MAGNETIC SIGNATURES OF GOLD-COPPER-ZINC-LEAD-SILVER MASSIVE SULPHIDE DEPOSITS IN EXTENSIONAL SEDIMENTARY BASINS

BY P. J. GUNN

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PREFACE

This study may be read two ways:

(i) readers can either use its factual reporting of deposit characteristics as a basis for recognising ore body responses.
or

(ii) readers can combine the approach of (i) with the author's syntheses which provide predictive models for recognising the magnetic responses of massive sulphide deposits.

The author strongly believes that the second approach which is based on an examination of the fundamental causes of magnetic responses of massive sulphide deposits is more likely to produce exploration success.

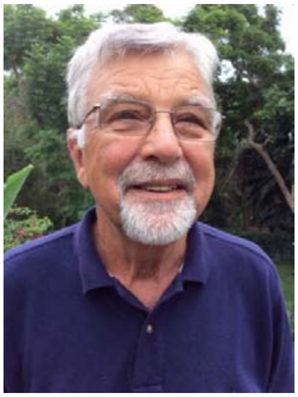
In researching this study the author has been amazed that since Fraser Grant's (1985) excellent introductory examination of magnetite distributions in ore environments so little work has been published on this subject. It is also surprising that, given the almost ubiquitous application of the magnetic method in contemporary mineral exploration, so few publications exist which present magnetic data, modelling results and rock property measurements for massive sulphide deposits. Few authors even bother to report on magnetite or pyrrhotite concentrations of ore bodies and virtually none report whether any pyrrhotite present is the magnetic monoclinic variety. The series of papers by Don Emerson and Dave Clark on the Cobar area which are described in the relevant chapters of this study are virtually unique in their thoroughness and detail and demonstrate the type of work required to provide an absolute basis for the application of the magnetic method in base metal exploration.

The study has deliberately emphasised the aspects of base metal deposits likely to influence the magnetic responses of such deposits. The author, whose background is heavily weighted towards the geophysical/structural/tectonic aspects of exploration, apologizes to any specialists who feel that their fields of expertise may have been oversimplified or downplayed.

The magnetic data presented has been chosen to illustrate particular situations. It has not been considered worthwhile to include every published example of magnetic data over massive sulphide deposits particularly as the majority of these consist of single profiles or formless "bulls-eye" anomalies compiled using low sensitivity acquisition systems and wide survey line spacings.

The author, who does not claim to have all the answers, offers what he believes to be a pragmatic and practical exploration methodology for applying magnetic survey techniques to locate massive sulphide base and precious metal deposits.

Postscript to "Magnetic signatures of gold-copper-lead-zinc-silver massive sulphide deposits in extensional sedimentary basins"; author Peter J. Gunn, 1993 (self-published).



The book was written in 1993. There was no internet search then. I did the research by tracking down hard copy articles in libraries. There was no general availability of downloadable aeromagnetic grids. Low level aeromagnetic surveys with close line spacings were in their infancy Imaging was in its infancy. I had to rely on crude line contour maps for my examples. This has now changed and it would be possible to revisit the examples to see what high quality magnetic datasets put through all the enhancement techniques that are now available would show.

I did not mention "black smokers". I am not certain that they had been identified. An incorporation of the current knowledge of sea floor massive sulphide deposits could add many insights.

I have worked on many rifts since I wrote the book. My impression is that the axial dykes as shown in Figure 2.1 have an important influence on where ore generating centres occur and the development of major deep penetrating faults that can tap and focus ore generating fluids. These axial intrusions can be imaged with gravity data.

I also suspect that the transfer faults that occur obliquely to rift axes and allow differential extension along rift axes may be important control of mineralisation.

I could probably produce a more unified description of the various rift settings these days. My most recent publication on rifts is an advance on the model I gave in the book. This paper is:

Gunn, P.J., 1997 Regional magnetic and gravity responses of extensional sedimentary basins. AGSO Journal of Australian Geology and Geophysics, 17, 115-132. (attached).

Projects I have been involved with since 1997 have confirmed and refined the ideas in this paper.

For the record I used the ideas in the book to identify a prospective target 50 km from the nearest mineral drill hole and about 50 km from the nearest outcrop. The first drill hole intersected pyrrhotite associated with copper and silver at a depth of 75 metres.

So as to allow wider dissemination of my book than the limited original publishing allow in 1993 (100 copies were produced), I have rescinded the copyright on the book thereby allowing for its free distribution.

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March 23, 2015,

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Note: ASEG April 2015 Preview carries a memoir of Gunn's career.

SUMMARY

Magnetite and the monoclinic variety of pyrrhotite are not the only magnetic minerals occurring in massive sulphide deposits and their environments but they are the only ones to do so in a systematic manner. This study identifies the probable and possible distributions and magnetic responses of these minerals which may indicate economic massive sulphide deposit locations.

Massive sulphide deposits are formed during all stages of crustal extension and rifting in intracontinental, island arc and greenstone belt settings. The deposit characteristics vary in relation to the stages of rift development. Distinct massive sulphide deposit types occur in volcanic rifts, turbidite basins with no volcanic activity, turbidite basins with igneous activity, oceanic sea floor settings, post-rift sag phase sediment sections and early pre-rift systems. The host lithologies of the deposit types are related to these tectonic settings.

Regardless of the stage of rifting in which the deposits form all massive sulphides appear to result from sea floor precipitation of minerals emanating from hydrothermal vents. This commonality of origin results in a remarkably similar series of mineral zonations and metal distributions for massive sulphide deposits in all tectonic settings. The classical exhalative massive sulphide deposit consists of a subcircular lens of massive sulphide underlain by a brecciated and/or veined stringer zone of mineralization formed during the vertical ascent of the mineralizing solutions. The deposits are typically overlain by an extensive non-economic chemical exhalite which may variably contain siliceous, sulphide, oxide or carbonate facies of iron minerals or barite. Massive sulphides tend to occur as Cu and Cu-Zn or Pb-Zn-Ag varieties although intermediate compositions occur. The Cu and Cu-Zn deposits occur in areas exhibiting the greatest crustal extension and higher heat flows. Economic grades of Au occur in many massive sulphide deposits but appears to occur in greater concentrations in the Cu and Cu-Zn types. The upper portions of the deposits tend to contain more Pb and Zn and the lower portions tend to contain more Cu. Magnetite and pyrrhotite, when present as primary minerals tend to occur in the lower portions of the deposits including the stringer zone. The dominant gangue sulphide is normally pyrite although significant concentrations of pyrrhotite occur in some deposits.

Primary differentiation processes can produce magnetically detectable concentrations of pyrrhotite and magnetite in massive sulphide deposits.

Variations in deposit geometry appears to be related to the mode of the vertical ascent of the mineralizing solutions. Deposits related to discrete localized sea floor vents have symmetric sub-circular saucer shaped forms. Deposits resulting from vertical fluid migration up major fault systems have asymmetric plate-like forms which extend away from the feeder faults.

Horizontal compression may remobilize the massive sulphide body into tabular or ellipsoidal masses which are markedly elongate in the vertical dimension and which may be discordant with the enclosing lithology. Different mineral mobilities in such situations may result in mineral assemblages which differ from those produced by the original hydrothermal processes.

Not all massive sulphide deposits originally contain magnetic minerals however metamorphic processes may subsequently transform pyrite to pyrrhotite and/or magnetite and pyrrhotite to magnetite and result in non-magnetic deposits becoming magnetic. Metamorphism may also significantly alter the magnetic responses of country rocks containing massive sulphide deposits. In general, magnetic responses of rocks are increased as they are subjected to higher grades of metamorphism with exception of the highest grades of metamorphism which are responsible for decreases in magnetization. The net result of the primary mineral precipitation processes and any subsequent metamorphism is that base and precious metal massive sulphide deposits and their host rock have a constrained and semi-predictable range of magnetic responses.

By considering the above factors and combining case history studies with relevant published fundamental research, it has been possible to define the typical structural and tectonic settings, host-rock lithologies, geometries, dimensions, mineral associations and magnetic properties of Cu-Zn-Pb-Ag-Au massive sulphide deposits and their environments and to detail specific exploration methodologies for their detection using magnetic survey techniques.

In particular it has been possible to identify the magnetic responses of the various stages of rifting and structural settings which contain various massive sulphide deposits types. Within these settings specific magnetic patterns likely to arise from magnetite and pyrrhotite concentrations associated with massive sulphide deposits have been described. These minerals may be concentrated within massive chalcopyrite, sphalerite and galena deposits (which are commonly associated with economic gold and silver concentrations), and thus allow direct detection of such deposits using magnetic methods. Of paramount importance is the recognition that the chemical exhalite which frequently caps and extends laterally from massive deposits often contains sufficient pyrrhotite or magnetite that a magnetic "ore equivalent horizon" is created which can be used to precisely define localities with potential to contain economic mineralization. Mineral distributions associated with feeder vents may also be recognisable as a result of concentrations of magnetic minerals in the vent or its immediate vicinity or as a result of the destruction of magnetic minerals in alteration zones which commonly envelope such vents.

The study has considered the totality of influences on the magnetic responses of massive sulphide deposits in extensional sedimentary basins.

CONTENTS

CHAPTER 1

THE CAUSES OF MAGNETIC RESPONSES IN MASSIVE SULPHIDE OREBODIES AND THEIR HOST ROCKS

1.1 GENERAL BACKGROUND REVIEW OF MAGNETISM AND MAGNETIC PROPERTIES

Principal References: Clark (1983), Clark and Emerson (1991)

Magnetic anomalies occur if rocks have significantly different magnetizations to adjacent rocks. The phenomenon of magnetization arises as a result of alignments of electron spins in molecules. The magnetization with a rock results from two distinct processes.

(i) Induced magnetization:

The interaction of the earth's magnetic field and the magnetic minerals within a rock induces a magnetic moment within the rock. The product of the earth's magnetic field and the volume susceptibility of the rock determines the strength of this magnetic moment which can be regarded as a distribution of magnetic poles within the rock. Induced magnetization varies with the direction of the earth's magnetic field.

Expressed mathematically:

$$Ji = F \times Kv$$

where Ji = induced magnetic moment per unit volume
F = intensity of earth's magnetic field
Kv = volume susceptibility

(ii) Natural remanent magnetization (NRM)

Thermal, chemical and physical processes can develop permanent alignments of magnetism within mineral grains. This magnetism is fixed in its direction relative to a rock mass containing such magnetized grains and is independent of the direction of the earth's field. NRM is a vector expressed in terms of magnetic moment per unit volume and may differ significantly in magnitude and direction from the induced magnetic moment.

Magnetic anomalies are disturbances in the normal magnetic field of the earth caused by magnetic bodies. The anomaly caused by any rock mass will be the result of the vector addition of the fields produced by the induced magnetization and the NRM. As well as being dependent upon induced and remanent magnetization, anomaly shapes depend on the geometry and depth of the rock mass and its orientation relative to the earth's magnetic field. Anomaly shapes are normally complex due to the dipolar nature of magnetic fields (i.e. they always consist of positive and negative portions) and computer modelling is frequently required to interpret such features. Examples of type responses corresponding to simple magnetic bodies have been published by Vacquier et al. (1963) and Reford (1964).

The proportions of induced and natural remanent magnetization varies considerably in rock masses and depends on various factors including the exact mineral content, the grain size of the magnetic minerals and the thermal history to which the rock mass has been subjected. It is now being appreciated that NRM is a dominant factor in more rock bodies than previously assumed.

The ratio of the magnetic moment (magnetization) per unit volume due to NRM divided by the magnetic moment per unit volume generated by induced magnetization is referred to as the Koenigsberger or Q ratio.

The magnetization of a rock ceases to exist at certain temperature (the Curie temperature). This effect is due to thermal agitation causing random alignments of magnetization within the magnetic minerals. Different minerals have different Curie temperatures.

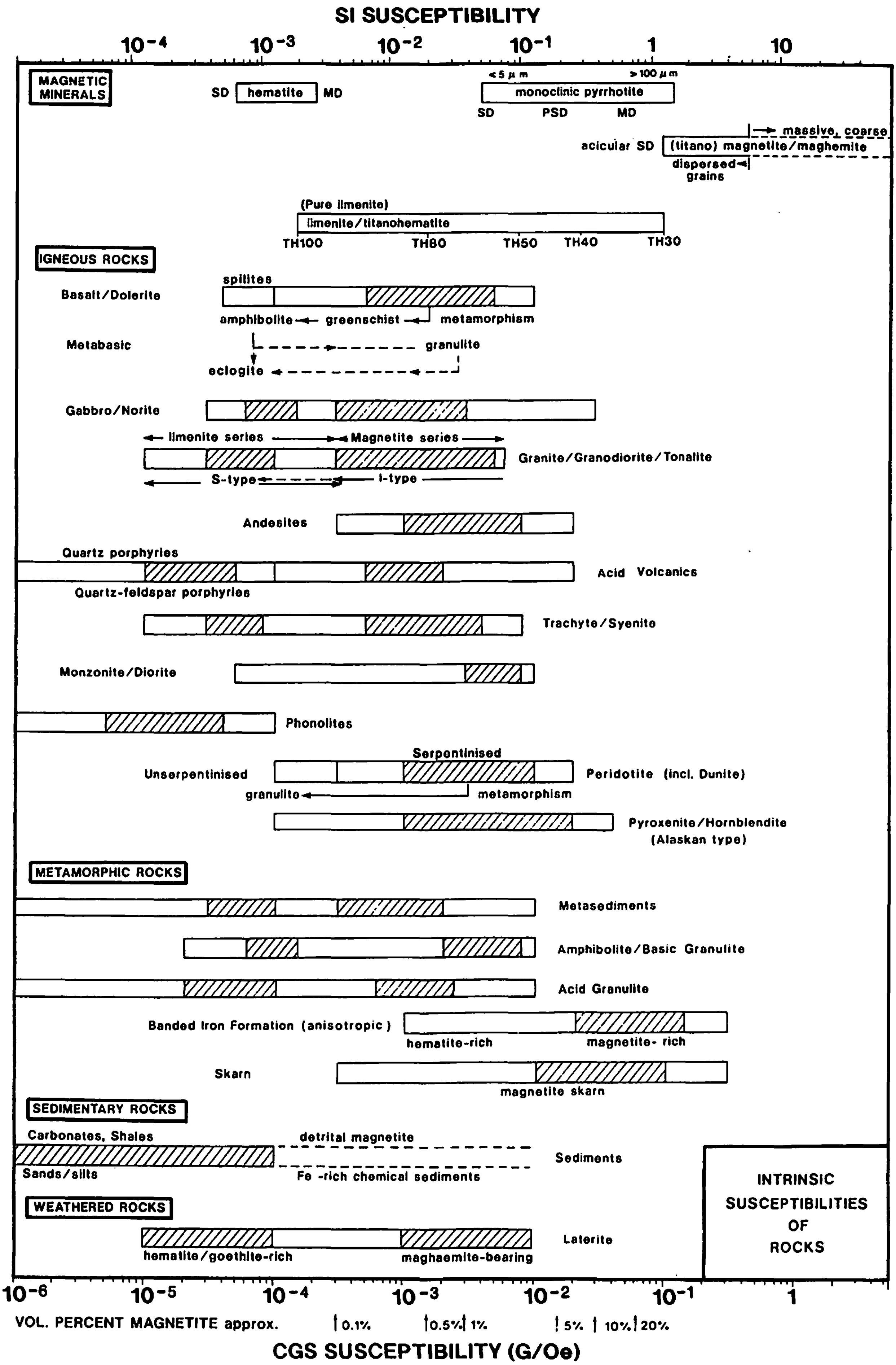
1.2 MAGNETIC MINERALS

Principal References: Schwarz (1975), McIntyre (1980), Clark (1983), Grant (1985), Clark and Emerson (1991)

For the purposes of this study a magnetic mineral is defined as a mineral whose presence in a rock unit is likely to generate a magnetic response which may be detected by magnetic surveys. All minerals and rocks are magnetic to some extent but only a limited number of minerals produce observable magnetic responses in an exploration context. As the precision of magnetic surveys improves it is likely that the threshhold of detection will be expanded to include progressively more minerals.

The magnetic properties of rocks depend on the magnetic minerals they contain. The common magnetic minerals are: magnetite, titanomagnetites, titanohematites and pyrrhotite. Figure 1.1 after Clark and Emerson (1991) compares the magnetic properties of these minerals. It should be noted that minerals can have different crystal forms and that within individual crystals magnetic domains with different alignments of atoms may be formed. A mineral particle may contain a single domain (SD) structure, a multidomain (MD) structure or an unstable (SPM) structure. Magnetic properties of minerals vary with crystal form and the magnetic domain structure. Figure 1.1 shows these differences.

All the common magnetic minerals except pyrrhotite belong to the Fe-Ti-O system.



After Clark & Emerson (1990)

Figure 1.1 Susceptibilities of Minerals and Rocks

1.2.1 The Fe-Ti-O System

Generalities:

Figure 1.2 after Grant (1985) is a ternary diagram which gives an overview of the relationships of minerals in the Fe-Ti-O system.

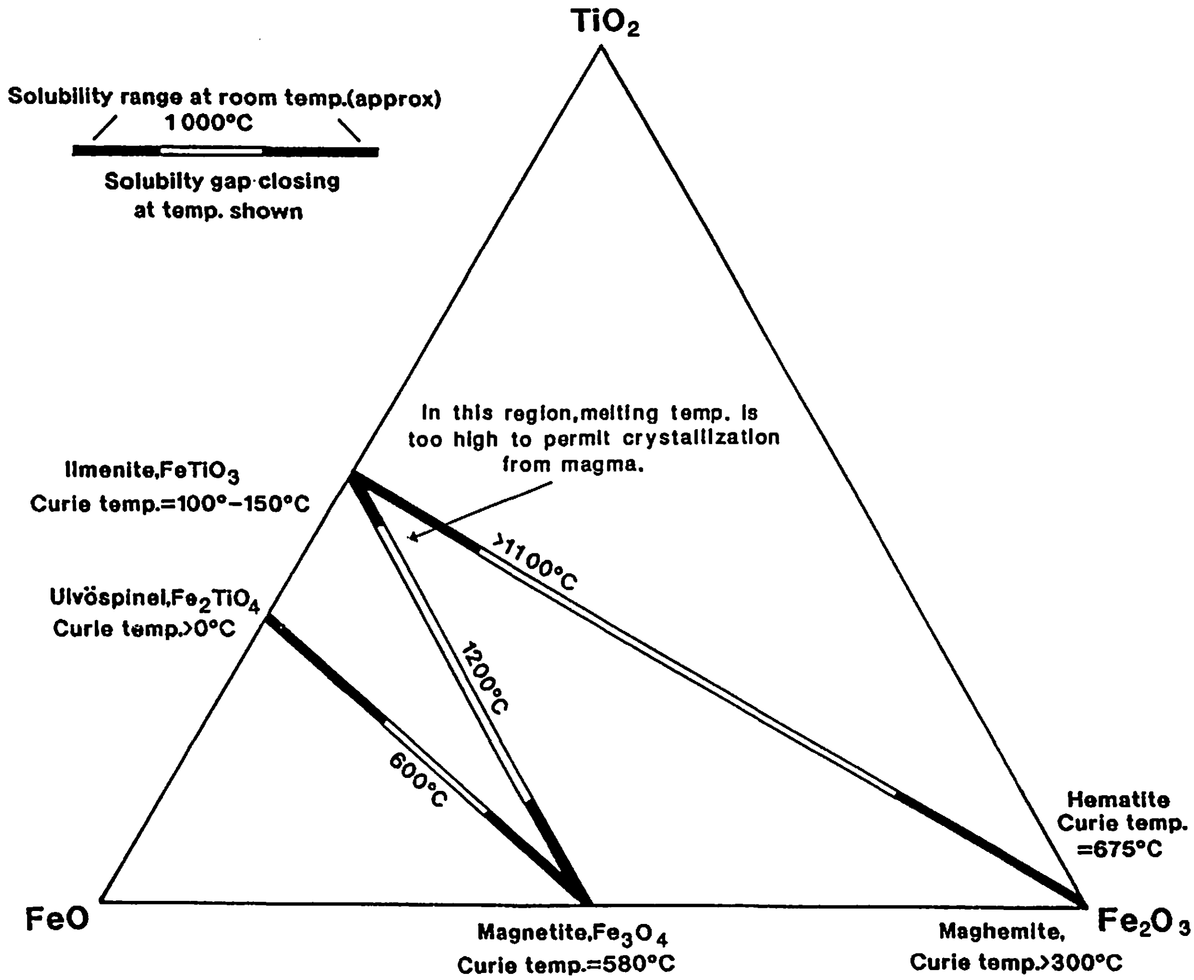


Figure 1.2 Relationships of minerals in the Fe-Ti-O System.

The minerals forming in the Fe-Ti-O system are:

Magnetite Fe_3O_4: Magnetite is the most significant magnetic minerals by virtue of its wide distribution and its high susceptibility. Magnetite forms solid solutions with ilmenite ($FeTiO_3$) and ulvospinel ($FeTiO_4$) however at room temperatures these solid solutions tend to exsolve spontaneously towards their end members.

The susceptibility of magnetite is relatively insensitive to titanium contents and titanium percentages greater than in $Fe_{2.75}Ti0_{0.75}$ are required before a significant decrease in susceptibility is noted.

Pure magnetite rarely develops remanent magnetization unless it is very fine grained however when contaminated with ulvospinel or ilmenite it can acquire significant remanence.

Ulvospinel (Fe_2TiO_4): is the end member of a solid solution with magnetite. At room temperature it has a very low susceptibility however there is a very narrow range of compositions approximating $Fe_{2.2}TiO_{0.8}$ which are strongly magnetic in cold climates.

Ilmenite ($FeTiO_3$): pure ilmenite has a very low susceptibility however it forms a solid solution series with hematite (Fe_2O_3) and at intermediate compositions titanohematites may have high susceptibilities and NRM.

Hematite (Fe_2O_3): fine grained hematite (c.15μm) has a low susceptibility (720 x 10^{-6} SI) but is capable of significant remanence. Coarser grained hematite (c.7100μm) which typically only occurs in massive ores can have large susceptibilities (2400 x 10^{-6} SI) as well as significant remanence.

Maghemite(Fe_2O_3): this mineral has a similar magnetic susceptibility to magnetite and exists in a solid solution with magnetite. It has been postulated that it forms from the oxidation of magnetite in the presence of water.

The principal determinant controlling the formation of minerals in the Fe-Ti-SiO_2-O system is oxygen availability (which is typically expressed in terms of oxygen fugacity). With increasing oxidation the order of mineral formation beginning from the lowest levels is:

(i) Fe silicates
(ii) titanmagnetites (magnetite-ulvospinel ratio increasing).
(iii) titanhematites (hematite-ilmenite ratio increasing
(iv) hematite

Temperature variations are important but tend to affect the ranges of oxygen fugacity in which the various minerals form rather that the order in which they form.

Chemical variations may produce different end products. This factor is discussed later in the text.

To a very good approximation the susceptibility of a rock that does not contain significant maghemite or pyrrhotite content can be related to its magnetite content by the empirical relationship determined by Balsley and Buddington (1958):

$$Kv = 33 \times 10^{-3} \times \text{Vol\% magnetite (SI units)}$$

It should be noted however that coarsely crystalline magnetite has a higher magnetic susceptibility than finely crystalline magnetite and that variations in the domain structure of the magnetite produce variations in susceptibility. Figure 1.3 based on the work of Clark and Emerson (1991) shows typical variations of susceptibility with magnetite content.

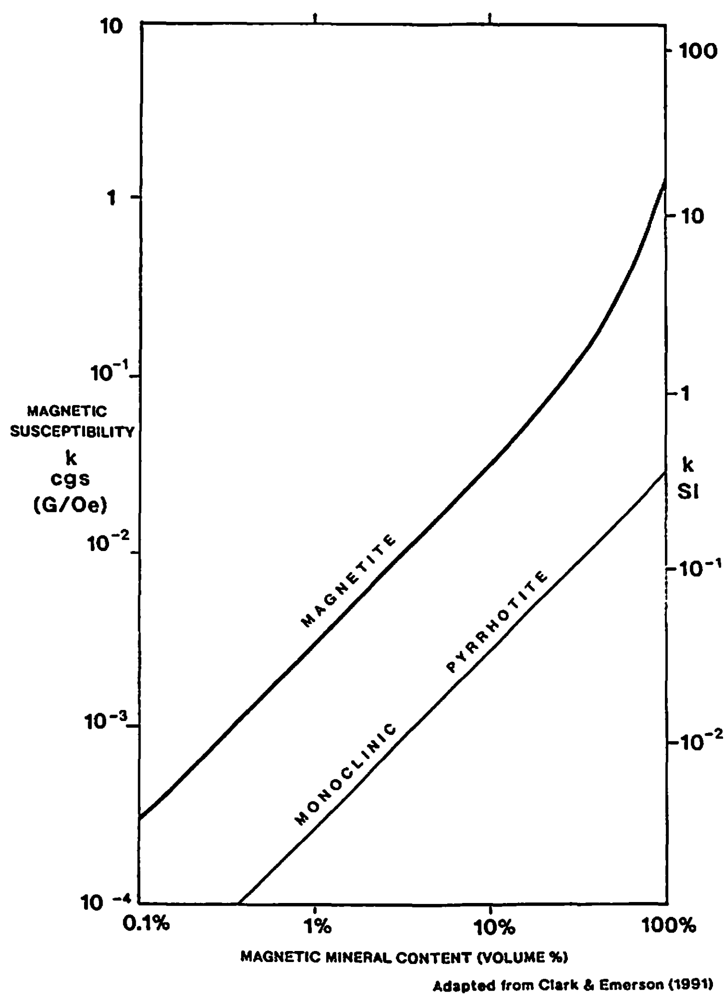


Figure 1.3 Variation of susceptibility with magnetite and pyrrhotite content

Susceptibility anisotropy may also exist on a microscale due to crystal alignments and magnetic grain shapes or on a macroscale due to layering of magnetic minerals in rocks.

If a rock has a high susceptibility due to a high magnetite content the anomalous field produced by the rock may have sufficient intensity to reduce the ambient field at the location of the rock and thus reduce the effective susceptibility of the rock. This process is known as demagnetization and must be accounted for when interpreting magnetic anomalies due to bodies with magnetic contents greater than approximately 10%.

As noted above, pure magnetite rarely develops significant NRM but can do so when contaminated with small amount of ulvospinel and ilmenite.

The hematite-ilmenite oxides which typically have negligible susceptibility can acquire significant remanent magnetization and it appears that the strongest manifestation of this is when the proportions of hematite and ilmenite are approximately 1:1.

1.2.1 Pyrrhotite

Pyrrhotite ($Fe_{1-x}S$ with $0<x<0.13$) can be an important contributor to magnetic anomalies although it should be noted that pyrrhotite has various crystal forms and it is only monoclinic pyrrhotite with an approximate formula of Fe_7S_8 which is magnetic at ambient temperatures.

The magnetic susceptibility of monoclinic pyrrhotite while less than that of magnetite, is substantial.

Its susceptibility is strongly dependent on grain size, decreasing as the grain size decreases and exhibits a marked anisotropy. Figure 1.3 shows the relationship between a rock's susceptibility and its volume percent pyrrhotite content.

Monoclinic pyrrhotite often carries relatively intense remanent magnetization with Koenigsberger ratios greater than unity. Because of the relatively low Curie temperature of monoclinic pyrrhotite (250^{0}C) the remanent magnetization can easily be reset and thus frequently dates from the most recent thermal event affecting the mineralization. Thompson et al. (1991) have compiled data indicating that Koenigsberger ratios of the order of 10 for pyrrhotite may be common. They also present evidence that pyrrhotite remanence in sediments is preferentially oriented along bedding or cleavage.

Pyrrhotite also occurs commonly in both hexagonal and intermediate forms. A phase diagram of the Fe-S system published by Power and Fine (1976) show that below 250^{0}C the primary determinant controlling whether monoclinic pyrrhotite is formed is the availability of atomic Fe. Above 50% atomic Fe pyrite is formed to the exclusion of pyrrhotite.

Both the magnetic and non magnetic varieties of pyrrhotite have widespread occurrences.

1.3 MAGNETIC PROPERTIES OF ROCKS

An understanding of the distribution of magnetic minerals in rock units is fundamental to the understanding of the likely magnetic responses of the rock units which is in itself a prerequisite basis for the interpretation for the interpretation of magnetic survey data.

1.3.1 Igneous Rocks

The primary source of iron minerals is the differentiation process by which igneous rocks are formed from crustal and mantle sources. Despite the importance of the subject, the understanding of the factors that control the occurrence and abundance of the magnetic minerals phases in igneous rocks (magnetic petrology) is acknowledged to be in its infancy (Frost, 1991; Clark et al., 1992). At the time of writing this report no comprehensive publications on the subject exist.

A starting point for many petrological studies is the recognition of suites of rocks which result from differentiation of magmas. Some uncertainty appears to exist whether these suites result from the differentiation of different magmas or are the result of differentiation of similar magmas under different conditions.

These igneous suites which consist of extrusive rock and their intrusive equivalent are defined by mean chemical compositions. Different igneous suites may contain the same rock type (e.g. basalt) and the classification of a particular rock to a particular suite is largely dependent on chemical analyses. The igneous suites which the following chapters show to have particular relevance to the occurence and distribution of massive sulphide deposits are:

(i) the tholeiitic series whose extrusive components are dominated by basaltic lavas with lesser volumes of iron rich basaltic andesites and andesite.

(ii) the calc-alkaline series where the extrusive rocks are dominated by andesites with associated dacites and rhyolites. Basaltic rocks do however occur in this suite.

(iii) the alkali series which contains various alkaline basalts.

A review by Middlemost (1985) indicates that agreement on the precise definition of these series eludes petrologists and that several subdivisions of the series have been proposed. Such details are outside the scope of this study.

From the aspect of magnetic interpretation it is significant that rocks of the tholeiitic suite contain more iron than those of the calc-alkaline suite. Grant (1985) has concluded that rocks of the calc-alkaline suite show generally lower magnetizations because of their low iron and hence low magnetite producing capacities. Grant has further reviewed the relationship between magnetic properties and various rock types and has concluded that intermediate members of differentiation series may be more magnetic than end member with higher and lower silica contents. This is because the iron minerals that initially form in rock types with low silica contents are iron titanium oxides with low magnetizations and while the iron minerals that form in rocks with high silica contents consist of almost pure magnetite they do so in low concentrations because most of the iron minerals have already been precipitated from solution before this stage is reached. This conclusion is consistent with extensive magnetic property measurements made by Whiting (1988) on granites, granodiorites, gabbros and ultrabasic rocks.

The following generalizations can be made:

- although acid igneous rock contain a higher proportion of magnetite to ilmenite than basic rocks, the total quantity of titanium-iron minerals is much less in acid rocks than basic rocks (typically 1% Fe-Ti oxides in acid rocks and about 5% in basic rocks). The net result is that basic igneous rocks are generally more magnetic than acid igneous rocks.

- intermediate basic rocks such as dacites may have higher susceptibilities than basalts or andesites due to the magnetite concentrations maximizing in such ranges of silica contents.

- while unaltered basic and ultrabasic rock may have moderate or low susceptibilities due to high percentages of iron titanium minerals serpentinization processes may result in the production of magnetite and thus considerably enhance the magnetization of such rocks.

- extrusive rocks generally have lower susceptibilities than intrusive rocks because volatile components can escape during cooling leaving the titanium and iron oxides in metastable equilibrium. Slowly cooling intrusives tend to develop more magnetite than extrusive rocks. Larger grain sizes resulting from slower cooling also tend to favour higher susceptibilities.

- extrusive igneous rocks may have a spotty magnetic character due to irregular cooling and a resultant variable production of magnetite and/or remanence.

- the ranges of susceptibility values for various igneous rocks is shown in Figure 1.1. These frequently cover several orders of magnitude and show bimodal distributions for a single rock type. While it is possible to use Figure 1.1 to make broad generalization relating susceptibility to specific igneous rocks it is virtually impossible to predict average susceptibilities or to use susceptibility to identify an igneous rock without the benefit of a database of susceptibility measurements which apply to the area being studied.

1.3.2 Sedimentary Rocks

The following discussion elaborates on the distribution of all iron minerals in sedimentary rocks because as is explained below, the iron content is a primary factor controlling the formation of magnetite and pyrrhotite during diagenetic and metamorphic processes which may subsequently transform the sediments.

Iron minerals in sediments may have detrital or chemical sources.

Detrital iron minerals in sediments may originate from:

- erosion of volcanic, intrusive or metamorphic rocks which contain iron in silicates or as ilmenite, hematite or magnetite.

- erosion of sediments containing iron minerals

- from soils which are generally enriched in iron as hydrous ferric oxides.

The general fate of iron minerals in a weathering/depositional environment is:

(i) chemical weathering and oxidation to hydrated ferric oxides which are fine grained and usually colloidal.

(ii) formation of laterites as soils are leached of the more soluble components.

(iii) attachment of the fine grained ferric oxides to clay or organic particles followed by transportation and deposition. The iron oxides rarely attach to sand or carbonate grains.

(iv) compaction of argillaceous sediments accompanied by the formation of hematite.

Magnetite has a limited field of stability and can only form under extreme conditions of low Eh and high pH. Magnetite rarely forms in significant quantities by diagenetic processes.

The following facies can be the eventual outcome of sedimentary diagenesis:

Oxide facies: These are formed in aerobic environments with hematite stained red beds and oolitic iron ores being classic examples.

Sulphide facies: Pyrite is formed in organic and/or bacteria rich reducing environments. Typical host rocks are mudstones and shales. Examples of authigenic pyrrhotite production are known but they are significantly less frequent than those where pyrite is formed.

Carbonate facies: The production of siderite requires conditions occuring mainly in fresh water swamps (high CO_2, low sulphur).
Silicate facies: These are developed when clay minerals which incorporate iron are produced.

Magnetite is unstable in low temperature highly oxidizing environment of chemical weathering and is rarely found in unmetamorphosed sedimentary rocks. It may be present as beach sand, river placers or in other sedimentary formations. Grant (1985) quotes an example of a greywacke containing significant magnetite, however the general continuity of the oxidation process after burial normally results in an eventual transformation of magnetite to hematite.

Maghemite which is apparently produced as a result of oxidation processes affecting magnetite is stable in oxidizing environments and is precipitated in laterites which may occur as sheet-like bodies or as sinuous branching ribbons following drainage systems.

Banded iron formations (BIF) which occur in many sedimentary environments have chemical rather that detrital origins. Two mineralogically similar variants exist.

Precambrian BIFs which can extend semicontinuously over hundreds of kilometres and which can have thicknesses of hundreds of metres are thought to have originated as chemical precipitates under conditions involving significantly less atmospheric and marine oxygen that occurs at the present time. These BIFs consist mainly of interbedded magnetite and hematite although they have sulphide, silicate and carbonate facies. No BIFs of equivalent dimensions occur in the Phanerozoic.

BIFs of similar composition do occur in younger rocks however their extents can be measured in kilometres and their thicknesses in terms of metres and their origins can be related to hydrothermal vents and volcanic processes (see Section 1.4.1). It is improbable that such heat related mechanisms could account for the massive volumes of the Precambrian BIFs.

Urquart (1989) presents an example of a Precambrian BIF which abruptly changes from a magnetic facies to a non-magnetic pyritic facies.

Gunn (1975) has published a detailed study of the magnetic properties of a suite of Australian banded magnetite quartzite formations.

1.3.3 Metamorphic Rocks

1.3.3.1 Regional Metamorphism

Magnetite may be produced during regional metamorphism with primary controls on its development being the amount of iron available and the oxidation ratio $(Fe_3^+) / (Fe_3^+ + Fe_2^+)$ of the original sediments. As these two factors are largely unaffected by metamorphism the composition of the original sediments tends to control the capacity for magnetite development. Sediments which originally contain more iron, such as shales, are transformed into more magnetic units such as chlorite schists than iron poor quartzites or carbonates whose metamorphosed descendents are relatively non-magnetic quartz schists and calc schists. Iron poor rocks can never form significant quantities of magnetite whatever their oxidation state.

The partitioning of iron between oxides and silicates in metamorphic rocks depends on the oxidation ratio. Magnetite takes up a significant proportion of the iron for ratios between 0.4 and 0.6 and iron is preferentially concentrated in silicate phases for lower ratios and in hematite and ilmenite for higher ratios.

Reheating and recooling during metamorphism tends to promote the exsolution of magnetite with the result that the metamorphosed products of rocks containing iron are normally more magnetic than the original unmetamorphosed rock. This phenomenon is reinforced by the fact that heating and mechanical deformation tends to cause opaque oxide minerals to recrystallize into coarser textures which in the case of magnetite have higher susceptibilities than their finer grained precursors. Tenfold increases in magnetic susceptibility due to metamorphism have been reported.

Grant (1985) describes several reactions which produce magnetite during metamorphism. These relate to the breakdown of hydrous (Fe, Mg) silicates into progressively simpler compounds with increasing temperature. Temperature and, by association, metamorphic grade is a primary control on the actual minerals formed.

It is worth noting that hematite-magnetite boundaries present in original unmetamorphosed rock are preserved through all levels of metamorphism due to a buffering effect arising from the tendency of any oxygen produced to remain in the vicinity of the reaction site and thus inhibit chemical change.

Other factors favouring the formation of magnetite during metamorphism which have been listed by McIntyre (1980) are:

- low silica
- low titanium
- low pressure, with the opportunity for hydrous diffusion
- excess Al
- absence of carbon

The presence of carbon reduces the stability field of magnetite by lowering the oxygen fugacity. The results of this effect are manifest by the frequent complete absence of magnetite in graphitic metasediments and rocks which have undergone carbonate alteration.

While the general tendency for iron bearing rocks to become more magnetic with increasing metamorphic grade is clear, extreme metamorphism appears to be accompanied by a reduction in magnetic strength. With the transformation of meta-igneous and metasedimentary rocks into migmatites and granite-gneisses susceptibility declines sharply. This is apparently due to the reformation of magnetite-ilmenite solid solutions which have lower magnetizations than magnetite. Results published by Kruitikouskaya et al. (1975), discussed by Grant (1985), and by Whiting (1988) appear to demonstrate this phenomenon.

Pyrite can be transformed to pyrrhotite or magnetite by metamorphic process (see Section 1.4.4).

Possible metamorphic equivalents of primary rock types commonly associated with massive sulphide deposits:

Primary or Low-Grade Metamorphic Rock	**Medium-Grade Metamorphism**	**High-Grade Metamorphism**
Chert	Siliceous schist	Quartzite
Pyritic, cherty iron-formation	Pyrite-pyrrhotite-magnetite mica schist	Pyrrhotite-magnetite-mica quartzite
Rhyolite	Quartz-feldspar-sericite gneiss	Quartz-feldspar gneiss
Rhyolite tuff	"	"
Rhyolite breccia	"	"
Rhyolite agglomerate	"	"
Andesitic tuff (chlorite-schist)	Biotite-chlorite-quartz schist	Biotite-quartz gneiss
Andesite (chlorite-schist)	Epidote-plagioclase-amphibolite	Hornblende-plagioclase-amphibolite gneiss
Basalt (chlorite-schist)	Epidote amphibolite	Amphibolite (gneiss)

1.3.3.2 Contact Metamorphism

Magnetite and pyrrhotite may be concentrated in sedimentary rocks as a result of the heating effects associated with igneous intrusions.

Skarns are lime bearing silicates which have been derived from nearly pure limestones and dolomites into which large amounts of Si, Al, Fe and Mg have been introduced as a result of contact metamorphism/metasomatism. Significant accumulations of magnetite can be produced by this process.

Contact effects between intrusions and non-calcareous country rock can concentrate magnetite and pyrrhotite into aureoles which occur in the country rock adjacent to the contact with the intrusion.
Thompson et al. (1991) present a well documented example of contact metamorphic effects due to granites forming pyrrhotite in argillaceous sediments.

1.3.3.3 Weathering

Weathering can transform the properties of magnetic minerals. All in situ rocks are subject to weathering processes, the most obvious of which are the chemical and mechanical processes that produce the regolith. Pronounced weathering is apparent to depths in excess of 100 m in many parts of Australia.

