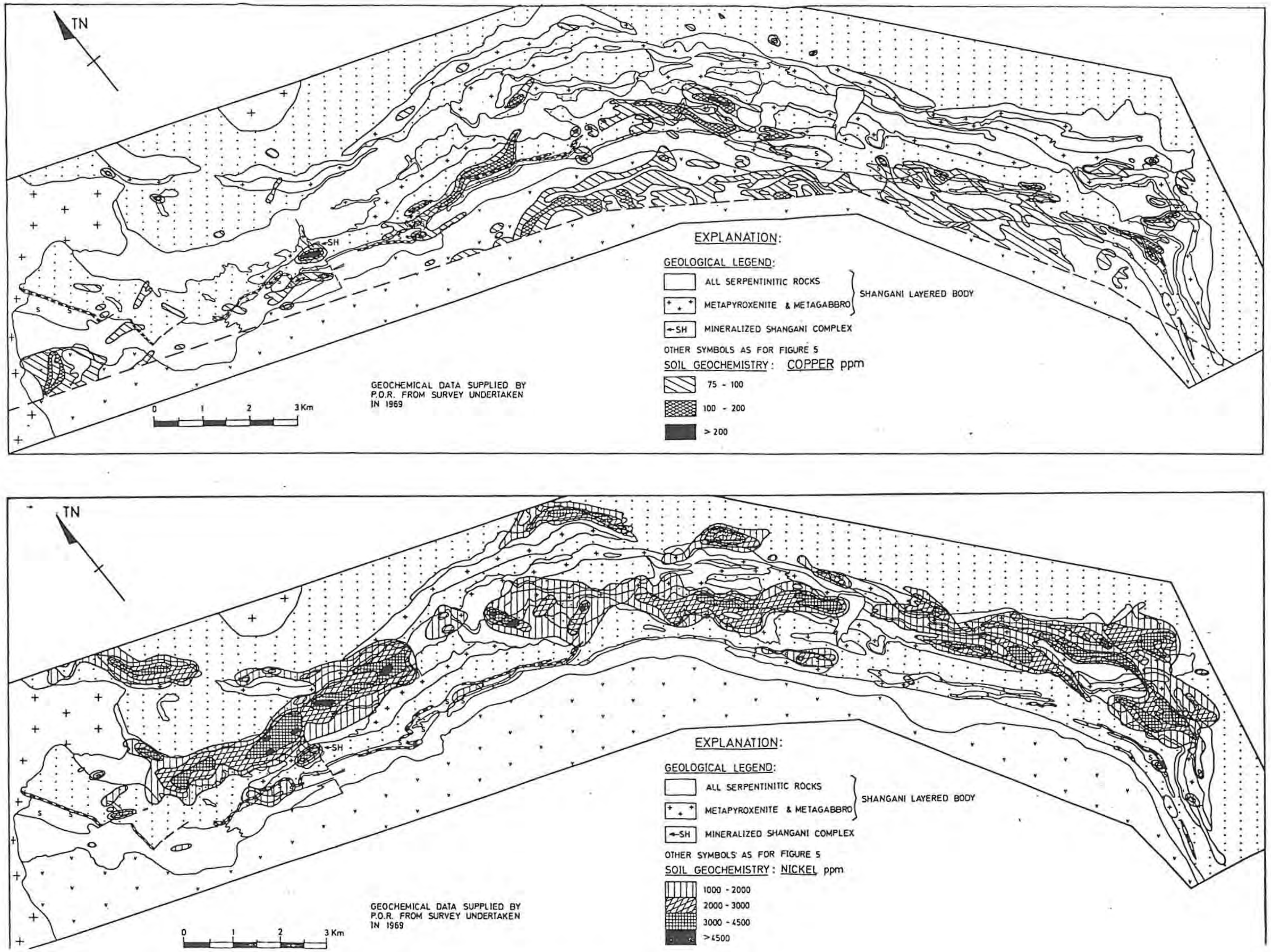


Fig. 7.52. Results of reconnaissance soil survey over the Shangani area (after Viljoen et al., 1979).

Cu values were generally more uniform. The most outstanding anomaly was located at Bronzite Ridge (Fig. 7.53) where more or less coincident values of Cu (3400 p.p.m.) and Ni (2000 p.p.m.). were encountered.

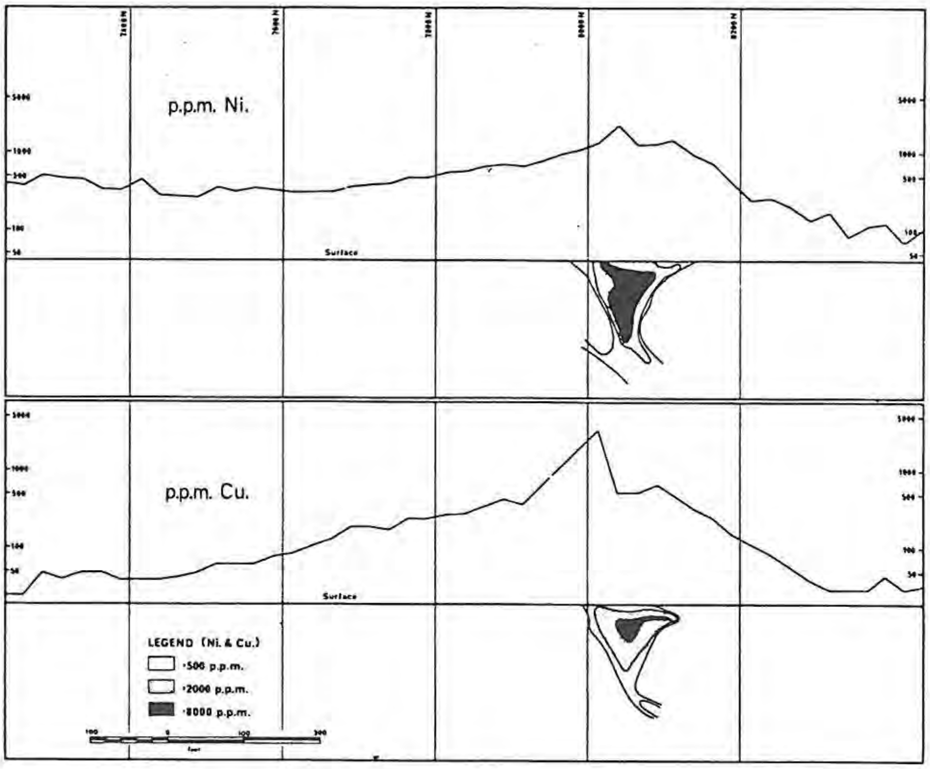


Fig. 7.53. Ni and Cu distribution in soils and bedrock at Bronzite Ridge prospect (after Mazzuchelli and Robbins, 1973).