The process with the greatest effect on magnetite is oxidation by exposure to air and percolating groundwater to produce hydrated iron oxides, hematite and in some situations, maghemite. Laterites may be deposited as a result of weathering processes. Gossans containing hydrated iron oxides may be produced by weathering of iron sulphides. All these processes obviously reduce the magnetization of lithologies.

Remnants of the original magnetic minerals or occurences of maghemite and/or remanently magnetized hematite are the origin of the erratic magnetic fields which are frequently observed over weathered terrains.

Weathering processes at depth are related to fluid circulation in faults or shear zones which in most cases result in oxidation of any magnetite present to hematite. The pervasive seepage of such groundwaters into the rock adjacent to the faults or shears tends to produce wide zones of oxidation. This process can explain why fault zones observed in magnetic data often appear much wider that the known geological widths of such features.

1.4 Magnetite and Pyrrhotite in the Massive Sulphide Ore Environment

1.4.1 The Production of Magnetite and Pyrrhotite

As well as being produced as a result of igneous differentiation, sediment diagenesis and metamorphism, magnetite and pyrrhotite may be formed as byproducts of ore forming processes and as a consequence they may be spatially related to economic deposits of sphalerite, galena and chalcopyrite.

A widely quoted model of massive sulphide ore formation which explains the above process has been published by Large (1977). This model, which may not necessarily be correct in absolute detail but which nevertheless illustrates the types of principles involved, can be best appreciated by considering the phase diagram of Figure 1.4.

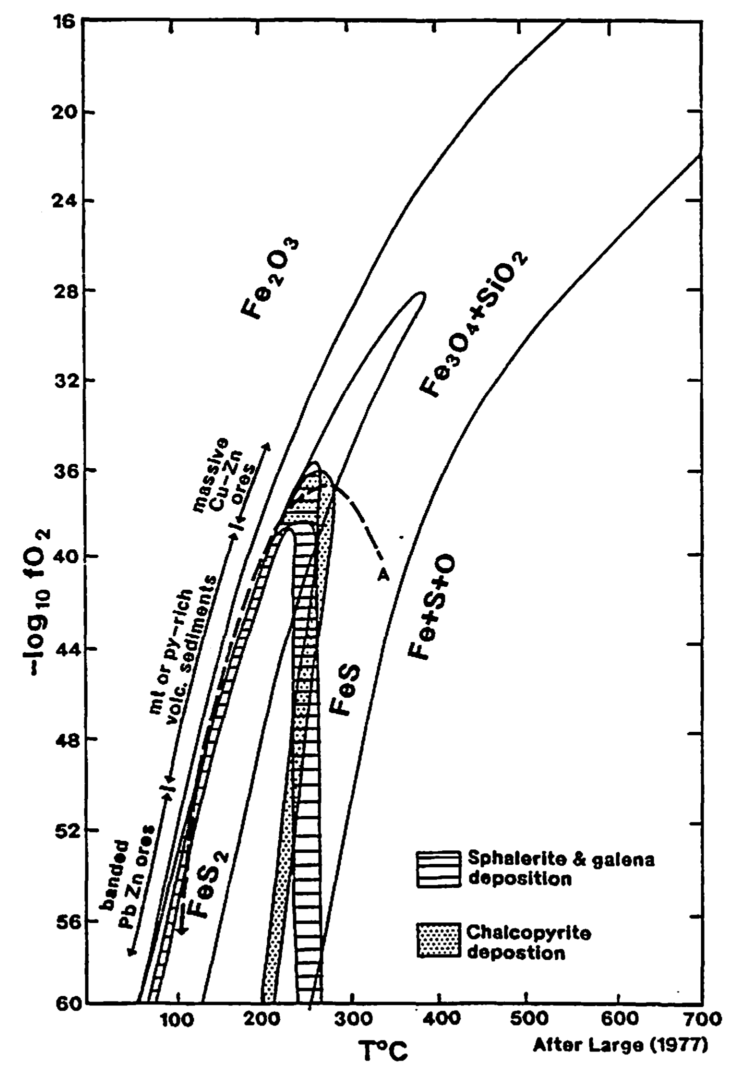


Figure 1.4 Formation of minerals in the Fe-S-O System related to temperature and oxygen fugacity

For a situation with hot acidic metal bearing brines rising through a hydrothermal vent and mixing with sea water at a temperature of about $230\text{-}250^0$ the sudden lowering of the pH and temperature together with the availability of sulphur in the sea water causes metals to precipitate. The order of precipitation and the actual minerals precipitated will depend on the cooling path followed. For path A, pyrrhotite will be the first mineral precipitated followed by magnetite. These will be followed in order, by chalcopyrite, pyrite and finally sphalerite, chalcopyrite and pyrite with or without galena.

According to this model pyrite and/or magnetite will deposit as the fluids move further from the vent and cool. This phenomenon will produce pyrite/magnetite flanks to the massive sulphide deposit. It is possible for sphalerite and galena to be carried in solution and precipitated in localities distant from the source vent to produce "distal" massive sulphide deposits.

The presence of higher sulphur contents or lower pH will cause the pyrrhotite-magnetite boundary to move upwards with the results that pyrrhotite rather that magnetite will occur in association with certain deposits.

The utility of this model is that it shows the likelihood of magnetite and/or pyrrhotite occuring with Cu-Zn-Pb massive sulphides deposited in proximity to hydrothermal veins. We note also the possibility of distal Pb-Zn ores being stratigraphically associated with magnetite or pyrite rich sedimentary horizons.

1.4.2 Destruction of Magnetite and Pyrrhotite by Alteration

Hydrothermal fluids associated with the emplacement of massive sulphide bodies frequently affect much larger rock volumes than that occupied by the massive sulphides. These fluids may penetrate and transform significant amounts of adjacent country rock. Such alteration is frequently observed as cone shaped funnels beneath the mineralization but in certain cases it is known to extend into the hanging wall as well as laterally from the mineralization.

Chemical transformations in these alternation haloes may destroy any magnetite present in the country rock with the net effect of producing a "magnetic quiet zones" or magnetic lows surrounding the mineralization.

Common alteration processes associated with massive sulphides which tend to destroy magnetite include chloritization, the process of conversion into or introduction of chlorite, sericitization, the production of the fine grained mica sericite and silicification. Solutions rich in silica are generally oxidizing and silicification tends to produce magnetic lows.

1.4.3 Physical Deformation of Massive Sulphide Deposits

Principal references: Sangster (1972), Sangster and Scott (1976), Vokes (1976)

The relative geometrics of mineral distributions within massive sulphide bodies can be significantly altered by deformation during metamorphism. The pressure component of such metamorphism will obviously have a dominant influence during such processes however temperature levels will effect mineral ductility. Deformation effects in order of magnitude are:

(i) sulphide bodies may be sliced by faults.

(ii) in rocks where deformation is expressed by shearing and folding without well developed lineations, sulphide bodies tend to be flattened parallel to the schistosity. This may be a result of transposition along shear planes.

(iii) in areas of medium to high metamorphic grade the sulphides are remobilized into rod shaped bodies aligned parallel to fold axes or corrugations in foliation planes. Such bodies have high plunge to strike length ratios.

(iv) intense polyphase deformation may produce "amoeba" shaped bodies, particularly if significant heat is involved.

The mineral zoning of these remobilized sulphide masses depends on the relative mobilities and ductilities of the constituent minerals. Vokes (1976) lists a general order of increasing mobility as:

Most mobile: galena, sulphosalts, chalcopyrite
Mobile: pyrrhotite, sphalerite
Least mobile: pyrite, magnetite

Intense deformation is capable of moving the entire sulphide mass and in extreme examples results in it having a diapiric relationship with the enclosing sediments (see for example, Elura in Section 4.9.1.8).

1.4.4 Metamorphism of Massive Sulphide Deposits

Principal References: Macdonald (1967), Sangster (1976), Vokes (1976), Dimroth (1976), Frost (1991)

Thermal effects can alter the mineral assemblages of massive sulphide deposits. While chalcopyrite, sphalerite and galena appear to survive high temperature effects the iron minerals may undergo significant transformations.

The formation of pyrrhotite from primary pyrite is perhaps the most common change and most of the pyrrhotite occuring in metamorphic deposits may have this origin although the pyrrhotite occurring in the basal portions of such deposits is considered to be a primary constituent.

Pyrrhotite is apparently more stable in reducing metamorphic environments and pyrite is more stable in oxidizing environments. Pyrrhotite is reportedly the major Fe sulphide in high temperature metapelites whereas pyrite is more common in metabasites.

Sangster (1976) reporting on the Archean massive sulphide deposits of Canada, which are commonly metamorphosed, records that the pyrrhotite in these deposits is commonly an intergrowth of hexagonal and monoclinic pyrrhotite.

Vokes (1976) has correlated pyrrhotite occurrence with metamorphic grade in 12 Norwegian massive deposits and has concluded that by the beginning of amphibolite facies pyrrhotite is normally the dominant sulphide.

The breakdown of pyrite to form magnetite can occur and it has been suggested that some magnetite rich banded iron formations and magnetite fractions associated with massive sulphide deposits had their origin as pyritic black shales, pyrite-carbonates or massive pyrite. Such transformations however are not possible in graphitic rocks (Section 1.3.3). The conversion of pyrrhotite to magnetite is possible when sufficient oxygen is available (Frost (1991)).

CHAPTER 2
THE CHARACTERISTICS OF EXTENSIONAL SEDIMENTARY BASINS

Principal References: Gunn (1984,1988), Kearey and Vine (1990)

For the purposes of this study extensional sedimentary basins are sedimentary basins which have formed as a result of extensional processes affecting the earths crust. Significant fracturing and thinning of the earths crust is a characteristic of such basins. These processes result in abnormally high heat flows and the initiation of igneous activity and, as is explained in the following sections, such regimes are the environments of most, if not all, economic massive sulphide deposits.

The most recognisable result of crustal extension is the formation of rift systems. Rifts are developed in both intracontinental settings and on convergent margins associated with subduction zones. The process of intracontinental rifting of which the splitting of the continental crust and the development of new continental margins is an ultimate result has been intensely studied because of its fundamental role in the definition of the earth's morphology and its recognised relevance to petroleum exploration. Rifting processes associated with subduction have received significantly less attention.

2.1 INTRACONTINENTAL RIFTS

Intercontinental rifts result from tension associated with crustal extension or continental collision. Crustal extension which is the most important process generating intracratonic rift systems is associated with crustal thinning and this phenomenon accounts for most of the specific structural, igneous, sedimentological and geophysical characteristics of these rift systems.

2.1.1 Basin Development

A typical continental rift system evolves through a series of stages (Figure 2.1). This development may terminate at any stage with the resultant preservation of the geometry developed to that time. Erosion may expose the deeper levels of preserved rift systems and thus an appreciation of the spatial as well as the temporal development of rift systems is important.

The stages of intracontinental rift development are:

(i) Broad extension with downwarping and a limited amount of normal faulting. Sediments deposited in such depressions are frequently terrestrial coarse clastics and argillaceous swamp sediments. Alkaline igneous activity may be associated with this stage. These sequences are termed the pre-rift section.

(ii) Continued extension resulting in significant faulting which ends to be concentrated in zones 60-80km wide. The normal result of this faulting is the development of a downfaulted linear rift zone floored by tilted blocks of pre-rift sediments. The deep central rift zone is frequently filled with argillaceous sediments although coarser clastic may be input as erosional fans at various localities. Any igneous activity may become more tholeiitic as extension progresses. The sediments filling the central rift are termed syn-rift sediments. Syn-rift sediments are often marine as a result of the rifting process allowing marine incursions.

Further basin development depends on whether the crustal extension terminates at this stage or whether it proceeds to complete splitting of the continental crust and the emplacement of oceanic crust.

(iii) If crustal extension terminates at the syn-rift phase a general subsidence occurs due to the combined effects of sediment loading and cooling following dissipation of heat associated with the rifting process. Sediments deposited during this stage are termed post-rift sediments. These sediments generally have a lens like section reflecting the profile of the subsidence.

(iv-v) If crustal splitting occurs oceanic crust is generated between the two fragments of the original rift. The splitting of the continental crust may be preceded by the intrusion of an axial dyke of basic/ultrabasic upper mantle composition. Post-rift sedimentation builds over the rift fragments and the junction of the continental and oceanic crust.

2.1.2 Structural Styles

Rifts exhibit characteristics geometries and internal structuring:

- rifts may develop as single troughs or as a series of sub parallel troughs.
- the principal troughs of rift systems have widths of the order of 60 - 80 km although subsidiary troughs may be much narrower.
- rifts may form branching systems which incorporate three way junctions (triple junctions)
- faults cutting the basement and the pre-rift section are typically normal.
- faults in argillaceous sediments such as occur in the syn-rift section are typically listric and sole out above the pre-rift section.
- rifts frequently exhibit half graben symmetry.

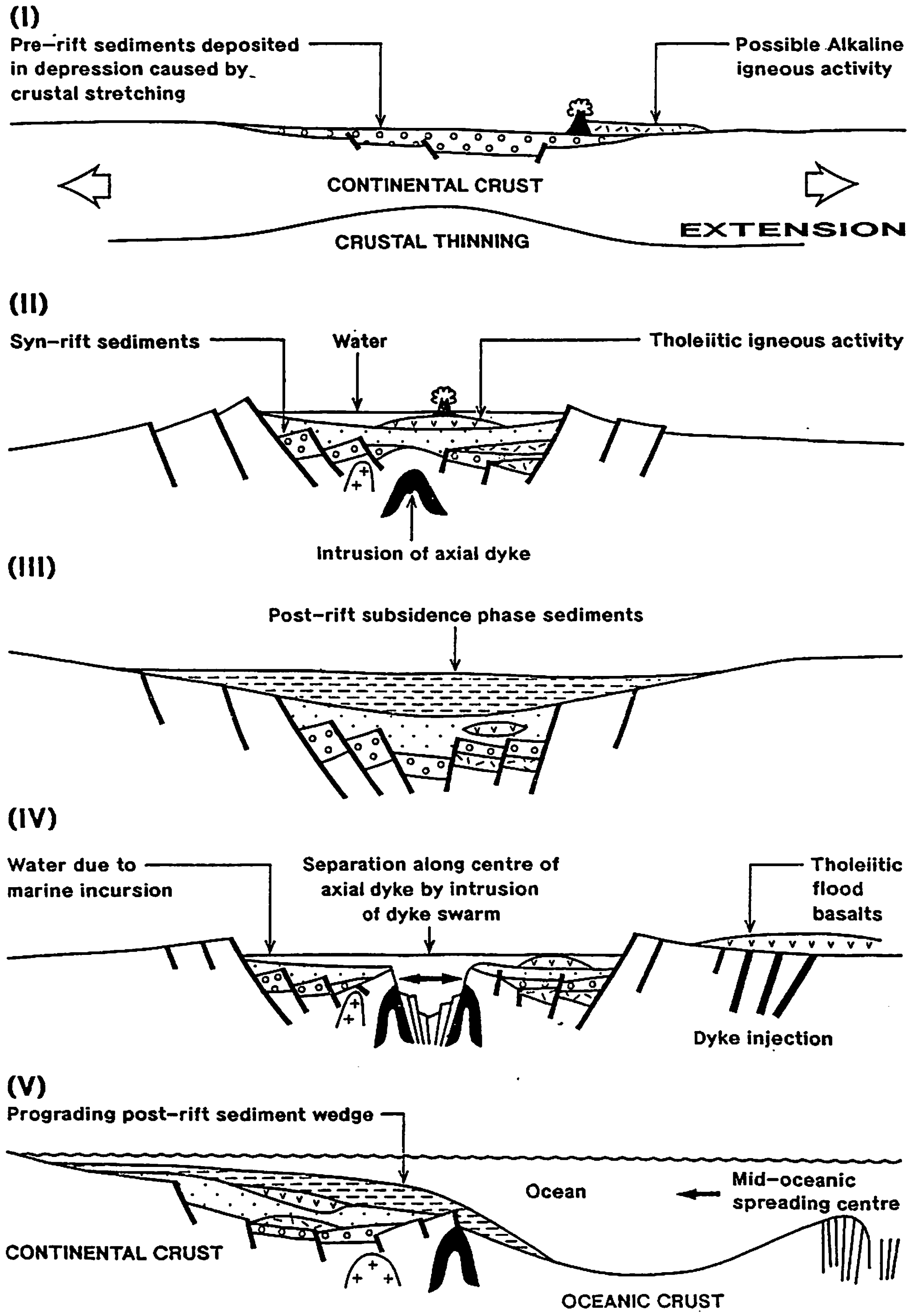


Figure 2.1 Stages of continental rifting. (See text for an explanation of details)

- the polarity (i.e. deep side) of the half graben symmetry may switch across "transfer fault" zones. Transfer fault strike normally or obliquely to rift axes and accommodate differential crustal extension along the rift's length.

- transfer fault zones tend to be developed along lines of pre existing basement rifting in the area of the rifting.

- lateral movements during rifting may result in transcurrent faults and transpressional and transtensional structures.

- rifted areas may be subjected to orogenic processes which superimpose additional structures and metamorphic overprints. Compression during such events produces folding.

2.1.3 Igneous Activity

Principal References: Windley (1977), Kearey and Vine (1990), Latin et al. (1990)

Igneous activity may occur in rifts as a result of elevated thermal gradients and crustal thinning associated with the basin forming process. The combined effects of these processes are thought to modify geothermal gradients to the extent that partial melting of the upper mantle and lower crust occurs. As a general rule the early stages of crustal extension are associated with alkaline igneous activity (alkali basalts, nephelinites, carbonatites, trachytes) and a subsequent gradual change to tholeiitic igneous activity is observed as the crust is increasingly thinned in the progression towards crustal splitting and the emplacement of tholeiitic (mid-ocean ridge basalt) oceanic crust.

Despite this generalized scenario the occurence of igneous activity in rift zones is by no means ubiquitous. While some rift basins are characterized by numerous igneous intrusions and violent eruptions others are "dry" and lack significant amounts of igneous rock. Current research relates such variations to the occurence of mantle plume hot spots, the degree of crustal thinning and the original composition of the crust under the basin.

The intensely explored North Sea Mesozoic rift systems provide an excellent example of the distribution of igneous activity in a well developed rift system whose extension ceased after the development of a significant synrift section (Blundell and Gibbs, 1990). In this trilete rift system the only significant development of volcanics is the alkali basalt Forties province in the area of maximum extension at the triple junction. Other igneous occurences have been noted but they are isolated and limited in extent.

As crustal extension proceeds, crustal thinning may be associated with the ascent along the axis of the rift of basic/ultrabasic material which ultimately reaches the basin floor as a manifestation of oceanic crust. This basic/ultrabasic material may form a major axial dyke beneath rift systems. The earliest indication of such a feature may be a series of major intrusions aligned along the rift axis.

2.1.4 Regional Geophysical Signatures

Principal Reference: Gunn(1984)

Intracontinental rift systems have different gravity signatures at each stage of their development:

- broad gravity lows may be associated with the earliest stages of crustal extension. These appear to be due to crust whose density has been lowered by thermal processes associated with the initiation of the rifting.

- the creation of a distinct linear down faulted rift systems infilled with low density syn-rift sediments produces a linear gravity low.

- the combination of crustal thinning and the ascent of the axial dyke produces broad gravity highs over the more evolved rift systems.

- where the gravity effects of the low density syn-rift sediments are dominant a low will occur superimposed on the broad high due to crustal thinning. This will produce a low flanked by gravity highs.

- in cases where the axial dyke is well developed the last described scenario will include an extra high in the centre of the gravity low.

The axial dyke may manifest itself as a major linear magnetic anomaly or as a series of magnetic highs aligned along the rifts axis.

Faulting in the rift and its adjacent areas which disrupts magnetic intrusives or extrusives may produce magnetic patterns which outline the fault geometry. The principal bounding faults of the rift are frequently defined in this manner.

2.2 RIFTS RELATED TO SUBDUCTION

Rift systems are also created at convergent margins where subduction is occurring. The ultimate development of these are marginal seas which are small ocean basins which occur landward of subduction zones and island arcs and which are floored by crust which is virtually indistinguishable from normal oceanic crust (Figure 2.2) .

It has been noted that the formation of these "marginal basins" is initiated by rifting along the axes of island arcs with the initial manifestation of the process being the formation of a "volcanic rift". As the name implies, such rifts have a significant volcanic content. This is a direct consequence of the association of island arc environments with volcanism. A result of such rifting is the existence of rift zones and marginal basins flanked by remnants of island arc systems.

The processes forming backarc basins which are obviously different to those creating continental rifts are not well understood. A variety of thermal and tensional effects associated with Benioff zones have been proposed.

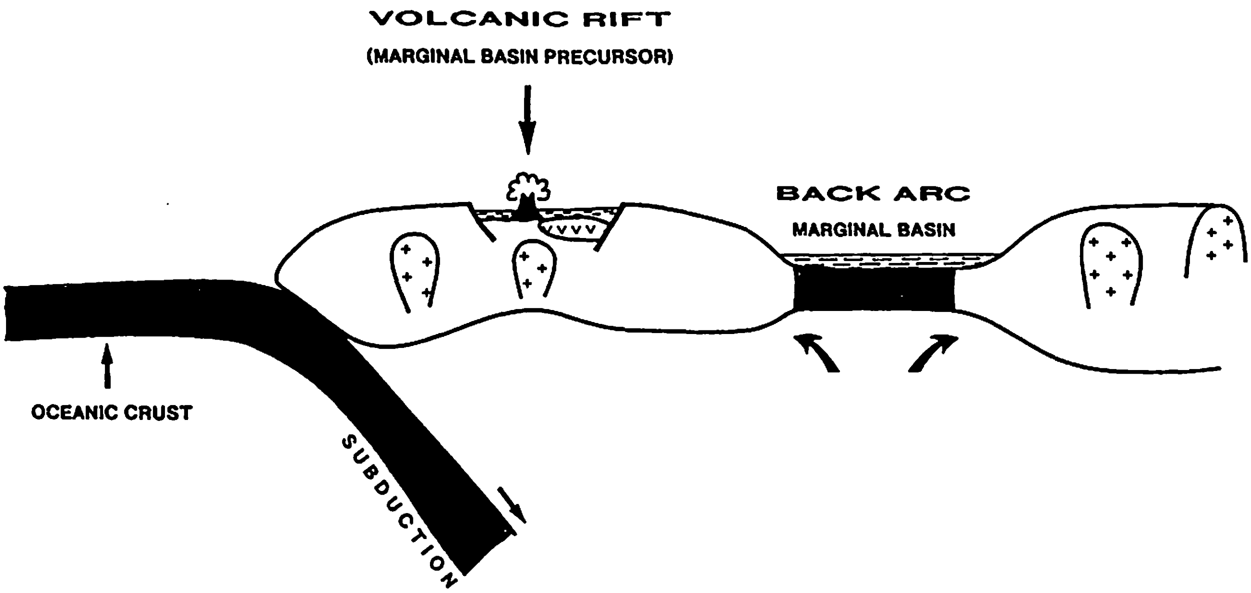


Figure 2.2 Rift development in island arcs. Volcanic rifts may evolve to backarc marginal basins

Literature relating to these basins does not clarify whether they undergo the same stages of sedimentary and structural development as intracontinental rifts. While general similarities are probable significant differences must occur such due the fact of their oceanic locations favouring volcaniclastic input and their settings in what are essentially compressive environments increasing the probability of subsequent structuring.

The igneous development of island arc systems is well studied and a progression from the low potassium tholeiitic series dominated by basalts with lesser volumes of andesites to the calc-alkali series dominated by andesites with some rhyolites and dacites and finally to the alkali series which includes alkali basalts and shoshonitic lavas can be observed with increasing age of the island arc and increasing distance from the subduction zone. Although it is not stressed in the literature, deviations in this trend back toward tholeiitic igneous activity must be expected as crustal thinning proceeds towards the emplacement of oceanic crust in the marginal basins.

The continuity of volcanism in both space and time in volcanic rifts and marginal basins is unclear but the example of the Green Tuff belt of Japan which has been interpreted to be a volcanic rift suggests that volcanism is episodic rather than continuous. It is possible that some rifts in island arc settings have relatively little igneous activity just as is the case in continental rifts.

The rifting processes occurring in the larger island arcs such as Japan and on Andean-type continental margins where subduction takes place appears to exhibit the same general characteristics as noted for the oceanic subduction systems.

Rifts formed in island arc settings are likely to have similar geophysical signatures to those formed in intracontinental settings although the gravity effects of rifts in the proximity of subduction may be superimposed on extensive regional gravity highs caused by underthrusting of dense oceanic crust along Benioff zones..

2.3 GREENSTONE BELTS

Archean and Proterozoic greenstone belts have been interpreted as having originated by processes analogous to those forming marginal basins with Cretaceous Rocas Verdas Complex in the Chilean Andes being frequently cited as a classic analogue (Kearey and Vine, 1990). Studies on the three dimensional structure of greenstone belts, as reviewed by Dentith et al. (1992), are relatively few and do not appear to have produced a simple, generally applicable model other than the idea that they are typically about 5 km thick and contain, in ascending order, ultramafics, calc-alkaline volcanics and sediments.

Grant (1985) has noted that greenstone belts in the Canadian Shield generally correspond to areas of low magnetic intensity. This phenomenon is related to the relatively low iron contents of calc-alkaline rocks (Section 1.3.1). BIFs and ultramafics in greenstone belts give localized linear zones of high magnetic intensity.

For the purposes of this study greenstone belts are regarded as variants of marginal basins which possibly developed in areas where crustal thicknesses were thinner than is typical for present day crust.

CHAPTER 3
VOLCANIC HOSTED MASSIVE SULPHIDES (VHMS)

Principal References: Sangster (1972), Franklin et al., (1981), Lydon (1990a, 1990b), Large (1992)

Because of the excellent literature which exists on the subject of volcanic hosted massive deposits (VHMS), in particular Large (1992), this section summarizes the result of previous workers and only elaborates on details which are relevant to the magnetic responses of the deposits.

3.1 INTRODUCTION

Volcanic hosted massive sulphide deposits are massive sulphide accumulations containing varying relative concentrations of Cu, Zn, Pb, Ag and Au which occur in volcanic districts within volcanic rifts. The deposits which can generally be categorized as being Cu or Cu-Zn rich or of a Zn-Pb-Cu type, typically occur as flat sheets or mounds of massive sulphides with or without underlying stringer zones of disseminated sulphides. Figure 19 of Large (1992) shows a range of observed geometries. Pipe-like bodies, asymmetric cones and multiply stacked sheets have been recorded. Structuring or remobilization during metamorphism may alter original geometries. Figure 3.1 shows the idealized form of VHMS deposits which are considered to originate from volcanic or hydrothermal vents in the proximity of volcanic activity. More tabular like deposits are known to occur at the same stratigraphic level as these vents but some distance from them. These distal deposits are thought to have formed by processes involving sulphide erosion or sulphide transport in brines.

The characteristics of the occurences and zoning of magnetic and non-magnetic minerals in these well documented deposits are extremely relevant to the other deposits in this study many of which have obvious hydrothermal, albeit non-volcanic origins and show similar mineral associations and configurations.

3.2 SETTING OF THE DEPOSITS

VHMS deposits occur in volcanic rifts associated with submarine volcanic rocks. They appear to have a preferential affinity with calc-alkaline volcanism although tholeiitic associations do occur. According to Large (1992) the volcanic packages enclosing VHMS deposits are dominated by rhyolite (60-80% of the pile). Lesser amounts of andesite, dacite, basalt and sediments are present. The sediment fraction typically contains pyroclastics, volcaniclastics, shales and greywackes.

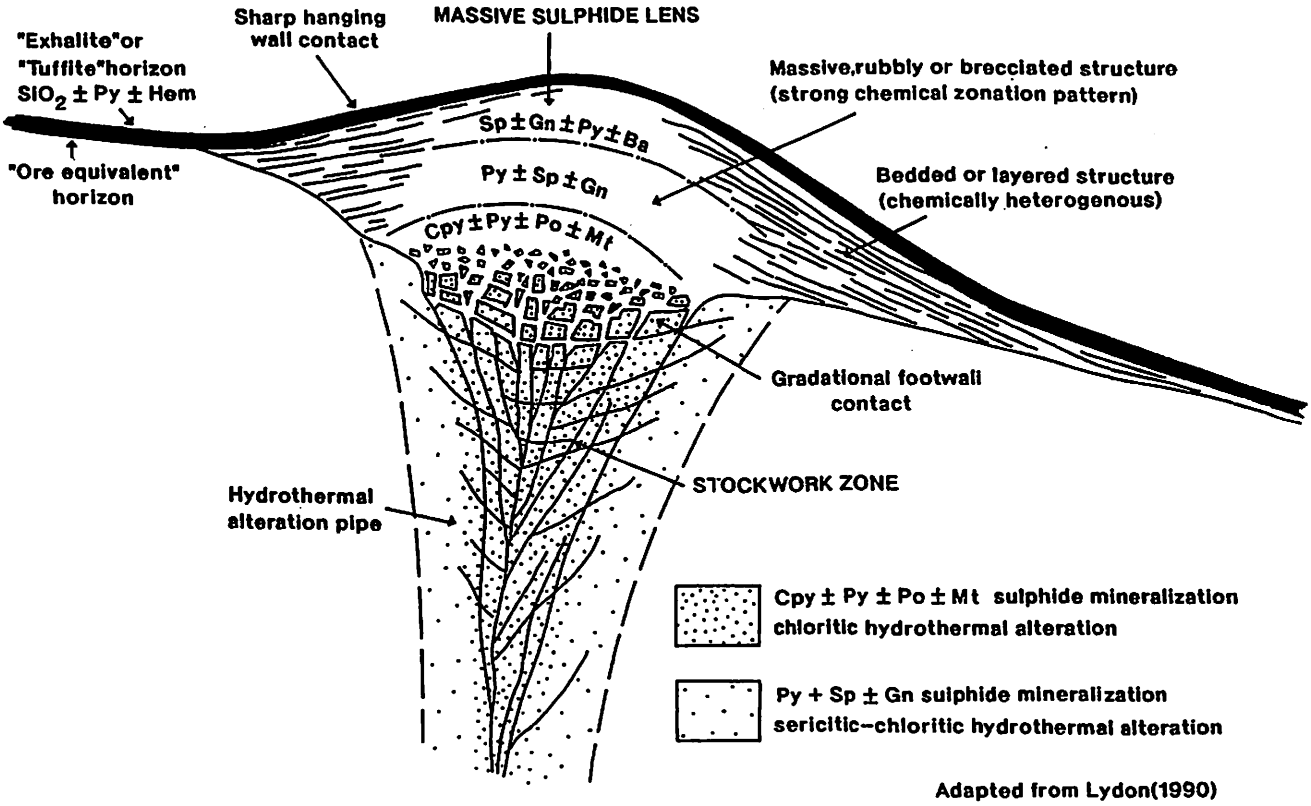


Figure 3.1 Idealized form and mineral distribution of a VHMS deposit. Actual deposits have varying proportions of the mineral distributions illustrated and may be much more laterally extensive and have a significantly greater horizontal/vertical ratio of dimensions than shown here.

The volcanic rifts hosting VHMS deposits may be Archean greenstone belts, Phanerozoic rift systems incorporated into fold belts or volcanic rifts in island arc systems.

As noted in Section 2.3 a marginal basin origin is likely for the Archean greenstone belts. Sawkins (1990) p. 142 notes that rift settings have been interpreted for many of the North American and European VHMS deposits. Scheibner and Markham (1976) and Degeling et al. (1986) have identified "volcanic rifts" in the Lachlan Fold Belt of eastern Australia such as the Hill End Trough which contains the Woodlawn VHMS (McKay and Hazeldene, 1987) and the Captains Flat Trough which contains the Captains Flat VHMS (Davis,1975) as originating as marginal seas. The island arc volcanic rift setting of VHMS deposits is typified by the Miocene Area Tuff Belt of Honshu and Hokkaido in Japan which contains the Kuroko VHMS deposits (Tatsumi,1970). Cathles (1983) has interpreted this belt to be the product of an island arc rifting episode.

The above examples and the common association of VHMS deposits with calc-alkaline igneous activity suggests their occurrence may be restricted to rifts formed on convergent margins where subduction is occurring.

3.3 STRATIGRAPHIC ASSOCIATIONS

VHMS deposits occur principally in the Archean, the Palaeozoic and the Mesozoic. VHMS deposits do occur in the Proterozoic (Rickard, 1987) but with an apparent lesser frequency. This phenomenom may be related to the relative absence of convergent type continental margins during the Proterozoic.

The host lithologies of VHMS deposits vary considerably within the ranges described in Section 3.2. What does seem consistent however is that within volcanic rifts VHMS deposits tend to occur in clusters within areas about 50 km in diameter and to be restricted to particular stratigraphic horizons in these areas (Lydon, 1990b). The areal clusters of deposits may be related to the dimensions of underlying magma domes or hydrothermal convection cells.

3.4 MINERALIZATION

VHMS deposits may have dimensions ranging from a few metres in minor occurrences to thicknesses measured in tens of metres and lengths measured in hundred of metres for the larger deposits. Table 3.1 adapted from Large (1992), which summarizes the metal contents and tonnages of many Australian VHMS, deposits gives a good indication of the variation in deposit sizes and ore grades. It should be noted that many equivalent size deposits which have uneconomic ore grades have been found and evaluated. Such deposits rarely appear in statistical compilations.

TABLE 3.1 Details of Significant Australian VHMS Deposits

Deposit	Geological Reference	Geophysical Reference	Mt, Po	Magnetic
Cu TYPE				
Mt Chalmers	Large and Both (1980)	-	Mt, Po	Probable
3.6mt , 1.8%Cu, 1.0%Zn, 0.2%Pb,15.0g/t Ag, 2.0g/t Au				
Mt Morgan	Lawrence (1967)	-	Mt, Po	Probable
50mt, 0.7%Cu, 0.1%Zn, 6g/t Ag, 4.7g/t Au				
Prince Lyell	Markham (1962)	Bishop(1984)	Mt, Po	Probable
87.6mt, 0.9%Cu, 33g/t Ag, 0.4g/t Au				
Balcooma	Huston et al. (1992b)	-	Mt, Po	Probable
1.0mt, 2.7%Cu, 3.0G/t Au				
Gossan Hill	Frater (1983)	Mill (1990)	Mt, Po	Yes
16.7mt, 3.1%Cu, 1.5%Zn, 0.2%Pb, 21g/t Ag, 0.3g/t Au				
Mons Cupri	Miller and Gair (1975)	Gunn and Chisholm (1984)	None	No
13.0mt, 1.0%Cu, 0.3%Zn, 0.2%Pb, 4.7g/t Ag				
Whundoo	Reynolds et al. (1975)	-	Po	Possible
2.0mt, 2.0%Cu, 1.3%Zn				

Cu-Zn TYPE

Wilga	Allen (1992)	Bishop and Lewis(1992)	Minor mt	?
4.0mt, 3.0%Cu, 6.2%Zn, 0.4%Pb, 23g/t Ag, 0.5g/t Au				
Scuddles	Mill et al. (1990)	Mill (1990)	Mt, Po	Yes
26.1mt, 1.2%Cu, 6.9%Zn, 0.5%Pb, 59g/t Ag, 0.9g/t Au				
Teutonic Bore	Greig (1984)	Fritz and Sheehan (1984)	None	No
2.2mt, 3.5%Cu, 11.1Zn, 0.9%Pb, 148g/t Ag, 0.2g/t Au				
Whim Creek	Reynolds et al. (1975)			
1.0mt, 1.5%Cu, 1.3%Zn, 0.6g/t Au				
Nangaroo	Reynolds et al.(1975)	Cowan et al (1975)	Magnetic Po	Probable
Magpie	Mulholland (1991)	-	Po	Probable
Salt Creek	Richards and Blockley (1984)	Gunn and Chisholm (1984)	None	No
0.5mt, 1.25%Cu, 8.4Zn, 3.3%Pb				
Gurubang	Company reports EL786(NSW)	Company reports EL786 (NSW)	Po	Yes
20mt, <1%Cu, <5%Zn				
Freddies Well	Reynolds et al (1975)	Annam and Lockwood (1991)	Mt, Po	Yes
800,000t, 0.2%Cu, 7%Zn				

Zn-Pb-Cu TYPE

Woodlawn	Malone et al. (1975)	Whitely (1981)	<1%Po	No
17.7mt, 1.7%Cu, 9.9%Zn, 3.8%Pb, 80g/t Ag, 1.4g/t Au				
Captains Flat	Davis (1975)	-	Rare Po	Probably no
4.2mt, 0.7%Cu, 6.0%Zn, 0.7%Pb, 55g/t Ag, 1.7g/t Au				
Currawong	Allen (1992)	-	None Reported	Probably no
9.5mt, 1.7%Cu, 4.3%Zn, 0.9%Pb, 38.0g/t Ag, 1.3g/t Au				
Rosebery	Huston and Large (1988)	Bishop and Lewis (1992)	Rare	Probably no
19.4mt, 0.7%Cu, 16.2%Zn, 5.0%Pb, 155g/t Ag, 2.9g/t Au				
Que River	McArthur and Dronseika (1990)	Webster and Steeg (1977)	None	No
3.1mt, 0.6%Cu, 13.5%Zn, 7.5%Pb, 200g/t Ag, 3.4g/t Au				
Hellyer	Mc Arthur and Dronseika (1990)	Eadie and Silic (1984)	None	No
16.0mt, 0.4%Cu, 13.0%Zn, 7.0%Pb, 160g/t Ag, 2.3g/t Au				
Thalanga	Gregory et al. (1990)	Irvine et al (1985)	Rare	No
6.4mt, 2.2%Cu, 12.3%Zn, 3.9%Pb, 99g/t Ag, 0.6g/t Au				
Dry River South	Huston et al. (1992a)	Shalley (1987)	Minor	Probably no
1.5mt, 1.1%Cu, 9.4%Zn, 3.4%Pb,970g/t Ag, 0.8g/t Au				

Mineral zoning is pronounced in VHMS deposit. Table 3.2 summarized from Large (1992) shows zones which have been recognised in Australian deposits (which are apparently consistent with the zoning recognised in the Japanese Kuruko VHMS deposits). We note that magnetite and pyrrhotite occurs:

(i) in stringer Cu ore which may contain Au (Zone 7)
(ii) associated with massive pyrite which may contain Cu (Zone 6)
(iii) with massive Cu-pyrite ore which may contain Au (Zone 5)
(iv) as minor occurrences with low grade Zn-Cu+/-Pb (Zone 4)

Magnetite may also occur in silica rich chemical exhalitives at the top of the deposit.

TABLE 3.2 Zoning of VHMS Deposits

Zone Number	Zone	Major Minerals	Minor Minerals
(Top)			
1	Laminated or massive Iron-silica chemical sediment or exhalite	Quartz, pyrite +/- hematite +/- magnetite	Barite sphalerite
2	Massive or bedded barite	Barite, pyrite sphalerite	Galena +/- hematite +/- chalcopyrite
3	Laminated or bedded massive high-grade Zn+/-Pb	Sphalerite, pyrite, galena	Chalcopyrite
4	Massive low grade Zn-Cu+/-Pb	Pyrite, sphalerite, galena, chalcopyrite	+/-Pyrrhotite magnetite
5	Massive Cu pyrite	Pyrite, chalcopyrite +/-pyrrhotite, magnetite	Sphalerite, galena
6	Massive pyrite	Pyrite +/-pyrrhotite, magnetite	Chalcopyrite
7	Stringer Cu	Pyrite, chalcopyrite, +/-magnetite, pyrrhotite	Sphalerite, galena
8	Stringer Zn-Pb	Pyrite, sphalerite, galena	
9	Stringer pyrite	Pyrite	Chalcopyrite
(Bottom)			

It must be stressed that while this zoning is consistent with that recognised by numerous workers in many VHMS deposits in various parts of the world few such deposits exhibit all the zones listed. Some deposits only exhibit one or two prominent zones and lack the others. Particularly noticeable variations exist between the Cu rich deposits in which the Zn and Pb contents may be low or virtually non-existent and the Pb-Zn rich deposits in which the inverse is true. The idealized model of mineral zoning in VHMS deposits shown in Figure 3.1 illustrates the case with a significant development of all zones. The likelihood of the relative proportions of the zones having significant deviations from those illustrated must be expected. The complete absence of some zones can be expected in many cases.

These mineral associations are consistent with the Large (1977) model for the order of mineral formation in massive sulphide deposits which was explained in Section 1.4.1.

What is noticeably lacking from this tabulation is the association of pyrrhotite with massive high grade Zn +/- Pb in the upper part of VHMS deposits. While this phenomenon is consistent with the Large (1977) model, we might expect some extremes of oxygen fugacity, Eh, pH, iron supply or temperature would induce pyrrhotite formation at this level in preference to the formation of pyrite. It has nevertheless proved difficult to identify in the geological literature an equivocal example where pyrrhotite is the dominant or even a significant sulphide in the massive Zn-Pb portions of VHMS deposits.

At higher grades of metamorphism pyrrhotite may be produced by loss of sulphur from pyrite (Vaughan and Lennie, 1991). Sangster (1972) considers that this process may explain many pyrrhotite associations with massive sulphides. Pyrite may also be transformed to magnetite. A consequence of these processes is that the magnetite and pyrrhotite distributions in VHMS deposits could exceed the above model in metamorphic terrains (refer to Section 1.4.4).

3.5 MINERALIZATION ASSOCIATIONS

A most significant association which has been described in detail by Large (1992) is the "ore equivalent" horizon which is a characteristic sediment or exhalite which occurs at the same stratigraphic level or close to the same stratigraphic level as many VHMS deposits. These horizons which often cap VHMS deposits may contain iron oxide silicates including magnetite rich units, or be pyritic facies equivalents. The formation of these chemical sediments is related to the same exhalative processes thought to have produced the massive sulphide bodies. "Ore equivalent horizons" have been variously reported as barite-pyrite shale, hematite rich jasper, pyritic carbonaceous black shale, chert, hematitic chert, barite, pyrite, quartz magnetite, pyritic quartzite, pyritic siltstone, magnetite carbonate, iron formations, banded iron formations ferruginous chert, hematite-magnetite quartz schists and umbers.

As noted in Section 3.1.2 VHMS deposits have preferential associations with calc-alkaline volcanic suites and in particular with rhyolite units. Acid pyroclastics (tuffs etc.) commonly occur in the same volcanic unit as massive sulphides or stratigraphically above the massive sulphides.

Sangster (1972) has commented on the common linear alignments of VHMS deposits in particular districts. These are especially obvious in the example of the Noranda district which has been published by Sangster. These alignments imply fault control of deposit locations.

Alteration zones may be associated with VHMS deposits. These zones, when present, can have discrete transgressive pipe like geometrics which extend downwards from the mineralization or can be semiconformable in the footwall in which case it may be more extensive. Siliceous, sericitic, chloritic and pyritic alteration is common. Lydon (1990b) gives an idealized representation of a VHMS alteration zone. Details of this alteration model have been incorporated in a simplified form into Figure 3.1.

3.6 ORIGIN OF THE MINERALIZATION

Lydon (1990b) reviews the three main models which have been proposed to explain VHMS deposits. All the models involve:

(i) a metal source
(ii) hydrothermal fluid movement
(iii) an energy source for the fluid movement

The models are:

Convection Cell - waters penetrating the sea floor leach metals from crustal rocks and these metals are precipitated when the fluids return to the sea floor. The fluid circulation is controlled by convection cells resulting from heat associated with igneous intrusions.

Magmatic Hydrothermal - this model is similar to convection cell model with the difference being that the hydrothermal fluids are derived from the volatile fractions of magmas.

Stratal Aquifer - the metal sources in this model are pore fluids originally locked into sediments but which migrate vertically when burial or other factors result in the pore pressure exceeding the confining pressure.

In all of these models a fracture system or volcanic vent traversing the subsurface would concentrate the migrating fluids, aid the vertical movement of the fluids and provide a focus for the eventual precipitation of the metallic minerals.

Sea floor deposition of VHMS deposits has actually been observed in present day oceanic settings.

Lydon (1990b), on the basis of his review, concludes that no ore process appears to fully explain all the characteristics of VHMS deposits. A spectrum of origins which encompasses all the above models may be the reality. Figure 3.2, simplified from Lydon, illustrates all the above concepts.

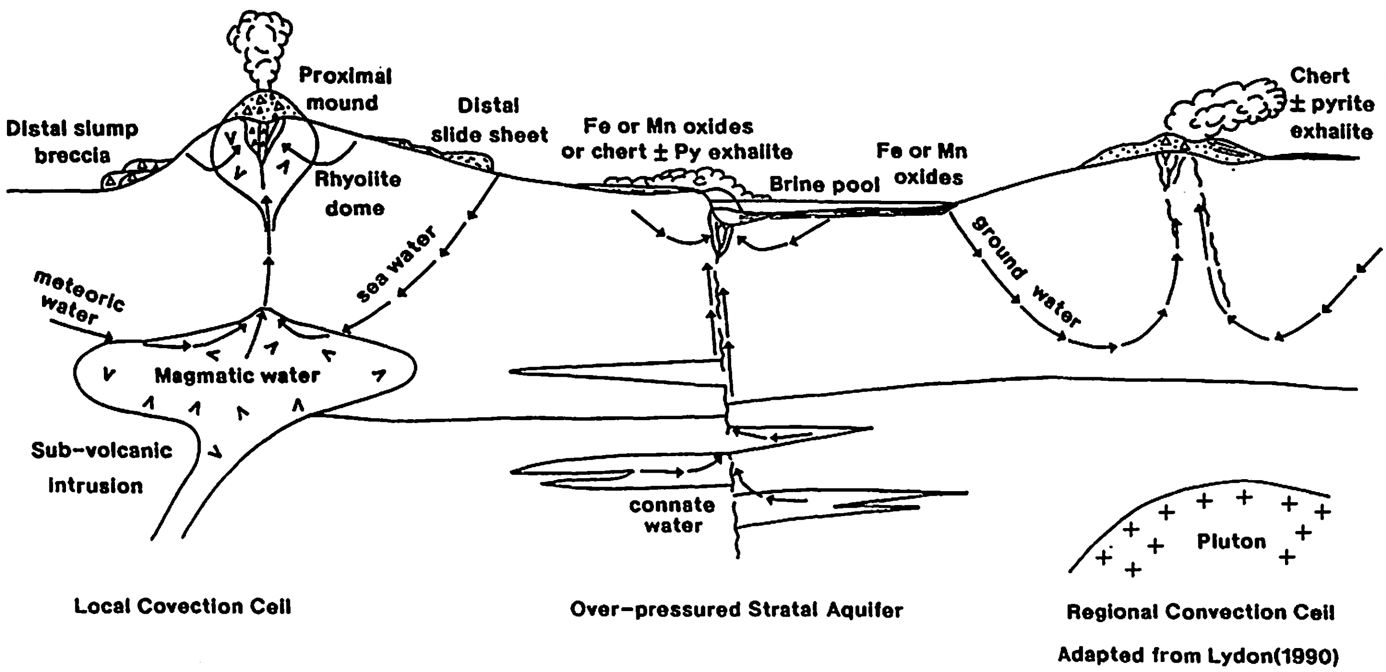


Figure 3.2 Models illustrating possible variants of hydrothermal processes forming VHMS deposits

Despite differences in detail, all models involve the exhalative debouchment of metal bearing solutions on to the sea floor where metallic minerals are precipitated as mounds or sheets that are broadly conformable with the enclosing sediments and any contemporaneous volcanics. The exhalative model elegantly explains the existence of pipe and inverted cone-like areas beneath many deposits of alteration and brecciation, veining, and "stringer" disseminated mineralization. These phenomena are considered to be results of the vertical ascent of the mineralizing solutions. The exhalative model also explains the vertical mineral zoning which characterizes VHMS deposits.The "ore equivalent horizons" can be considered a result of a final extensive precipitation of the chemicals emanating from a particular vent.

Large(1992) describes the factors that are thought to control the morphology and mineral contents of VHMS deposits. These are:

Permeability of footwall rocks - an impermeable footwall will generally only allow hydrothermal fluid ascent along faults. This will result in focussed discharges and mound type deposits. Permeable footwalls will allow unfocussed discharges over broad areas. These will be more likely to creates sheet like deposits.

Volcanic association - deposits with tholeiitic associations are likely to be of the Cu or Cu-Zn type. Deposits with calc-alkaline associations are more likely to be of the Pb-Zn-Cu-Ag type.

Temperature and pH - high temperature and low pH favour the formation of Cu-Au rich deposits.

Oxygen and hydrogen sulphide in ore fluids - low oxygen fugacity combined with moderate hydrogen sulphide favours the development of pyrrhotite.

Depth of seawater - shallow seawater allows boiling below the sea floor with the resultant development of extensive stringer zones.

The exhalative model as defined above has great relevance to the understanding of the other deposit types considered in this study as many of these also appear to have exhalitive origins.

3.7 ADDITIONAL REGIONAL DETAILS

As explained in Section 2.1.4 rifts may cause gravity highs or gravity lows depending on the relative contributions to the gravity field caused by crustal thinning and sediment infill. A third factor with influence in the case of volcanic rifts is the proportion of volcanic infill. If this is high the rift may be associated with a gravity high.

Aeromagnetic data provides an excellent indication of volcanic provinces in rifts in the cases where the volcanics contain magnetic units. Grant (1985) makes the observation that greenstone belts in the Canadian Shield correspond to regional magnetic lows albeit with internal localized zones of high magnetic intensity due to iron formations and serpentinized ultramafic intrusions. He suggests that calc-alkaline differentiation processes beneath these areas produced end members that are low in iron and hence had low magnetite producing capacities.

3.8 MAGNETIC SIGNATURES

From the discussion in Section 3.4 it is obvious that some VHMS deposits can be expected to give magnetic responses by virtue of their magnetite content. Other deposits can be expected to give magnetic responses if they contain monoclinic pyrrhotite. As demonstrated by the case histories described below field examples of these situations occur.

It is important to note from the discussion in Section 3.4 that any magnetic minerals present will tend to be concentrated in the basal portions of VHMS deposits and that VHMS deposits may not contain any magnetic minerals.

The "ore equivalent horizon" may be a valuable stratigraphic marker if it contains magnetite. Grant (1985) has commented on using the magnetic response of this indicator to precise prospective zones. Pyritic "ore equivalent horizons" could be metamorphically transformed to pyrrhotite and/or magnetite and thereby become magnetic.

It should be appreciated that the volcanic associations of VHMS deposits means that they frequently occur in association with magnetic extrusives and intrusives whose magnetic effects may obscure any magnetic response arising directly from the mineralization or the "ore equivalent" marker horizon.

Table 3.1 includes an effort to determine the percentage of Australian VHMS deposits that have magnetic responses. This has proved a difficult exercise. Many deposits have no published magnetic survey data. It is also rare for mineralogical descriptions to report on whether any pyrrhotite is the magnetic monoclinic variety. Despite these problems it appears that a significant proportion of the Cu and Cu-Zn VHMS deposits are likely to be magnetic. There appears to be a lack of magnetic Zn-Pb-Cu deposits in Australia although Harley (1983) reports that the Mount Bulga deposit (1Mt 0.55% Cu, 6.0% Zn, 2.03% Pb) contains disseminated pyrrhotite in a stringer zone so the possibility of magnetic versions of such deposits does exist.

No deposits have been identified with a magnetic massive upper Pb-Zn rich component. Although this phenomenon was predicted in Section 3.1.4 exceptions may be found and in any case metamorphic processes could transform the pyrite into these deposits into pyrrhotite. Mulholland (1991) describes the retrogression of pyrite to pyrrhotite in the Magpie deposit in Queensland, Australia. This process apparently resulted from high temperature metamorphism due to an adjacent granite.

The Golden Grove deposit, now called Gossan Hill, in Western Australia (Frater, 1983) is most atypical in that it contains massive magnetite associated with massive sulphide mineralization. This deposit is similar to many classic VHMS deposits except for its elevated magnetic content. The magnetite is pseudomorphous after hematite and goethite. Frater has speculated two mineralizing phases for the deposit with the sea floor development of hematite and goethite during the first phase and their subsequent reduction to magnetite during the second phase. This deposit thus appears to be a special case.

Magnetic lows or magnetic quiet zones adjacent to or surrounding VHMS deposits which are thought to be the result of the destruction of magnetic minerals in alteration zones have been reported for some VHMS deposits viz. Teutonic Bore (Fritz and Scheehan, 1984), Salt Creek (Gunn and Chisholm, 1984), Hellyer and Que River (Leaman, 1987).

3.9 DETAILS OF INDIVIDUAL DEPOSITS

3.9.1 Scuddles, Western Australia

Principal References: Mill et al. (1990), Mill (1990), Robinson and Belford (1991)

3.9.1.1 Introduction

The Scuddles deposit provides a well documented example of a classic magnetic Archean greenstone belt Zn-Cu deposit.

3.9.1.2 Setting of the Deposit

The deposit is hosted by a sequence of felsic lavas, tuffs, volcaniclastics and sediments which have been intruded by numerous mafic and felsic dykes (Figure 3.3). This succession is located in the Warriedar Greenstone Belt in the Murchison Province of the Archean Yilgarn Block of Western Australia. This area which has been subjected to greenschist grade regional metamorphism hosts at least 14 other base metal/pyrite occurences including the Gossan Hill deposit (Frater, 1983) which is located 8km south east of Scuddles.

3.9.1.3 Stratigraphic Associations

The deposits in the area are contained in a mineralized succession up to 400 m thick which is predominantly composed of dacitic to rhyolitic pyroclastics and which separates a 400 m footwall succession dominated by andesitic and basaltic volcaniclastics from a 850 m hanging wall succession dominated by rhyodacite to andesitic lavas.

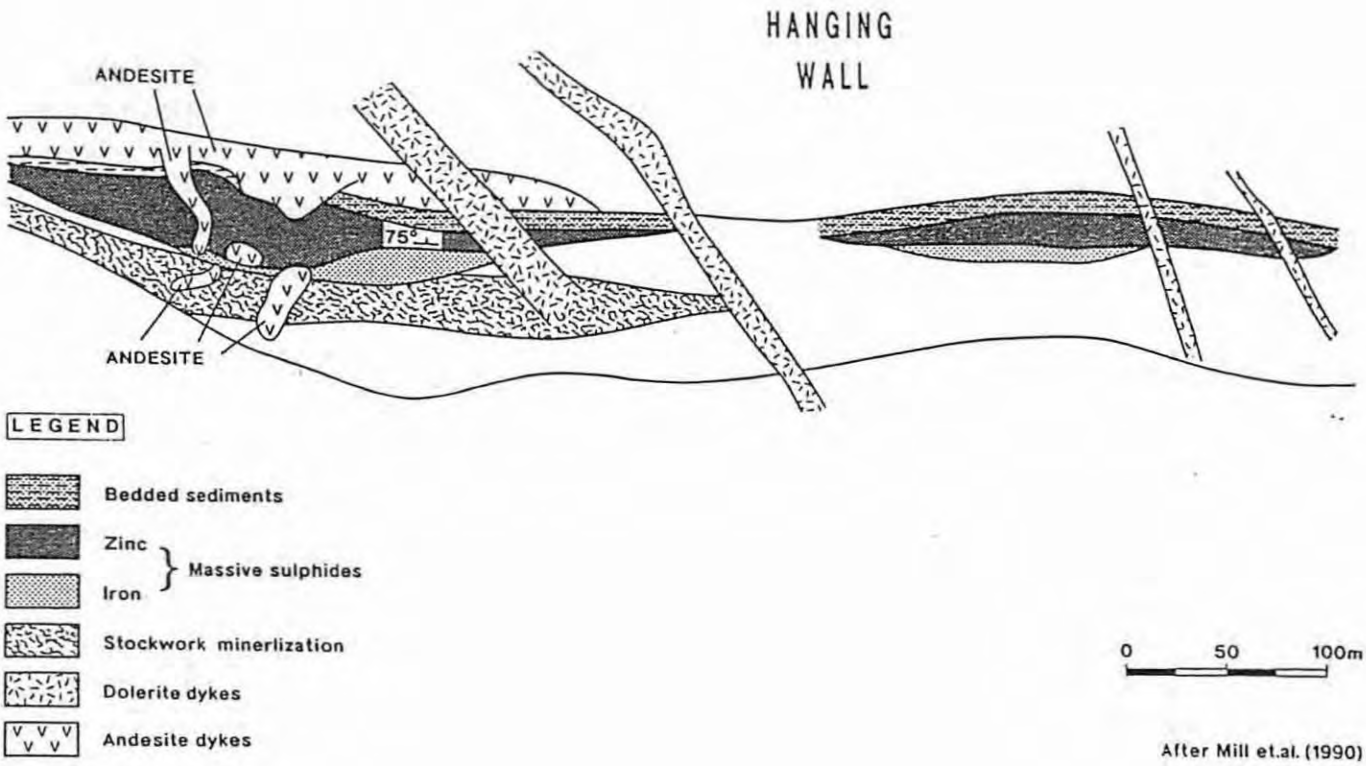


Figure 3.3 Geological plan of the Scuddles deposit

3.9.1.4 Mineralization

The deposit is over 600 m long and up to 50 m wide. It is separated into Main Lens and a Central Lens both of which are broadly conformable with their steeply dipping host rocks.

Tonnages and grades are:

	Tonnes $x10^6$	Cu%	Zn%	Pb%	Ag g/t	Au g/t
Massive sulphide zinc	9.3	0.5	15.8	1.3	108	1.2
Massive sulphide copper	1.3	5.1	1.7	0.1	44	1.3
Stringer copper	4.0	2.9	0.2	-	10	0.3

The deposit contains three types of massive sulphides which are stacked on each other and which are from top to bottom:

(i) massive (>50%) sphalerite plus pyrite
(ii) massive pyrite (sphalerite <50%) - types (i) and (ii) interfinger
(iii) copper rich (>5%) massive pyrite

The massive sulphides overlie a 40-50 m wide zone of stockwork pyrite-chalcopyrite mineralization with sulphide contents decreasing from an initial 80% adjacent to the massive ore to less than 10% away from it. Intensely silicified and chloritized rocks are spatially associated with the stockwork.

The massive pyrite ore contains minor pyrrhotite and magnetite. The copper rich massive sulphide zone contains significant pyrrhotite as well as minor magnetite. The stockwork zone contains minor pyrrhotite and magnetite.

3.9.1.5 Mineralization Associations

The "mineral horizon" at Scuddles consists of epiclastic, hemipelagic and chemical sediments (cherts). All the stockwork and massive sulphide mineralization is contained in this horizon. The mineralized horizon which is generally strongly pyritic (averaging 3-5% pyrite) appears to be an "ore equivalent horizon".

3.9.1.6 Origin of the Mineralization

The Scuddles deposit appears to have all the characteristics of a classical exhalative volcanogenic massive sulphide deposit.

3.9.1.7 Additional Regional Detail

The "mineral horizon" at Scuddles appears to have a total strike length of approximately 30 km (Figure 2 of Robinson and Belford (1991)). The numerous mineral occurrences in the area all appear to be along the strike of this apparently non-magnetic "ore Equivalent unit".

3.9.1.8 Magnetic Responses

Figure 3.4 illustrates aeromagnetic and ground magnetic data showing that the Scuddles deposit gives a discrete, albeit weak magnetic response. What is significant is that the basalts, dolerites and andesites that have been mapped in the area do not appear to be producing obscuring magnetic anomalies. The increase in intensity to the west of the deposit is due to magnetite rich banded iron formations located more that 1km from the deposit.

Because of the steep dip of the deposit a side view of the mineral zoning is exposed to the magnetic surveys. However no details such as the stringer zone or the alteration zones can be detected from the low sensitivity published magnetic data.

It is not certain what proportion of the magnetic response arise from magnetite and what proportion arise from pyrrhotite. Both minerals may contribute. Published susceptibility values are as follow:

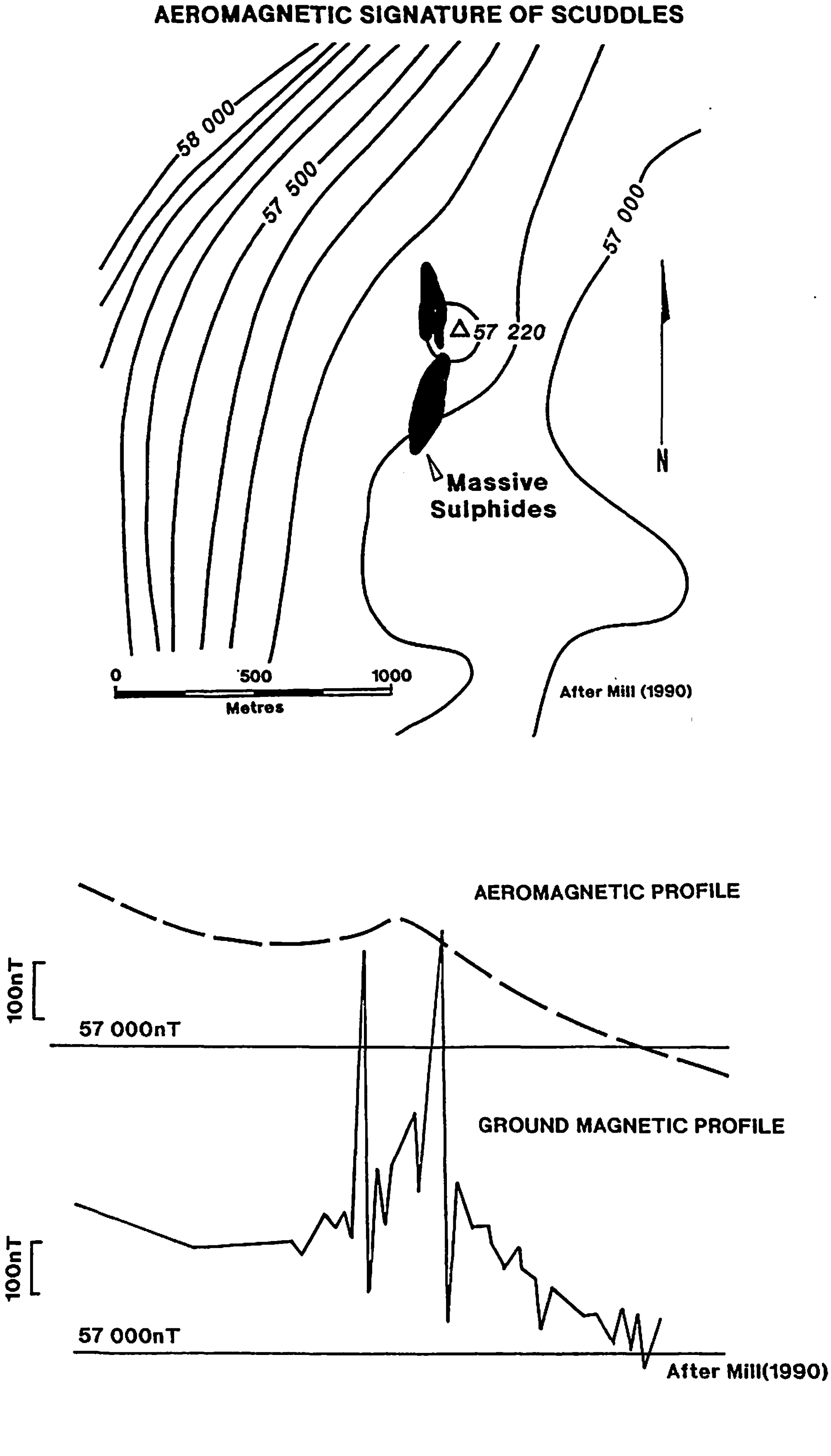


Figure 3.4 Magnetic responses of Scuddles. The coarsely contoured aeromagnetic data suggests that the deposit is magnetic but is not associated with a magnetic "ore equivalent horizon". The noise in the ground magnetic data is due to surficial maghemite.

Rock type	Susceptibility (SI units)	Comments
Hanging wall	30 - 1000	some erratic values
Upper sediments	30 - 10000	erratic values
Massive sulphides	1000 - 60000	usually above 50000
Stringer sulphides	1000 - 10000	erratic values
Footwall	30 - 100	low and uniform
Dolerite dykes	5000 - 10000	uniform result
Andesite dykes	10 - 50	low and uniform

3.9.2 Gurubang, Lachlan Fold Belt, New South Wales

Principal Reference: Geological Survey of New South Wales, Open File report for permit EL786

3.9.2.1 Introduction

The Gurubang deposit is an example of a pyrrhotite rich Cu-Zn massive sulphide deposit occuring in relatively unmetamorphosed sediments and volcanics of Silurian age in Eastern Australia. Details of this subeconomic mineralization have not been published and the following account is based on the author's personal involvement with the project supplemented by open file data contained in statutory reports submitted to government departments (as above).

3.9.2.2 Setting of the Deposit

The deposit occurs at the southern extremity of the Cowra-Yass synclinal zone (volcanic rift) of the Lachlan Fold Belt of eastern Australia. Davis (1990) provides a reference to the mineral deposits in this tectono-stratigraphic unit and the Gurubang deposit is located in close proximity to the Dartmoor deposit shown in Figure 3 of Davis' paper.

3.9.2.3 Stratigraphic Association

The deposit is located in a linear zone identified as consisting of sandstone and shale on published maps. Detailed mapping suggests a footwall of siliceous volcanics and a hanging wall of tuffs, shales and limestones

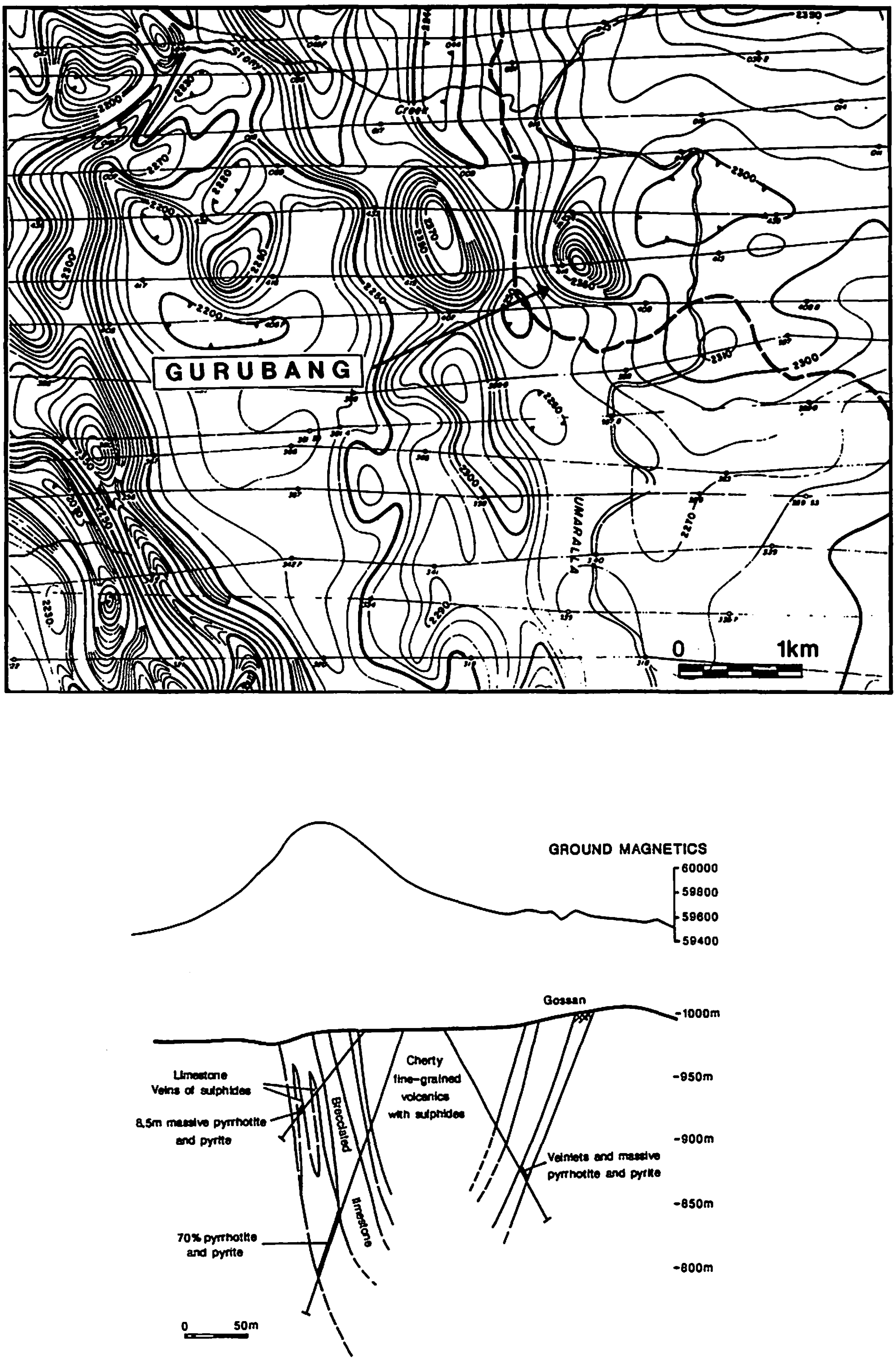


Figure 3.5 Geology and magnetic responses of the Gurubang deposit. The magnetic ridge in the aeromagnetic data extending north from the deposit may be due to a magnetic "ore equivalent horizon". The magnetic low to the east of the deposit could be due to an alteration zone.

3.9.2.4 Mineralization

The deposit is approximately 600 m long and contains an estimated 20 mt of sulphides with the principal sulphide being pyrrhotite (reaching concentrations of 35% by volume) and containing subeconomic concentrations of chalcopyrite (1% maximum) and sphalerite (5% maximum) and minor amounts of galena. Pyrite contents are significant. A stringer sulphide zone occurs in the footwall. The deposit appears to consist of a tabular massive sulphide body overlying a feeder zone. The zoning of the various sulphides in the deposit is unclear (Figure 3.5).

3.9.2.5 Mineralization Associations

The deposit is overlain by cherty banded semimassive sulphides and cherty fine grained volcanics. These levels appear to represent the ore equivalent horizon.

3.9.2.6 Origin of the Mineralization

The characteristics of the deposit are consistent with an exhalative origin.

3.9.2.7 Additional Regional Detail

None noted

3.9.2.8 Magnetic Response

Butt (1985) has published a profile of aeromagnetic data over this deposit. Figure 3.5 shows the aeromagnetic and ground magnetic responses. The Gurubang deposit gives a distinct magnetic high relative to the host sediments and adjacent siliceous volcanics. Complexities associated with computer modelling of the magnetic response and the relatively intense amplitude of the ground magnetic anomaly (400 nanoteslas) suggest that the pyrrhotite has a significant component of NRM.

The aeromagnetic data suggest that the deposit may be associated with a linear low amplitude magnetic ridge. This could be a reflection of pyrrhotite in an "ore equivalent horizon".

The magnetic low evident which occurs to the east of the deposit could be due to destruction of magnetic minerals in an alteration zone.

3.9.3 Orchan, Quebec, Canada

Principal References: Hallof (1966), Large (1977)

The Orchan deposits in the Mattagami District of Quebec Canada consist of three distinct Cu-Zn massive sulphide lenses within an Archean greenstone belt andesite-dacite-rhyolite volcanic pile which has undergone greenschist facies metamorphism. The deposits provide good examples of magnetite rich Cu-Zn massive sulphide deposits. The Orchan No. 3 lens has in fact been presented by Large (1977) as a classic example of metal zoning in a massive sulphide deposit (Figure 3.6).

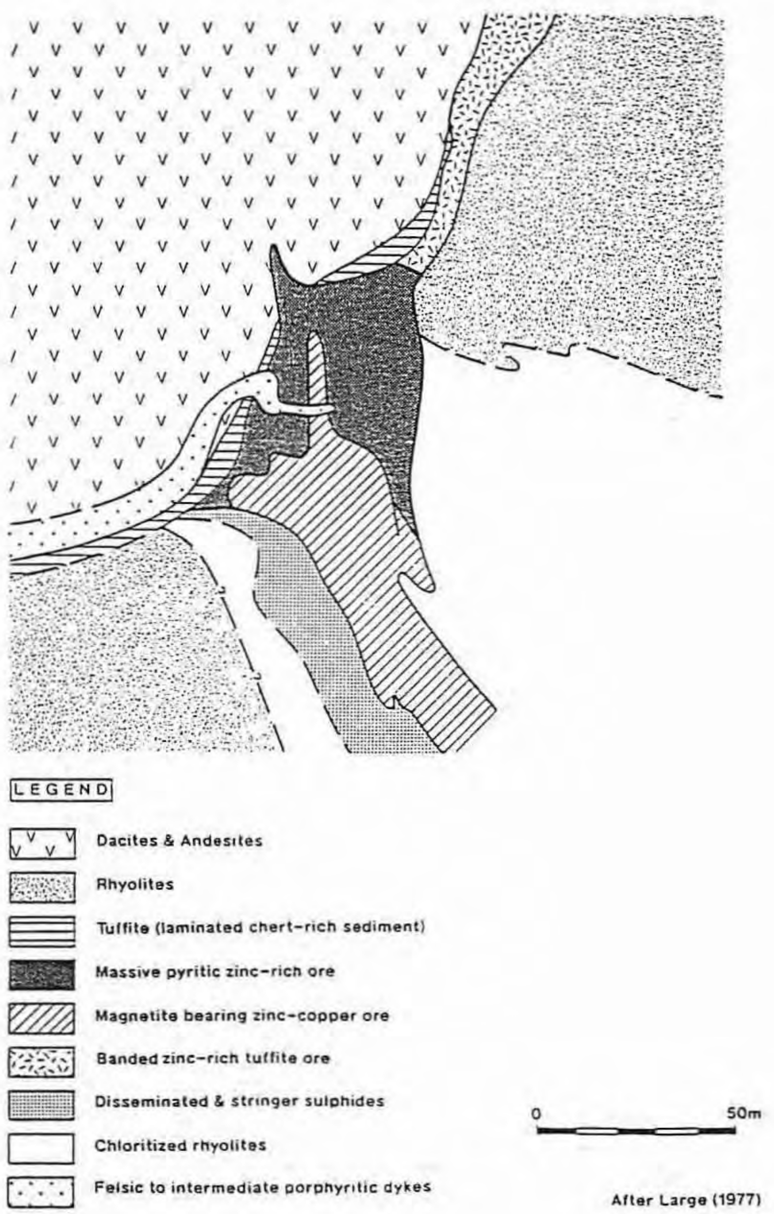


Figure 3.6 Mineral zoning in the Orchan No. 3 deposit.

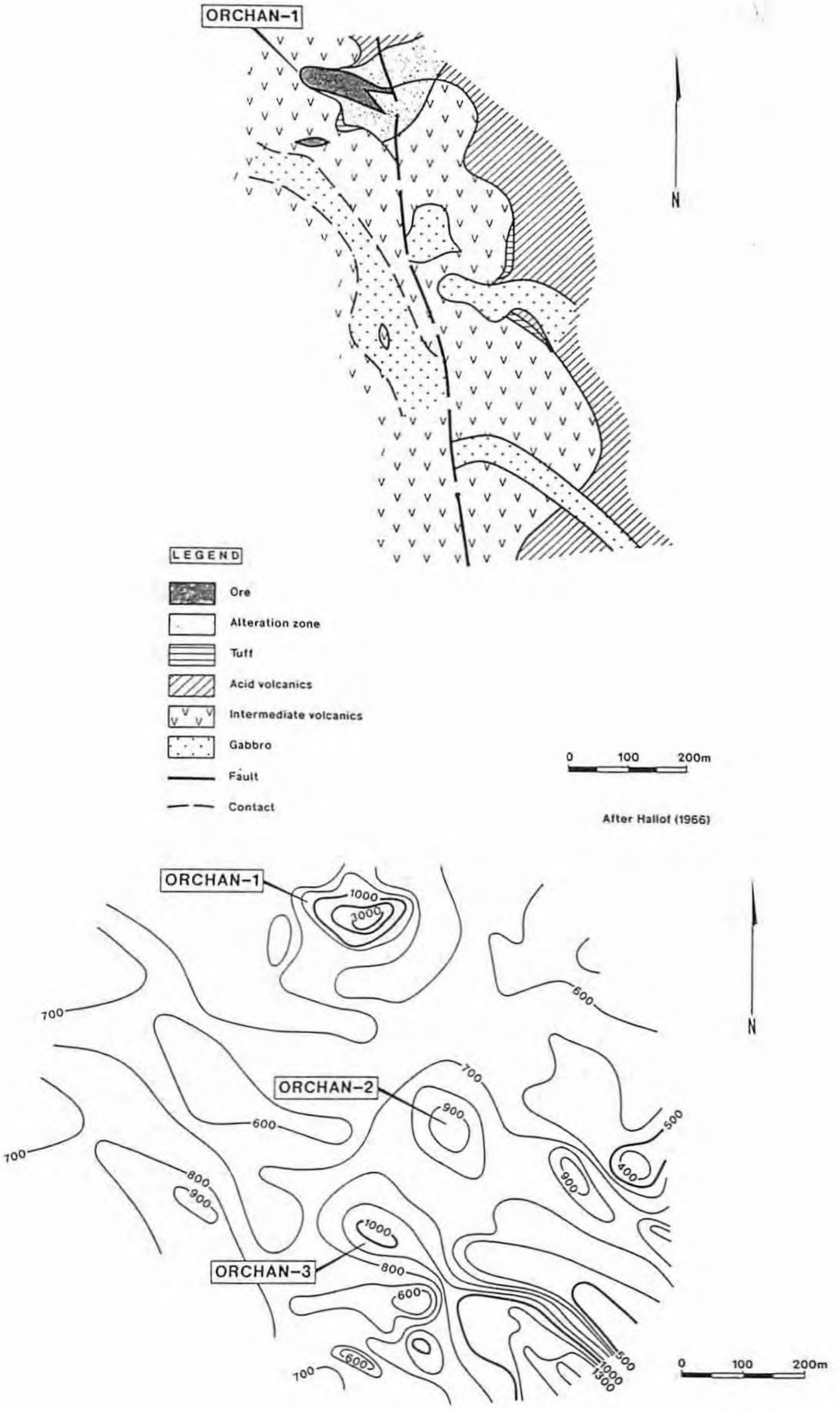


Figure 3.7 Comparison of outcrop geology and ground magnetics in the Orchan area. Note that the Orchan No. 2 and 3 deposits which do not outcrop give distinct magnetic highs. The contour interval is too coarse to allow confident mappings of alteration zones or "ore equivalent horizons". The high magnetic amplitudes are due to the magnetite contents of the deposits.

Hallof (1966) has published ground magnetic data over the three Orchan deposits (Figure 3.7) and it can be seen by correlating Hallof's geological maps at different subsurface levels with the ground magnetic contours, that all three deposits correlate with discrete magnetic anomalies with amplitudes of several hundred nanoteslas. The magnetite content in the deposits which, if the example of Orchan No. 3 is typical, appears to be concentrated in the basal portions of the deposits is undoubtedly the principal cause of these anomalies. The reported pyrrhotite contents may contribute to these anomalies but any magnetic effect of the pyrrhotite is most probably subordinate. Hallof's statement (1966) that the Orchan No. 2 and No. 3 deposits do not contain magnetite or pyrrhotite may date from an early stage of exploration when only the upper parts of the bodies had been drilled.

It is significant that the flanking volcanic rocks which are variously reported by Hallof (1966) and Large (1977) as dacites, andesites, rhyolites and gabbros give significantly weaker responses than the mineralization. The magnetic responses of many of these igneous units are effectively negligible.

3.9.4 Other Deposits

In addition to the areas mentioned in the previous sections of this chapter significant groupings of well documented VHMS deposits occur in the following localities:

the Iberian Pyrite Belt
the Fennoscandian Shield
the Norwegian Caledonides
the Canadian Shield
Buchans, Newfoundland

Franklin et al. (1981) provide an excellent introduction to the characteristics of these deposits which, while generally conforming to the generalities outlined above, often show particular local variations.