During detailed follow-up soil sampling, gossan float assaying 1% Ni, 0,5% Cu, and 1 p.p.m. Pt was located. Subsequent drilling showed the anomaly to be related to a small pipe-like body of oxidized sulphides assaying up to 2% Ni and 2% Cu in a noritic lens separated from the main mass of the intrusion. Anomalous Cu and Ni values extended over a total strike length of over 2000 m. In the Bronzite area several holes were drilled to test for possible extensions or repetitions of the mineralization along strike. In each case there was an excellent correlation between the intersection of disseminated sulphides in drillholes and weakly anomalous Cu in surface soils. This correlation was found to be a feature throughout the subsequent exploration in the area. Weakly anomalous Cu geochemical targets (>60 p.p.m.) were drilled at Dundas Hills, Spinfex and Cowan prospects and in all cases the geochemistry was found to correlate with zones of disseminated or stringer sulphide. Although no occurrence of economic sulphides or platinoids was located, Cu was found to be an extremely sensitive indicator of mineralization, despite the extensive soil cover prevalent in the area.

It is apparent that iron oxides rather than clay minerals are the most important fixers of Cu and Ni in soils. Although manganese is a more important scavenger of heavy metals, the volumetric excess of iron over manganese in ultramafic and mafic intrusions, particularly in greenstone belts, and in zones of disseminated and massive mineralization renders the latter of more importance in geochemical exploration for Ni-Cu sulphides. Wherever possible, the fraction containing the highest proportion of iron oxides should be analysed. This point is illustrated by a geochemical survey over the Durkin Shoot at Kambalda (Mazzuccheli, 1972). The semi-arid area is characterized by a sporadic rainfail of 22,8 cm- 30,5 cm and alkaline soils which range in depth from 15 cm to 30 cm. The soils were sampled at a depth varying between 15 and 30 cm and the -80 mesh fraction was assayed by atomic absorption following total acid attack (nitric/percholoric). Initial reconnaissance soil sampling was on a 466 m x 17 m grid, and it should be noted that all suboutcropping and outcropping ore bodies in the Kambalda area were discovered in this manner. In areas of interest the spacing was closed down to 100 m x 17 m and 33 m x 17 m. A strong coincident Cu-Ni soil anomaly is developed over the main ore zone at the Durkin Shoot (Fig. 7.54). Pitting at this site showed a number of significant relationships, namely (Fig. 7.55): that the apparent depletion of nickel in the -80 mesh fraction reflects the concentration of Ni in the coarse soil fractions over the suboutcropping mineralization, that there are Ni concentration peaks in the silt at all depths except in topsoils, that the clay fraction has the lowest Ni and Cu abundances of all fractions present, that there is a marked decrease in the clay fractions below three inches, and that the very low concentration of Ni in the clay fractions correlates with a marked drop in the Fe content with respect to the other fractions. Mazzuccheli (1972) concluded that, although Ni and Cu should be concentrated in the clay minerals, the distribution of Ni, and to a lesser extent of Cu in the silt fraction, indicates that Ni and Cu are associated principally with the colloidal iron oxides.

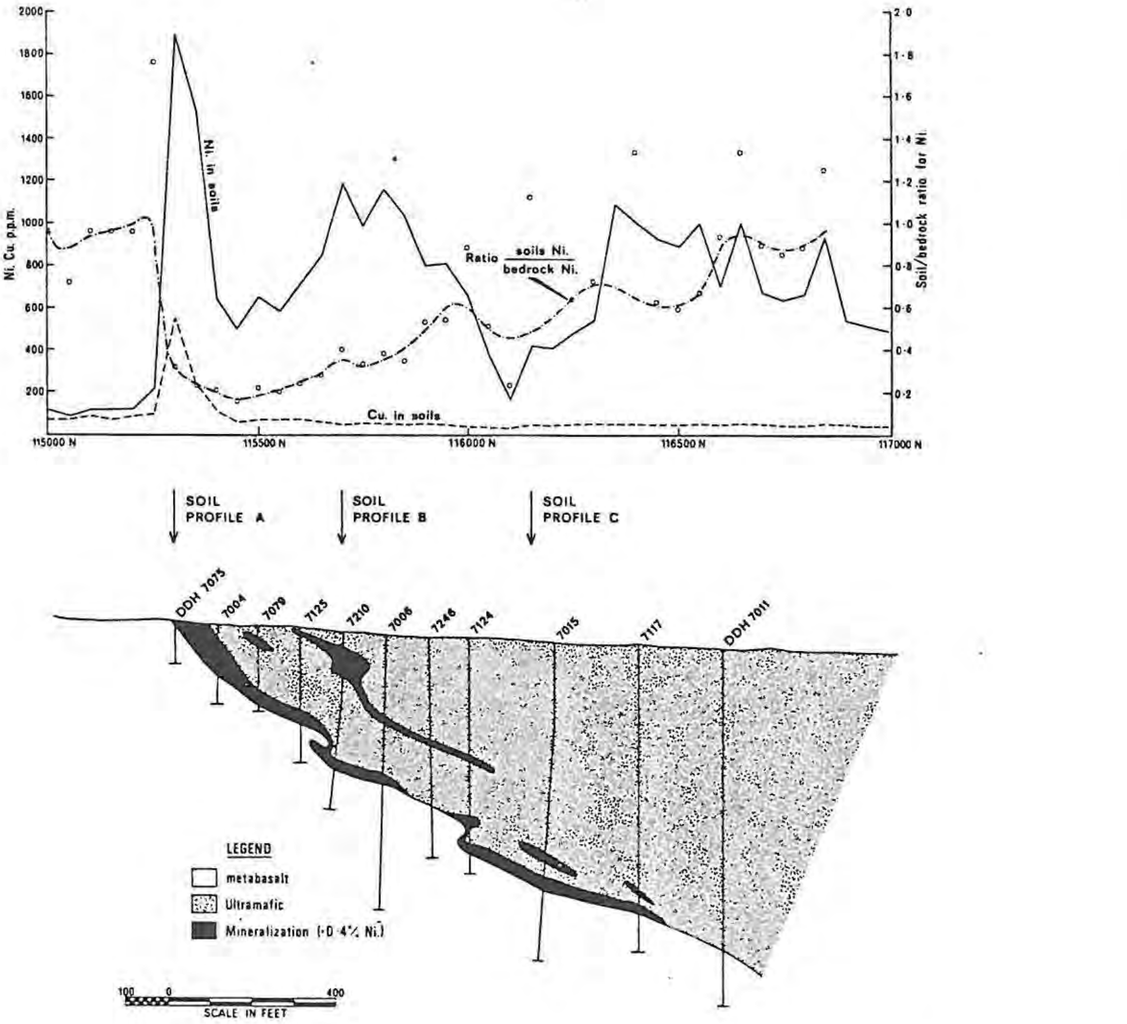


Fig. 7.54. Cross section and geochemical profiles at 107000W, Durkin Shoot area (after Mazzuchelli, 1972).

When assaying for nickel in soil samples it is preferable to use cold extractable methods as these techniques readily discriminate between sulphide and silicate nickel. Figs. 7.56 and 7.57 show the results of soil sampling from a single traverse across a suboutcropping nickel sulphide gossan at the Pioneer Prospect near Norseman, Western Australia (Hall et al., 1973). In contrast to Kambalda where nickel is preferentially concentrated in the coarse fraction, here silts, clays, and Fe-Mn oxides associated with the fine fraction contain the most significant proportion of trace metals. The samples were screened to -89 mesh and assayed for the metal content associated with the leachable secondary Fe and Mn oxides following both total and partial acid attack. The results from the

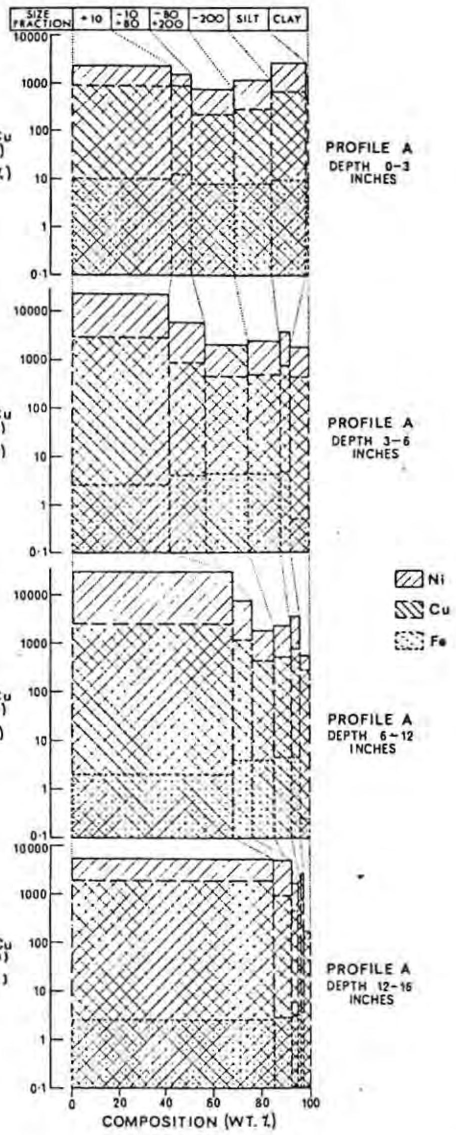


Fig. 7.55. Particle size distribution in soil profie over Durkin Shoot (after Mazzuchelli, 1972).