3.10 EXPLORATION GUIDE LINES

1. Locate a volcanic rift (as per the definition of volcanic rift given in Section 3.1.2).

2. Regional magnetics and regional gravity data may be useful for delineating the boundaries and the extent of the rift. The magnetic data may indicate the extent and limits of volcanic units within the rift. A rift may correspond to either a gravity high or a gravity low (Section 3.1.7).

3. Areas within 50 km of known VHMS deposits within the rift should be regarded as most prospective (Section 3.1.3).

4. Rhyolitic volcanic provinces within the rift should also be regarded as most prospective (Section 3.1.2).

5. Geologically mapped or aeromagnetically indicated fault zones should be regarded as favourable localities especially if they pass through known deposits (Section 3.1.5).

6. Geologically mapped or aeromagnetically indicated marker horizons or contacts which pass through known deposits should be regarded as most prospective (Section 3.1.3).

7. Narrow linear anomalies with extents of a few kilometres which could be due to magnetic "ore equivalent horizons" (Section 3.1.4) should be regarded as indicating prospective zones.

8. Isolated magnetic anomalies up to a few hundred metres in length should be regarded as most prospective particularly if they are adjacent to or coincident with an "ore equivalent horizon" (Section 3.1.4) or if they are unlikely to be due to volcanics or igneous intrusions. If these anomalies have amplitudes of several hundred nanoteslas they may indicate magnetite rich massive bodies. Lesser amplitudes may indicate pyyrhotite rich bodies or deposits with low magnetite contents.

9. Quiet magnetic zones or subtle magnetic lows surrounding isolated magnetic anomalies may be interpreted as indicating an alteration zone associated with a mineral deposit (Section 3.1.5).

10. Quiet magnetic zones or subtle magnetic lows adjacent to "ore equivalent" horizons (Section 3.1.4) may be interpreted as an alteration zone associated with a non magnetic mineral deposit (Section 3.1.5).

11. Modelling of any anomaly associated with a VHMS deposit may prove difficult because of irregular distributions of magnetic minerals in the deposit, the disseminated nature of magnetic minerals in the deposit and the propensity of pyrrhotite to acquire significant remanent magnetization (Section 3.1.4 and 1.2.2).

12. Indications of remanence such as obvious conflicts between magnetic modelling and known geological dips may possibly indicate remanently magnetized pyrrhotite (Section 1.2.2).

13. Drills targetted on the magnetic parts of VHMS deposits may encounter lower stringer portions or Cu rich portions of orebodies and miss upper zinc-lead rich portions of the orebodies (Section 3.1.4).

14. A magnetic stringer zone may trend perpendicular from an upper massive non magnetic portion of an orebody (Section 3.1.1).

CHAPTER 4
DEPOSITS HOSTED BY TURBIDITIC SEDIMENTS AND WHICH HAVE NO OBVIOUS ASSOCIATION WITH IGNEOUS ACTIVITY

Principal References: Fox(1984), Morganti (1990), Sawkins (1990)

A significant number of massive sulphide gold-copper-zinc-lead-silver deposits occur in turbiditic sequences and have no obvious association with igneous activity. The majority of such deposits appear to contain significant percentages of magnetite and/or pyrrhotite and are known to give or are likely to give observable magnetic responses relative to their non magnetic or weakly magnetic sedimentary hosts. Such deposits have been well described in the literature on an individual deposit basis but published compilations are contradictory. Various authors (e.g. Lambert (1976), Fox (1984), Morganti (1990), Sawkins (1990) have produced different classifications which include some of the deposits described below. The grouping used in this chapter, based on turbidite hosts and absence of igneous activity, may appear overly simple however it does identify a large number of deposits having remarkable similarities. This phenomenon appears to reflect the fact that a turbidite sequence lacking an igneous component implies a particular stage of basin/rift development and actual position in the basin. Turbidite deposition requires the existence of a significant slope such a shelf edge in a basin. This implies the existence of a well developed depositional trough such as typically exists during the syn-rift and early post-rift stages of rifting. Turbidites are most likely to be deposited on the slope or at the base of the slope. The absence of contemporaneous igneous activity is less definitive but could imply a rift with limited crustal extension.

The following overview of such deposits is based on the descriptions given in the later sections of this chapter.

4.1 INTRODUCTION

Massive sulphide bodies hosted in turbidite sequences and which have no obvious association with igneous activity occur principally as flat sheets or saucer shaped bodies which are conformable with the enclosing sediments. Feeder pipes and alteration zones have been identified beneath some deposits. Some deposits occur as ellipsoids exhibiting various degrees of discordance with their sedimentary hosts. Such deposits appear to have undergone remobilization during tectonic compression.

The geometry and mineral zoning together with the obvious exhalative hydrothermal origin of many of the deposits has led various workers to consider them to be direct analogues of the VHMS deposits albeit in a non-volcanic settings.

As with the VHMS deposits, mineralization tends to occur as Cu, Cu-Zn, or Pb-Zn-Ag varieties. Magnetite, pyrrhotite and gold appear preferentially associated with the Cu and Cu-Zn deposits although a large number of the Pb-Zn-Ag deposits do contain significant amounts of pyrrhotite. With these distinct differences in deposit characteristics a case can be made for studying them separately. This has not been done because compositions intermediate between the extremes do occur and in at least one area (Cobar, Section 5.9.1)), the complete range of variations occur in close proximity to each other.

Deposits of the Cu and Cu-Zn type can be recognised in the Cobar area of New South Wales, Australia, the Kanmantoo Trough of South Australia, the Ducktown area of Tennessee, USA and the Labrador Trough, Quebec, Canada. Deposits of the Pb-Zn-Ag variety can be recognised in the Cobar area (Elura),the Sullivan area of British Colombia, the Selwyn Basin of western Canada, and at Rammelsberg and Meggen in Germany. The Rouez deposit in France appears to be an intermediate variety.

The Sullivan deposit (Section 4.9.1) is a well documented example of the Pb-Zn variety and the Soucy deposit in the Labrador Trough (Section 4.9.2) is a well documented of a Cu-Zn counterpart. The Cobar area (Section 4.9.3) contains examples of both types which have been significantly deformed and remobilized as a result of compression perpendicular to the bedding.

4.2 SETTING OF THE DEPOSITS

The Cobar, Kanmantoo, Ducktown, Sullivan, Selwyn Basin, Labrador Trough, and the German deposits have all been interpreted to occur in rift settings. No interpretation describing the tectonic setting of the Rouez deposit has been located. It is not fully clear which of these rifts have intracratonic settings and which ones may be regarded as marginal basins. The Kanmantoo area has been interpreted as a marginal basin, the Ducktown area is thought to be located in a rift developed during a continental splitting process.

Recent crustal seismic studies have resulted in interpretations that the Cobar Basin hosting the Cobar deposits is an extensional basin.

Minor igneous intrusions which may have similar ages to the sediments hosting the mineralization occur in the Ducktown, Cobar and Rouez areas.

4.3 STRATIGRAPHY

The deposits described range in age from Proterozoic to Devonian. As noted above their host rocks are typically deepwater siltstones, mudstones, shales, greywackes, sandstones etc. or their metamorphosed equivalents.

The Cobar and the Selwyn Basin areas are the only localities where a sufficient number of deposits occur for any conclusions to be made regarding stratigraphic controls and lithologic associations. Around Cobar some degree of correlation can be noted between the deposits and fine grained sediments and particular stratigraphic units. The Selwyn Basin deposits are confined to particular stratigraphic horizons however no particular lithologic affinities are obvious from published details.

4.4 MINERALIZATION

As remarked in Section 4.1 and as is obvious in the following descriptions of individual deposits the mineral compositions of the turbidite hosted deposits which are not associated with igneous activity range from Cu and Cu-Zn to Pb-Zn-Ag. Intermediate compositions exist however the deposits exhibit a tendency to occur in the extremes of these compositions. The mineralization masses vary from subcircular saucer shaped lenses (approximately 2000 m in diameter and 100 m thick in its centre) in relatively undeformed deposits such as Sullivan through cigar shaped or flattened ellipsoids in the case of the deformed Cobar deposits to thin (10-20 m), elongate (1000 by 1000 m) sheets in the case of the Ducktown deposits.

Detailed models for mineral distributions can be inferred from the Cobar and Labrador Trough deposits for the Cu and Cu-Zn deposits and from the Sullivan, Selwyn Basin and the German deposits for the Pb-Zn-Ag deposits. The Kanmantoo and Rouez deposits are not well defined in the literature and the Elura deposit shows definite signs of remobilization. The characteristics of these deposits show considerable consistency.

Sangster (1979) has noted the following ore types in the Cobar district:

(i) massive pyrite-sphalerite-galena with minor pyrrhotite and chalcopyrite
(ii) massive magnetite in pyrrhotite-chalcopyrite
(iii) siliceous chalcopyrite-pyrrhotite

Based on published spatial relationships, Sangster has interpreted four examples of deposits minerals zoning conforming to the zoning occuring in classic VHMS deposits (Section 3.4) i.e. a progression upwards through siliceous chalcopyrite + pyrrhotite +/- magnetite zones to massive pyrite-lead-zinc. Sangster interprets these deposits as having an exhalative origin with siliceous and chalcopyrite/pyrrhotite zones originating in feeder pipes.

Sangster identifies reports of quartz veins, iron silicates and siderite as possible portions of an "ore equivalent horizon" (although Sangster does not explicitly use this term). He interprets the shale beds containing pyrrhotite disseminations with which many of the Cobar deposits are obviously spatially associated as a possible manifestations of the same exhalitive processes.

Mineral zoning in the Soucy deposit of the Labrador Trough which is described in detail in Section 5.9.2.4 is virtually identical to that identified for the Cobar deposits with the main difference being that the "ore equivalent horizon" lateral to the deposit consists of pyrite rather than pyrrhotite disseminations in shale.

The Sullivan deposit, as observed by Sangster (1972), has many zoning similarities with VHMS deposits despite being entirely hosted in sediments. This massive body consists of an upper subcircular lens of pyrite-galena-sphalerite which overlies a less extensive zone of massive pyrrhotite. These massive sulphides overlie a brecciated zone of tourmalization which is heavily mineralized in places. This assemblage is interpreted as the feeder pipe to the upper massive mineralization. Minor chalcopyrite occurs in fracture fillings. Pyrrhotiferous siltstone and shale are an apparent "ore equivalent horizon".

Published geometries and mineral zonings for the Anvil and Macmillan Pass Camps in the Selwyn basin and the Rammelsberg and Meggen deposits in Germany are very similar to Sullivan with notable differences being that these deposits contain more barite in their upper portions and Meggen and Rammelsberg lack significant pyyrhotite.

The Elura lead-zinc orebody which is a vertical ellipsoidical pipe showing clear evidence of significant remobilization has a central core of pyrrhotite which is enveloped in a zone of massive pyrite, sphalerite and galena which is itself surrounded by a zone of siliceous ore. Such a mineralized mass could be the result of a ductile sulphur rich mass (such as the Sullivan orebody) being intruded through and into overlying strata during deformation.

The Rouez deposit in France which has mineral concentrations intermediate between the Cu and Cu-Zn types and the Pb-Zn-Ag types occurs in a pyrrhotiferous shale which could be an "ore equivalent horizon".

From the above discussion it appears that the mineral zoning of the turbidite hosted massive sulphide deposits not associated with igneous activity has a definite probability of being similar, if not identical, to that observed for VHMS deposits which as has been noted in Section 3 and illustrated in Figure 3.1. It is proposed that this model be used as an exploration guide for the turbidite hosted deposits as well as volcanic hosted deposits. It should be noted that it is not necessary to assume any particular origin for the deposits to apply the model as the mineral distributions are based on observations. As in the case of the VHMS deposits it is necessary to be aware that not all deposits will necessarily contain the full range of mineral compositions shown in Figure 3.1. Cu and Cu-Zn rich deposits may lack the upper sphalerite-galena rich section shown in Figure 3.1. Conversely, Pb-Zn-Ag deposits may have little or no development of the basal Cu rich portions. A final point that must be stressed is that the massive sulphide mineralization in these deposits may have a significantly greater lateral extents than shown diagrammatically in Figure 3.1 (refer to the dimensions quoted above).

4.5 MINERAL ASSOCIATIONS

As is demonstrated most markedly in the Cobar area and the Selwyn Basin, the deposits tend to occur in clusters.

Turbiditic sediments, particularly argilaceous sediments host the mineral deposits. In the cases of Rouez, Cobar and Sullivan the mineral deposits occur in argillaceous layers containing disseminated pyrrhotite. The exact extent of the pyrrhotiferous layer at Sullivan is not known but in the Cobar area and at Rouez the mineral deposits are aligned along extensive narrow linear magnetic anomalies arising from and defining the extent of the pyrrhotiferous layers. It is not certain if the pyrrhotite formation is a regional phenomenon or if it is limited to the immediate vicinity of the deposits. It is assumed that deposits of this type may also show preferential spatial relationships with disseminated pyrite horizons in situations where pyrite has developed in preference to pyrrhotite. The Soucy deposit in the Labrador Trough appears to be an example of this situation.

No clear evidence is presented in the literature that these deposits show preferential spatial associations with fault systems although this must be considered a strong possibility.

For the deformed deposits the mineralization appears to show a preferential remobilization into fold axes and zones of shearing and cleavage.

4.6 ORIGIN OF THE MINERALIZATION

The origins proposed for these mineral deposits are:

(i) Epigenetic origin whereby ore bearing fluids percolate an existing sedimentary pile and are deposited in faults and/or shears.

(ii) Syngenetic origin in which sulphides originate as exhalations from submarine hydrothermal vents and are deposited contemporaneously with their enclosing sediments.

Deposits such as those in the Cobar area have undergone modifications during metamorphism and structuring which has remobilized the mineralization into preferred localities such as fold axes, faults and shear zones but this fact does not preclude an original syngenetic hydrothermal origin.

Sato (1977) and Hodgson and Lydon (1977) have proposed that the metal contents of such deposits can be related to seawater salinity and temperature with high temperatures and low salinities favouring the development of copper rich deposits.

While it is not possible to adamantly conclude that one origin explains all the deposits, the characteristics of mineral zoning, alteration and the indications of feeder pipes described in Section 4.4 suggest to the author that a syngenetic exhalative origin is the most probable.

4.7 ADDITIONAL REGIONAL DETAILS

The Cobar Trough, the Kanmantoo Trough and the rift containing the Ducktown deposits are all associated with contemporaneous rift systems which contain different styles of mineralization and different types of igneous activity. These situations demonstrate how mineralization styles may vary with the stages of rift development.

As noted by Suppel and Scheibner (1992), the Cobar Trough, which contains the turbidite hosted Cobar deposits in sedimentary sections devoid of volcanic activity can be considered to extend south of a transverse zone known as the Lachlan River Lineament into two narrow troughs known as the Mount Hope Trough and the Rast Trough. These southern troughs contain similar sediments to the Cobar Trough but they also contain acid volcanic sequences. Small mineral deposits in the area such as the Mount Hope Mine (Gilligan, 1974) have been interpreted by Degeling et al. (1986) as having the characteristics of VHMS deposits. Suppel and Scheibner (1992) have interpreted greater crustal extension in the Cobar Trough than in the Mount Hope and Rast Troughs and that the Lachlan River Lineaments was a transfer fault accommodating different degrees of extension in the two areas. The implication of these interpretations is that VHMS and turbidite hosted massive sulphides may be developed in the same rift system with their localities of emplacement being related to the degree of crustal extension.

The Dundas Trough volcanic rift in Tasmania contains Cambrian VHMS deposits and calc-alkaline volcanics which are contemporaneous with the sediments in the Kanmantoo Trough marginal sea in South Australia. Degeling et al. (1986) correlate these two troughs whose offset they explain by the existence of a Gambier-Tasman Fracture Zone. This situation is another example suggesting contemporaneity of VHMS and turbidite hosted deposits in the same rift system or system of rifts where the style of mineralization is related to the degree of crustal extension and the differencing degrees of extensions are accommodated by transverse faults zones.

These cases suggest a correlation of the turbidite hosted deposits with rifts having undergone greater extension than the volcanic rifts associated with calc-alkaline igneous activity and VHMS deposits. They also suggest a cessation of calc-alkaline igneous activity as crustal extension progresses.

The Ducktown deposits which have many similarities with the copper rich deposits of the Cobar area occur in turbidite sequences which contain minor amounts of amphibolite. Their host rocks, the Ocoee Supergroup have been interpreted by Williams and Hatcher (1983) and others as having been deposited in a rift formed during a continental break up process. This rift is separated by a basement ridge from a second rift which contains the Gossan Lead deposits (Gair and Slack, 1984) which are similar to the Ducktown deposits and which are hosted by the Ashe Formation in which tholeiitic metabasalt and basalt related rocks are more abundant. The difference has been interpreted as indicating greater crustal extension in the Gossan Lead area than the Ducktown area. Quartzite thought to be recrystallized chert and masses of magnetite are often found interbedded with massive sulphides at Gossan Lead may indicate limited developments of the "ore equivalent" or banded iron formation. Chapter 5 describes a group of deposits which includes the Gossan Lead Deposits which appear to have a characteristic association with banded iron formations, amphibolites and basic igneous activity. The relationships of the Ducktown and Gossan Lead areas appears to demonstrate the progression from simple turbidite hosted deposits with little or no igneous associations towards the BIF/amphibolite/basic igneous associated deposits in direct relationship with greater crustal extension.

The amounts of pyrrhotite and magnetite associated with these deposits may be enhanced by metamorphism. This is suggested by the fact that the unmetamorphosed Meggen and Rammelsberg deposits contain virtually no pyrrhotite or magnetite whereas deposits subjected to higher metamorphic grades (such as Kanmantoo) have higher concentrations of magnetite.

4.8 MAGNETIC SIGNATURES

All the Cu and Cu-Zn and intermediate deposits of this class as well as many of the Pb-Zn-Ag deposits are either known to give magnetic responses or would be expected to give magnetic response by virtue of their published mineralogy. Unfortunately however the best examples of published magnetic data are from poorly described deposits or from deposits which are probably atypical as a result of extensive remobilization. These facts limit the generalizations that may be based on observation of actual data.

If, as is probable, these deposits have an exhalative hydrothermal origin and the model distributions of magnetite and pyrrhotite as shown in Figure 3.1 apply, we could expect magnetic responses similar to those observed for many VHMS deposits. We could also expect in certain ideal situations to be able to make interpretations of magnetic data identifying specific portions of orebodies and predicting particular mineral assemblages.

None of the magnetic responses in the Cobar area appear capable of being interpreted in this manner as they almost uniformly have a bulls-eye form which is apparently reflecting the extreme vertical elongation of their mineralized sources.

The magnetic properties of the Elura deposit which are extremely well known as a result of rock property measurements and magnetic modelling exercises are most illustrative in demonstrating the magnitude of the response that may be expected. The 27mt Elura ore body which is completely oxidized (non magnetic) to a depth of approximately 100 m gives a ground magnetic anomaly with an amplitude of 150 nanoteslas. 90% of this anomaly amplitude is due to remanent magnetism in pyrrhotite which has a direction approximating that of the present day earth's field. The remaining 10% of the anomaly amplitude is due to inductively magnetized pyrrhotite. Without the remanent magnetization the Elura ore body would only cause a 15 nanotesla ground magnetic anomaly.

The source of the magnetic anomaly at Rouez is pyrrhotite which is also reported to contain an intense component of remanent magnetization whose direction approximates that of the earth's present magnetic field. The Rouez deposit subcrops as two distinct massive sulphide lenses. Ground magnetic surveys in the area define the areas of higher pyrrhotite concentrations.

Magnetite rich deposits such as Kanmantoo and Great Cobar produce anomalies with amplitudes of several hundred nanoteslas.

A most diagnostic characteristic of such mineral deposits is their often observed association with "magnetic ridges" which are narrow linear magnetic anomalies due to disseminated pyrrhotite in particular argillaceous horizons. These are most prominent in the Cobar area where mineral deposits occur at various localities along the lengths of these features where they are indicated as local "bulls-eye" culminations in the magnetic field. The Rouez deposit has a similar relationship with a linear magnetic zones which drilling has shown to also be due to pyrrhotite disseminations in argillaceous sediments.

These pyrrhotite horizons are thought to be the equivalents of the "ore equivalent horizons" (Sections 3.4 and 4.4)

4.9 DETAILS OF INDIVIDUAL DEPOSITS

Because magnetic massive sulphide deposits hosted by turbidite sequences which have no obvious association with igneous activity have never previously been comprehensively studied as a group the following section give detailed topic-consistent descriptive summaries for most of the deposits of this type which have been identified. These summaries have been used as a basis for the overview given in the previous sections as well as the exploration guidelines given in Section 4.10.

4.9.1 Sullivan Area British Colombia Canada

4.9.1.1 Introduction

The Sullivan area of British Columbia, Canada hosts the massive Sullivan lead-zinc deposit (Hamilton et al., 1982). Until the end of 1979, 111,600,000 tonnes of ore containing 6.8%Pb, 5.9%Zn and 82g/t Ag had been produced from this mine. At this time the remaining diluted reserves were 49mt, 4.5%Pb, 5.9%Zn and 37g/t Ag. The small adjacent Vulcan occurrence (Gifford, 1971) appears to have a similar setting and mineral composition. Several other relatively minor deposits occur in the area. Details of these are summarized by Hoy (1982) however it is not obvious that they can be classed as analogues of Sullivan.

4.9.1.2 Setting of the Deposits

The deposits of the Sullivan area lie within a belt of Middle Proterozoic (Helikan) sediments of the Aldridge Formation of the Purcell Supergroup. The most significant deposit (Sullivan) occurs as conformable mineralization at the contact between the Lower and Middle Divisions of the Aldridge Formation. The Lower Division consists primarily of thin bedded pyritic argillites and the transition to the Middle Aldridge is marked by an abrupt charge to turbidite deposition which is characterised by a discontinuous sheet of slump deposits and intraformational conglomerates. Turbidites are well developed near the base of this division and become thinner and less well developed towards the top. Upper Aldrige sediments consist of thin bedded carbonaceous argillites. Abundant "sills" of diorites and granophyres occur in the Lower Aldridge Formation. No igneous rocks are known to be contemporaneous with the Sullivan mineralization. Kanasewich et al. (1969), on the basis of deep seismic data, identified a rift beneath flat lying Palaeozoic and Mesozoic rocks in Alberta by using correlations with a negative Bouguer gravity anomaly and magnetic anomaly trends, has postulated that the rift continues into the Sullivan area. Fault patterns and isopach thickening described by Hoy (1982) suggest that the Sullivan deposit is located in a rift setting.

Purcell rocks are folded about north trending axes to form the Purcell anticlinorium which contains open gentle folds. Regional metamorphism in the area has attained greenschist facies.

4.9.1.3 Stratigraphic Associations

The stratigraphy of the area which was described in Section 4.9.1.2.

4.9.1.4 Mineralization

The mineralization of the Sullivan deposit is described in Section 4.9.1.9

4.9.1.5 Mineralization Associations

Both the Sullivan Mine and the Vulcan Deposit are on the contact between the Lower and Middle Aldrige Formation. Isopach evidence at Sullivan suggest that the immediate host rocks of the mineralization were deposited in a local sub basin. Hoy (1982) has speculated that mineral deposits in the Sullivan area are related to major transverse faults.

The Sullivan deposit occurs in a pyrrhotiferous shale horizon, the extent of which is not clear in published literature.

4.9.1.6 Origin of the Mineralization

It is generally accepted that the mineralization was deposited on the sea floor directly over a conduit now evinced by brecciated zones of footwall sediments and sulphide stringer zones.

4.9.1.7 Additional Regional Detail

None noted.

4.9.1.8 Magnetic Signatures

See below.

4.9.1.9 Sullivan Mine

Principal references: Ethier et al. (1976), Hamilton et al. (1982)

Host Rocks: The footwall rocks are composed of intraformational conglomerate and massive lithic wacke overlain by quartzwacke and pyrrhotite laminated mudstone. The ore zone is overlain by several upward fining sequences of quartzwacke and mudstone. Intercalations of mudstone occur in the mineralization.

Form of the Mineralization: The orebody (Figure 4.1) is gently dipping and has a roughly circular outline approximately 2000 m in diameter. It is up to 100 m thick in its western part. In the east it consists of five distinct conformable layers of mineralization. A roughly funnel shaped zone of brecciation occurs beneath the ore zone which in places has been heavily mineralized by pyrrhotite.

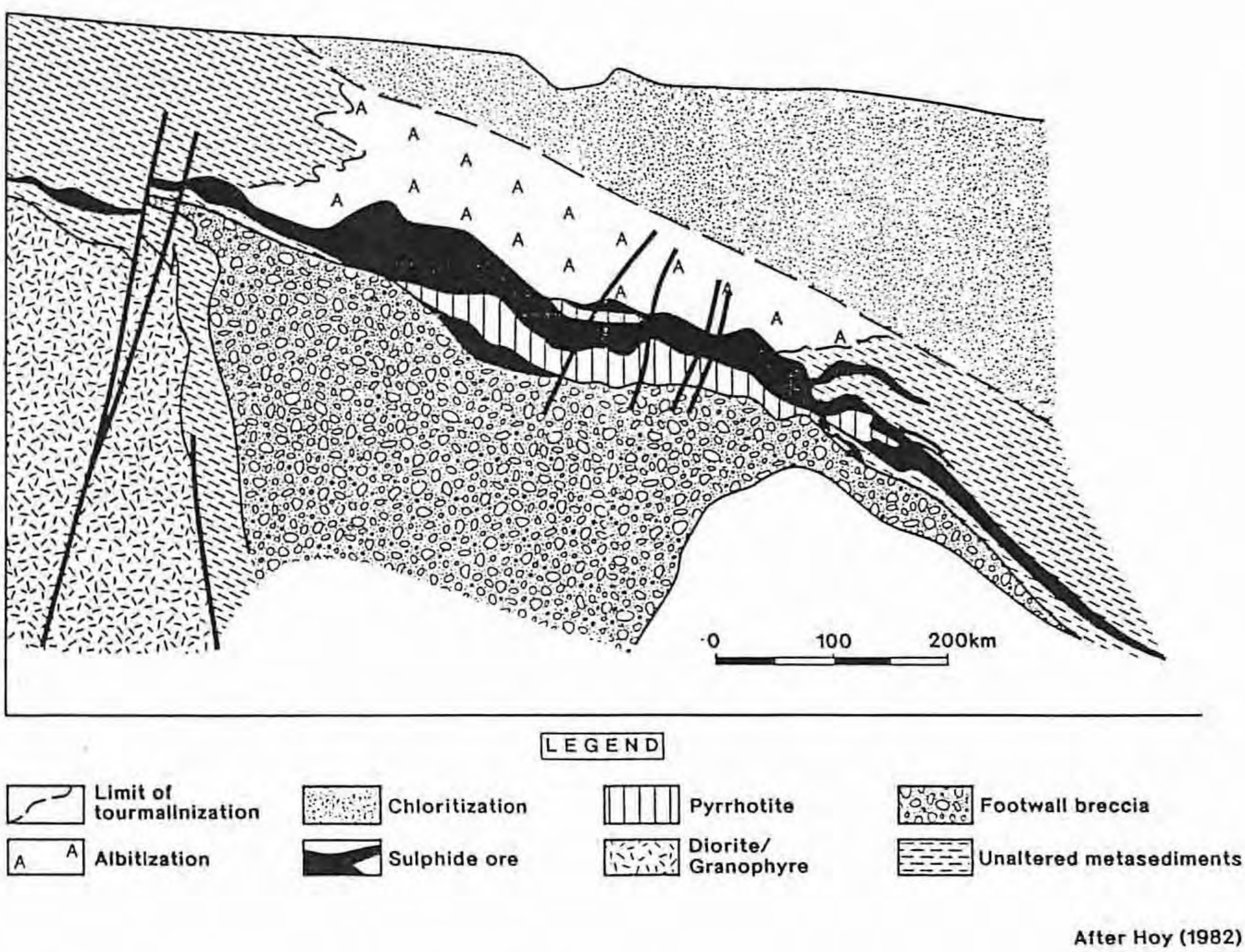


Figure 4.1 The Sullivan deposit - a classic example of zoning in a Pb-Zn rich turbidite hosted massive deposit. The pyrrhotite zone consists of monoclinic pyrrhotite and the shales which extend away from the deposit contain disseminated pyrrhotite (an "ore equivalent horizon"?). The brecciated feeder zone is clearly apparent.

Mineralization: Pyrrhotite and pyrite in the ratio 7:3 are the most important sulphides and galena and sphalerite are the principal ore minerals. The magnetite content is less that 1%. Quartz and calcite make up 50-70% of the non sulphide ore and chlorite makes up 30% of the remainder. As shown in Figure 4.1 the orebody contains a "massive" pyrrhotite zone. This portion contains significantly less sphalerite and galena than the remainder of the deposit.

Deposit Size: At the end of 1979 the mine had produced 111,600,000 tonnes of one grading 6.8%Pb, 5.9%Zn and 82g/t Ag. Remaining diluted reserves at the time were 49,000,000 tonnes containing 4.5%Pb, 5.9%Zn and 37g/t Ag.

Structural Setting: The deposit is on the folded and faulted limb of an anticline. The main lenses of mineralization are conformable to the bedding. It has been postulated that the deposit was localized in a depression at the intersection of major faults.

Magnetic Responses: No magnetic survey data or rock property measurements have been located for the Sullivan Mine and consequently its magnetic responses are not known. These could be difficult to ascertain from a magnetic survey given the existence of mine workings and the fact that gabbro intrusions flank the ore body (these are shown on maps published by Hamilton et al. (1982)).

Although the overall magnetite content of the deposit is less that 1%, magnetite is reported as being "common in places". It is possible that the body could have a magnetic response due to its magnetite content.

Detailed studies by Ethier et al. (1976) show that both monoclinic pyrrhotite and hexagonal pyrrhotite coexist and that "both are volumetrically significant". Inversion of hexagonal pyrrhotite to monoclinic pyrrhotite appears to have occurred. Given the massive volume of pyrrhotite in the orebody it appears most probable that the monoclinic pyrrhotite would cause a recognisable magnetic response.

4.9.2 Labrador Trough, Quebec, Canada

Principal Reference: Barrett et al. (1988)

4.9.2.1 Introduction

The Labrador Trough of Quebec (Dimruth, 1972; Dimruth and Dresser, 1978; Wardle and Bailey, 1978) contains four sediment hosted massive sulphide deposits (Wares et al., 1988). The Soucy No. 1 deposit which has been described in detail by Barrett et al. (1988) is significant in that it is a relatively rare example of such a deposit of Proterozoic age and that its relative lack of deformative and metamorphism has allowed a detailed appreciation of its mineral zoning.

4.9.2.2 Setting of the Deposits

The deposits are hosted in turbidite sequences containing conglomerates, quartzites, greywackes, siltstones and mudstones of variable thicknesses and relative proportions. Voluminous tholeiitic volcanism occurs in the section at levels significantly higher than the horizons containing the mineral deposits although mafic sills do intrude the section in the vicinity of the deposits. Barrett et al. (1988) suggest that some of the sills may be synsedimentary although it is obvious that most, if not all, are coeval with the overlying basalts.

The region has been metamorphosed to middle greenschist facies.

Tectonic interpretations of the area are hindered by lack of significant relevant exposures however the consensus of most workers favours a rift setting above attenuated continental crust. Barrett et al. (1988) consider the area may have evolved to a continental margin.

4.9.2.3 Stratigraphic Associations

All four mineral deposits of the area are contained within the Baby Formation which is subdivided into:

Lower Baby: turbidites containing conglomerates, quartzites, greywackes, siltstones and mudstones.

Middle Baby: this level which contains all four deposits is approximately 50 m thick and is known as "iron formation". It contains oxide, carbonate, silicate and sulphide facies of iron minerals. In the vicinity of the Soucy No. 1 deposit it consists of pyritic graphitic slate. Although Barrett et al. (1988) imply that the Middle Baby "iron formation" is basin wide geologists may well be recognising different exhalative formations related to different deposits.

Upper Baby: consists mostly of rythmically banded distal turbidites and mudstones.

Basalts are rare within the Baby Formation and have not been mapped anywhere in the region of the Soucy deposit.

The Baby Formation is overlain by the tholeiitic Hellancourt Basalts.

All these formations are of Lower Proterozoic age.

4.9.2.4 Mineralization

The Soucy deposit contains 5.44mt, 1.49%Cu, 1.80%Zn, 13.7g/t Ag and 1.61g/t Au. In its original undeformed form it consisted of a massive sulphide lens up to 40 m thick and 400 m in lateral extent. Detailed zoning in the deposit has been described by Barrett et al .(1988):

(i) a feeder pipe alteration zone occurs in sediments below the deposit. This pipe consist of veins at high angles to the bedding which contain ankerite stiplomelane, pyrrhotite and minor chalcopyrite.

(ii) an alteration zone approximately 5 m thick immediately below the ore lens which lacks the veins of the pipe and in which primary sedimentary features have been obliterated and replaced by a fine grained assemblage including stiplomelane, magnetite and pyrrhotite and traces of chalcopyrite and pyrite.

(iii) a massive sulphide lens having a sharp contact with the foot wall and which contains pyrite in a matrix of pyrrhotite, chalcopyrite and sphalerite with traces of galena. Magnetite is also reported.

(iv) laminated sulphides of pyrite-pyrrhotite-iron-silicate-quartz and minor chalcopyrite.

(v) banded sediments which consist of regular alternations of mm scale sulphide layers and silty turbidite layers. These pass laterally into silicate and sulphide facies iron formation which apparently includes pyrite disseminations in shale. These "iron formations" apparently extend laterally for several kilometres from the deposit.

4.9.2.5 Mineralization Associations

The association of the Labrador Trough mineral deposits with the Middle Baby "iron formations" (i.e. iron facies silicates, sulphides, carbonate oxides) appears to be a classic example of an association with an "ore equivalent horizon". Barrett et al. (1988) have inferred that these deposits are associated with hydrothermal vents whose locations were controlled by faults related to the extensional regime affecting the locality of the deposits.

4.9.2.6 Origin of the Mineralization

On the basis of the mineral zoning in the deposit Barrett et al. (1988) have interpreted a hydrothermal origin for the deposit involving metal ascent through the feeder pipe and subsequent deposition on a sea floor.

4.9.2.7 Additional Regional Detail

None has been located. Such data could be difficult to interpret because of thrusting and imbrication in the Labrador Trough.

4.9.2.8 Magnetic Signatures

It is obvious that the Soucy deposit contains significant amounts of pyrrhotite plus a magnetite component. Unfortunately no mention is made of whether the pyrrhotite is magnetic monoclinic pyrrhotite and no percentages are given for the pyrrhotite and the magnetite in the deposit. The deposit would probably give a distinct magnetic anomaly if monoclinic pyrrhotite is present. It is interesting to note that pyrrhotite appears to be distributed throughout the deposit at all levels from the feeder to the upper laminated sulphides.

Pyrrhotite also appears to occur in the laminated ores which pass laterally into the "ore equivalent" iron facies formations. It is not clear to what extent these iron facies formation contain magnetite quartzites although from the descriptions of Barrett et al. the existence of such magnetic units is possible.

The magnetic response of the gabbros which have extensively intruded the turbidite section in the vicinity of the Soucy deposit are likely to obscure any magnetic anomalies arising from the mineralization.

4.9.2.9 Details of Individual Deposits

Soucy Deposit

Principal reference: Barrett et al. (1988)

Host Rocks: turbidites consisting of conglomerates, quartzites, greywackes, siltstones and mudstones.

Form of the Mineralization: originally a massive sulphide lens up to 40m thick and 400m long but presently consisting of two separate synclinal keels as a result of structuring.

Mineralization: chalcopyrite and sphalerite contained within pyritic and pyrrhotitic massive sulphide (see Section 5.9.6.4 for a detailed description).

Structural Setting: the deposit is conformable to the bedding. It lies on the east limb of a major syncline and has been folded into the keels of two minor synclines. The host sediments have been extensively intruded by gabbro.

Other Deposits in the Labrador Trough

See: Wares et al. (1988).

4.9.3 Deposits in the Cobar Area, N.S.W., Australia

4.9.3.1 Introduction

The Cobar district of western New South Wales, Australia hosts clusters of massive sulphide lenses which contain varying relative concentrations of copper, zinc, lead, gold and silver (Russell and Lewis, 1965; Brooke, 1975; Suppel and Clark, 1990). The orebodies which are markedly elongated in the vertical direction and variably discordant to bedding occur in deepwater turbidite sequences which consist predominantly of mudstones and siltstones and which are devoid of igneous rocks.

The magnetic responses of these deposits are probably better studied and reported than for any other group of massive sulphide deposits.

4.9.3.2. Setting of the Deposits

Principal references: Glen (1985), Degeling et al.(1986), Glen, (1987)

The majority of the deposits are located in the vicinity of the township of Cobar. The Elura deposit (Schmidt, 1990) which has significant differences in form and mineral content to the deposits in the vicinity of Cobar occurs 43 km north of the township of Cobar.

The host rocks are thick (6 km) Devonian Cobar Supergroup sediments. These consist predominantly of turbidites deposited in deepwater portions of the Cobar Basin (Suppel and Scheibner, 1990) which is north north west trending trough approximately 40 km wide which was formed as a result of Devonian crustal extension. A metamorphosed and folded Cambro-Ordovician landmass lay at the eastern margin of the Cobar Basin which is marked by a major fault (the Rookery Fault). The western margin of the basin is obscured by younger cover.

A deep crustal seismic reflection survey (AGSO 1993) indicates that the basin is markedly asymmetric (a half graben) with the maximum sediment thickness in the west. The basin appears to have formed over a zone of midcrustal detachment associated with an extension of approximately 24 km towards the northeast.

Structuring has created tight folds and prominent cleavage and resulted in lower greenschist facies metamorphism. Evidence assessed by Binns (1985) and Glen et al. (1986) suggest that the most recent deformation in the area occurred in the Early Devonian shortly after sedimentation.

4.9.3.3 Stratigraphic Associations

The Cobar Supergroup contains the Kopje, Nurri and Amphitheatre Groups. The Kopje Group was deposited in a shelf setting on the eastern basin margin and is the shallow water equivalent of the deepwater Amphitheatre Groups and underlying Nurri Group. The Nurri Group consists of lithic sandstone, minor conglomerate and siltstone of the Chesney Formation overlain by mudstone and siltstone of the Great Cobar Slate and was deposited as a series of fans extending westwards. The Amphitheatre Group which overlies and interfingers the Nurri Group and consists of siltstone (CSA siltstone) and minor sandstone was derived from the west and was also deposited as a series of fans.

4.9.3.4 Mineralization

The mineralization in the Cobar area occurs in lenses up to several hundred metres long and a few tens of metres wide which can have depth extents over 1000 m. The mineralization at Elura has the form of vertically elongate ellipsoids with diameters up to 100 m. The mineralized lenses are frequently clustered in groups with varying degrees of interconnection and with common northerly trending orientations. They are located in zones of deformation and shearing and transgress the bedding.

The mineralization consists of areas of weak disseminated sulphides, silica and disseminated sulphides and accumulation of massive sulphides. Various ore types have been recognised however the classifications of different authors vary and in any case it appears that the "types" are frequently gradational. The subdivisions do not even strictly apply between different deposits. The broad types that appear to have been recognised are:

Siliceous ore: containing up to 50% silica in various forms with sulphide content less than 25%. At Elura the sulphide content of this ore is principally pyrite sphalerite and galena whereas at other localities it contains pyrrhotite and chalcopyrite.

Massive ore: containing more than 50% sulphides. The massive ores include pyrrhotite-chalcopyrite-magnetite (Great Cobar); pyrite, sphalerite and galena and pyrite, pyrrhotite, sphalerite and galena at Elura; pyrite, pyrrhotite, chalcopyrite and pyrrhotite, galena and sphalerite at the CSA Mine.

Several deposits have significant gold and silver contents.