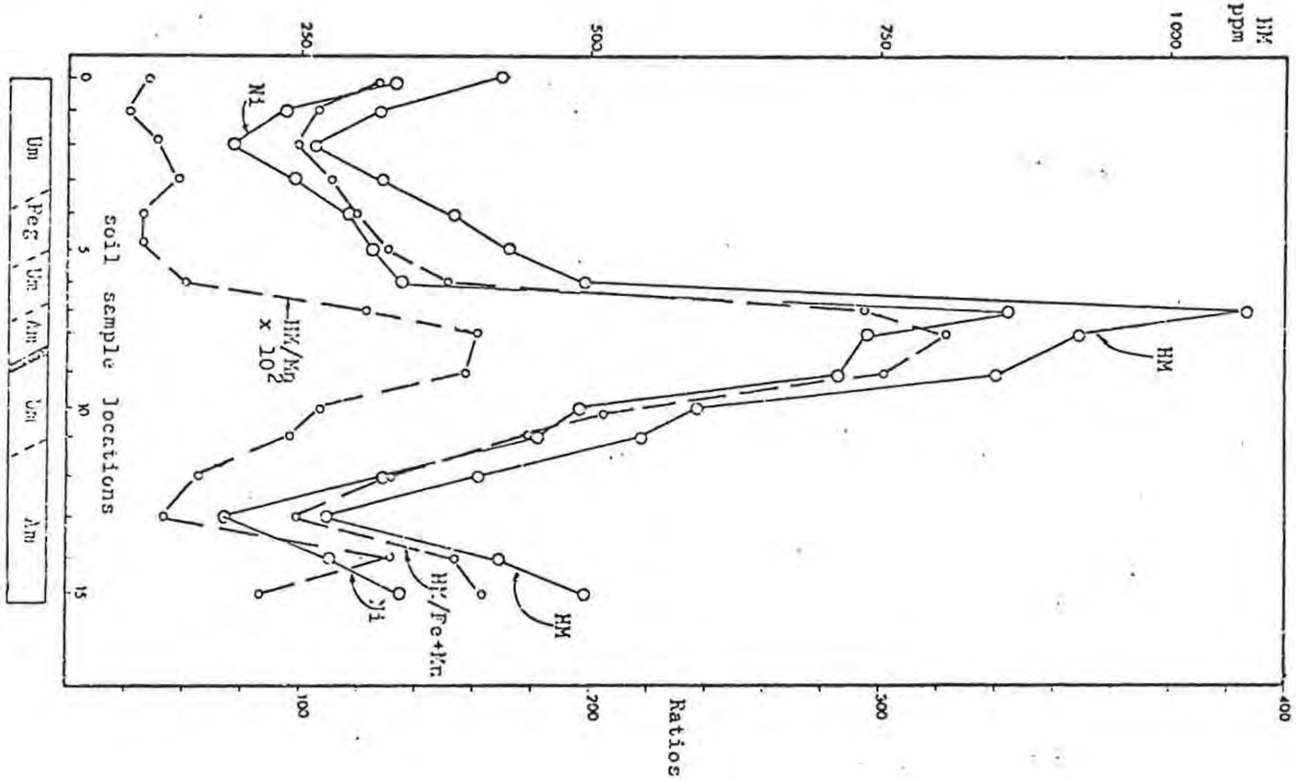


Fig. 7.56. Pioneer BB Prospect. Hot extractable HM, Fe and Mn contents of -80 mesh soil fraction (after Hall et al., 1973).

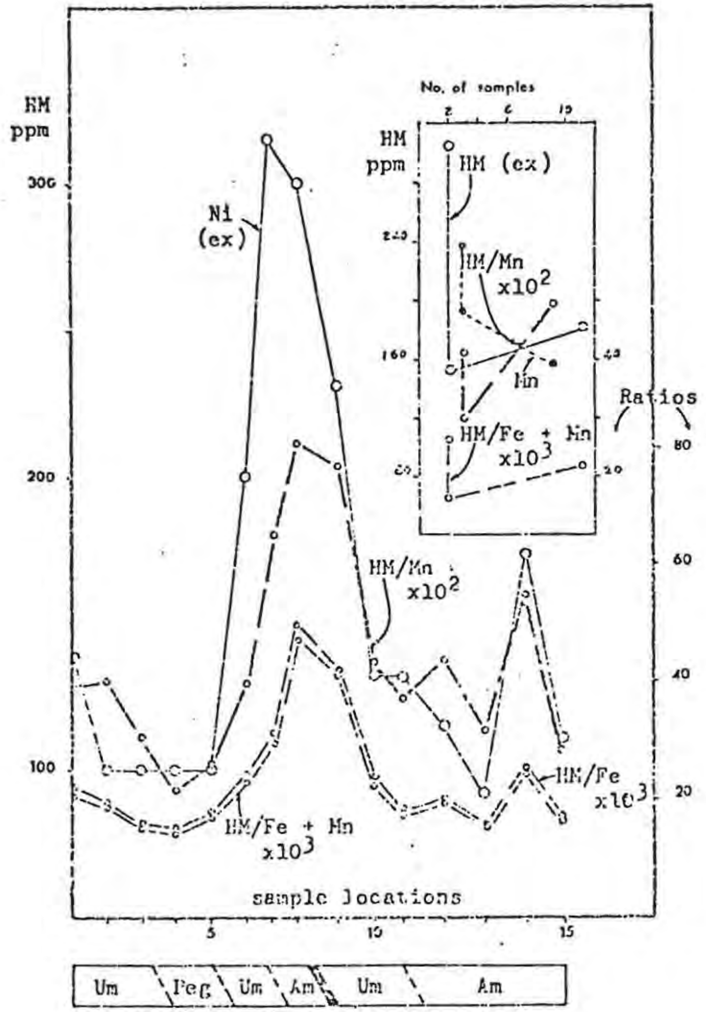


Fig. 7.57. Cold extractable HM, Fe, and Mn contents of -80 mesh soil fraction from a traverse over Pioneer BB Prospect (after Hall et al., 1973).

two graphs are similar, with higher metal contents in Fig. 7.56 being due to the total attack employed and, away from the gossan, to the contribution of nickel in the silicate minerals. The assymetery of the curves over the gossan is due to the down slope dispersion and possibly to some disseminated mineralization in the hangingwall. The results clearly illustrate that cold extractable methods record known mineralization with a marked anomaly contrast.

The Gladesville norite, a north-east trending pluton about 13 km long and 1½ - 4 km wide, is located in southwestern Jasper Country, Georgia. Although the principal lithology is norite, gabbros and olivine gabbros occur. Country rock consists mainly of interlayered quartz-feldspathic and hornblende gneisses metamorphosed to almandine-amphibolite facies. Copper and nickel anomalies in stream alluvium were delineated in the northern and central portions of the outcrop (Fig. 7.58). Concentrations of Ni up to 358 p.p.m. and Cu up to 227 p.p.m. were encountered. These anomalies were later verified and delineated by detailed soil sampling on a spacing of 30 m. The samples were taken from the top of the B horizon and assayed following hot (total) acid attack. Concentrations of up to 1000 p.p.m. Ni and 1200 p.p.m. Cu were encountered and several of the anomalies were coincident with magnetic anomalies. Subsequent geochemical surveys and drilling proved that the majority of the anomalies were false. The results of these surveys are discussed below.

The -80 mesh fraction of the soils was initially subjected to a variety of cold acid attacks. A summation of the partitioning relationships is given in Table 7.6. An average of 75% of the total Ni is extracted by the selective leaches, and almost 50% resides in the iron oxide coatings. The coatings are a less important site for Cu and just over 50% of the total Cu is extracted by a combination of selective leaches. These results appeared to indicate that the metal not extracted by the selective leaches probably resided in the silicates. This was verified by digesting rock samples with ascorbic acid/hydrogen peroxide, a method which has been shown to be almost totally specific for metal residing in the sulphide phases of a mafic rock. The results indicated that a considerably greater proportion (67,1%) of the total Cu is partitioned amongst the sulphides than Ni (27,5%).

TABLE 7.6. Partitioning of copper and nickel in the B-horizon, minus 80-mesh soil samples, as determined by selective leaching techniques (after Robertson et al., 1979).

Residence site	Percent of total metal	
	Cu	Ni
Adsorbed cations	5	2
Associated with organic matter	9	16
Associated with iron oxide coatings	21	46
Concentrated in clay lattices	18	11
	53	75

TABLE 7.7. Copper and nickel extracted from outcrop samples by ascorbic acid/hydrogen peroxide (after Robertson et al., 1979).

Sample No.	Cu (ppm)	Total Cu (%)	Ni (ppm)	Total Ni (%)
R-1	30	61.2	260	28.4
R-2	80	75.5	135	29.6
R-3	50	48.6	45	16.1
R-4	130	83.8	95	27.5

Mean Cu and Ni concentrations in individual mineral phases of four outcrop samples were established quantitatively by electron microprobe analysis. As Table 7.8 indicates, spinel contains high concentrations of both Cu and Ni, and olivine contains substantial quantities of Ni. Both the pyroxenes and amphiboles also have fairly high concentrations of Cu and Ni.

The origin of the false anomalies in the soil overlying the Gladesville norite results from a combination of factors. The association of metal with clay minerals, absorption of metal by Fe-Mn oxides, the contributions of Ni from a high background source rock, and the abundance of silicate-held Ni and Cu in the bedrock, all contribute to high metal concentrations. The original soil-grid anomaly pattern provides some important clues which indicate a lack of significant mineralization (Fig. 7.58). The Ni anomalies tend to cover large areas and are fairly continuous. Such a distribution is more suggestive of high background levels of Ni than sulphide

TABLE 7.8. Mean copper and nickel concentrations of individual mineral phases in outcrop samples, determined by electron microprobe (after Robertson et al., 1979).

	Cu (ppm)	Ni (ppm)
Labradorite	67	105
Orthopyroxene	137	278
Clinopyroxene	160	266
Hornblende	55	284
Spinel	579	1721
Actinolite	176	402
Olivine	40	1067
Serpentine	89	698
Carbonate	—	—
Pyrrhotite	371	217
Pentlandite	675	44.16%
Chalcopyrite	33.75%	1545
Ilmenite	—	—
Magnetite	—	—

— = below detection limit.

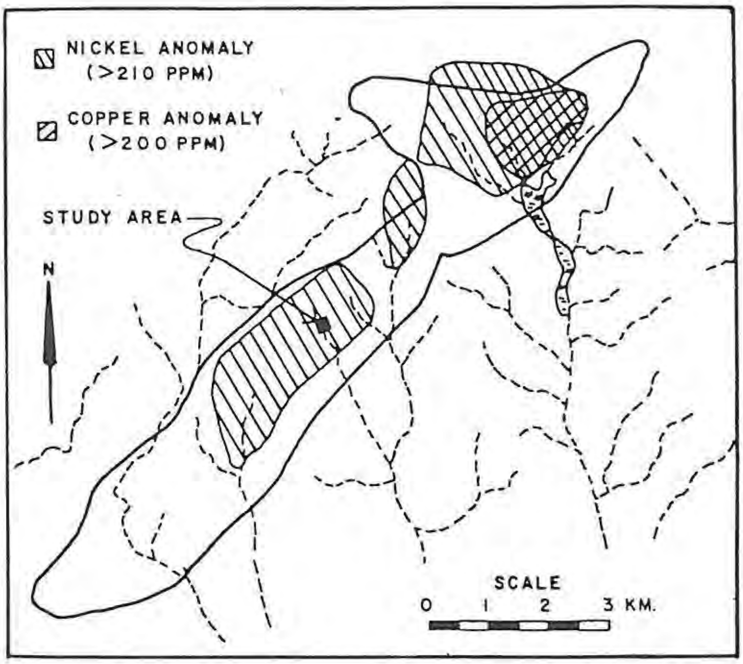


Fig. 7.58. Map showing anomalous concentrations of Cu and Ni in stream alluvium, Gladesville norite area (after Robertson et al., 1979).

mineralization. The values of soil/bedrock Ni ratios over the anomalies averaged 0,7. Mazzucchelli (1972) showed that in the Kambalda area the values of Ni in the soil showed a 2x to 6x depletion compared to those in the underlying bedrock. These ratios are much lower than those encountered in this study and consequently, make the anomaly look even less promising. Although the soil anomaly pattern for Cu is less continuous than that for Ni and is more indicative of mineralization, the anomalies do not seem as promising when one considers the soil/outcrop ratios of Cu. Soils, such as those developed over the Gladesville norite, in which the peak abundance of Cu is 5 x 15 peak outcrop value, suggest some secondary mechanism of Cu accumulation. It is unlikely that any "scavenging" mechanism could produce metal concentrations in soil greater than those that would be present in bedrock covering significant sulphide mineralization. Furthermore, the results of the cold extraction suggest that Cu is strongly associated with montmorillonite and Ni with iron oxide coatings, indicating the possibility of a scavenging anomaly in both cases.