4.9.3.5 Mineralization Associations

In the Cobar area the ore occurs in three different lines with three different settings. These are:

(i) within the CSA siltstone
(ii) within the Great Cobar Slate
(iii) at the contact between the Great Cobar Slate and the Chesney Greywacke.

The host rocks for the Elura deposit are lithologically equivalent to the CSA siltstone.

The mineralization shows a preference for finer grained sediments.

All the ore bodies appear to be associated with zones of cleavage and many appear to be associated with fold axes, kinks or culminations in local structures. The Elura mineralization is located in tight domes formed by dip reversals along a plunging anticline.

The mineralization is discordant to the bedding.

Persistent linear zones of higher magnetic intensity correlate with each line of mineralization (Brooke, 1975; Sheard et al., 1991 and Clark and Tonkin, 1993) and these have been identified as due to zones of higher relative concentrations of magnetic pyrrhotite in the country rock.

4.9.3.6 Origin of the Mineralization

Two basic models have been proposed for the origin of the mineralization in the Cobar area:

(i) Epigenetic (replacement origin) in which ore bearing fluids have been channelled through the sediment pile to levels where they deposited mineralization in faults and shear zones (Andrews, 1919; Sullivan, 1950; Mulholland and Rayner, 1958; Rayner, 1969; O'Connor, 1980; Kirk, 1983; Binns and Appleyard, 1986; Glen, 1987; De Roo, 1987). This model requires the expulsion of mineralizing fluids from the sedimentary pile or a magmatic source for the fluids.

(ii) Syngenetic origin (Robertson, 1974; Gilligan and Suppell, 1978; Sangster, 1979; Marshall and Sangameshwan, 1982; Marshall et al., 1983; Pogson, 1983) in which the sulphides formed as submarine exhalative deposits. Such deposits typically exhibit mineral zoning from basal pyrrhotite through massive pyrite to siliceous (cherty) upper levels. A syngenetic origin for the Cobar ores requires subsequent modifications during metamorphosing and structuring to intrude ductile sulphur rich bodies into overlying sediments.

4.9.3.7 Additional Regional detail

Regional gravity data (published by the Bureau of Mineral Resources) shows that that the Cobar Basin corresponds with a regional gravity high. This phenomenon is consistent with the rifting/crustal thinning processes inferred for the area. The Cu and Cu-Zn deposits appear to be clustered over the maximum of the gravity anomaly. The Elura Pb-Zn deposit is located well off the gravity peak.

4.9.3.8 Magnetic Signatures

As is demonstrated by the examples in the following sections the deposits of the Cobar have distinct magnetic responses by virtue of their pyyrhotite and magnetite contents. The magnetite rich deposits are recognisable by their greater amplitudes. The deposits are commonly hosted by linear shale horizons which contain disseminated pyrrhotite and which give linear magnetic anomalies. The Cobar deposits frequently appear as "bulls-eye" anomalies superimposed on weaker linear magnetic trends (Figure 4.2).

Significant surficial maghemite has been precipitated in the Cobar area and the magnetic effects of this mineral produce numerous zones of high frequency erratic magnetic readings which could be obscuring magnetic responses due to mineralization. This problem has been described by Wilkes (1979) and Sheard et al. (1991).

4.9.3.9 Details of Individual Deposits

CSA Mine

Principal references: Brooke (1975), Scott and Phillips (1990)

Host Rocks: CSA siltstone thin bedded rythmically banded siltstone containing a few fine to medium grained greywackes at irregular intervals.

Orebody Form: six groups of variably interconnected elliptical north trending tabular bodies. Average length 60-170 m, average width 12 m, steep dip and plunge. Some mineralized bodies have depth extents of at least 1000 m.

Mineralization: varies according to body and group of bodies. Ranges through pyrrhotite-chalcopyrite, pyrite-chalcopyrite, pyrite, sphalerite and galena. Minor magnetite is present.

Deposit Size: 18mt 2.7%Cu, 0.6%Pb, 2.0%Zn.

Structural Setting: The bodies dip at 75^0 and are located on a monoclinal flexure which is prominently cleaved in the vicinity of the orebodies.

Magnetic Signature: As documented by Thompson (1953) and Wilkes (1979), the CSA mine corresponds to a subcircular 160 nanotesla ground vertical field magnetic anomaly. This anomaly is distinct in aeromagnetic data shown in Figure 4.2 and in data published by Sheard et al. (1991) The magnetic response of the CSA Mine is superimposed on a linear magnetic "ridge" (linear anomaly). This "ridge" has been investigated in detail by Hone and Gidley (1986) and Clark and Tonkin (1993). The source of the anomaly are concentrations of up to 1% pyrrhotite in thin interbeds of siltstone and calcareous quartzite. Magnetic property measurements on

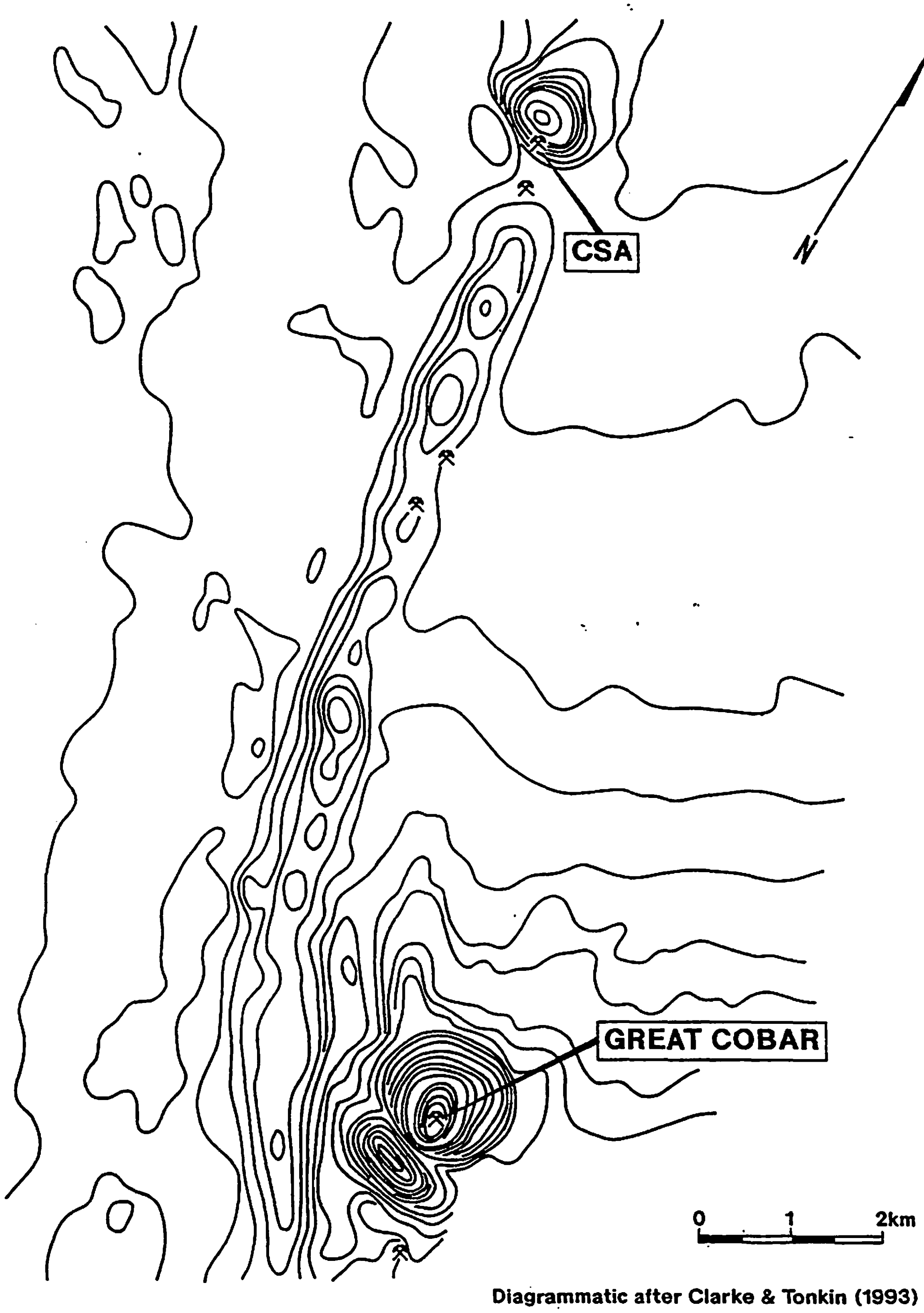


Figure 4.2 Aeromagnetic data from the Cobar area (contour interval 5 nanoteslas). The CSA Mine is a pyrrhotite rich deposit. The Great Cobar deposit which corresponds to a higher amplitude magnetic anomaly is a magnetite rich deposit. The linear magnetic anomalies upon which the magnetic anomalies due to the CSA and Great Cobar deposits are superimposed are due to "ore equivalent" shales containing disseminated pyrrhotite.

drill cores and computer modelling by Clark and Tonkin (1993) show that the measured susceptibility of the pyrrhotite zone of 880 x 10^{-6} SI units relative to a country rock susceptibility of 500 x 10^{-6} SI units could only explain approximately 10% of the amplitude of the magnetic ridge anomaly. It is evident that a significant component of remanent magnetization contributes to the magnetic ridge anomaly. It should be noted that concentration of pyrrhotite along the magnetic ridge cause culminations in the magnetic field which have similarities (albeit of smaller amplitude) with those caused by economic mineralization. It was the drill testing of such a feature which prompted the studies of Hone and Gidley (1986) and Clark and Tonkin (1993).

Elura

Principal references: Emerson (1980), Schmidt (1990a, 1990b)

Host Rocks: a monotonous turbidite sequence of mudstone and siltstone equivalent to the CSA siltstone at Cobar.

Form of Mineralization: at least 7 elliptically shaped vertical pipe like bodies the largest of which has a maximum diameter 100 m and a vertical extent of at least 700 m.

Mineralization: sphalerite and galena in association with pyrite and pyrrhotite. Dominant gangue minerals are siderite and quartz. Concentric zoning as shown in Figure 4.3.

Deposit Size: reserve potential of 27mt, 8.4%Zn, 5.6%Pb, 139g/t Ag.

Structural Setting: discordant to sedimentary host located in a zone of cleavage along the axis of an anticline.

Magnetic Signature: the magnetic characteristics of the Elura orebody are extremely well documented (Wilkes, 1979; Davis, 1980; Emerson, 1980; Blackburn, 1980; Gidley and Stuart, 1980; Tonkin et al., 1988; Sheard et al., 1991; Clark and Tonkin, 1993). A distinct magnetic response arises from the pyrrhotite which has a predominantly monoclinic form and which, as is shown in Figure 4.3 is generally confined to the core of the orebody.

The discovery of the deposit resulted from ground follow up of a distinctive circular aeromagnetic anomaly (Figure 4.4). The aeromagnetic data suggests that the source of the Elura magnetic anomaly is associated with a weaker version of a magnetic ridge associated with the CSA Mine which has been shown to be due to pyrrhotite disseminations in a sedimentary layer.

Ground magnetic follow up to the airbourne anomaly revealed a circular anomaly with a 150 nanotesla amplitude (Figure 4.5).

The most significant study of the rock properties of the Elura ore body is by Tonkin et al. (1988) who have shown that the measured average values of susceptibilities of samples taken below the 100 m depth of complete oxidation (52800 x 10^{-6} SI units) only accounts for approximately 10% of the ground magnetic anomaly. A significant component of remanent magnetization (Konigsberger ratio 9.4) was measured by Tonkin et al. who subsequently accurately modelled the Elura orebody by incorporating this remanence and using an ellipsoid model. The direction of the remanent magnetization suggests that it dates from the Cretaceous.

Tonkin et als. study has also indicated that the susceptibility of the mineralization is markedly anisotropic (K_1:K_2:K_3=1.6:1.2:1.0) with the maximum susceptibility being in a subvertical direction.

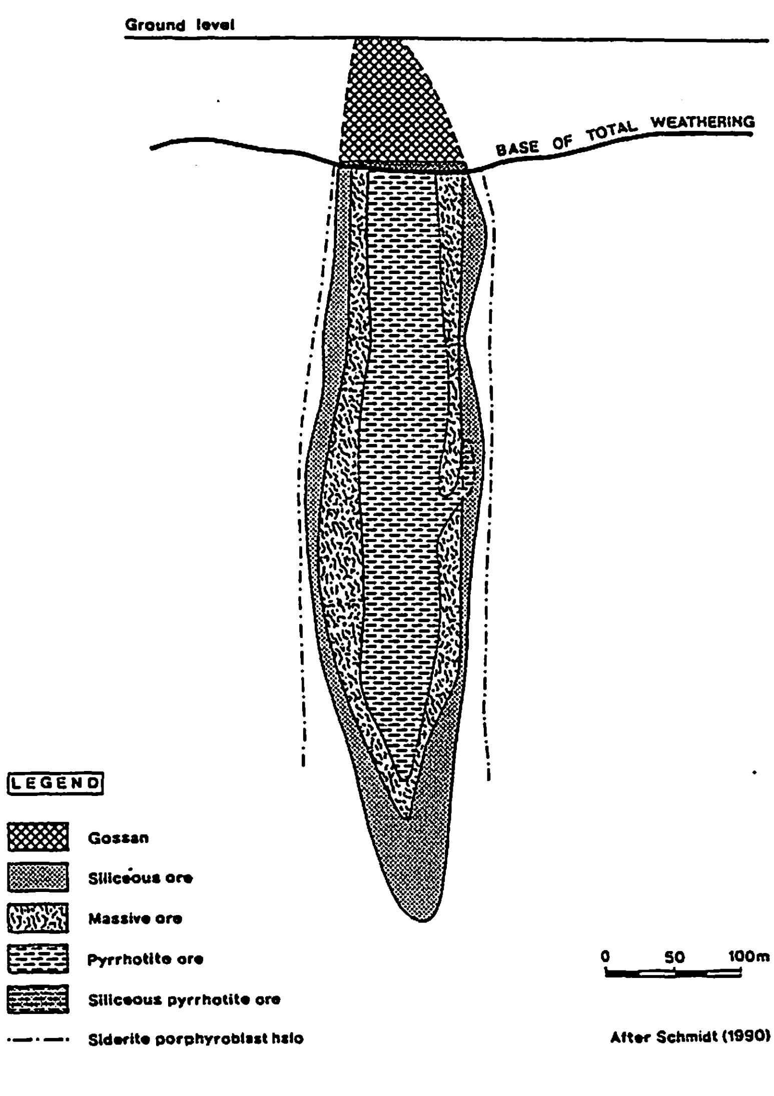


Figure 4.3 Geometry and mineral zoning of the Elura deposit This deposit appears to have been extensively remobilized.

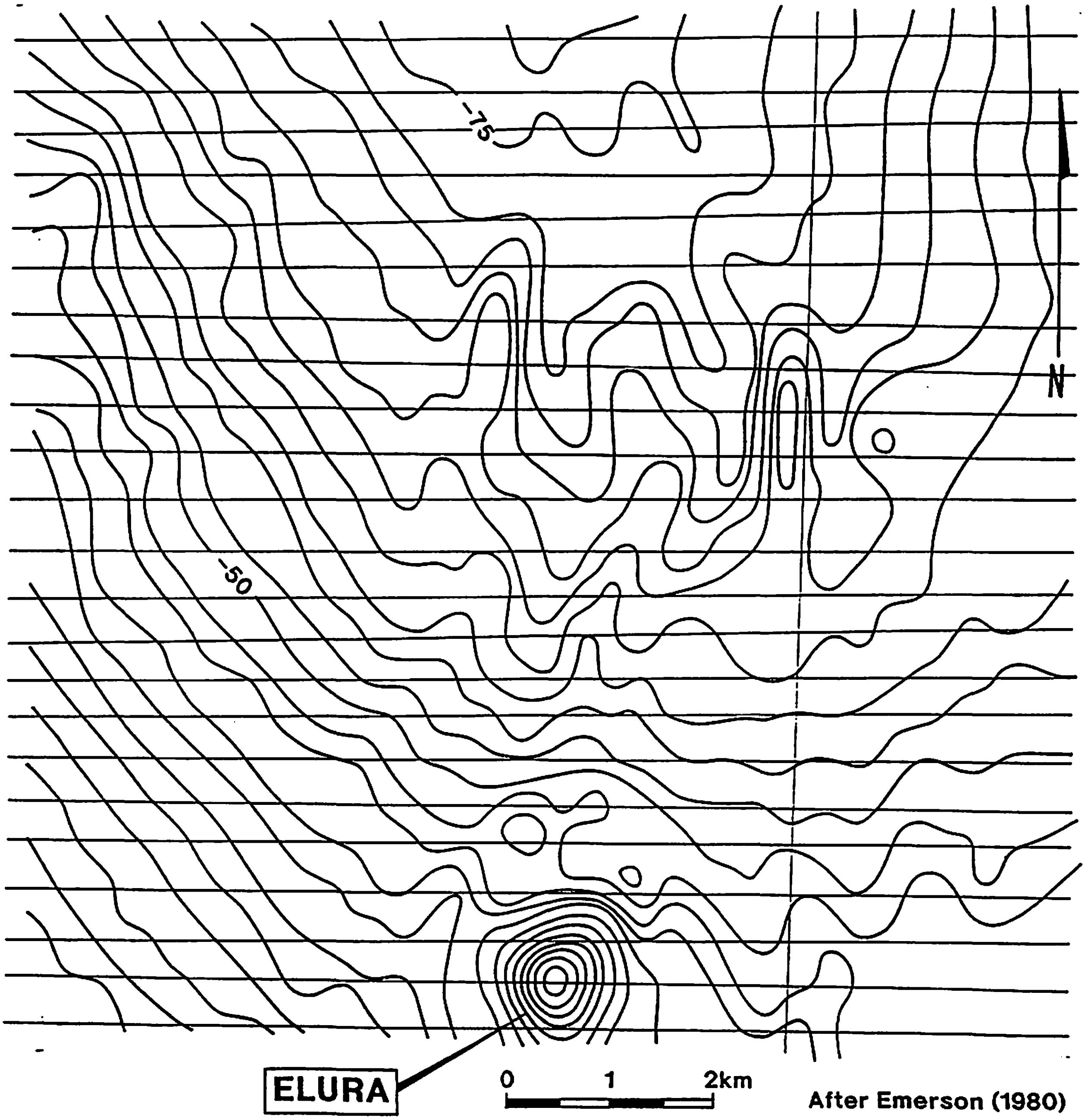


Figure 4.4 Aeromagnetic data over the Elura deposit. The deposit appears to be superimposed on a "magnetic ridge" which may be due to an horizon of pyrrhotiferous shale similar to those which are colinear with the Cobar deposits to the south. If so, this would appear to be another example of a magnetic "ore equivalent horizon". The small high 1 km due north of Elura is possibly an expression of one of the smaller deeper mineralized bodies known to occur in this area.

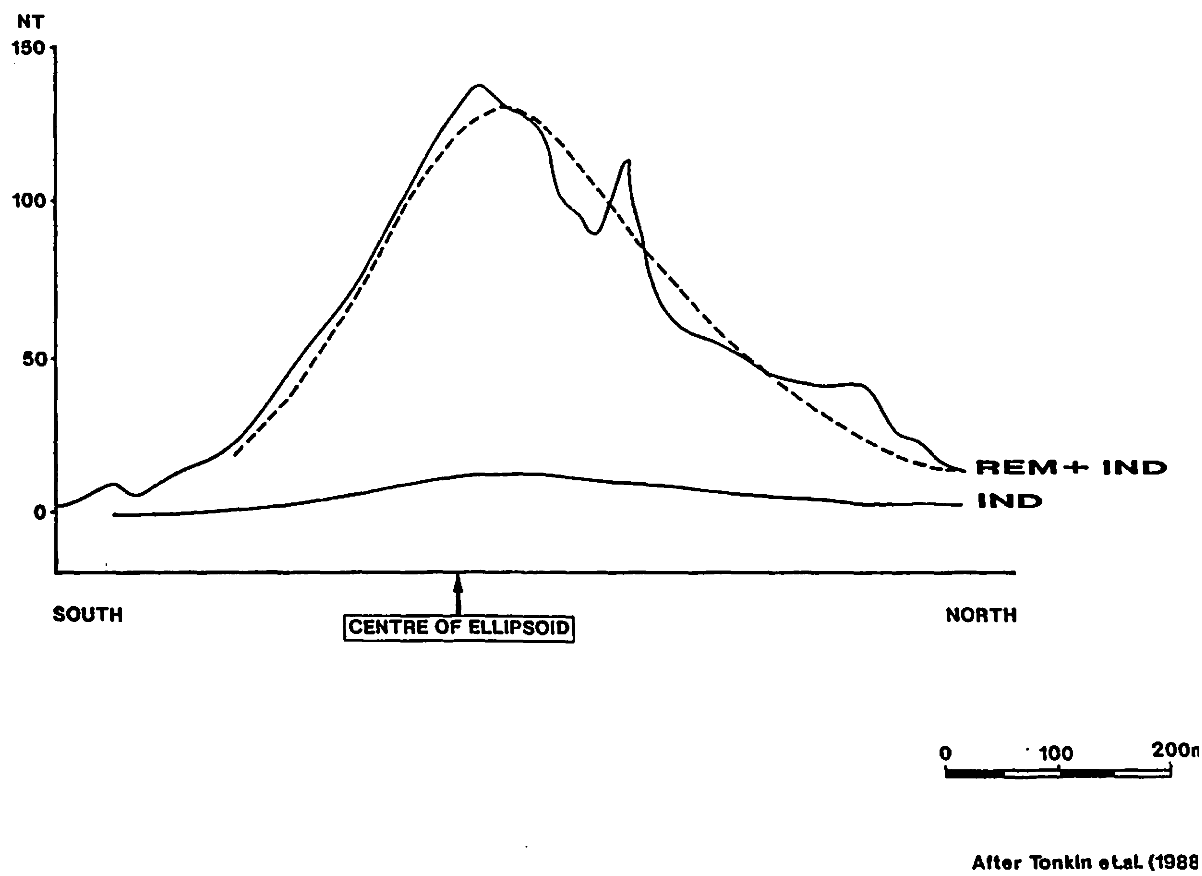


Figure 4.5 Ground magnetic data over the Elura deposit. The dashed line is the theoretical response of an ellipsoid model accounting for both induced and remanent magnetization. The curve marked "IND" shows the response if the remanent magnetization is not included.

Great Cobar

Principal references: Thompson (1953), Russell and Lewis (1965)

Form of Mineralization: the lode is 400 m long, up to 30 m wide and consists of 3 lenticular bodies which drilling has shown to have vertical extents of at least 1000 m, steep dips and a northerly pitch.

Mineralization: ore consists predominantly of chalcopyrite, pyrrhotite and magnetite with a low silica content which is flanked by siliceous ore consisting of veins and disseminations of pyrrhotite, chalcopyrite and magnetite. Stiplomelane is a common gangue mineral.

Deposit Size: until 1919 an estimated 3.5mt of ore was mined with a recovered grade of 2.8%Cu and 2g/t Au.

Structural Setting: quartz filled shear zones.

Magnetic Responses: The aeromagnetic data published by Clark and Tonkin (1993) (Figure 4.4) indicates that the Great Cobar mine corresponds to a dipolar magnetic anomaly with a greater amplitude than the anomaly corresponding to the larger CSA Mine. The greater presence of magnetite at the Great Cobar Mine would explain this difference. The Great Cobar mine is associated with a linear magnetic trend similar to but weaker than the trend associated with the CSA Mine (Figure 4.4 and Figure 1 of Sheard et al., 1991). Thompson (1953) has published ground magnetic contours which confirm the anomaly over the mine.

The Peak

Principal references: Thompson (1953), Hinman and Scott (1990)

Host Rocks: straddles the contact of the Great Cobar Slate and the Chesney Greywacke. Siliceous rock types with volcanic affinities at the base of the mineralization are believed to be local basement faulted into the base of the Cobar Supergroup.

Form of Mineralization: the mineralization occurs as veins, splashes, fracture fillings and disseminations in five distinct steeply dipping lenses with strike lengths of the order of 300 m, widths between 60 and 150 m and depth extents of at least 350 m.

Mineralization: pyrite, pyrrhotite, galena, sphalerite, chalcopyrite, gold and silver. Significant quartz gangue.

Deposit Size: indicated resource of 4.5mt, 0.7%Cu, 1.5%Pb, 1.7%Zn, 7g/t Au and 21g/t Ag.

Structural Setting: located on the western limb of an anticline in an area where several faults and shears cut the sedimentary units. The mineralization, faults and shears are all subparallel to cleavage.

Magnetic Response: Hinman and Scott (1990) report that a 250 nt anomaly which occurs 250 m east of the mineralization has been interpreted as being due to fine grained pyrrhotite disseminations in fine grained rocks. Hinman and Scott state that no obvious anomaly can be related to the mineralization whose effects may be obscured by the adjacent anomaly and which in any case may not be significant due to the depth of the mineralization and its low overall pyrrhotite content.

A contour map of a ground magnetic survey over the Peak area published by Thompson (1953) however shows a bulge in the contours over the Peak mineralization which suggests that the deposit does give a magnetic response which is partly obscured by the magnetic effects of the adjacent magnetic "ridge". Standard filtering techniques (e.g. vertical gradient) would be expected to enhance the resolution of the anomalies.

Occidental

Principal references: Mulholland and Rayner (1953), Russell and Lewis (1965).

Host Rocks: Great Cobar Slate at its contact with the Chesney Greywacke. Part of the lode occurs within the greywacke.

Form of the Mineralization: main orebody consists of two sheets separated by highly cleaved slate. Strike lengths are of the order of 160m and widths are 3-12 m. Sheets dip 85-90^0 east and plunge at 80^0 to the north. The vertical depth extent is at least 400 m.

Mineralization: pyrite, pyrrhotite, chalcopyrite and gold. Minor galena, sphalerite and magnetite.

Deposit Size: when mining ceased in 1952, 1,440,922t at a recovered grade of 9.35g/t Au had been produced.

Structural Setting: breccia zone, a bedding flexure occurs near the end of the orebody.

Magnetic Responses: not described in any specific publication however a regional data set published by Sheard et al. (1991) indicates that it occurs on a magnetic "ridge" (c.f. the CSA Mine) and it appears to correspond to a distinct area of higher magnetic intensity.

Other Deposits in the Cobar Area

Several smaller, less well documented deposits of the Cobar type occur in the Cobar area. These are:

Dapville Lode (Thompson, 1953; Russell and Lewis, 1965). A ground magnetometer survey over this deposit published by Thompson (1953) shows a 50 nanotesla magnetic anomaly over a mineralized shear zone.

Queen Bee Mine (Thompson, 1953)

Gladstone Mine (Russell and Lewis, 1965)

Chesney Mine (Russell and Lewis, 1965)
The presence of magnetite as well as pyrrhotite is reported for this deposit.

New Cobar (Mulholland and Rayner, 1953)

4.9.4 Deposits in the Kanmantoo Area, South Australia

4.9.4.1 Introduction

The Kanmantoo area of South Australia (Thompson, 1975; Spry et al., 1988; Both, 1990) hosts copper and lead-zinc deposits in what appear to be highly metamorphosed turbidite sequences.

4.9.4.2 Setting of the Deposit

Principal reference: Parker (1986)

The host rocks are metamorphosed Early Cambrian pelites and greywackes of the Kanmantoo Group originally deposited in a tectonic unit known as the Kanmantoo Trough (Thompson, 1975; Both, 1990). Various workers such as Von der Borch (1980) and Jenkins (1990) have interpreted the Kanmantoo Trough as a rift which developed into a marginal sea. Degeling et al. (1986) postulated that this marginal sea existed between a western continent which terminated in the vicinity of Adelaide and an eastern "Victoria Microcontinent". A section published by Thompson (1975) shows a platform area in the vicinity of Kangaroo Island with a deepening of the basin towards the south and east. Faulting may account for deepening and facies changes by observed (Parker, 1986). Studies by Flint (1978), Daily and al. (1980) are consistent with this regional model. The source of sediments in the Kanmantoo area was from a cratonic area to the north west (Preiss, 1987). Evidence exists for a sudden influx of siltstones and sandstones into a rapidly subsiding basin or marginal shelf during Kanmantoo Group deposition. These flyshoid sediments contain local turbidites.

The Kanmantoo Group was intensely deformed and metamorphosed by compression and heating associated with the Middle Cambrian - Early Ordovician Delamerian Orogeny. Three subsequent structuring events have been noted. Metamorphism in the vicinity of the Kanmantoo Mine has reached amphibolite grade.

It should be noted that the principal deposit in the area, the Kanmantoo Mine, is located in what appears to have been one of the thickest portions of the Kanmantoo Trough.

4.9.4.3 Stratigraphic Associations

Both (1990) summarizes the stratigraphic relationships in the Kanmantoo Trough. The copper and lead zinc mineralization occur in the Tapanappa formation for which there is no evidence of contemporaneous igneous activity. Metamorphism has obscured much sedimentary detail in the area. The Kanmantoo Mine is located in a garnet andalusite schist flanked by quartz mica schists. According to Verwoerd and Cleghorn's (1975) interpretation the garnet andalusite schists were originally argillaceous sediments and the quartz mica schists were originally arenaceous.

4.9.4.4 Mineralization

The lack of a larger sample of well documented deposits precludes making generalizations about the style of mineralization in the area. Details of individual deposits are given in Section 4.9.4.9. It should be noted that the Kanmantoo Mine is the only significant deposit and the only deposit for which significant data is available.

4.9.4.5 Mineralization Associations

The ore at the Kanmantoo Mine is enclosed in a chlorite schist which has been interpreted as a metamorphosed product of wall rock alteration. Thompson (1965) has suggested a northeast trending zone passes through both the Kanmantoo and Bremer Mines but Spry et al. (1988) reports that this feature has not been substantiated by field evidence. Lambert (1987) proposed that the mineralization is related to a north south lineament. Parker (1986) suggested that there is a common association of mineralization at the intersection of pyritic horizons with fracture zones but Spry et al. (1988) report that this idea cannot be substantiated. Sulphur isotope studies by Seccombe et al. (1985) suggest that there is a genetic association with pyritic sedimentary horizons rather that a structural relationship.

4.9.4.6 Origin of the Mineralization

Textural studies by Seccombe et al. (1985) indicate that the chalcopyrite, pyrrhotite, magnetite and pyrite of the Kanmantoo Mine deposit were constituents of the ore prior to metamorphism. Verwoerd and Cleghorn (1975) have suggested a syngenetic origin with subsequent remobilization during metamorphism and tectonism. The Kanmantoo and Bremer Mines contain discordant veins, stockwork and disseminated mineralization suggestive of subsurface vents (Seccombe et al., 1985).

4.9.4.7 Additional Regional Detail

None noted

4.9.4.8 Magnetic Signature

See below

4.9.4.9 Details of Individual Deposits

Kanmantoo Mine

Principal references: Verwoerd and Cleghorn (1975), Both (1990).

Host Rocks: the immediate host rocks are a garnet chlorite schist. This is enclosed in a garnet andalusite schist which is flanked by a quartz mica schist.

Form of the Mineralization: according to Verwoerd and Cleghorn (1975) "the orebody consists of a number of lenses of mineralization flattened parallel to the axial plane schistosity. Together these lenses have the overall shape of an elongated pipe striking 10^0 east, dipping 75^0 east and plunging 80^0 to the north. Maximum horizontal dimensions of the orebody are 120 m by 180 m. The vertical extent has not been determined; the deepest intersection to date being 450 m below ground surface".

Mineralization: equal proportions of chalcopyrite, pyrrhotite and magnetite. Lesser amounts of pyrite occur. The gangue is quartz-chlorite-garnet.

Within the individual ore lenses the mineralization occurs as:

(i) veinlets parallel to the axial plane schistosity (most of the mineralization occurs in this form)
(ii) massive accumulations
(iii) cross cutting veinlets
(iv) fine grained disseminations

Deposit Size: 4.05 mt of ore averaging 1%Cu was produced from the Kanmantoo Mine until its closure in 1976. At least 8 mt of 1.1%Cu mineralization remain in the deposit. Only minor traces of Pb, Zn, Ag and Au have been reported.

Structural Setting: discordant to relict bedding. Mineralization is on the limits of a fold and parallels the schistosity.

Magnetic Signature: Verwoerd and Cleghorn (1975) report that the pyrrhotite of the deposit is hexagonal however Figure 2 of their paper presents a profile showing that the orebody corresponds to a 1000 nanotesla ground magnetic anomaly. This is apparently due to the magnetite content of ore.

Bremer Mine

Principal references: Dickinson (1942), Duncan (1973), Spry (1976), Seccombe et al. (1985)

Host Rocks: biotite schist

Form of Mineralization: two shoots, one was worked over a strike length of 100 m and measured in width from 0.3 m near the surface to a maximum of 6 m at a depth of 79 m and then decreased with further depth.

Mineralization: reportedly generally similar to those from the Kanmantoo Mine. Chalcopyrite and pyrite are the dominant sulphides with lesser sphalerite and pyrrhotite. Some magnetite.

Deposit Size: very small. 37,000 tonnes of ore were produced during the period 1845-1907.

Structural Setting: in shear zones.

Magnetic Signature: not known.

Other Deposits in the Kanmantoo Area

As indicated by syntheses published by Thompson (1965, 1975), Spry et al. (1988) and Both (1990) the Kanmantoo region contains numerous small mineral deposits. In the Tapanappa Formation which hosts the Kanmantoo and Bremer Mines these appear to be of two types:

(i) copper deposits similar to the Kanmantoo and Bremer Mines and which occur as minor occurrences at the South Hill Prospect and several other localities.

(ii) lead, zinc deposits which occur at Alcare, Wheat Ellen, Strathalbyn, St Ives, Scotts Creek, Glenalbyn and Talisker. The exact settings and magnetic responses of these deposits are difficult to ascertain.

4.9.5 The Rouez Deposit

4.9.5.1 Introduction

The Rouez deposit (Icart and Safa, 1981) which contains 100 mt of mineralization grading 45%Fe, 32%S, 0.3%Pb, 1.5%Zn, 0.6%Cu, 21g/t Ag and 1.5g/t Au is situated in Brioverian (Proterozoic) detrital sediments in western France. It is the only deposit of its type known in the region.

4.9.5.2 Setting of the Deposit

On a regional scale the Brioverian formations consist of alternations of greywackes, siltstones and clayey siltstones with intercalations of pebbly mudstones. Volcanic facies have not been recognised and carbonates are rare. The sedimentary assemblage is devoid of marker horizons and appears to be the result of turbidite deposition.

The Brioverian of the Rouez area occurs in an isolated 10 km x 30 km outcrop and its continuation is obscured by younger granite intrusives and by Palaeozoic and Mesozoic sediments. The tectonic setting of the area is not obvious and no references on this subject have been located.

The Brioverian series has undergone a moderate synschistose deformation associated with very weak metamorphism attributed to the Variscan (Carboniferous) orogeny which occurred 300 million years after the deposition of the Brioverian.

4.9.5.3 Stratigraphic Associations

The deposit occurs in the Upper Brioverian. No detailed stratigraphic subdivision of this unit has been reported. The sediments indicate deep water deposition.

4.9.5.4 Mineralization

See Section 4.9.5.9.

4.9.5.5 Mineralization Associations

No marker horizons have been mapped in the vicinity of the deposit however aeromagnetic data indicates that the deposit is located on a linear zone corresponding to an elevated magnetic intensity with respect to adjacent areas. As discussed in Section 4.9.5.9 this regional anomaly has been interpreted as due to pyrrhotite disseminations in a sedimentary horizon.

The aeromagnetic data does not show any fault system which can be related to the deposit.

4.9.5.6 Origin of the Mineralization

The deposit is stratiform and the presence of chloritic and sericitic alteration zones and chert suggest a hydrothermal origin. Geochemical studies by Icart and Safa (1981) indicate that the massive sulphides have a hydrothermal origin while sulphides in the country rock have a sedimentary origin. No stringer zone evincing a feeder pipe has been found although this could be the result of limited drilling into the footwall or a remobilization of the body.

4.9.5.7 Additional Regional Detail

None noted.

4.9.5.8 Magnetic Signatures

See Section 6.9

4.9.5.9 Rouez Deposit

Principal references: Icart and Safa (1981), Sapin and Babu (1981).

Host Rocks: deepwater turbidite sequence containing shales, siltstones and greywackes.

Form of the Mineralization: steeply dipping lenses which taper downwards towards their extremities and which appear to be interconnected. The largest lenses have lengths of 100 and 300 m and thicknesses up to 50m. The mineralization extends from the surface to at least 350 m in depth (Figure 4.6).

Mineralization: pyrite (43%), pyrrhotite 22% and siderite (22%) with subordinate sphalerite, chalcopyrite and galena. Several types of ore have been distinguished:

- dominantly pyrrhotite: massive fine grained and preferentially associated with copper.
- banded pyritic ore: rich in lead zinc with beds of siderite and interbedded sphalerite and galena
- dominantly pyritic ore, massive, finely brecciated occasionally copper bearing.
- sericitic or silico chloritic matrix ore, chert facies and sulphide stockworks.

Deposit Size: 100mt containing 45%Fe, 32%S, 6.3%Pb, 1.5%Zn, 0.6%Cu, 21g/t Ag, 1.5g/t Au, 0.11`%As.

Structural Setting: the orebody is apparently conformable to the bedding which is steeply dipping. It may be located in the axis of an anticline.

Magnetic Signatures: Lebouteiller (1981) discusses the magnetic responses of the Rouez body which are shown in Figures 4.7 and 4.8. Pyrrhotite is the only mineral causing the magnetic response. It should be noted that difference in responses between the eastern and western lenses of the deposit can be explained by the relative rarity of pyrrhotite in the western lens.

The base of the zone of oxidation in the area is at a depth of 40 m below ground surface.

Magnetic modelling using known geometries of the pyrrhotite bodies and measured susceptibilities has shown that the pyrrhotite has a strong component of remanent magnetization which is closely aligned to the present direction of the earth's magnetic field.

The author has personally worked with the aeromagnetic data from the Rouez area and has produced computer models which duplicate the magnetic response of the linear magnetic zone in which the Rouez deposit is situated. Despite the fact that very close matches between the observed and calculated data were obtained the resultant model was geologically implausible. Drilling has intersected disseminated pyrrhotite. It is thought that this linear magnetic effect is due to remanently magnetized pyrrhotite disseminations in sediments (c.f. the effect noted by Clark and Tonkin (1993) in the Cobar area of Australia).

The occurrence of a magnetic low at the western end of the deposit is intriguing as it does not fit with the body geometry or the remanence. It could be due to destruction of pyrrhotite in the host rocks by alteration processes.

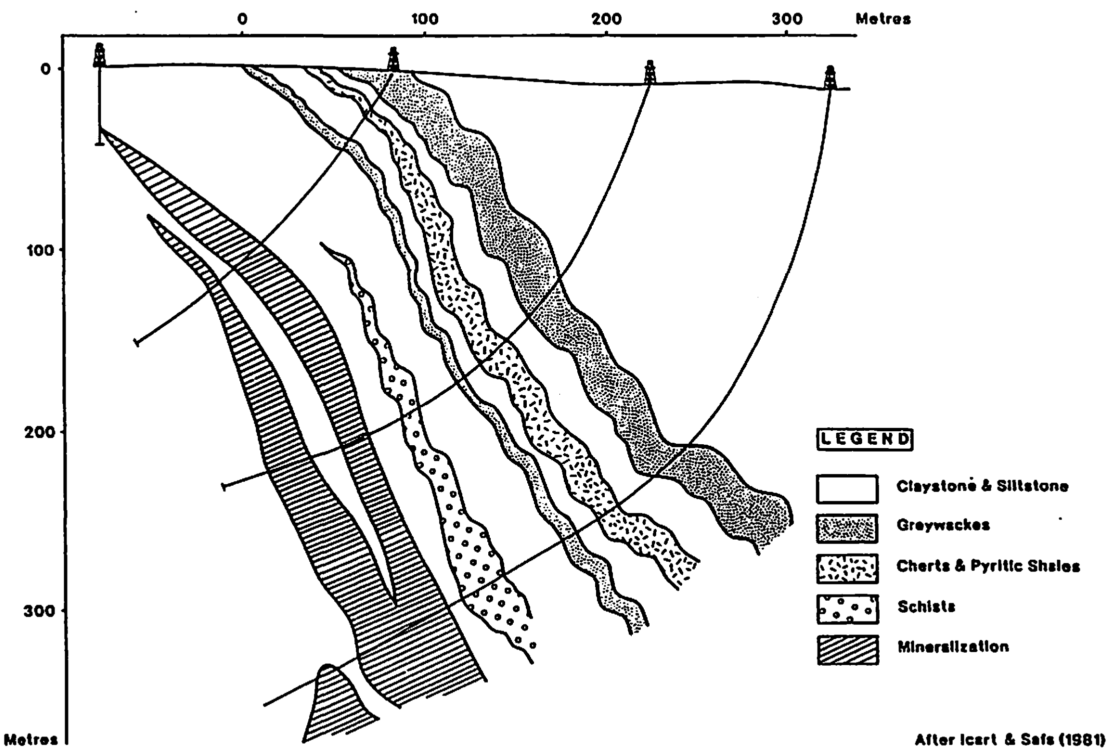
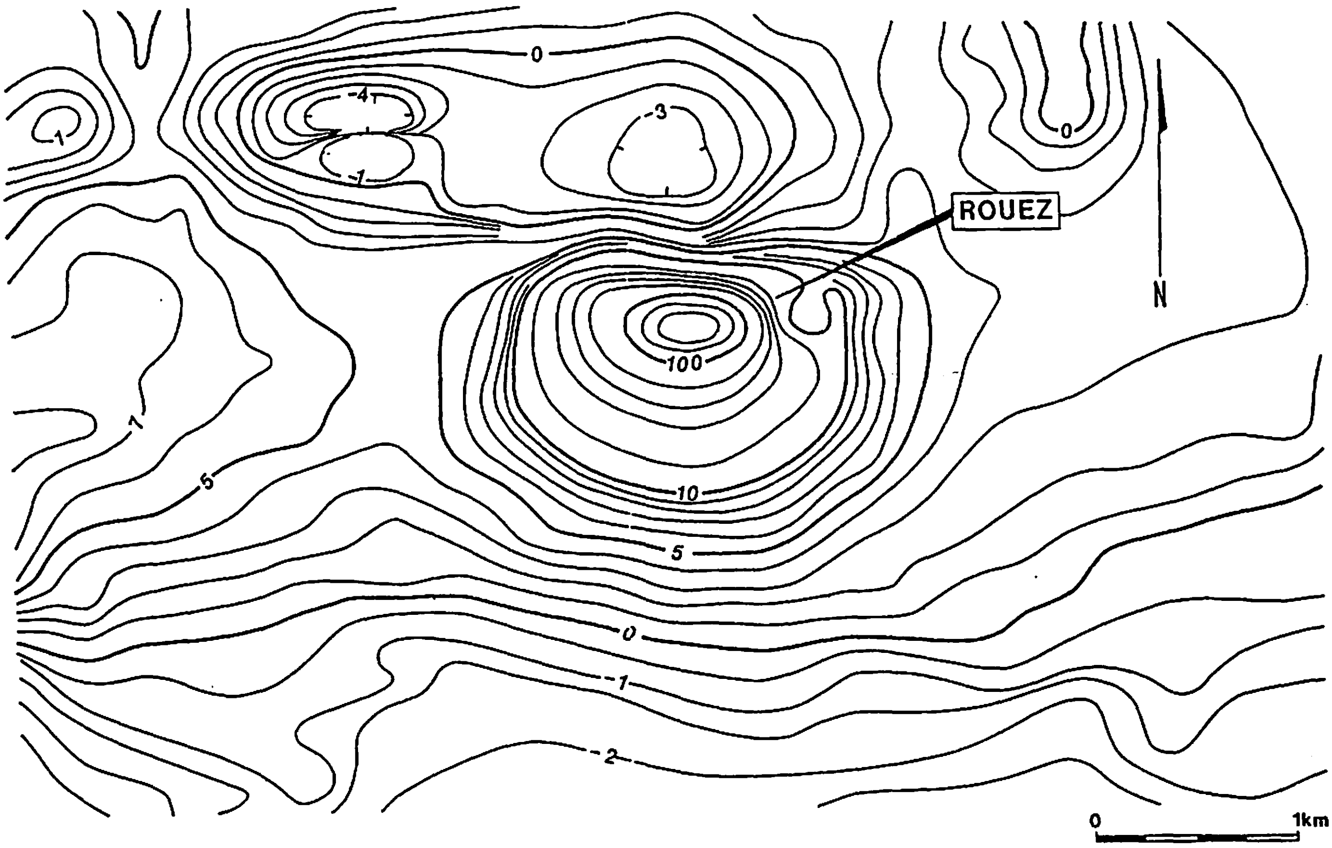
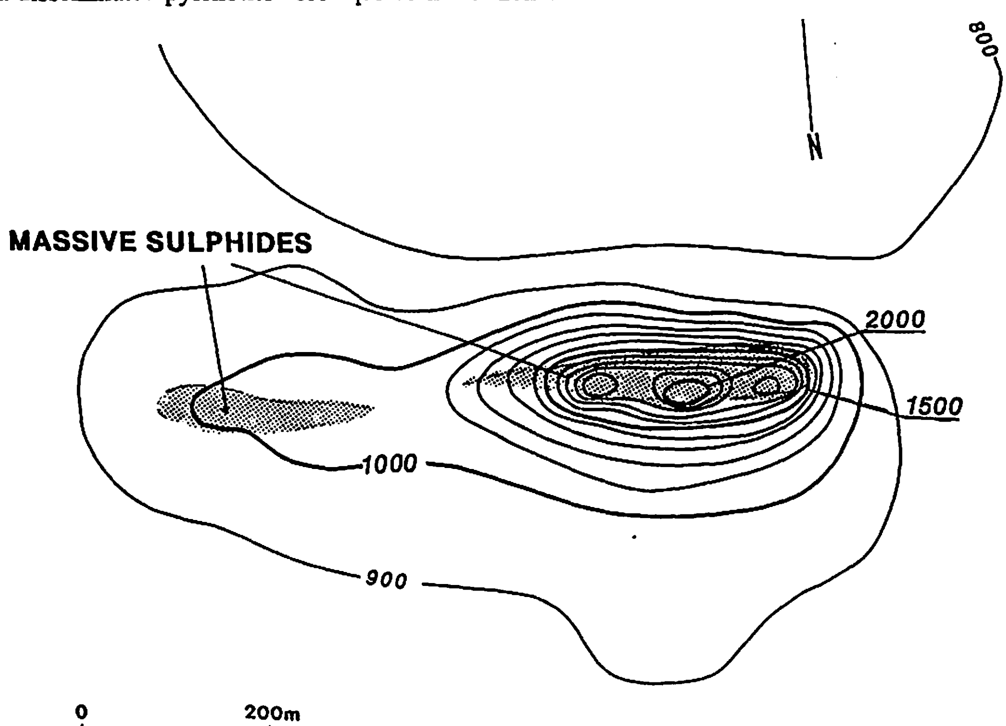


Figure 4.6 Geological section of the Rouez deposit



Diagrammatic after Lebouteiller (1981)

Figure 4.7 Aeromagnetic response of the Rouez deposit (ground clearance 150 m). Note that the anomaly due to the deposit is located within a weaker linear anomaly which has been interpreted as due to a disseminated pyrrhotite "ore equivalent horizon".



After Lebouteiller (1981)

Figure 4.8 Ground magnetic data over the Rouez deposit

4.9.6 Ducktown Area, Tennessee, US

4.9.6.1 Introduction

The Ducktown area in the Southwestern corner of Tennessee in the U.S.A. hosts a number of copper zinc deposits (Magee, 1968). Smaller similar deposits occur in equivalent rocks along strike .

4.9.6.2 Setting of the Deposits

The Ducktown mining district is located within the Blue Ridge Province of the Southern Appalachians in the extreme southeastern corner of Tennessee. The rocks in the area are Precambrian metagreywackes and schists belonging to the Great Smokey Group of the Ocoee Supergroup which unconformably overlies Grenville age basement rocks. Hadley (1970) interpreted the metagreywackes, schists and associated metaconglomerates quartzites and calcsilicate hornfels as originating in turbidity currents derived from granitic sources to the northwest. Minor bodies of amphibolite and intrusive diorite or gabbro occur in the vicinity of the Ducktown mines and adjacent to similar mineral occurences along strike at Fontana and Hazel Creek. Most of the amphibolites are conformable and have been interpreted as mafic sills. The palaeotectonic setting of the Ducktown area has been interpreted by Hatchter (1980), Gair and Slack (1980) and others to be an intracratonic rift developed along the eastern margin of an ancient continent (Laurentia) during a crustal extension process which led to the breakup of the continent to create what has been called the Iapetus Ocean. The area has subsequently been metamorphosed and folded as a result of westward thrusting episodes related to orogenic events affecting the Appalachians. The vicinity of the Ducktown mines has been metamorphosed to amphibolite grade.

4.9.6.3 Stratigraphic Associations

The Ducktown mining district is located in the Copperhill Formation of the Late Pre Cambrian Great Smokey Group of the Ocoee Super Group. The Copperhill Formation consist of interbedded greywackes, greywacke conglomerate and mica schists with sericite biotite schists, chlorite garnet schists, chlorite staurolite garnet schists and biotitic quartzites conspicuous near the mineralization. The only evidence of igneous activity in the Ducktown district is an amphibolite sill 1.5 km south of the district and several smaller occurences near two of the deposits (Boyd and Eureka).

4.9.6.4 Mineralization

The deposits are generally tabular in shape with lengths up to 1000 m and known depth extents up to 800 m. Average widths are of the order of 10 metres although folding has produced localized thickenings.

The deposits are approximately 65% massive sulphides with 35% gangue minerals with average compositions of 60% pyrrhotite, 30% pyrite, 4% chalcopyrite, 4% sphalerite, 2% magnetite and traces of silver and gold. Wide variations occur in these percentages. For example zones of almost pure pyrrhotite, 20% magnetite and 15% sphalerite have been recorded.

Magnetite is widely disseminated but occurs most frequently in the pyritic sections of the ore. Quartz, calcite and lime silicates are typical gangue minerals.

The Burra Burra, London, East Tennessee, Calloway and Mary Polk County deposits contain about 1.6%Cu, 1.2%Zn and 1% magnetite. The Eureka, Boyd and Cherokee deposits contain on average 0.7%Cu, 1.2%Zn and 3% magnetite.

4.9.6.5 Mineralization Associations

Although no stratigraphic markers exist in the district it has been suggested that the mineralization occurs in beds which were originally lime bearing muds (Magee, 1968). Strike faulting appears to have controlled the ore deposition. Shearing is evident in these faults. The deposits conform to the regional trend of the strike and dip of the bedding.

4.9.6.6 Origin of the Mineralization

Metamorphism of the country rock and recrystallization and remobilization of the ore has masked the original form and setting of the mineralization. Both syngenetic and epigenetic origins have been proposed.

4.9.6.7 Additional Regional Detail

None has been located.

4.9.6.8 Magnetic Responses

No magnetic survey data or rock property measurements have been located for the Ducktown area and consequently the magnetic responses of the deposits are unknown. The minimum 1% magnetite content in the mineralization (frequently much more) should be sufficient to give a distinct magnetic response.

Magee (1968) report that the pyrrhotite of the deposits is hexagonal in form however his remarks that the pyrrhotite is "only slightly magnetic" suggest that the hexagonal form coexist with some magnetic monoclinic pyrrhotite. If this is so then the monoclinic pyrrhotite would contribute to the magnetic response.

It is concluded that the Ducktown deposits probably give magnetic responses.

4.9.6.9 Details of Individual Deposits

Burra Burra Mine

Principal reference: Magee (1968)

Host Rocks: the footwall rocks are greywacke and mica schist with some zones of "bleached" sericite schist. The hanging wall is composed of a sandy quartz chlorite schist with some garnet and a few staurolites.

Form of the Mineralization: a thin warped tabular lens 1000 m long with a vertical depth extent of 800 metres and a down dip depth extent of 1100 m. Local folds have produced thickenings up to 60 m.

Mineralization: 1.6%Cu, 1.2%Zn with a total sulphide content of about 57%(60% pyrrhotite, 30% pyrite), 1% magnetite. Quartz, calcite and limesilicates are the most common gangue.

Deposit Size: 20mt 1.6%Cu, 1.7%Zn.

Structural Setting: on the limb of an anticline, the ore minerals were probably deposited along a shear zone and as a replacement in fold structures.

Magnetic Responses: probably magnetic.

Other Deposits in the Ducktown Region

The Burra Burra deposit described above is the largest in the Ducktown area. Its general characteristics are typical of the other deposits which are :

Cherokee described by Magee (1968) and Brooks (1987)

London, East Texas, Eureka, Boyd Calloway and Mary Polk County (all described by Magee, 1968).

Two small similar deposits occur approximately 100 km northeast of Ducktown at Fontana and Hazel Creek (Gair 1982a,b).

4.9.7 Selwyn Basin, Western Canada

Principal References: Carne and Cathro (1982), Morganti (1990)

4.9.7.1 Introduction

Major zinc lead shale hosted mineral deposits in three separate ages of shale or its metamorphic equivalent in the Selwyn Basin of Western Canada. At least twenty such deposits have been recognised. These deposits tend to occur in clusters or "camps" of which the Lower Cambrian Anvil Camp, the Silurian Howards Pass Camp and the Upper Devonian Macmillan Pass and Gataga Camps are the most important. A rift origin has been interpreted from the area and although no detailed tectono-stratigraphic analysis of the area has been located the diverse ages of these deposits implies that they probably developed during different crustal extension events an/or stages of rift development.

All the deposits of the Selwyn Basin are included in this Chapter. While the Macmillan pass Camp (Winn et al., 1987) deposits are reported as being hosted by turbidites, the setting of the metamorphosed Anvil Camp deposits and the Howards Pass and Gataga deposits are less clear.

The Howards Pass deposits which have simpler mineralogies and geometries than the other Selwyn Basin deposits are located at the base of a slope adjacent to a platform area in a setting which would typically receive turbidite deposition. The deposits however appear to have formed under starved basin conditions.

The Anvil Camp host rocks may be metamorphosed turbidites.

Although thin turbidites underlie the Gataga Camp deposits the deposits appear to occur at the interface between a succession of pyritic carbonaceous black shales, siliceous argillites and cherts and a succession of deep water black shales. It is possible that these deposits should be classed with the deposits of Chapter 6 which have associations with pyritic/carbonaceous/ dolomitic shales.

The Anvil Camp deposits have been reported to give magnetic responses. The Macmillan Pass Camp deposits contain significant pyrrhotite but it is uncertain whether the pyrrhotite is monoclinic and whether the deposits give magnetic responses. The magnetic mineral contents of the Gataga deposits has been reported as "low" and no magnetic response have been reported. The Howards Pass deposits appear to be devoid of pyyrhotite and magnetite.

4.9.7.2 Setting of the Deposits

The Selwyn Basin which is a subprovince of the Canadian Cordillera is an elongate trough extending for at least 1200 km from northeastern British Colombia to the Alaskan border. The basin consist primarily of chert and shale and coarser grained clastic sedimentary rocks with minor volcanics. The boundaries of the basin are poorly defined. Basinal facies exist in the Road River Formation which consists of carbonaceous pelitic sedimentary rocks with minor coarse clastic components. The Road River Formation which hosts the Anvil and Howards Pass Camps is flanked by the Cassia and Mackenzie Platforms. The "Black Clastic Group" which overlies both the platforms and the Road River Formation hosts the Gataga and the Macmillan Pass Camps. The Black Clastic Group contains shales and cherts and was deposited in an environment characterized by block faulting and rifting. The Road River Formation was apparently deposited in quieter conditions. An intracratonic setting has been interpreted for the Road River Formation.

The Macmillan Pass graben which hosts the Macmillan Pass Camp is reported as a flysh basin containing turbidite sediments. The Gataga Camp deposits were deposited contemporaneously with synsedimentary faulting related to rapid crustal subsidence. Turbidites occur in the host rock sequences. The Howards Pass Deposits are interpreted as base of slope deposits adjacent to a platform area (Morganti, 1990).

4.9.7.3 Stratigraphy

The broad stratigraphy of the basin was described in Section 4.9.2.2..

4.9.7.4 Mineralization

The mineralization typically occurs as pyrite-sphalerite-galena-barite associations.

The Anvil Camp deposits tend to be relatively enriched in Cu and Fe relative to the other deposits and to have a characteristic vertical zoning (in descending order):

- barite massive sulphides
- pyritic massive sulphides
- pyritic quartzite
- ribbon banded graphitic quartzite
- chalcopyrite-pyrrhotite stringer zones (beneath some deposits), white mica alteration (most deposits), best developed in footwall.

Mineral percentages quoted by Brock (1973) and listed in Section 4.9.7.8 imply that significant percentages of pyrrhotite must occur in some portions of the body described as "pyrite".

Anvil Camp contains at least 8 deposits including the Faro deposit of 75mt, 9.5% Zn+Pb and 37g/t Ag.

The Tom deposit in the Macmillan Pass Camp (Ansdell et al. 1989) consists of a lens of massive ore pyrrhotite-galena-sphalerite-ankerite-chalcopyrite) which passes vertically upward and laterally into laminated ore (sphalerite-galena-pyrite-barite-chert). A footwall feeder zone contains pyrite and pyrrhotite stringers with minor sphalerite, galena and chalcopyrite. The mineralization is concentrated in a basin shaped lens approximately 100 m thick and 1200 m in diameter. Morganti (1990) has published a cross section showing the geometry of the Tom deposit.

The Jason deposit in the Macmillan Pass Camp (Gardner and Hutcheon, 1985) consists of an upper zone of well bedded sphalerite, chert and barite overlying massive to thick bedded galena and sphalerite with abundant pyrrhotite and pyrite. An underlying zone of cross cutting galena bearing quartz siderite and quartz ankerite veins are an apparent relic of a feeder zone.

The Howards Pass deposits XY, Anniv and OP (Morganti, 1977) have a simple sphalerite-galena-pyrite mineralogy with no other sulphides being present except for a few traces of chalcopyrite in the OP deposit. Pyrite (less than 5% of the XY deposit), barite and silver contents are low. The mineralization in these deposits occurs in rhythmically laminated saucer shaped bodies. No feeder pipes have been identified.

The Gataga Camp contains nine major occurrences namely Driftpile Creek, Mount Alcock, Cirque, Fluke, Pie, Elf, Kwadacha, and Sika (MacIntyre, 1982). These deposits consist of bedded barite, pyrite, sphalerite and galena. They have very low copper contents and a general lack of footwall alteration beneath the deposits.

4.9.7.5 Mineralization Associations

The Anvil Camp deposits occur in a bed of Lower Cambrian graphitic phyllite that marks the transition between calcareous and non calcareous pelites. The Anvil deposits occur in rocks of "high metamorphic grade".

Host rocks to the Howards Pass Camp are an assemblage including limestone, carbonaceous mudstone, cherty mudstone and chert.

The mineralization in the Macmillan Pass Camp occurs near the transition from a lower assemblage of coarse clastics to an overlying carbonaceous and siliceous shale.

The Gataga Camp are hosted in mineralized horizons containing a black banded chert, siliceous argillite, laminated siliceous shale, black siltstone and black carbonaceous shale. Beds of pelagic limestone are locally present.

4.9.7.6 Origin of the Mineralization

The deposits are generally recognised as having a sedimentary exhalative origin and the abbreviation "sedex" which refers to such deposits was apparently coined by workers on the Selwyn Basin. Basically the model involves the ascent of metal rich brines through faults, fracture systems or feeder vents with subsequent syndiagenetic or early diagenetic precipitations of metallic minerals as conformable, frequently layered sheets. The mineral deposits are often underlain by alteration and mineralized stringer zones resulting from the ascent of the mineralizing fluids. The mineralizing process can result in vertical zoning of the mineralized masses. Depressions on the sea floor are perceived as favouring the precipitation of mineralization in particular areas.

4.9.7.7 Additional Regional Detail

None has been located. The relationship of such deposits to major fault systems could be an important factor in controlling their locations.

4.9.7.8 Magnetic Signatures

Brock (1973) has published magnetic data over the Faro, Vangorda and Swim deposits in the Anvil Camp. It is difficult to relate the magnetic responses described by Brock to any particular portions of the deposits nevertheless the deposits do have magnetic signatures due to pyrrhotite contents as the following table illustrates:

		FARO		VANGORDA	SWIM
Pyrite	%	35	35	35	35
Sphalerite	%	10	10	25	10
Galena	%	5	5	15	5
Pyrrhotite	%	10	5	10	5
Chalcopyrite	%	1	1	6	1
Gangue		39	40	9	44
Aeromagnetic Anomaly (nt)		125	400	200	30

The different aeromagnetic responses and mineral contents refer to different ore lenses. The airbourne surveys were at levels approximately 140 m above the mineralization.

Pyrrhotite stringer zones are reported beneath some of the Anvil Camp deposits. The Anvil Camp has been metamorphosed to "high metamorphic grade". It is not clear whether the pyrrhotite present resulted from transformation of pyrite.

The Tom and Jason deposits in the Macmillan Pass Camp (Andsdell et al., 1989; Gardner and Hutcheon, 1985) are reported as containing significant pyrrhotite contents. However neither the exact percentage of pyrrhotite nor its crystal form is obvious from published accounts. No reports of magnetic surveys over these deposits have been located although the publication by Carne and Cathro (1982) implied that these deposits do not give magnetic responses. This observation may have been a product of low quality magnetic data or the obscuring effects of igneous intrusions which have been mapped in the area of the deposits. Carne and Cathro (1982) also imply that neither the Gataga Camp nor the Howards Pass Camp deposits give magnetic responses. This would be consistent with the apparent absence of pyrrhotite and magnetite in these deposits.

4.9.8 Meggen and Rammelsberg, West Germany

Principal references: Krebs (1976), Morganti (1990)

The Meggen deposit of approximately 60 mt, 10%Zn, 1.3%Pb, 0.2%Cu and the Rammelsberg deposit of 25 mt 19%Zn, 9%Pb, 1%Cu%, 22%$BaSO_4$ occur in Middle Devonian sediments in western Germany which have been interpreted as having been deposited during a rifting process.

The Meggen deposit is hosted by the Meggen Beds which consist of dark grey to black pelagic shales containing various amounts of siltstone and sandstone. Limestone detritus intercalated with the siltstones resulted from the contemporaneous growth of an adjacent reef. The Meggen ore is composed of banded pyrite, spalerite and galena interlaminated with discontinuous beds of black siliceous shale. Sulphide ore grades upward and outwards into barite. Iron sulphides are reported as "mostly pyrite" implying little or no pyrrhotite.

Rammelsberg occurs in a sequence of slates containing interbeds of sandstones and limestones. Rammelsberg exhibits a geometry and metal zoning very similar to many classic VHMS deposits. The deposit is underlain by a brecciated chalcopyrite zone interpreted to be a relic of a feeder pipe. No pyrrhotite or magnetite is reported.

4.10 EXPLORATION GUIDELINES

1. Locate an intracratonic or marginal basin rift system. These may be recognised by:

   (i) geological mapping (fault bound sediment troughs)
   (ii) detail on regional seismic data
   (iii) gravity highs indicating thinned crust
   (iv) (possible) magnetic highs indicating magma ascent under the rift.

2. Turbiditic sequences within such rifts are prospective. Characteristics to recognise are deepwater sedimentation and lithologic assemblages including shales, siltstone, mudstones, greywackes with lesser sandstones and even lesser conglomerates. Areas containing such rocks are expected to have a subdued magnetic character resulting from the generally non magnetic nature of the sediments.

3. It is normally essential for deformation and/or erosion to have exposed cross sections of prospective lithologies. It is difficult to detect such mineralization when it is in horizontally stratified sequences unless the host horizon is fortuitously uppermost.

4. Areas containing known deposits are most prospective. (c.f. Cobar, Selwyn Basin)

5. Narrow (a few hundred metres), linear, extensive (several kilometres) magnetic zones could indicate prospective "ore equivalent horizons" such as the shale beds containing disseminated pyrrhotite which host mineral deposits at Cobar, Sullivan and Rouez. The anomalies of these features will typically have amplitudes of the order of a few tens of nanoteslas. Non-magnetic horizons of disseminated pyrite can be equally prospective. It should however be remembered that not all such horizons are formed by mineralizing processes associated with hydrothermal vents.

6. Distinct magnetic highs along the lengths of these magnetic marker horizons should be considered as indicating possible minerals deposits (c.f. Cobar, Rouez). These anomalies would be expected to be elongated in the direction of the marker horizon in relatively undeformed terrains but if the mineralization has been remobilized into shapes such as elongate tabular bodies or cigar like ellipsoids then the anomalies may have circular for (c.f. Cobar area deposits). Amplitudes of anomalies due to mineralization may range from a few nanoteslas for bodies containing inductively magnetized pyrrhotite, a few tens of nanoteslas for bodies containing pyrrhotite with significant remanence, to several hundred nanoteslas for bodies containing magnetite.

7. It is not essential that the magnetic anomalies due to mineralization in the turbidite sequence be directly associated with linear magnetic marker horizon. Any discrete anomaly with lengths up to several hundred metres (or possibly slightly longer (c.f. Ducktown) should be investigated unless it has an obvious surficial source.

8. Indications of magnetic remanence such as obvious inconsistencies between dip directions interpreted from magnetic data and the known dip directions in an area may be interpreted to indicate the possible presence of pyrrhotite.

9. Cross faults indicated from geology or interpreted from aeromagnetics which pass through isolated magnetic anomalies significantly enhance possibility that the anomaly indicates mineralization (faults may localize feeder vents).

10. It is possible that fine magnetic details could delineate zoning of magnetic minerals in an orebody similar to the zoning occurring in the VHMS exhalative deposits. In an ideal situation where a total section of such

deposit is exposed in plan view we might expect to see some or all of the following magnetic responses :

(i) a narrow linear anomaly due to a disseminated (or possibly massive) ore equivalent horizon.
(ii) no magnetic anomaly associated with an upper pyritic Pb-Zn rich portion of the orebody which may underlie the ore equivalent horizon.
(iii) an anomaly due to a massive Cu rich portion of the orebody which may contain pyrrhotite or magnetite.
(iv) a weak anomaly due to disseminations of pyrite and chalcopyrite in a stringer zone which may contain pyrrhotite or magnetite. This would trend perpendicular to bedding.
(v) a magnetic low flanking or superimposed on (iv) due to magnetite and/or pyrrhotite destruction in an alteration zone.

Any of the pyritic portions described above could be converted to pyrrhotite and/or magnetite by metamorphism. Pyrrhotite may also be converted to magnetite by metamorphism. The above magnetic responses would vary accordingly. Allowance must be made for physical deformation and deposit rotation resulting from folding and structuring when searching for such magnetic patterns.

11. All the above observations are based on the assumption that the mineralization will contain monoclinic pyrrhotite and magnetite. It is possible that non-magnetic bodies of this class occur. In this case all of the above indicators will be relevant with the exception of the direct ore responses.

12. Magnetite development in argillaceous sediments is likely during metamorphism. Metamorphosed areas are thus likely to contain more linear magnetic anomalies than non metamorphosed areas. This phenomenon could hinder the identification of potential magnetic "ore equivalent horizons".

13. Developments of surface laterites and maghemites will create magnetic noise and may pose problems relative to the identification of weak bedrock anomalies (Section 4.9.3.8).

14. It is important to appreciate the variations in target dimensions which ranges from saucer-like sheets with diameters up to 2 km (c.f. Sullivan) to pipe-like ellipsoids which may only have horizontal diameters of 100 m (c.f. Elura). As horizontal compression is known to cause sulphide remobilization into elongate tabular or cigar shaped bodies with their long axes oriented in the vertical direction these differences in target geometry may be predictable.

CHAPTER 5
MASSIVE SULPHIDE DEPOSITS ASSOCIATED WITH BANDED IRON FORMATIONS / AMPHIBOLITES / BASIC IGNEOUS ACTIVITY

Principal References: Kanehira and Tatsumi (1970), Franklin et al. (1980), Fox (1984), Gair and Slack (1984), Breitkopf and Maiden (1988), Sawkins (1990)

A significant number of important massive sulphide base and precious metal deposits have close associations with banded iron formations (BIF), amphibolites and/or basic igneous activity. Although several workers, notably Fox (1984), have made credible syntheses of the characteristics of these deposits and have related their occurrences to particular plate tectonic settings it is clear from the current literature that the recognition of such deposits as a specific deposit type is by no means universal. The following review supplements the ideas of previous workers with conclusions based on the characteristics of the deposits described in the following sections.

5.1 INTRODUCTION

Massive sulphide deposits of the BIF/amphibolite/basic igneous association are tabular massive sulphide bodies conformably hosted in clastic sedimentary sequences which characteristically, but not necessarily, contain both exhalative iron formations and mafic extrusives and intrusives of oceanic or intraplate geochemistry. The bodies typically show extreme flattening. They often have strike lengths greater than 1 km and thicknesses of the order of 10-20 m. The exhalative iron formations are frequently classic magnetite rich banded iron formation (BIF) although associations with pyrite and pyrrhotite facies BIF occur. The massive sulphides may be enclosed by the BIF, adjacent to the BIF or at distances up to several hundred metres from the BIF. The association of these deposits with amphibolites is a result of metamorphic transformation of mafic rocks.

The deposits occur as Cu and Cu-Zn and Pb-Zn-Ag types although gradational concentrations of metal contents occur between these end members and the precise attribution of some deposits is difficult. Gold is preferentially associated with the Cu and Cu-Zn deposits where it sometimes attains economically significant concentrations. Deposits with the above characteristics are variously referred to as banded cupriferous iron sulphide, Besshi-type, BIF-amphibolite, BIF hosted or simply not classified.

It can be argued that this deposit grouping overlaps with the turbidite hosted deposits not associated with obvious igneous activity which were described in the previous chapter because they too may have associations with iron facies marker horizons. The discussion in Section 4.7 suggests there is in fact a gradation between the two types related to the the stage of rifting in which they are formed. The deposits of this chapter are associated with advanced stages of rifting in which basic igneous rocks are produced.

The correct definition of a BIF includes all iron mineral facies (oxide, silicate, sulphide, carbonate) and the association of massive sulphide deposits with BIFs is not a real classification characteristic because, as already noted, both the VHMS deposits of Chapter 3 and the turbidite hosted deposits of Chapter 4 may have BIF associations. Furthermore many of the deposits described in the later chapters of this study also have BIF associations. Judged on these criteria it is perhaps false to include "BIF" as a descriptive term for the deposits of this chapter. The term has however been retained because of the number of deposits described below which are associated with magnetite quartzite BIFs and which as a result have similar magnetic responses.

The significance of the magnetite quartzite association is itself contentious because, as is progressively revealed in the ensuing pages, the magnetite quartzites may be metamorphosed pyritic formations. It is necessary to be aware that some of the deposits described in this chapter may well be metamorphosed versions of deposit types which are fully described elsewhere in this study

Major groups of BIF/amphibolite/basic igneous associated deposits occur in the Sanbagawa Belt of Japan (Kanehira and Tatsumi,1970), the Matchless Belt in Namibia (Goldberg,1976), Namaqualand District of South Africa (Anhaeusser and Maske,1986) and in the Bathurst District, New Brunswick, Canada (Franklin et al., 1981). Several recent discoveries in the Mount Isa area of Australia such as Starra and Osborne (Davidson et al., 1989) appear to be of this type.

5.2 SETTING OF THE DEPOSITS

The BIF/amphibolite/basic igneous associated massive sulphide deposits occur in intracratonic and/or marginal basin rift settings where they are typically associated with mildly alkalic tholeiitic igneous rocks in environments suggesting advanced rifting or initial ocean floor spreading. Host sediments are variable. Greywackes, argillites, arkoses and conglomerates have all been reported. Turbidite deposition has been identified.

Folding and metamorphism seems to have affected most deposits of this class. This may reflect the fact that marginal basins in island arc or Andean type convergent margins are prone to be subjected to orogenic deformation.

5.3 STRATIGRAPHY

The ages of the BIF/amphibolite/basic igneous deposits ranges from the Proterozoic to the Mesozoic and present day analogues appear to have been found (Fox, 1984). The lack of classic rifting during the Archean many explain the absence of such deposits during this era.

The mineralization is generally conformable with the enclosing rocks and as stated in Section 5.1 they are characteristically associated with exhalitive iron facies. These may consist of magnetite quartzite and may actually enclose the mineralization. They may also occur at levels above and in close proximity to the mineralization or at equivalent stratigraphic levels to the mineralization. The iron formations have strike lengths which are limited to several kilometres and typically have thickness from the order of 1-20 m. Basic rocks or amphibolites within the section are normally conformable. Sediment hosts are frequently deep water turbidites.

It is not clear if the deposits in a particular area are restricted to specific stratigraphic horizons. This may be the case. In Japan for example, most, but not all the deposits, occur in an argillite formation with a maximum thickness of 2500 m.

5.4 MINERALIZATION

No publications appear to exist which describe characteristic mineral zonations in the BIF/amphibolite/basic igneous associated massive sulphides in the same detail as has been done for the VHMS deposits (c.f. Section 3.4). While this fact can be attributed to a lesser recognition of this deposit class it must be admitted that the prevalence for the BIF/amphibolite/basic igneous deposits to occur in deformed and metamorphosed terrains has posed difficulties in the understanding of field relationships.

The deposits show a tendency to segregate into Cu, Cu-Zn and Pb-Zn assemblages with a range of deposits falling between the end members. Gold appears to be preferentially associated with copper. Copper content appears to decrease as the lead-zinc increases.

Ryan et al. (1986) have noted a systematic variation in mineral contents of deposits in the Aggenys area of the Namaqualand Belt which contains the Black Mountain (0.75% Cu, 0.59%Zn, 2.67%Pb), Broken Hill (0.34%Cu, 1.77%Zn, 3.57%Pb), Big Syncline (0.04%Cu, 2.45%Zn, 1.01%Pb) and Gamsberg (0%Cu, 7.00%Zn, 0.50%Pb) deposits. This gradation which occurs over a 20 km distance in the order in which the deposits are listed tends to confirm the idea of a single deposit class which encompasses both the Cu and the Pb-Zn varieties.

The clearest description of mineral assemblages and mineral zonings for the Cu type are given by Kanehira and Tatsumi (1970) for the Besshi deposits in Japan, Klemd et al. (1987) and Haussinger and Okrush (1983) for the Matchless and Gorob deposits in Namibia and by Davidson et al. (1989) for the Starra and Osborne deposits in the Mount Isa area of Australia.

The Besshi deposits consists of compact ore containing pyrite, chalcopyrite and sphalerite banded ore containing a mixture of sulphide and silicates and chalcopyrite rich ore containing minor pyrite. Pyrrhotite and magnetite occur in minor concentrations with pyrrhotite tending to be concentrated at the lower levels of the deposits. Magnetite is concentrated throughout the deposit but preferentially in thin layers in both the hanging wall and the footwall of the sulphide ore bodies and this is interpreted as the product of the exhalitive iron oxide facies. The Besshi deposit thus appears to be enclosed within the exhalative iron oxides. It is not clear from the literature whether Besshi type deposits are underlain by stringer zones formed in hydrothermal vents although veins containing chalcopyrite are reported in the country rock.

Pyrrhotite is the dominant sulphide in some of the Japanese deposits although it is not clear to what extent this has resulted from the metamorphism of pyrite.

The specific model developed for the Osborne and Starra deposits by Davidson et al. (1989) involves a feeder pipe underlying an exhalative magnetite quartzite BIF enveloping massive copper-gold-pyrite mineralization in the immediate vicinity of the feeder pipe. Chloritic alteration surrounds the feeder pipe which contains pyrite and magnetite. A tabular (presumably disc like) massive sulphide cap to the feeder pipe contains chalcopyrite, gold and pyrite. Despite the emphasis on pyrite in this model it is obvious from the examples described in Section 5.4 that pyrrhotite can be a dominant or accessory mineral in the parts of the model shown as containing pyrite. The field examples also show that magnetite is frequently the dominant iron mineral in the BIF. Variable developments of the BIF occur. At Osborne it has thicknesses up to 20 m. At Starra it has a total strike length of approximately 20 km.

With the Cu type deposit of the banded iron formation/amphibolite/basic igneous association Cu-pyrite +/- pyrrhotite mineralization may be enclosed by the banded iron formation or below it. Amphibolite or basic igneous rocks may occur anywhere in the section. Sphalerite or (less likely) galena, may also occur in these deposits. These minerals will tend to be concentrated in the upper portions of the sulphide zones.

The mineral zoning in the lead-zinc varieties is less clear. Gamsberg (Rozendaal, 1986) contains sphalerite and galena in associated with pyrite and pyrrhotite enclosed between thin magnetite bearing units. Magnetite is only present in the upper zinc rich portions or the orebody. The South African Broken Hill orebody (Ryan et al.,1986) contains two distinct layers of pyrrhotite-pyrite-sphalerite and galena each of which is overlain by a magnetite quartzite.

The Australian Broken Hill deposit (Johnson and Klinger, 1975) contains six lenses of mineralization which consist of galena and sphalerite with pyrrhotite and chalcopyrite as minor constituents. Pyrite is rare. Eight separate BIFs occur in association with this deposit. They range in thickness from a few centimetres to up to 2 m. One is known to have an extent of 15 km. These BIFs do not enclose the ore but at least two are thought to be stratigraphic equivalents of the ore.

The only suggestion of an alteration pipe association with the lead-zinc variety is at Black Mountain which Ryan et al.(1986) report as showing metal concentrations which are concentric and superimposed over a localized garnet quartzite which some company geologists interpret to represent the metamorphosed equivalent of an alteration zone. As with the Cu types the mineralization of the Pb-Zn varieties can occur within or below the banded iron formation. Amphibolite or basic rocks can occur anywhere in the section. The Pb-Zn-Ag deposits appear more likely to occur as multiple lenses of mineralization than the Cu types.

From the above, we note a close resemblance between the mineral zoning and geometry of these deposits and the VHMS and turbidite hosted deposits not obviously associated with igneous activity described in the previous chapters. In fact all these the deposits appear virtually identical except for the notable differences of:

(i) their host rocks (which can be explained by different tectonic settings and metamorphism).

(ii) the common association of the deposits in this chapter with magnetite rich BIFs in the role of an "ore equivalent horizon" (this may merely be a product of the metamorphic transformation of pre-existing pyritic or pyyrhotitic "ore equivalent horizons").

It is proposed the the exhalative model of deposit geometry and mineral zoning as described in Section 3.4 and illustrated in Figure 3.1 applies to the deposits with the BIF/basic volcanic/amphibolite associations with the only real difference being these deposits having host sequences of sediments with intrusives and extrusives of probable tholeiitic affinities and their metamorphic equivalents and metamorphic transformation of some of the pyritic and pyrrhotitic portions of the model of Figure 3.1 to pyrrhotite and magnetite respectively. The elaborations of this model which were explained for the turbidite hosted deposits not associated with obvious igneous activity in Section 4.4 are applicable to the BIF/amphibolite/basic igneous associated deposits.

5.5 MINERALIZATION ASSOCIATIONS

Kanehira and Tatsumi (1970) report that the Besshi deposits tend to occur in clusters. This phenomenon can be noted elsewhere with a particular example being the proximity of the Black Mountain, Broken Hill, Big Syncline and Gamsberg deposits (Ryan et al., 1986).

The terrains containing such deposits typically contain linear zones of basic igneous rocks which are relics of lava flows and intrusive sills. These are considered to be an indication of a tectonic/igneous regime associated with advanced rifting and are not thought to have any direct control on the formation and localization of the mineralization. In metamorphic terrains the metamorphosed equivalents of these units are amphibolites.