Chrome and cobalt are important pathfinders for nickel-copper sulphide mineralization and should always be assayed for in any soil survey programme. Cox (1974) has discussed the use of Cr and Co in soil surveys in the exploration of nickel-copper sulphides located at the base of serpentinized ultramafic bodies around the Pioneer Dome, Western Australia. Outcrop in this strongly dissected terrain is minimal and the only visible expression of mineralization is the sporadic occurrence of gossan float. The soil cover is shallow, varying in depth from 10 cm to 1 m, and is typically composed of strongly alkaline solonized brown soils. A 0,5 m to 1,5 m thick calcrete cover overlies the bedrock. Orientation studies were carried out to determine the lateral and vertical distribution of Ni, Cu, Co, Cr and Zn within the soil profile. Strong mushroom-shaped dispersion patterns for Ni, Cu, Co, Cr, and Ni/Cr ratio were present in the soil and calcrete cover, the greatest lateral dispersion being encountered in the top soil. On the basis of these studies, a detailed soil geochemical survey was completed over most of the ultramafic bodies around the Pioneer Dome. Initially 122 m x 15,2 m or 61 m x 15,2 m grids were used. Where initial results warranted more detailed work, the spacing was closed down 61 m x 7,6 m or 30,5 m x 7,6 m. Samples were taken from the base of the topsoil some 10 cm to 20 cm below the surface. Three major Ni, Cu, Co, and Ni/Cr soil anomalies were located on or close to the basal contact of a favourable ultramafic body (Figs. 7.59 and 7.60). The anomalies

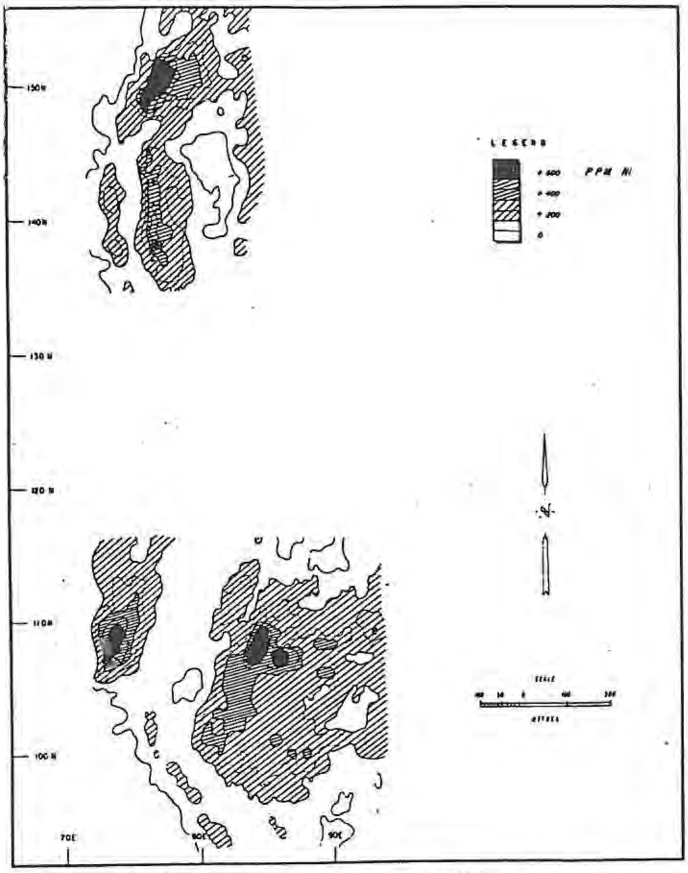


Fig. 7.59. Geochemical soil survey, JH-BB prospect area, nickel contour plan (minus 80-mesh fraction). Copper anomalies coincident with nickel ones (after Cox, 1975).

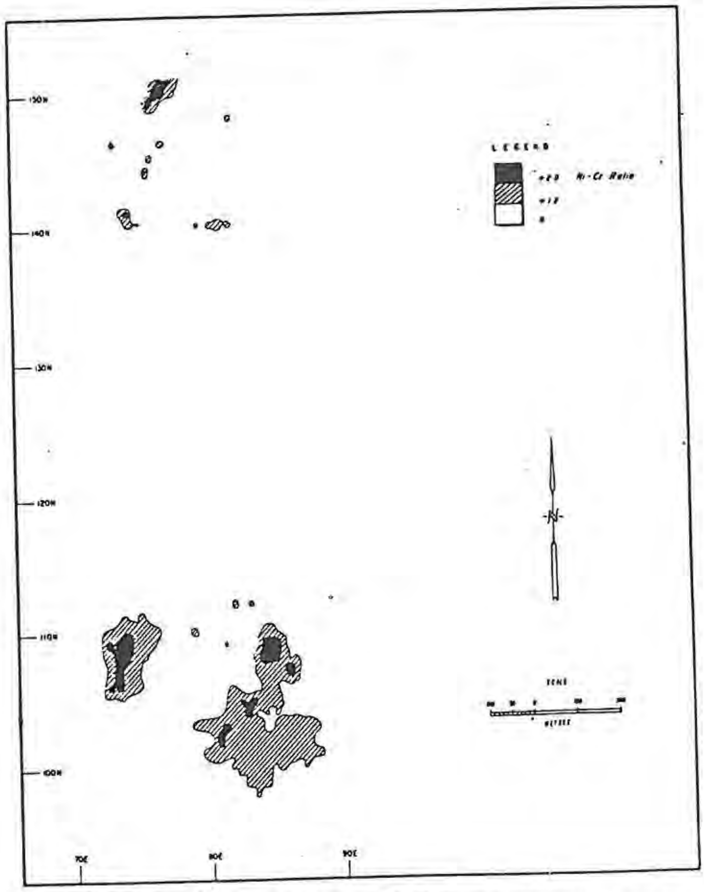


Fig. 7.60. Geochemical soil survey, JH-BB prospect area, Ni/Cr ratio contour plan (minus 80-mesh fraction)(after Cox, 1975).

coincided exactly with the position of gossans exposed during subsequent trenching. The main purpose of determining the Ni/Cr for soil samples is to establish whether a nickel soil anomaly reflects an ultramafic source in areas of deep soil cover and to define the contact zone of the ultramafic. Cox (1974) found that Ni/Cr ratios greater than 1,0 to 1,5 are related to nickel sulphide mineralization. In areas barren of sulphide mineralization the Ni/Cr ratio is less than 1,0.