Exhalitive oxides frequently occur in the vicinity of the mineralization. In many cases these exist as magnetite bearing iron formations. The iron formations have a direct association with the mineralization and are thought to be products of the same hydrothermal vents which produced the mineralization (see Section 5.6). The iron formations are an "ore equivalent horizon" (c.f. Section 3.4). The mineralization may have various spatial relationships with this "ore equivalent horizon":

Enclosed by BIF	Besshi Osborne	Kanehira and Tatsumi (1979) Davidson (1992)
Capped by BIF	Gorob Breitkopf and Gamsberg	Maiden (1988) Rozendaal (1986)
Adjacent to BIF	Broken Hill Australia Rozyn Bush Prospect South Africa	Johnson and Klinger Campbell and Mason (1979)

5.6 ORIGIN OF THE MINERALIZATION

Similar hydrothermal processes used for to explain the origin of the VHMS deposits (Section 3.6) have been invoked to explain the deposits with the BIF/amphibolite/basic igneous associations. A possible modern day analogue exists in the restricted Guaymas Basin in the Gulf of California (Fox, 1984) where massive sulphide samples containing equal proportions of pyrrhotite, chalcopyrite and sphalerite have been dredged from a locality directly overlying an oceanic spreading centre. The host rocks are turbidites although basaltic sills apparently occur within 100 m of the sea floor. The deposits occur in a ferruginous talc which appears to be a precursor of an iron oxide "ore equivalent horizon".

This mineral assemblage is interpreted to be a result of exhalations from a hydrothermal vent.

In areas of high metamorphic grade pyritic units may be metamorphically oxidized to form magnetite rich banded iron formation (Dimroth, 1976) thus many of the iron formations associated with more intensely metamorphosed examples of these deposits (especially the Namaqualand and Broken Hill, Australia examples) may have originated as sulphide facies exhalations such as appear more common with less metamorphosed exhalitive deposits described in Chapters 3 and 4.

5.7 ADDITIONAL REGIONAL DETAILS

Rift settings have been interpreted for all the areas containing these deposits. The occurence of basic igneous rocks which in many areas have been identified by chemical analyses as belonging to the tholeiitic suite is interpreted as indicating advanced stages of crustal extension and in some cases the initial stages of oceanic crust emplacement (c.f. the Guayamas Basin example quoted in Section 5.6). Breitkopf and Maiden (1988) even relate deposit size to whether the rift is underlain by continental or oceanic crust as determined from basalt analyses. The largest deposits appear to occur in sequences containing tholeiitic basalts of oceanic composition.

As discussed in Section 4.7 the BIF/amphibolite/basic volcanic deposit type seem occur in rifts exhibiting greater extension than the rifts containing the turbidite hosted deposits with no apparent association with igneous activity. Apart from the presence or absence of the BIFs and igneous rocks the actual deposits have many similarities. When we remember that not all rifts produce significant volcanic outpourings and igneous intrusion and that magnetite and pyrrhotite rich BIFs may be produced by metamorphism of pyritic horizons we realise that that the deposit types may be equivalent or at least overlap. At the very least the two types appear to be end members of a continuing process of rift development.

The tendency for these deposits to be associated with advanced stages of rifting means that they are likely to be associated with significant crustal thinning and resultant major positive gravity anomalies. Such a situation can be observed for the Osborne and Starra deposits which are located on a major linear gravity high (Gravity Map of Australia, Bureau of Mineral Resources).

5.8 MAGNETIC SIGNATURES

A province or rift system hosting BIF/amphibolite/basic igneous associated massive sulphides would typically contain numerous linear magnetic trends arising from the BIFs where they contain magnetite or pyrrhotite and the amphibolites/basic igneous rocks. Figure 5.1 from Campbell and Mason (1979), which covers the Hope and Gorob deposits in the Matchless Belt of Namibia, illustrates such a situation. Magnetite quartzite BIFs can normally be distinguished by the high amplitude magnetic anomalies they produce. Identification of BIFs allows the definition of prospective trends i.e. the BIFs themselves and the vicinity of the BIFs. Magnetic maps also allow the identification of fault zones which may have channelled mineralizing solutions.

The actual magnetic signature of the mineralization will depend on its magnetic mineral content and whether it is enclosed by, adjacent to or distant from the BIF.

It is obvious from the compilation of Section 5.9 that a significant number these of deposits contain pyrrhotite but none of the geological reports define whether the pyrrhotite is the magnetic monoclinic variety or not. If the pyrrhotite is not magnetic we could expect some local diminution of the anomalous intensity of a BIF containing pyrite and/or pyrrhotite in association with economic base metals. Such an effect may however be very difficult to distinguish given that both the BIFs and the deposits tend to be very elongated. If the pyrrhotite is magnetic we may notice anomalous field patterns in cases where the pyrrhotite fulfils its tendency to acquire significant NRM. It may be significant that the magnetite quartzite at the Gamsberg zinc deposit has a large component of remanent magnetization (Campbell and Mason, 1979). The absolute amplitude of the BIF associated magnetic anomaly does not appear significant although Campbell and Mason (1979) report that major ore bodies appear to be associated with higher magnetite contents. This may be a function of the proximity of orebodies to their formative vents. Tectonic thickening due to drag folds increases the anomalous magnetic field of the BIFs. In some examples (e.g. the Hope deposit, published by Campbell and Mason (1979)) the relative competency of the sulphide mass may have controlled the location of the fold. Despite all these possible magnetic indicators it should be remembered that the relatively high magnetite contents in BIFs may cause demagnetization effects which distort anomalous responses. Anderson and Logan (1992) report that demagnetization is significant at the Osborne deposit and that its effects caused initial misinterpretations of the magnetic data.

If the sulphide body is below or distant from the BIF we may expect to detect anomalous magnetic responses in situations where the deposits contains magnetite or monoclinic pyrrhotite. This magnetic response is likely to be a bulge in the contours associated with the BIF or a discrete anomaly. In ideal circumstance a feeder pipe perpendicular to the BIF may give a recognisable anomaly due to magnetite and/or pyrrhotite in the feeder pipe. The distal portions of this feeder pipe may correlate with a magnetic quiet zone or magnetic low caused by magnetite destruction in the chlorite alteration zone surrounding this pipe.

5.9 DETAILS OF INDIVIDUAL DEPOSITS

5.9.1 Deposits in the Matchless Amphibolite Belt, Namibia

Principal reference: Breitkopf and Maiden (1988)

5.9.1.1 Introduction

Massive sulphide Cu-Zn (Ag,Au) deposits occur along a 350 km strike length in the Matchless Amphibolite Belt of the Damara Orogen in Namibia. Killick (1982) lists these deposits of which the most important are the Gorob, Hope, Vendome and Luigi group of deposits in the west (Preussinger et al.,1987) and the Matchless (Adamson and Teichman,1986) and Otjihase (Goldberg,1976) deposits in the east. The host rocks are metasediments containing amphibolites and all the deposits occur adjacent to or within magnetite-rich banded iron formations. The geological and magnetic characteristics of these deposits are well documented and as such they provide excellent type examples.

5.9.1.2 Setting of the Deposits

Breitkopf and Maiden (1988) have interpreted a rift basin setting for the 756 Ma Matchless Amphibolite Belt. The Kuiseb Schists which host the deposits are thought to have been largely derived from turbidites (Haussinger et al., 1993). Extensive amphibolites in the section (Matchless Member amphibolite) have a tholeiitic character and are interpreted to have originated as extrusive lavas. Metagabbro intrusions also occur. Breitkopf and Maiden (1988) note that the iron enrichment of the amphibolites increases from east to west. This is interpreted to indicate an increase in crustal extension in the easterly direction. The rift may have evolved to a small ocean basin in the east. The massive sulphides are thus thought to have formed in a tectonic setting of advanced continental rifting and initial ocean floor spreading.

Clusters of deposits occur at both ends of the basin. The area has undergone several phases of deformation and has undergone high temperature metamorphism. Staurolite-kyanite-sillimanite metamorphic grades are reported in the western areas of the belt.

5.9.1.3 Stratigraphic Associations

The ore deposits are contained in the footwall of the Matchless Member amphibolites in the Kuiseb Formation schists which as stated above are metamorphosed turbidites.

5.9.1.4 Mineralization

The deposits are copper dominant with pyrite, chalcopyrite, pyrrhotite, subordinate sphalerite and rare galena. Small amounts of silver and gold have been recovered during mining operations.

The deposits occur as clusters of bodies, many of which have been deformed into cigar or pencil shapes.

The Gorob deposit (Breitkopf and Maiden, 1988, Haussinger et al. 1993) occurs as the following assemblages:

9 m of magnetite quartzite (top)
3 m of banded and massive ore
10 m of stringer ore

Amphibolites occur 80 m above and 140 m below this package.

The magnetite quartzites are a group of rocks ranging from almost pure quartzites to almost pure magnetite (hematite). Typically small layers of magnetite occur within a matrix of quartz grains. Pyrrhotite is the only sulphide present in the iron formations in the vicinity of Gorob.

The sulphide ore occurs in lenses of variable sizes partly enveloped by the magnetite quartzite and consists of pyrite, pyrrhotite, chalcopyrite minor sphalerite and rare galena. The stringer mineralization which consists of veinlets chalcopyrite is discordant to the bedding, and has been interpreted as a feeder pipe. An alteration zone has been mapped as a tapering cone extending for at least 500 m from the massive sulphides. Similar structures, mineralogy and field relationships have been reported for the Matchless Mine (Klemd et al., 1989).

5.9.1.5 Mineralization Associations

The deposits are associated with magnetite quartzites which are interpreted to be exhalative components of the ore forming process.

The deposits are also closely spatially associated with amphibolites however no direct relationship is obvious other than the tholeiitic amphibolites indicating a particular tectonic setting.

5.9.1.6 Origin of the Mineralization

The following account taken from Preussinger (1990) elegantly explains what appears to be a common origin for the deposits:

(i) submarine extrusion of tholeiitic basalts and contemporaneous deposition of turbidites in an elongate oceanic trench.

(ii) turbidite sedimentation continues as hydrothermal activity begins at an ocean floor vent.

(iii) precipitation of base metals into unconsolidated sediments as massive stratiform ore lenses with a stringer zone of mineralization and its enveloping alteration zone marking the vertical pathway of the mineralizing fluids.

(iv) hydrothermal activity ceases but turbidite deposition and basalt extrusion continues.

5.9.1.7 Additional Regional Details

None noted.

5.9.1.8 Magnetic Signatures

Figure 5.1 from Campbell and Mason (1979) shows the magnetic expressions of the amphibolites and iron formations in the area. The survey was flown with a mean terrain clearance of 100 m and a line spacing of 400 m. Unfortunately the coarse contour interval of this data does not allow the recognition of any details associated with individual deposits. Some of the strong linear responses on this map are due to amphibolites. The magnetite quartzite associated with the Hope Mine deposit gives a strong magnetic response. Some of the other banded iron formations give weaker responses which in several cases are obscured by the anomalies due to the amphibolites. This may be a function of limited thicknesses (9 m at Gorob for example) of the iron formations.. Figure 5.2, also after Campbell and Mason (1979) shows ground magnetic data and drill results over the Hope Mine. The responses appear to be indicating the intensely folded banded iron formation. No separate details due to the mineralization appear obvious. Campbell and Mason (1979) have also published aeromagnetic data over the Otjihase deposit area (Figure 38.3 of their paper). The only obvious feature in this relatively low quality data is an anomaly associated with the iron formation.

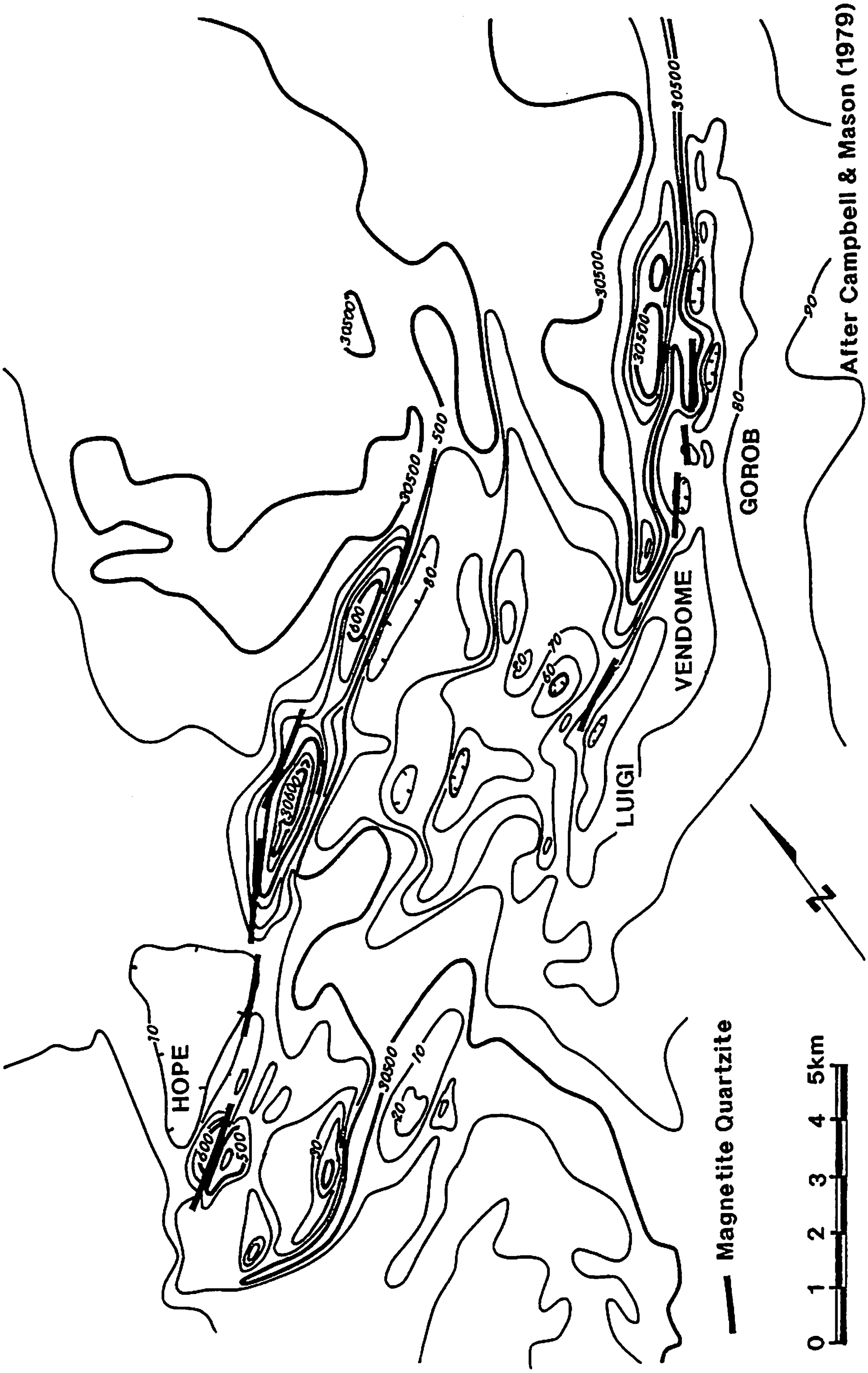


Figure 5.1 Aeromagnetic data, Hope Mine - Gorob area, Matchless Belt, Namibia

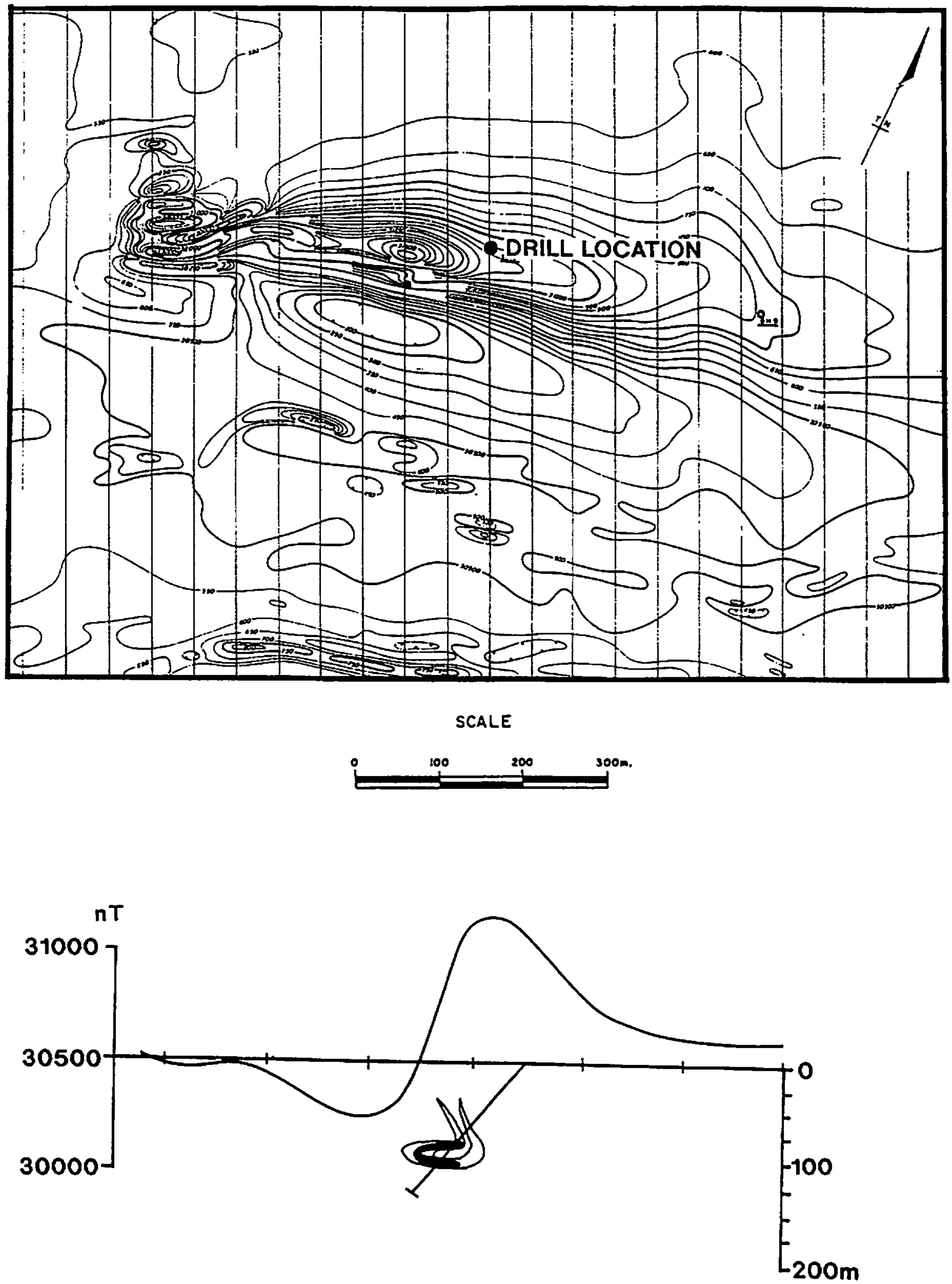


Figure 5.2 Ground magnetic data, Hope Mine, Matchless Belt, Namibia. (Adapted from Campbell and Mason (1979))

5.9.1.9 Details of Individual Deposits

Matchless

Principal references: Adamson and Teichman (1986), Klemd et al. (1987)

Host rocks: sericite quartzite, schist, schist, and amphibolite with lenses of magnetite bearing quartzite.

Form of the mineralization: a mine horizon of 3 km which contains three closely associated strata bound pyritic ore sheets each of which is approximately 250 m long.

Mineralization: The mineralized units are:

amphibolite (including magnetite quartzite)
Amphibolite Schist
Intermediate Schist
Sericitic quartzite

The sericitic quartzite has a true thickness of 15 m in the main host of the sulphide mineralization and contains 70% by volume of pyrite together with chalcopyrite and pyrrhotite.

Pyrite and chalcopyrite are interbedded with laminae of amphibolite in folded lenses of magnetite quartzite in the Hanging Wall Amphibolite.

Deposit Size: 2mt, 2%Cu.

Structural Setting: some of the mineralization has been concentrated in zones of resulting from the three phases of deformation that have affected the area.

Magnetic Signature: None published

Gorob

Principal references: Preussinger et al. (1987), Haussinger et al. (1993)

See details in previous sections.

Otjihase

Principal reference: Goldberg (1976), Campbell and Mason (1979)

5.9.2 Deposits in the Namaqualand Metamorphic Complex, South Africa

Principal Reference: Anhaeusser and Maske (1986)

5.9.2.1 Introduction

The Namaqualand Metamorphic Complex (Joubert, 1986) contains a highly deformed and metamorphosed terrain which hosts several mineral deposits exhibiting various spatial associations with amphibolites and banded iron formations. The most significant of these are the Aggenys Cu-Pb-Zn-Ag deposits (Ryan et al., 1986), the Gamsberg Zn deposit (Rozendaal, 1986), the Putsberg Cu deposit (Viljoen, 1986), the Areachap Cu-Zn deposit (Voet and King, 1986) and the Preiska Zn-Cu deposit (Wagener and Van Schalkwyk, 1986).

5.9.2.2 Setting of the Deposits

As reviewed by Jpobert (1986), various rifting models have been proposed for the Precambrian Namaqualand Metamorphic Complex however the extreme deformation and metamorphism of the area appears to have prevented a consensus of ideas. The Complex itself consists of of different ages which have different origins.

The Aggenys, Gamsberg and deposits are located in the 1200 Ma Bushmanland Subprovince whose constituent lithologies appear to have originated as sediments and volcanics. Extensive parts of the area have been metamorphosed to granulite facies.

The deposit occurs in the Gordonia Subprovince in a sequence of biotite-garnet schist enclosed mainly by gneiss and amphibolite. The biotite-garnet schist is probably of sedimentary origin and the other rocks in the section are probably metamorphosed lavas.

The deposit occurs in gneisses of probable sedimentary origin in a transition zone at the edge of the Namaqualand Complex.

5.9.2.3 Stratigraphic Associations

The generalized stratigraphic succession at Aggenys consists of basal augen gneiss overlain by pink gneiss, aluminous schist, white quartzite and the Aggenys Ore Formation, a variable sequence of conglomerate, amphibolite and leucocratic grey gneiss. The deposit is associated with magnetite-rich banded iron formations. The succession at Gamsberg consist of a basal quartzo feldspathic gneiss overlain by a thickness of up to 450 m of sillimanite bearing pelitic schist in metaquartzite overlain by 0-80 m thick iron formation succeeded by psammitic schists, lenses of conglomerate quartzite and amphibolite.

Putsberg is located in a sequence of quartzo feldspathic gneisses, quartzite, aluminous schist, minor carbonate rocks and amphibolite. A magnetite-rich banded iron formation occurs within 200 m of the deposit.

Areachap is in a biotite garnet schist enclosed by amphibole gneiss and amphibolite. No ironstone associative is evident.

The Preiska mineralization forms part of a 10-100 m wide stratabound layered sequence of pyritic metasediments within a succession of sulphide poor fine grained laminated gneiss. A manganese rich magnetite zone 0-10 m thick occurs above the deposit. Amphibolites occur above and below the deposit.

5.9.2.4 Mineralization

Aggenys (consists of 3 deposits: Broken Hill, Black Mountain, Big Syncline) pyrite, pyrrhotite, chalcopyrite, galena and sphalerite.

Gamsberg: pyrite, pyrrhotite, sphalerite and galena.

Putsberg: pyrite, pyrrhotite, chalcopyrite and galena.

Areachap: pyrite, pyrrhotite, chalcopyrite, sphalerite.

Preiska: pyrite, chalcopyrite, sphalerite, pyrrhotite.

See Section 5.9.2.9 for details.

5.9.2.5 Mineralization Associations

A variety of associations with magnetite quartzites occur.

Broken Hill - sulphides enclosed by magnetite quartzite.

Gamsberg, Black Mountain - sulphides capped by magnetite quartzite

Putsberg - sulphides offset 200 m from magnetite quartzite.

Areachap - no magnetite quartzites reported but amphibolites occur near sulphide zone.

Preiska - no magnetite quartzite. A manganese rich magnetite zone occurs adjacent to part of the mineralization. Deposit occurs in pyritic metasediments.

Variable associations with amphibolites also occur.

Broken Hill - a magnetite amphibolite contains some mineralization

Black Mountain - a magnetite amphibolite contains some mineralization

Gamsberg - only amphibolite present lies unconformably above deposit.

Putsberg - amphibolites in hangingwall

Areachap - amphibolite minerals are reported in metasediments but amphibolites are not described

Preiska - amphibolites are reported in host metasediments

5.9.2.6 Origin of the Mineralization

Ryan et al. (1986) favour an exhalative origin for the Aggenys mineralization but note that the only possible evidence for a feeder pipe is a garnet quartzite zone under the Black Mountain deposit which some geologists have interpreted as an alteration zone.

Rozendaal (1986) notes that the Gamsberg deposit has many of the characteristics found in exhalative mineral deposits known in the Red Sea.

A submarine exhalative origin has been proposed for the Putsberg deposit by Viljoen et al. (1986) and for Areachap by Voet and King (1986).

Theart (1989) recognize a stockwork equivalent and an alteration pipe at Preiska and propose a hydrothermal origin for this deposit.

5.9.2.7 Additional Regional Detail

As described in Section 5.4 the Aggenys and Gamsberg deposits appear to exhibit a systematic variation of metal contents with respect to a geographic direction.

The Aggenys deposits have been compared by many workers with the Broken Hill deposit in New South Wales, Australia.

5.9.2.8 Magnetic Signatures

The magnetic responses of Aggenys are well documented by Campbell and Mason (1979) and Ryan et al. (1986). Their data which were recorded at a line spacing of approximately 1 km and which have a contour interval of 50 nanoteslas over the iron formations, indicate the position of the high amplitude anomalies over the iron formations but do not show any detail that can be related to mineralization.

The magnetic response of the Putsberg deposit have been published by Campbell and Mason (1979) and Vijoen et al. (1986). These data show a narrow linear magnetic anomaly due to a magnetite quartzite however, as was reported above, in this area the mineralization is displaced approximately 200 m from the magnetite quartzite. Although ground magnetic profile and contour data has been published by Campbell and Mason (1979) it is not clear if the mineralization causes its own magnetic response. Small inflections in both the contour and profile data do occur in the vicinity of the mineralization. It is possible that a weak response of the order of a few tens of nanoteslas could arise from the mineralization but confirmation of this would require higher quality data than that which has been published.

Pyrite appears to be the dominant sulphide in all deposits with the exception of Broken Hill. Pyrrhotite is reported in all deposits although in Preiska its concentrations appear to be low. No percentages of pyrrhotite are reported and no descriptions of crystal form are given with exception of Preiska where Theart et al. (1989) have inferred the presence of both monoclinic and hexagonal pyrrhotite. It is impossible to know from the published literature whether these deposits would give magnetic responses due to their pyrrhotite contents.

5.9.2.9 Details of Individual Deposits

Aggenys

Principal reference: Ryan et al. (1986)

Aggenys consists of three separate deposits within a 5 km by 4 km area viz. Broken Hill, Black Mountain and Big Syncline.

Broken hill

Host Rocks: see Section 5.9.1.3.

Form of Mineralization: the mineralization occurs in two sheets. The upper sheet has a maximum mineralized thickness of 30 m and the lower sheet has a minimum mineralized thickness of 5 m. The mineralization appears to occur in an area at least 600 m long and to have a down dip extent of at least 1200 m.

Mineralization: the zoning from top to bottom is:

- ferruginous garnet quartzite which includes thin bands of magnetite
- magnetite quartzite which includes disseminated galena
- sphalerite and chalcopyrite
- magnetite amphibolite
- baritic and banded massive sulphide units (limited distribution)
- baritic massive sulphide

- well banded pyrrhotite-pyrite chalcopyrite, galena, sphalerite massive sulphide (15-50% pyrrhotite + pyrite - pyrrhotite dominant)
- sulphide quartzite
- sillimanite quartz schist
- ferruginous garnet quartzite
- magnetite amphibolite
- massive sulphide
- magnetite amphibolite
- ferruginous garnet quartzite
- pyritic schist

Deposit Size:

Upper body
85mt, 0.34%Cu, 1.77%Cu, 3.57%Pb, 48.10g/t Ag, 48.90% magnetite

Lower body
37.9mt, 0.45%Cu, 2.87%Zn, 0.45%Cu, 82.25%Ag, 43.19% magnetite

Structural setting: the originally conformable mineralization has been deformed by four phases of structuring and has undergone medium to high grade metamorphism.

Magnetic Responses: maps published by Campbell and Mason (1979) and Ryan et al. (1986) show intense anomalies associated with the enclosing host magnetite quartzites. The detail of this data is inadequate to indicate any characteristics associated with the mineralization.

Black Mountain

Host Rocks: see Section 5.9.1.3.

Form of Mineralization: 1.3 km long plunging sheet open in depth. The deposit probably consists of a single sheet however a separate lens of mineralization exists which could be a separate zone of mineralization.

Mineralization: zoning from top to bottom (excluding second zone of mineralization):
- magnetite barite
- magnetite amphibolite (contains pyrite, pyrrhotite, galena and chalcopyrite)
- magnetite quartzite (contains pyrrhotite, pyrite, galena and sphalerite)
- mixed zone consisting of gradations between garnet quartzite and various quartz schist (contains pyrite and chalcopyrite)

Deposit Size: 81.6mt, 0.75%Cu, 0.59%Zn, 2.67%Pb, 29.83g/t Ag.

Structural Setting: as for Broken Hill

Magnetic Response: As for Broken Hill

Big Syncline

101mt, 0.09%Cu, 2,45%Zn, 12.90g/t Ag.

pyrite, pyrrhotite, chalcopyrite and sphalerite in a schists and quartzites apparently offset from a magnetite quartzite containing pyrite-chalcopyrite disseminations. No amphibolites are reported in the immediate proximity of the mineralization.

Magnetic responses are as for Broken Hill.

Gamsberg

Principal reference: Rozendaal (1986)

Host Rocks: see Section 5.9.1.7.

Form of the Mineralization: a mineralized layer 5300 m long with a thickness of 0 to 50 m is reported.

Mineralization: pyrite, pyrrhotite, sphalerite and galena overlain by diverse magnetite rich rocks.

Deposit Size: 150 mt, 7.1%Zn, 0.5%Pb.

Structural Setting: the deposit occurs on the flank 7 km by 5 km syncline with local subsidiary folds.

Magnetic Responses: not reported.

Putsberg

Principal reference: Viljoen et al. (1986)

Host rocks: quartzofeldspathic gneiss, quartzite, aluminous schist, minor carbonate rocks and amphibolite.

Form of the Mineralization: three discrete co-linear stratiform sheets of disseminated sulphides. Two of the mineralized zones appear to be approximately 600 m long.

Mineralization: pyrite, pyrrhotite, chalcopyrite, sphalerite and galena.

Deposit Size:

	Tonnes	Cu%	Zn%	Pb	Ag g/t
Western Body	514304	0.97	0.26	0.22	9.58
Central Body	700560	1.27	0.26	0.22	17.97
Eastern Body	223860	2.02	0.55	0.22	21.29

Structural Setting: steeply dipping in highly deformed area.

Magnetic Signatures: publications by Campbell and Mason (1979) and Viljoen et al. (1986) present aeromagnetic data covering the deposit area. Campbell and Mason (1979) have also published detailed ground magnetic data. Significant observations (reported in Section 5.9.1.8) are:

(i) the mineralized zones are offset approximately 200 m from a linear magnetic zone due to a magnetite quartzite.

(ii) the mineralization may give a magnetic response but if it does it is of the order of 10's of nanoteslas.

Areachap

Principal reference: Voet and King (1986)

Host Rocks: biotite-garnet schist enclosed mainly by amphibole gneiss and amphibolite

Form of the Mineralization: Near vertical sheet approximately 600 m long, 20 m thick with a vertical depth extent of at least 700 m.

Mineralization: pyrite, pyrrhotite, chalcopyrite, sphalerite.

Deposit Size: 8.9 mt of massive and disseminated mineralization grading 0.4%Cu, 2.24%Zn or 6.7 mt of massive mineralization grading 0.95%Cu and 2.88%Zn.

Structural Setting: steeply dipping highly metamorphosed terrain.

Magnetic Responses: Voet and King (1986) state that the mineralization is in a non magnetic layer and that the suite of rocks containing the mineralization has a distinct magnetic signature. They do not report any magnetic response due to the mineralization.

Preiska

Principal references: Wagener and Van Schalkwyte (1986), Theart et al. (1989)

Host Rocks: the massive sulphide ore zone forms part of a 10 to 100 m wide stratabound layered sequence of pyritic metasediments within a succession of sulphide poor fine grained laminated gneisses. A smaller lesser mineralized body (the Annex) occurs approximately 5 km along strike.

Orebody Form: strike extent of more than 2000 m, a depth extent of at least 1000 m. Average thickness 7 m.

Mineralization: pyrite is dominant and amounts to 45% by weight chalcopyrite, sphalerite and pyrrhotite. A manganese rich magnetite zone abuts the mineralization at various localities.

Deposit Size: 47 mt, 1.7Cu, 3.8%Zn.

Structural Setting: tabular body with a plunge at 45^0 and dip generally exceeding 60^0. Conformable to bedding.

Magnetic Signature: not reported but the magnetite zone associated with the mineralization would give a magnetic response.

5.9.3 The Besshi Type Deposits, Japan

Principal References: Tatsumi (1970), Yamoka (1984), Fox (1984)

5.9.3.1 Introduction

More than one hundred mineral deposits and mineral occurences of conformable tabular pyrite-chalcopyrite deposits occur in the Sanbagawa Metamorphic Belt of Japan. Numerous similar less well documented deposits occur in other metamorphosed areas of Japan viz. the Akumba Metamorphic Terrain, the Sangun Metamorphic Terrain, the Maizuru Zone, the Shimanto Terrain, and the Hidaka Zone. These deposits are recognised as being distinctly different in character to the Kuroko VHMS deposits of Japan. The most notable differences are their common association with mafic volcanic rocks or their metamorphosed equivalents and their virtual lack of galena. Japanese literature refers to these deposits as the bedded cupriferous iron sulphide deposit type. Western literature generally refers to them as the Besshi type which implies that the Besshi Mine in Japan is the type model for the deposits.

The following descriptions largely relate to the best known group of deposits which are those in the Sanbagawa Terrain which hosts the Besshi deposit.

5.9.3.2 Setting of the Deposits

The deposits of the Sanbagawa Belt occur in a sequence of turbiditic argillite, arenite and basalt in a setting which Fox (1984) and other interpret as a Permian rift. The rocks have been subjected to blue schist metamorphism.

5.9.3.3 Stratigraphic Associations

Almost all of the Sanbagawa Belt deposits are situated in the Minawa Formation of the Yoshingowa Group. The Minawa Formation has a thickness of approximately 3000 m. Most of the deposits occur on a specific horizon which is a contact between a mafic volcanic rich member and an overlying argillite rich member.

5.9.3.4 Mineralization

The deposits contain pyrite, chalcopyrite and subordinate sphalerite. Galena contents are negligible. Magnetite and hematite layers are occasionally interbedded with the sulphides. Pyrrhotite is an accessory constituent. Pyrrhotite appears to be more common in deposits of this type in other areas of Japan. It has been noted that pyrrhotite contents tend to be highest in areas of high metamorphic grades. The deposits tend to be tabular and thin. The ore body in the Besshi Mine has a strike length of 1600 m, a down dip extent of at least 2000 m and an average thickness of 3 m.

The sulphides in the Besshi Mine occur as:

compact ore (chiefly pyrite, chalcopyrite and sphalerite).
banded ore (sulphides and silicates)
copper ore (chalcopyrite with minor pyrite).

Magnetite-garnet-quartz schist occurs in thin layers of both the hangingwall and the footwall of the orebody. Pyrrhotite occurs as one of the main constituents in the lower parts of the body. Magnetite and hematite tend to be concentrated in the upper parts of the mineralization. No feeder pipe has been described.

5.9.3.5 Mineralization Associations

Most of the deposits in the Sanbagawa Belt are associated with basic schists which are interpreted to be metamorphosed basic lavas. The Besshi deposit occurs in 100m thick layer of pelitic schists which is flanked by layers of basic schists.

5.9.3.6 Origin of the Mineralization

Japanese workers have considered both submarine exhalative and hydrothermal replacement origins for the deposits. They appear to show a preference for the exhalative model.

5.9.3.7 Additional Regional Details

Ishihara (1978) has concluded that the largest copper deposits in the Sanbagawa Belt occur in what was originally the centre of the basin where they are associated with tholeiitic metabasalts. The smaller deposits of the belt are situated on the margins of the basin associated with transitional or alkaline metabasaltic rock.

5.9.3.8 Magnetic Signatures

No reports describing the magnetic response of these deposits have been located. Their association with magnetite-garnet-quartz-schist and their variable contents of magnetite and pyrrhotite indicates that they may be mappable using magnetic data.

5.9.3.9 Details of Individual Deposits

Tonnages and grades of some Sanbagawa belt deposits are:

	Tonnes $x10^6$	Cu%	Zn%	Ag g/t	Au g/t
Besshi	33	2.6		20.6	0.7
Shirataki	5.5	1.3			
Limori	2.8	1.3			
Hitachi	33.0	1 .5	1.1		
Sazare	5.5	1.6			

5.9.4 Gossan Lead District, Virginia U.S.A.

Principal Reference: Gair and Slack (1984)

5.9.4.1 Introduction

The Gossan Lead district is a 45 km long belt of discontinuous stratabound massive sulphide lenses hosted in Late Proterozoic sediments of the Blue Ridge Province of south western Virginia. These deposits occur in metasedimentary sequences which contain conformable lenses of amphibolite. They appear to be associated with pyritic and pyrrhotitic iron formations rather than magnetite rich BIFs. Similar deposits occur at Ore Knob 55 km to the southwest and at Toncrae 35 km to the northeast (Kinkel, 1967).

This account is based on Gair and Slack's (1980) description of the Gossan Howard, Huey and Bumbarger deposits in the 5 km long Iron Ridge segment of the Gossan Lead belt.

In economic terms these deposits are relatively insignificant. They have been included in this study because their tectonic setting gives particular insights into the association of massive sulphides with rifting processes (see Section 5.9.4.7).

5.9.4.2 Setting of the Deposits

The deposits occur in the Ashe Formation which is a sequence of metasedimentary rocks and local conformable lenses of amphibolite and actinolite chlorite schist. The metasedimentary rocks included metapelite, metagreywacke and minor quartzite and carbonaceous schists which are interpreted to have evolved as marine turbidites. The amphibolites and other mafic rocks have the compositions of tholeiitic basalt.

The depositional environment is interpreted as a deep elongate marine basin which developed as a failed rift associated with the opening of the late Proterozoic Proto-Atlantic Ocean. The geochemistry of the mafic rock association and possible ophiolite fragments in the sequence suggest that a limited amount of ocean crust was produced in the rift.

The Ashe Formation has been regionally metamorphosed to amphibolite facies.

5.9.4.3 Stratigraphic Associations

The deposits are confined to metapelites, metagreywackes and quartzites. Pelitic schists sometimes contain disseminated pyrite and pyrrhotite.

5.9.4.4 Mineralization

The sulphide deposits consist of massive pyrrhotite, pyrite, sphalerite and minor chalcopyrite. Galena is rare. Average grades are 0.5%Cu, 2%Zn.

The deposits which have been variably deformed appear to have originally been extensive tabular sheets. The Gossan Howard deposit is a single lens of mineralization 12-20 m thick.

No feeder pipes or zoning are apparent from the literature.

5.9.4.5 Mineralization Associations

Although numerous amphibolite sheets are reported in the host section, none are in contact with the mineralization. The most proximal association appears to be an amphibolite 150 m above the mineralized level.

Graphitic zones and disseminated pyrrhotite and pyrite are common in the Ashe Formation. Their relationship to the mineralization is not clear.

5.9.4.5 Origin of the Mineralization

Gair and Slack (1984) propose a sea floor exhalative origin for the deposits.