The usefulness of Pd, Ir, and Pt as indicators of nickel sulphide gossans has already been mentioned. The mechanical breakdown of gossanous material containing these elements should produce secondary dispersion halos around the mineralization. Consequently, Pd, Ir, and Pt may be useful pathfinder elements when sampling soils over potentially mineralized mafic and ultramafic intrusions (McGoldrick and Keays, 1981).

Soil anomalies showing high coincident Ni and Zn values should not be discarded immediately until the cause of the high Zn values has been established. Anomalous Zn values in the soils overlying nickel-copper sulphide mineralization may be reflecting the breakdown of zinc-rich spinels often associated with the ores, or they may be derived from the weathering of zinc-rich exhalites spatially associated with many komatiitic ores.

Stream sediment sampling offers a fast and fairly sensitive method for detecting copper-nickel mineralization. The use of stream sediment sampling in the discovery of a previously unknown nickel-copper occurrence in the southern Grenville province of Quebec is outlined by Felder (1974). The Shawinigan nickel-copper properly occurs within the eastern lobe of a noritic intrusive emplaced into Precambrian Grenville gneisses and paragneisses. The drainage pattern consists of a series of lakes connected by streams. Where the topography is more dissected, as is the case around the Shawinigan complex a more mature drainage prevails. The presence of glacial moraine and fluvio-glacial deposits in the eastern part of the area gives rise to flat fertile ground. The -80 mesh fraction of the stream sediment samples was analysed for Cu, Pb, Zn, Ni, Mo, and Mn by atomic absorption spectrometery following a hot

HNO_3 - HCI mixed acid digestion. An area of 310 sq. kms was covered by the reconnaissance stream sediment survey, which had a sampling density of 2,5 samples per km^2. The streams were sampled every 550 m and above all confluences. The Ni and Cu contents of the stream sediments are shown in Figs. 7.63 and 7.64. The background concentrations are very low and concentrations exceeding 19 p.p.m. Cu and 35 p.p.m. Ni were considered anomalous. The survey delineated a highly anomalous area of approximately 12 km^2. The 19-40 p.p.m. Cu range outlined the favourable intrusive very well (Fig. 7.63). Within the Ni-Cu-bearing intrusive, stream sediments containing up to 2200 Ni and 600 p.p.m. Cu were recorded. Subsequently detailed soil surveys outlines a number of coincident Ni-Cu anomalies which were drilled, and in all cases, low grade Ni-Cu mineralization was encountered.

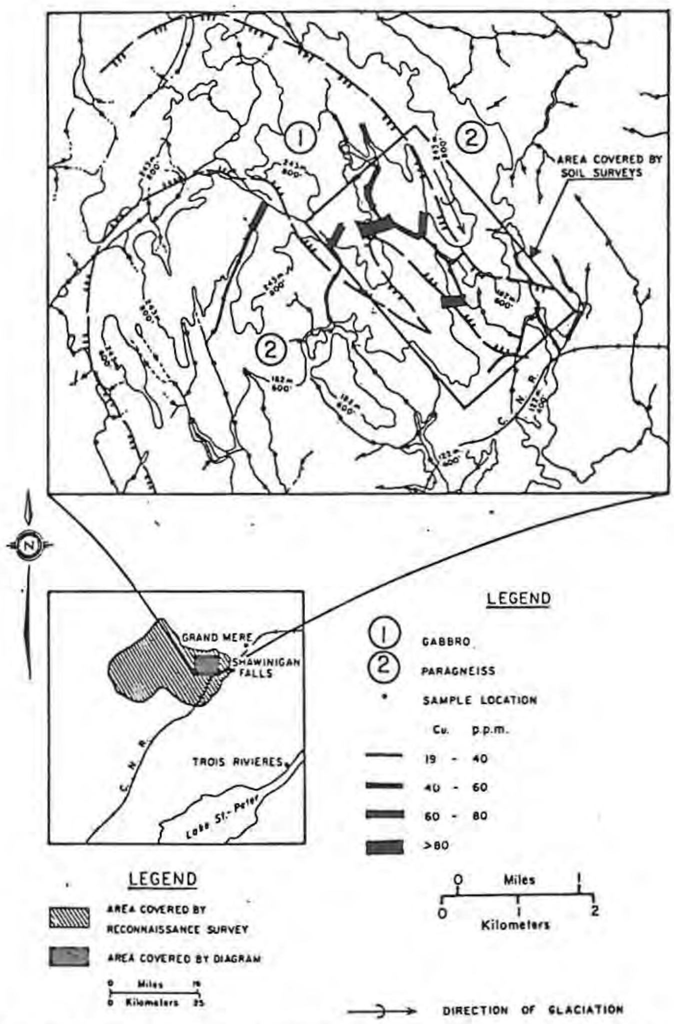


Fig. 7.63. Hot extractable copper content of stream sediments in the Shawinigan area with regional geology (after Beland, 1961, from Fedler, 1964).

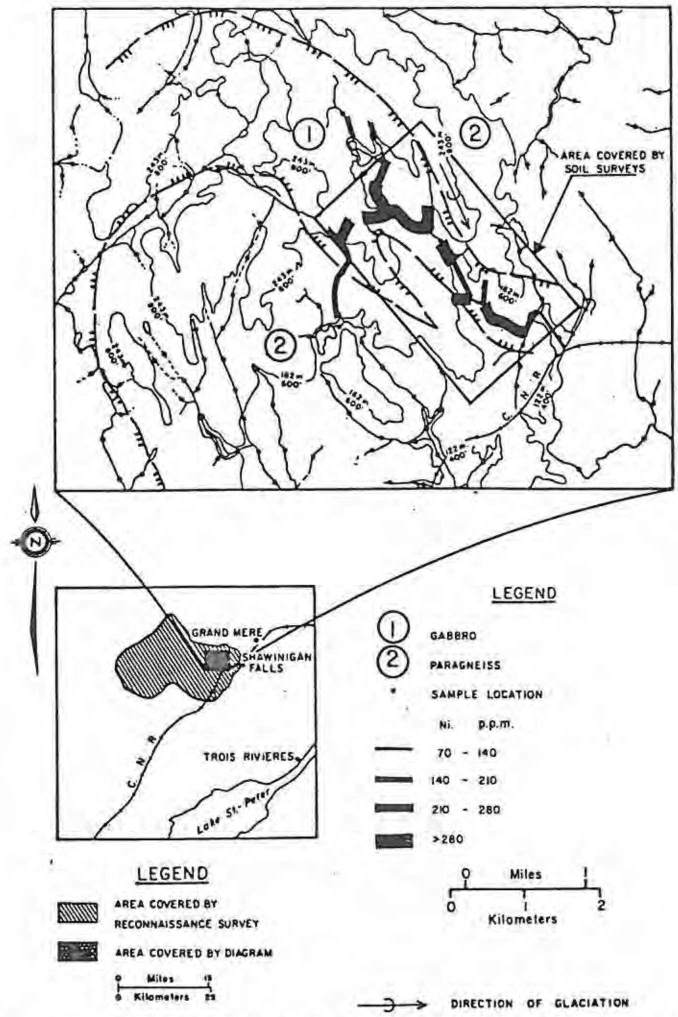


Fig. 7.64. Hot extractable nickel content of stream sediments in the Shawinigan area with regional geology (after Beland, 1961, from Felder, 1974).

In recent years some of the most important work in geobotanical methods has been concerned with nickel-sulphide exploration. Brooks et al. (1977) analysed some 2000 herbarium specimens and 232 species of the genera Homalium and Hybanthus for nickel in order to identify plant accumulators of nickel which were indicative of nickeliferous ultramafic rocks. The specimens were collected from all parts of the tropical and warm temperate World between latitudes $40^{\circ}N$ and $40^{\circ}S$ and represented a sampling density of about 1 specimen per 2000 km^2. The survey resulted in the identification of ten hyperaccumulators (>1000 p.p.m. on a dry weight basis) of nickel from the two genera (Table 7.9). The study showed that the hyperaccumulators and strong accumulators delineated many of the World's ultramafic areas in warm temperature and tropical regions, including Cuba, Puerto Rico, Philippines, Western Australia and New Caledonia.

TABLE 7.9. Hyperaccumulation (>1000 μg/g dry weight) of nickel (after Brooks et al., 1977).

Species	Total No.	No. above 1000 μg/g	Locality	Highest Ni conc. (μg/g dry weight)	Nature of substrate
Homalium					
austrocaledonicum Sleum.	6	4	New Caledonia	1805	ultrabasic
deplanchei Warb.	10	2	New Caledonia	1850	ultrabasic
francii Guillaumin	7	7	New Caledonia	14500	ultrabasic
guillainii Briq.	2	2	New Caledonia	6926	ultrabasic
kanaliense Briq.	6	5	New Caledonia	9420	ultrabasic
mathieuanum Briq.	3	1	New Caledonia	1694	ultrabasic
rubrocostatum Sleum.	2	1	New Caledonia	1157	ultrabasic
Hybanthus					
austrocaledonicus Schinz et Guillaumin	4	4	New Caledonia	13750	ultrabasic
caledonicus (Turcz.) Cretz.	11	2	New Caledonia	5917	ultrabasic for values >1000 μg/g
floribundus F. Muell.	13	2	W. Australia	6680	ultrabasic for values >1000 μg/g

Brooks and Wither (1977) collected 89 Herbarium species of the hyperaccumulator Rinorea bengalensis throughout south-east Asia and analysed them for their nickel content. Most of the areas underlain by ultramafic rocks were identified from the nickel content of the specimens and one previously unrecorded ultramafic body in Indonesia was located. This type of survey may therefore provide a simple, rapid and inexpensive method of locating potentially mineralized ultramafic bodies in heavily vegetated terrains.

Brooks (1979) has listed another 44 hyperaccumulators of nickel in the genus Alyssum, but further field work will have to be carried out to classify them.

The most extensively hyperaccumulator of nickel is Hybanthus floribundus (Brooks, 1979). Studies by Cole (1973) over many of the western Australian komatiitic - hosted nickel sulphide deposits clearly revealed that the shrub Hybanthus floribundus preferentially grew over serpentinized peridotite bedrock and was resistricted to nickeliferous soils. Nickel levels of up to 23% were found in the ash of leaves of several samples collected at Widgiemooltha. The plants are often preferentially concentrated along the margins of quartz-feldspar porphyry dykes intrusive into the ultramafics and along the contacts of mafic and ultramafic rocks. Consequently, although its distribution may be a valuable guide in mapping poorly exposed rocks, it's presence does not necessarily reflect the presence of nickel sulphide mineralization in the bedrock. The nickel content of the shrub however, does often bear some relation to the tenor of mineralization. At Widgemooltha, the lower soil pH over the orebody resulted in a greater quantity of released metal ions and a greater uptake of nickel in the plant.

Cole (1973) noted that the absence of vegetation may, or may not, reflect mineralization. At Kambalda there is a complete absence of trees and a major proportion of the shrubs over the eastern half of the soil anomaly, but abundant plant growth is present over the western half. This unusual feature is attributable to the presence of $CaCo_3$ in soils of the western half which reduced the mobility of nickel and chromium. The eastern half however, was devoid of calcium carbonate in the soil allowing greater mobility of metal ions with the result that plant growth was inhibited.

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