5.9.4.7 Additional Regional Detail

As discussed in Section 4.7 these deposits have marked similarities with the Ducktown deposits except for the greater amounts of amphibolites in the Gossan Lead area. The Gossan Lead area and the Ducktown areas are interpreted to have developed in contemporaneous associated rifts with the rifting process reaching a more advanced stage in the Gossan Lead area. The greater abundance of basic igneous activity in the Gossan lead area reflects this difference.

5.9.4.8 Magnetic Signatures

No reports of magnetic survey data or identifications of the mineral form of the pyrrhotite have been located for the Gossan Lead deposits however the 1.4mt Ore Knob deposit (Kinkel, 1967) which occurs 55 km along strike and which has a similar mineralogy has been shown by Heinrichs (1966) to give a ground magnetic anomaly.

5.9.5 Deposits in the Eastern Succession, Mount Isa Area and in the Broken Hill Area, Australia

Principal References: publications referred to in this section.

5.9.5.1 Introduction

The Mount Isa area of northern Australia (Blake et al., 1990) contains Early and Middle Proterozoic rocks in two north trending troughs separated by an intervening basement ridge. The sediments in the eastern trough which is referred to as the Eastern Fold Belt are themselves referred to as the Eastern Succession. Sediments in the western trough are referred to as the Western Succession. The Eastern Succession sediments which are more highly deformed and metamorphosed than sediments further west contain numerous Cu, Cu-Ag and Pb-Zn-Ag deposits which have close spatial relationships with banded iron formations and/or amphibolites and basic rocks (Figure 5.3).

These deposits include:

- Osborne (previously known as Tank Trough), Cu-Au, Davidson et al. (1992).
- Selwyn (previously known as Starra), Cu-Au, Davidson et al. (1992).

- Eloise, Cu, Brescianini et al. (1992).
- Pegmont, Pb-Zn, Vaughan and Stanton (1986).
- Cannington, Pb-Zn, Skrzeczynski (1993)

As explained below it is probable that metamorphosed equivalents of Eastern Succession rocks originally continued southwards to the Willyama Complex of the Broken Hill area of New South Wales (Stevens et al., 1990) which contains the Broken Hill Pb-Zn deposit which also has banded iron formation/amphibolite associations.

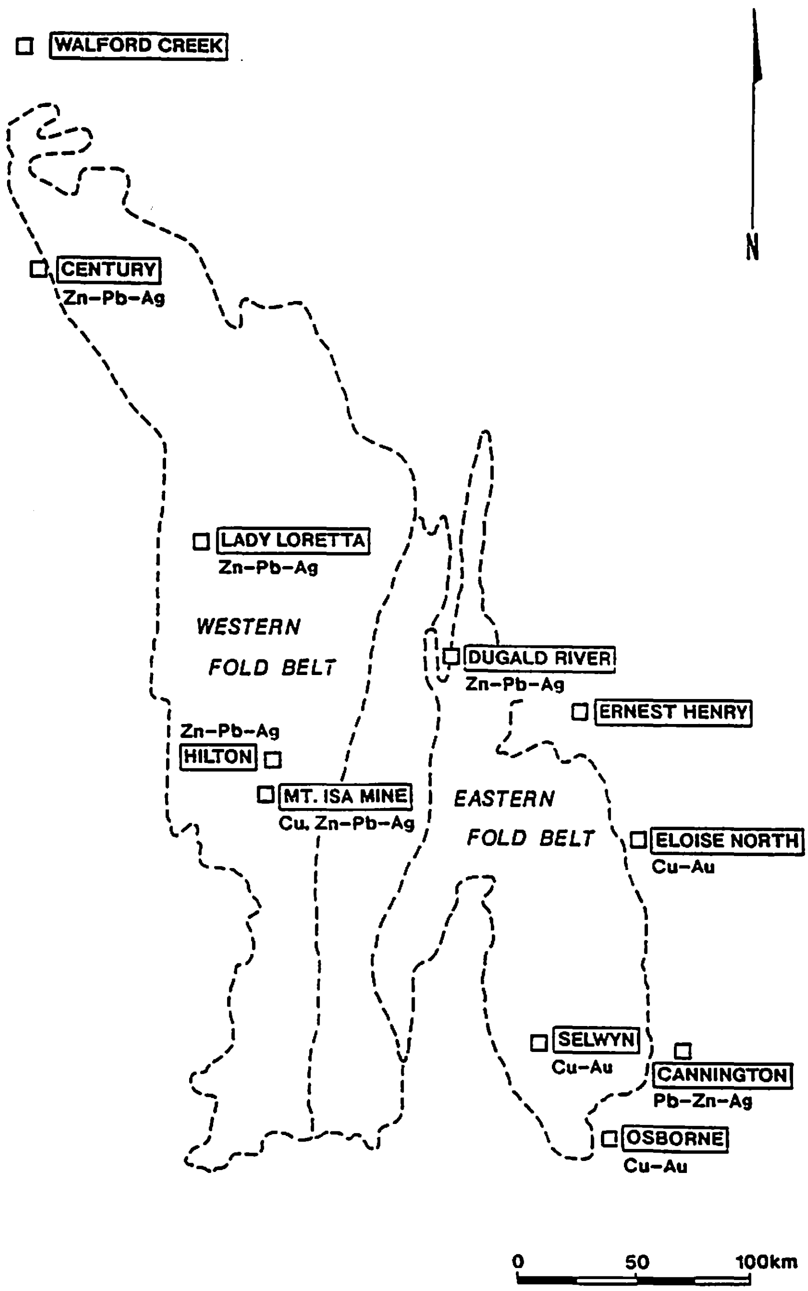


Figure 5.3 Mineral deposits in the Mount Isa area.

5.9.5.2 Setting of the Deposits

As reviewed by Blake et al. (1990) and Derrick (1991) the Eastern Succession and the Western Succession to the west originated in separate, parallel, apparently contemporaneous rift systems. The structure and stratigraphy of the area is complicated by the fact that the area has undergone three and possibly four periods of crustal extension with a consequential superposition of structural and igneous features. The Eastern Succession is more highly metamorphosed and deformed than the Western Succession. The metamorphic grade is upper greenschist to lower amphibolite in the Cloncurry area and increases southwards to such an extent that partial melting has occurred in areas 200 km to the south.

Several convincing lines of evidence, reviewed in detail by McConachie et al. (1993) suggest that the rift system in the Mount Isa area containing the Eastern Succession continued uninterrupted into the Broken Hill area 2000 km to the south. The present discontinuity between the two areas has been explained to be the result of episodes of Cambro-Ordovician and Permo-Triassic rifting. The high metamorphic grades in the Broken Hill area (hornblende-granulite) are consistent with the southerly increase in metamorphic grade in the Mount Isa area and is explained by the southern areas having been more deeply buried at one stage in their geological history.

The ages of many of the host rocks to the deposits in the Eastern Succession are not clear and it is difficult to relate their occurences to particular stages of rifting. The metamorphic overprint also confuses such interpretations by obscuring evidence of depositional settings. Despite these problems it can be recognised that many of the deposits appear to be hosted by turbidite sequences containing basic tholeiitic sills and volcanics.

5.9.5.3 Stratigraphic Associations

Host rocks to the mineralized sequences are:

- Osborne - quartzites, feldspathic quartzites, feldspathic schists
- Starra - turbiditic metasediments
- Eloise - meta-arenite (psammitic) and micaceous quartz schist (pelite)
- Pegmont - turbiditic metasediments
- Cannington - meta-arkose
- Broken Hill - original sediments are considered to have been shales, siltstones and sandstones

5.9.5.4 Mineralization

Two broad classes of mineralization can be recognised viz: Cu-Ag and Pb-Zn-Ag. For various reasons such as lack of published detail, structural deformation and intense metamorphism, Osborne (Cu-Ag) and Pegmont (Pb-Zn-Ag) are the only deposits for which a clear image of original mineral distributions emerge. These deposits are summarized below as being representative of the two types. As far as can be ascertained the characteristics of the other deposits, except where noted, are consistent with these descriptions.

Cu-Ag Type:

(Based on Osborne but generally consistent with Starra)
Cu-Ag mineralization is hosted mainly within concordant magnetite rich banded iron formations which consists of alternating 1cm wide bands of magnetite +/- apatite+/-pyrite +/- chalcopyrite. This mineralized area is underlain by discordant coarse grained silica dominated mineralization which contains pyrite and magnetite and which has been interpreted to be a feeder pipe (Davidson et al., 1989). An alteration zone has been identified surrounding the feeder pipe.

The mineralization has at least a 500 m strike length with the non feeder section having a possible thickness of 30 m. The host BIF has at least a 7 km strike length and appears to vary in thickness between 10 and 40 m.

The Eloise deposit is not associated with a BIF but occurs instead in a 1km long linear zone in what has been called a "pyrrhotite rich alteration envelope". Mineralization in the actual Eloise deposit consists pyrrhotite and chalcopyrite.

Pb-Zn-Ag Type:

(Based on Pegmont but could be similar to Cannington or even a small scale Broken Hill)

Bands of galena, sphalerite, pyrite, pyrrhotite and minor chalcopyrite occur within magnetite-rich banded iron formation. The mineralized zones thin and pass laterally into pyrrhotite, pyrite and grunerite-magnetite-garnet schists.

Both Broken Hill and Pegmont are relatively poor in pyrite.

5.9.5.5 Mineralization Associations

BIF Associations

Osborne - partly enclosed by magnetite BIF
Starra - partly enclosed by magnetite BIF
Eloise - enclosed in linear zone of disseminated pyrrhotite (BIF pyrrhotite facies ?)
Pegmont - enclosed by magnetite BIF
Cannington - reported BIF association
Broken Hill - several magnetite BIFs occur in deposits at levels above and stratigraphically equivalent to mineralization.

Amphibolite Associations

Osborne - conformable amphibolite sheets proximal to mineralization
Starra - tholeiitic basalts occur below BIF hosting Starra
Eloise - linear amphibolite parallelling deposits 300m to west of deposit
Pegmont - large sill like amphibolite bodies are associated with the mineralization
Cannington -subordinate lenses of amphibolite occur in proximity to the mineralization
Broken Hill - amphibolites occur in the "mine sequence".

5.9.5.6 Origin of the Mineralization

Davidson et al. (1989) have proposed an exhalative origin for Osborne and Starra. Their conclusions are largely based on the identification of pipe like feeder zones.

Vaughan and Stanton (1986) interpret Pegmont as being formed by hydrothermal exhalative processes.

5.9.5.6 Additional Regional Detail

According to the gravity data of the Mount Isa region (Wellman, 1992) the Osborne, Selwyn and Eloise Cu-Ag deposits all occur in areas of high north trending linear regional gravity features. The Pegmont and Cannington Pb-Zn-Ag deposits occur in linear north trending gravity low. This may indicate a tendency for the Cu-Ag deposits to be associated with areas of greater crustal extension.

5.9.5.7 Magnetic Signatures

Osborne (Anderson and Logan, 1992) : the host magnetite quartzite gives an intense magnetic anomaly. The response of the mineralization is not obvious (see Figure 5.4).

Starra (Collins, 1987) : the host BIFs give magnetic anomalies.

Eloise (Brescianini et al., 1992) : the deposit is located in a linear magnetic ridge due to a pyrrhotitic formation. The mineralization does not give an observable magnetic response relative to this background.

Pegmont : the host BIFs give an observable response in regional data.

Broken Hill (Johnson and Klinger, 1975) : It is not clear whether the deposit gives a magnetic response. Significant concentrations of pyrrhotite are reported at various locations (e.g. 60% pyrrhotite in an envelope 30 m high, 30 m wide and 500 m long). It is not clear whether the pyrrhotite at Broken Hill is magnetic.

5.9.5.9 Details of Individual Deposits

Osborne (formerly Trough Tank)

Principal references: Davidson et al. (1989), Anderson and Logan (1992), Davidson et al. (1992)

Host Rocks: magnetite quartzites, feldspathic quartzites, feldspathic schists.

Form of Mineralization: deformed tabular sheets (one is approximately 500 m long) concordant with host rock.

Mineralization: pyrite, chalcopyrite occuring as disseminated grains in magnetite and/or hematite bands.

Deposit Size: 36 mt, 2.0%Cu, 1.0g/t Au using a 1%Cu-Au equivalent cut off.

Structural Setting: partly enclosed by dipping magnetite rich BIF, possibly structurally thickened by local kink folding.

Magnetic Response (Gidley, 1988; Anderson and Logan 1992): host BIF gives 10000 nanotesla ground magnetic anomaly (Figures 5.4 and 5.5). An adjacent barren BIF gives an anomaly of the same magnitude. No magnetic effect due to mineralization is apparent. Local magnetic culminations could indicate the localities of feeder vents. The high magnetic susceptibility of the ironstones (2000×10^{-3} SI units) creates significant demagnetization effects which must be accounted for in order to obtain consistency between computer modelling and drill results.

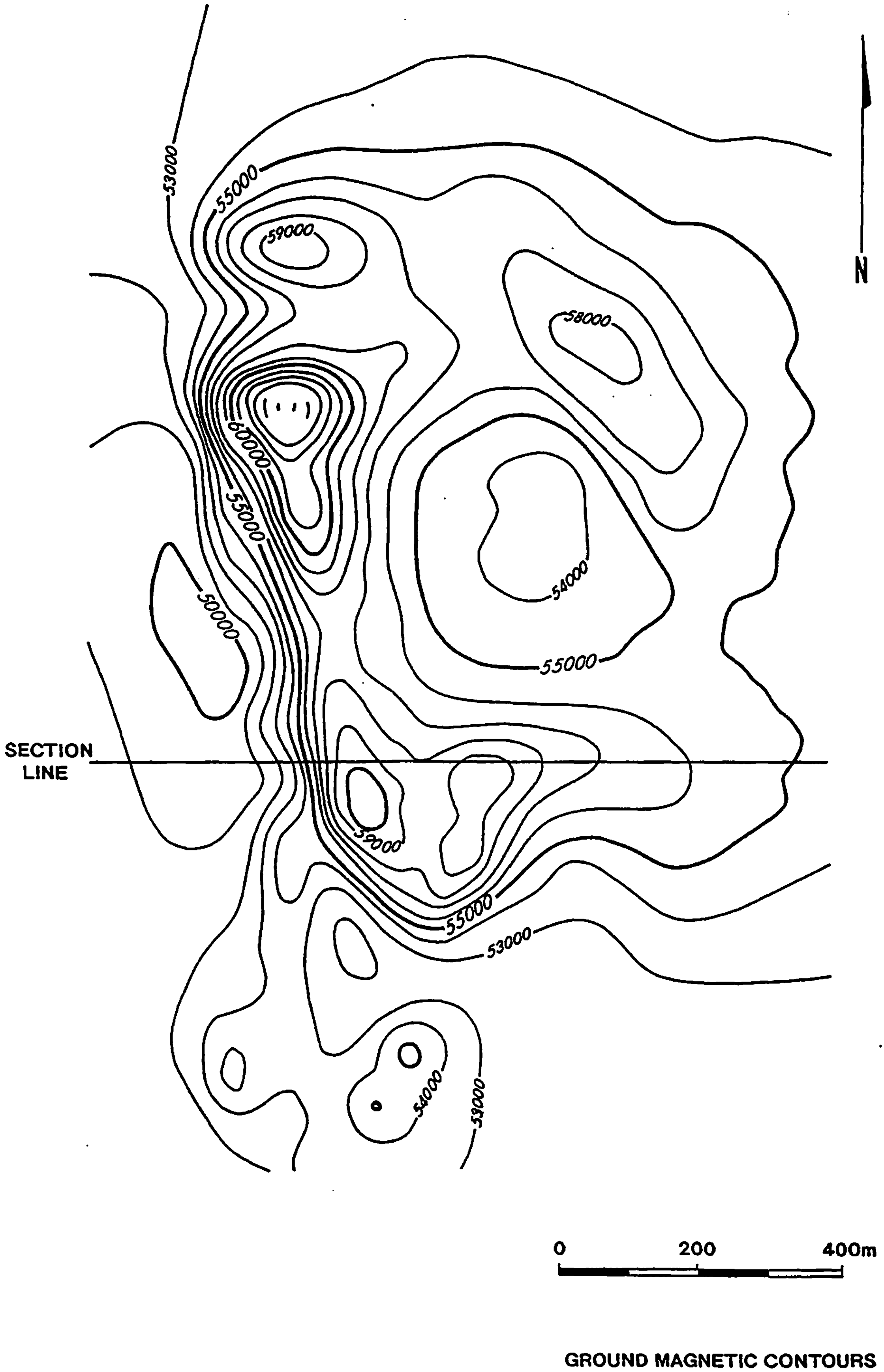


Figure 5.4 Ground magnetic results from the Osborne deposit.

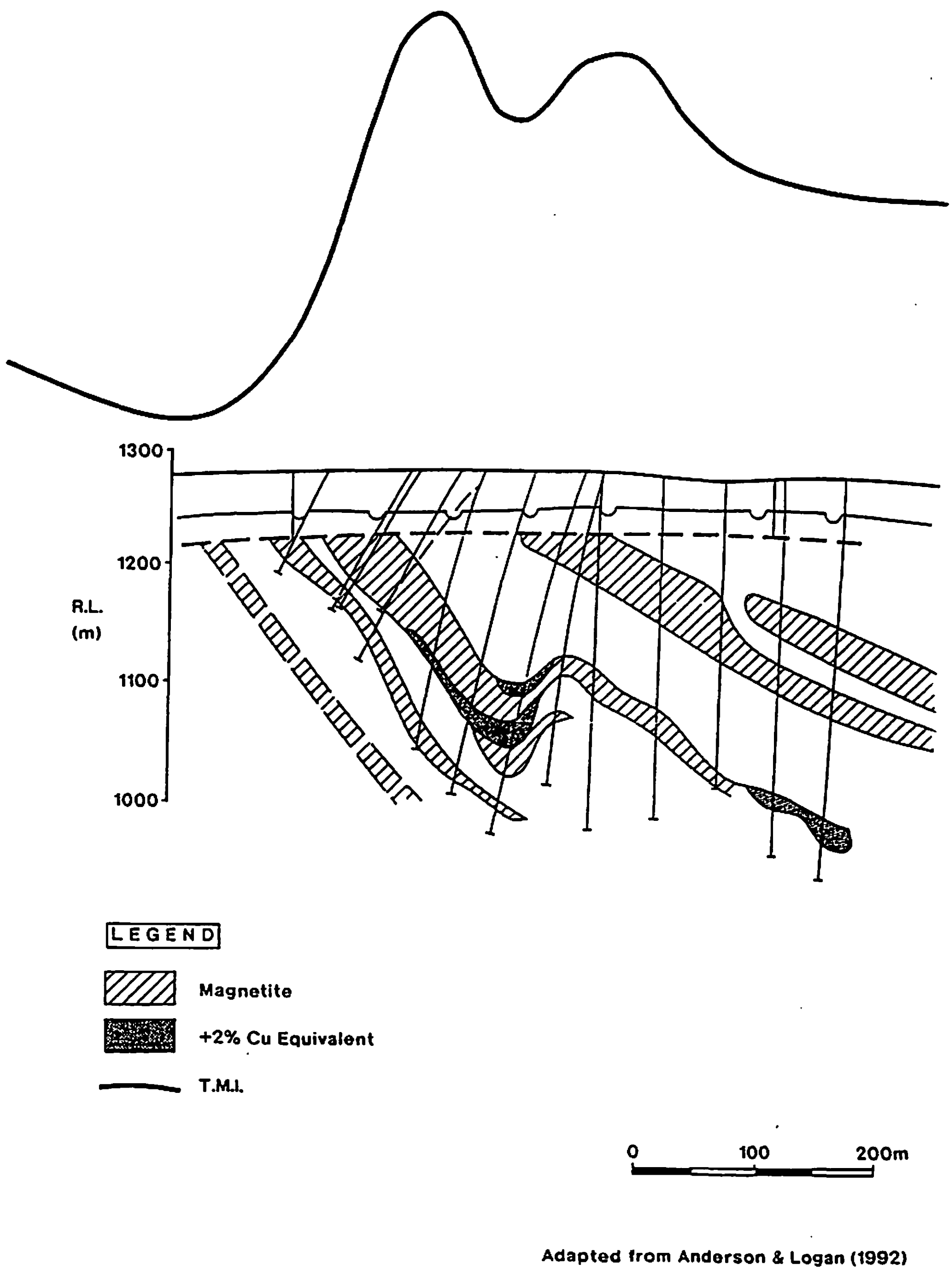


Figure 5.5 Section of the Osborne deposit. The location is shown on Figure 5.4.

Selwyn (formerly Starra)

Principal references: Collins (1987), Davidson et al. (1989), Davidson (1992)

The stratabound Selwyn deposit (5.3mt, 1.98%Cu, 5.0g/t Au) is hosted by stratiform magnetite-hematite iron formation. The mineralization consists of pyrite-chalcopyrite and the enclosing country rocks are metaturbidites. At least 4 separate areas of mineralization exist. The deposits occur adjacent to major shear and are extensively deformed by folding. The magnetite quartzites hosting the mineralization give magnetic responses (Collins, 1987) but barren hematite quartzites along strike are non magnetic. Magnetite bearing schists adjacent to the ironstones give strong anomalies.

Eloise

Principal references: Brescianini et al. (1992), Skrzeczynski (1993)

The 3.2 mt Eloise deposit which grades 5.8%Cu, 1.5g/t Au and 19g/t Ag comprises two plunging lenses of both stockwork and massive pyrrhotite-chalcopyrite mineralization. The main lens has a strike length of 200 m and a maximum thickness of 30 m and remains open beyond a vertical depth of 650 m. The mineralization is hosted within a metamorphosed sequence of meta-arenite, biotite rich quartz psammite and biotite and muscovite schists.

The deposit is associated with an extensive alteration halo.

The deposit occurs in a 1 km long zone of disseminated pyrrhotite which causes a linear magnetic anomaly (Brescianini et al. 1992). It does not appear possible to distinguish the magnetic response of the mineralization.

Pegmont

Principal reference: Vaughan and Stanton (1986)

The Pegmont lead zinc deposit (11 mt, 3.7%Zn, 8.4%Pb) consist of stratiform galena, sphalerite, pyrite, pyrrhotite and minor chalcopyrite enclosed within a magnetite BIF in a shallowly dipping but complexly folded quatz-feldspar-mica schist sequence. The BIF has an aeromagnetic response.

Ernest Henry

No geological publication exists for this deposit which various press reports describe as containing 69 mt of 1.6% Cu and 0.8 g/t Au. The deposit appears to be coincident with, or immediately adjacent to, an intense linear anomaly visible on regional aeromagnetic maps which could be due to magnetite quartzites.

Cannington

Principal reference: Skrzeczynski (1993)

A resource of 47 mt, 4.6%Zn, 10.7%Pb and 470g/t Ag has been outlined at Cannington.

The host is a siliceous and variably garnet-pyroxene amphibole altered meta-arkose locally referred to as a quartzite. This unit is in turn hosted by a regionally extensive sequence of quartzo-feldspathic gneiss. The resource is contained in a zone of approximately 1200 m strike extent and extends to 650 m. The mineralization consists of a magnetite-flourite-galena type and a galena-sphalerite-carbonate type. Brecciated pyrrhotite-sphalerite mineralization also occurs. The deposit is associated with a 1000 nanotesla aeromagnetic anomaly.

Broken Hill

Principal references: Johnson and Klinger (1975), van der Heyden and Edgecombe (1990), Mackenzie and Davies (1990)

The ore bodies at Broken Hill originally contained 180mt, 0.2%Cu, 9.8%Zn, 11.3%Pb, 175g/t Ag. Six ore lenses stacked approximately one above another form a mineralized zone 7.3 km long, 850 m wide and 250 m thick. The host rocks are high grade felsic gneisses. Although generally sheetlike the ore lenses have been extensively folded and the mineralization is locally thickened in fold axes. The mineralization consists of galena, sphalerite with minor pyrrhotite and chalcopyrite. Pyrite is rare. Massive pyrrhotite is reported in parts of the orebodies. It is not known whether this pyrrhotite is magnetic. The magnetic response of the orebody is not known and would be difficult to determine given the amount of ore that has been removed and the existence of mine works.

5.9.6 The Bathurst District, New Brunswick, Canada

Principal References: Franklin et al. (1981), Sawkins (1990)

5.9.6.1 Introduction

The Bathurst district of New Brunswick Canada contains approximately 30 massive sulphide deposits, predominantly of the Zn-Pb-Cu-Ag type which many authors have classed as VHMS deposits. While all these deposits are hosted by sequences containing significant felsic volcanic components two distant subtypes can be recognised. The smaller deposits which exhibit close spatial relationships with siliceous tuff breccias appear to be analogous to the VHMS deposit type which are frequently related to brecciated rhyolite lava domes. The second larger type of deposit such as Brunswick 6 and 12 and Orchan Brook which are laterally extensive conformable sediment hosted sheet like bodies associated with oxide, silicate and carbonate facies iron formations and which in many cases are overlain by mafic tholeiitic volcanic rocks have marked similarities with the other deposits described in this chapter. It is possible that the Bathurst district contains examples of both the classic VHMS deposits and the BIF/amphibolite/basic volcanic association deposits.

5.9.6.2 Setting of the Deposits

The deposits are hosted in a metamorphosed sequence commencing with arenaceous siltstones and feldspathic greywackes succeeded progressively by felsic volcanics, basaltic volcanics and eventually slates and greywackes. The apparent ages ranges from early to mid Ordovician. The volcanics have both alkaline and tholeiitic affinities. Calc-alkaline volcanics are absent. A backarc rift setting has been interpreted.

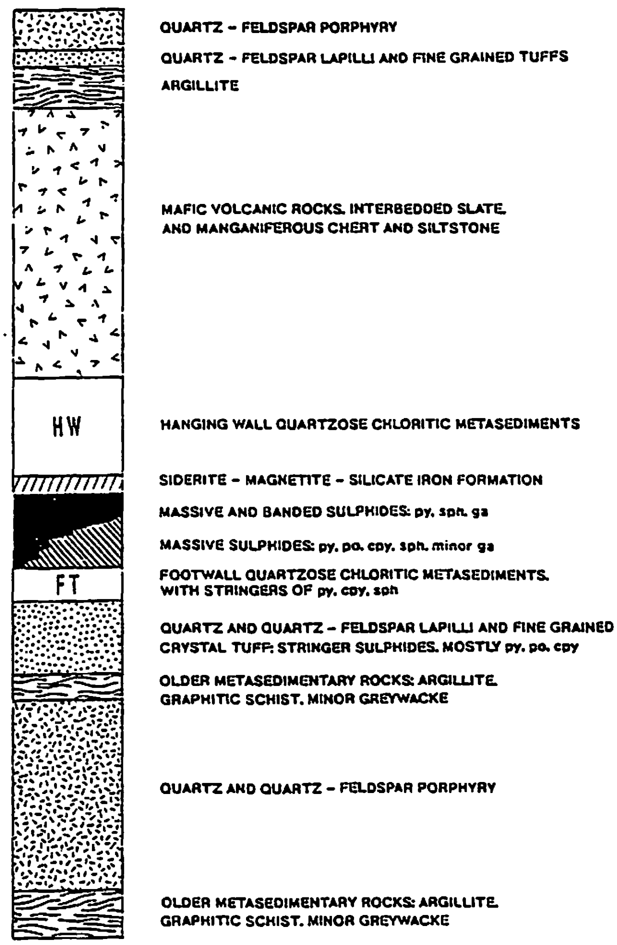


Figure 5.6 Mineral zoning in the Brunswick No 12 deposit (after Franklin et al. 1981)

5.9.6.3 Stratigraphic Associations

The massive sulphide deposits preferentially occur just above the lower sedimentary group or more commonly above the felsic volcanics that overly the lower sedimentary group. The iron facies associated with many of the deposits occur just above the felsic volcanics.

5.9.6.3 Mineralization

The Brunswick No 12 deposit, the largest in this area, is well described and appears to be representative of the deposits associated with the iron formations. This deposit consists of almost 100 mt grading 0.3%Cu, 9.2%Zn, 3.8%Pb, 0.79g/t Ag, 0.79g/t Au plus 14 mt, 1.1%Cu, 1.3%Zn, 0.4%Pb and 0.30g/t Ag. Figure 5.6 shows the zoning of this deposit. A pyrrhotite pipe shaped feeder zone has been identified in the footwall. The deposit has a length of approximately 1000 m.

A group of at least seven deposits in the south eastern portion of the area have iron formations above the mineralized horizon and iron formations are present on the ore horizon in several other deposits. The iron formations variably occur as sulphide, carbonate, silicate and oxide. Magnetite is common in the iron formations.

5.9.6.4 Mineralization Associations

A southern group of deposits occurs. As noted above iron formations are associated with many of the deposits in this group. Mafic volcanic rocks are in the hanging wall of many of these deposits.

A northwestern group of deposits occurs in a similar setting to the southern group but these deposits do not appear to have the same distinct ironstone association.

5.9.6.5 Origin of the Mineralization

Stringer sulphides and alteration zones are recognised in some deposits and a classical exhalative origin explanation appears applicable.

5.9.6.6 Additional Regional Detail

Most of the deposits occur in a roughly circular area about 50 km in diameter. Two volcanic centres have been interpreted to exist in the area. One of these is centred in the south eastern portion of the area where the iron formation associated deposits are most prevalent. It is possible that the area has undergone two mineralizing phases viz. a northern one which produced classic VHMS deposits and a southern one which produced deposits of the BIF/amphibolite/basic volcanic association.

5.9.6.7 Magnetic Signatures Ward (1958)

The recognised association of magnetite quartizites with massive sulphides in the Bathurst area provided a basis for the original exploration in the area. It does not appear the any characteristics of the magnetic responses were recognised to distinguish between those magnetite quartizites associated with mineralization and those that are not. No recent publications describing the magnetic data of this area have been located.

5.9.6.9 Details of Individual Deposits

Refer to Franklin et al. (1981)

5.9.7 Other Deposits

Deposits of the BIF/amphibolite/basic igneous association are comparatively widespread. Deposits which appear to be of this type but which have not been reviewed in this study are:

Connemara, Ireland (McArdle et al., 1986)

Elizabeth Mine area, Vermont, U.S.A. (Howard,1959)

Sherritt Gordon, Manitoba, Canada (Davies et al.,1962)

Bleikvassli, Norway (Vokes, 1963)

Fox (1984) also notes groups of similar deposits in the Trondheim region of Norway and the Outokumpu region of Finland.

Davidson (1992) in his Table 2 lists several deposits which, from the descriptions given by Davidson, could also belong to this class.

5.10 EXPLORATION GUIDE LINES

1. Locate an intracontinental or marginal basin rift system in an advanced stage of crustal extension (Section 4.2).

   These may be recognised by:

   (i) geological mapping. Fault bound areas 60-80 km wide containing deepwater sediments are most prospective (Section 4.2).
   (ii) regional seismic sections (c.f. Section 4.2).
   (iii) regional gravity highs indicating thinned crust (Section 3.1.7)

(iv) regional magnetic highs indicating imminent or actual ocean crust development (Section 3.1.7).

(v) areas of basic igneous (preferably tholeiitic) igneous activity. Basic igneous rock distributions should be evident in regional aeromagnetic data (Section 4.2).

2. Areas in the vicinity of known deposits of the BIF/amphibolite/basic igneous association are most prospective.

3. Localities with:
   (i) BIFs and amphibolites and/or basic igneous rocks.
   (ii) BIFs but no amphibolites and/or basic igneous rock.
   (iii) No BIFs but amphibolites and/or basic igneous rock,
   are all prospective with a ranking indicated by the numbers. Such areas should be identifiable using aeromagnetic maps because magnetite and/or pyrrhotite BIFs and the basic rocks and their derivatives normally produce narrow linear magnetic anomalies. The anomalies caused by magnetite rich BIFs can be recognised by the high amplitude anomalies they produce. These may be several thousand nanoteslas above background. BIF associated anomalies may have lengths up to approximately 20 km (Section 4.5).

4. Areas where massive sulphides are hosted within BIFs may be indicated by:

   (i) magnetic lows within the anomaly due to the BIF resulting from the presence of non magnetic mineralization (Section 4.8).
   (ii) areas of higher magnetite concentrations in the BIF, possibly indicating vent locations, which will be apparent as culminations in the linear anomalies caused by the BIFs (Section 4.8).
   (iii) areas where fault zones intersect the BIF. These may have localized hydrothermal vents producing the mineralization (c.f. Section 3.1.5). These may be identifiable using aeromagnetic data.
   (iv) areas with obvious remanent magnetization. These may be indicated by a significant change in anomaly form which does not have an obvious explanation. Remanently magnetized monoclinic pyrrhotite could cause such an effect (Section 4.8).
   (v) areas where the magnetic data indicates drag folding (Section 4.8).

5. Areas where massive sulphides are located immediately adjacent to BIFs may be indicated by:

(i) a bulge in the magnetic anomaly associated with the BIF due to the extra magnetite or monoclinic pyrrhotite minerals in the deposit (Section 4.4).

(ii) a weaker anomaly perpendicular to the BIF anomaly due to magnetic minerals in a feeder pipe (Section 4.4).

(iii) a magnetic low or quiet zone flanking the anomaly due to the deposit or the feeder pipe. This could be the effect of an alteration zone (Section 4.4).

6. Massive sulphides adjacent to BIFs but separated from them by distances up to 200 metres should be indicated by narrow linear magnetic anomalies parallelling the BIF related anomalies. Such deposits may show magnetic effects related to feeder pipes similar to (5) above . The magnetic anomalies of such bodies may be difficult to distinguish from the rocks and metamorphosed argillaceous horizons, however the ore related anomalies are likely to be narrower and shorter than the anomalies caused by these more regional units.

Not all BIF/amphibolite/basic igneous related deposits contain pyrrhotite and of those that do some will contain non magnetic varieties. Pyrrhotite contents are more likely in metamorphic terrains where pyrrhotite may be produced from pyrite (Section 1.1.2).

CHAPTER 6
DEPOSITS IN PYRITIC / CARBONACEOUS / CALCAREOUS SHALE SEQUENCES WHICH HAVE NO OBVIOUS ASSOCIATION WITH IGNEOUS ACTIVITY

Principal References: Wolf (1976), Gustafson and Williams (1981), Morganti (1990) plus contents of this chapter.

6.1 INTRODUCTION

Several major zinc-lead-silver massive sulphide deposits occur in sedimentary sections characterized by pyritic and/or carbonaceous shales interbedded with calcareous units. While igneous rocks frequently exist in the basins hosting these deposits, the deposits themselves have no obvious relationship with igneous activity. Barite frequently overlies and flanks the mineralization. The common host rock assemblage suggests a common tectono-stratigraphic setting which differs from those of the deposit groupings described in previous sections.

Some deposits in the class give magnetic response by virtue of pyrrhotite contents however the proportion which contain pyrrhotite appears to be significantly less than for the turbidite hosted deposits of Section 5. Only any minor traces of magnetite have been reported. These phenomena may reflect the low metamorphic grade of most of the deposits recognised to be in this class

The copper contents of the deposits are low and are often confined to underlying stringer zones.

The deposits of this type described in this chapter are restricted to the Mount Isa - MacArthur Basin area of northern Australia (Plumb et al. ,1990; Blake et al., 1990) and Ireland (Morganti, 1990). This is partly a function of the excellent documentation for these deposits because although similar deposits exist in other localities it difficult on the basis of their published descriptions to categorically assign them to this class.

In particular it should be noted that the Meggen and Rammelsberg deposits and some of the Selwyn Basin deposits which have been identified with the turbidite hosted deposits (Chapter 4) may belong here. It is possible that transitional type deposits occur. It is also possible that some of the deposits with BIF associations described in Chapter 5 are merely metamorphosed equivalents.

6.2 SETTING OF THE DEPOSITS

All the deposits of this type appear to have been formed in intracratonic rift settings.

The Mount Isa, Hilton, Lady Loretta, Century and Dugald River deposits in the Mount Isa area appear to have been emplaced during post-rift sedimentation. The timing of the other deposits in relation to the rift development is not clear. The Irish deposits may be hosted by post-rift platform sediments.

Many of the rift basins hosting these deposits have tholeiitic volcanic igneous components but this is never contemporaneous with the mineralization in the vicinity of the mineralization.

6.3 STRATIGRAPHIC ASSOCIATIONS

The common association with pyritic and/or carbonaceous shales suggest reducing environments possibly with restricted circulation in closed basins. It is not clear to what extent the pyrite in the country rock was produced by normal diagenetic processes and what proportion was produced by the same processes as formed the deposits. The presence of carbonate rich rocks suggest shallow water environments such as normally occur on platforms or epicontinental areas although rifted areas which have been filled as a result of high sedimentary influx are not precluded. Shallow water depositional environments have been interpreted for some deposits.

6.4 MINERALIZATION

Mineralization typically consists of massive pyrite with sphalerite and galena associated with elevated silver values. Copper contents are generally low and are not reported for some deposits. Barite contents may be significant.

The mineralization occurs in extensive sheets which are conformable to the sedimentary bedding. Lateral extents may be of the order of 1-2 km and vertical thicknesses are of the order of a few tens of metres.

In some deposits the mineralization consists of sulphide bands separated by bands of relatively barren host rock. "Massive" mineralization in these deposits consists of concentrations of mineralized bands. Most deposits consist of a single sheet of massive mineralization although situations with multiple overlays of massively mineralized sheets occur. The extreme example of this situation is at Mount Isa where 30 such sheets are reported.

Zoning has been described for some deposits but no consistent pattern emerges from the literature. This is probably a result of insufficient reporting of studies rather than an absence of systematic zoning. Barite appears to occupy the position of the "ore equivalent horizon". Some deposits appear to consist of agglomerations of extensive sulphide rich bands in particular host horizons and do not appear to have underlying feeder pipes. Some chalcopyrite rich stringer zones have been identified.

A massive copper orebody at Mount Isa was originally thought to represent a feeder pipe to the Zn-Pb mineralization in this deposit however it is now interpreted to be the result of a second later mineralizing process which deposited copper in the original feeder zone of the Zn-Pb mineralization (Section 6.9.1.9).

Magnetic pyrrhotite has been reported at Mount Isa, Hilton, and Dugald River (Section 6.9.1.9). Pyrrhotite is effectively absent from the other deposits. The deposits containing pyrrhotite have been subjected to higher metamorphism than the deposits without pyrrhotite. It is not obvious from the literature whether the pyrrhotite occurences resulted from metamorphism of pyrite.

6.5 MINERALIZATION ASSOCIATIONS

The mineralization is characteristically associated with pyrite and/or carbonaceous shales which may have intercalations of calcareous rocks.

All the deposits described occur adjacent to major fault systems. Several deposits occur at the intersection of major faults with cross faults.

6.6 ORIGIN OF THE MINERALIZATION

A sedimentary exhalative (sedex) syngenetic model is widely accepted for deposits of this type. Mineralizing solutions are thought to ascend to the seafloor along vents or fault planes to localized subbasins where metals are precipitated under reducing conditions. The setting of the deposits is thought to resemble that illustrated for the "over-pressured stratal aquifer" shown in Figure 3.2. In general terms the mineral zoning is likely to be similar to the generalized exhalative model illustrated in Figure 3.1 with a possible marked asymmetry due to the feeder zone being fault controlled and located to one side of the deposit.

In the cases for deposits where no underlying feeder pipe has been identified the metal contents may have reached the site by ascent along adjacent fault planes prior to precipitation in restricted basin environments. Synsedimentary fault movements may explain why many of these deposits consist of multiple lenses because the fault planes could have been variably seals and fluid paths. Such situations could give rise to mineralizing pulses.

If, as the evidence suggests, these deposits occur in post-rift cover of rift systems their apparent association with major fault systems can be explained by the fact no other plumbing systems connecting deep hydrothermal mineral sources to the sea floor are likely to be available in such settings.

Sato (1977) and Lydon (1977) have proposed that metal contents vary as follows:

Temperature	Salinity	Metal Content
Low	high	low Pb, high Zn, No Cu
Moderate	moderate	mod Pb, high Zn, minor Cu
High	low	high Pb, high Zn, minor Cu
Very high	low	high Cu

6.7 ADDITIONAL REGIONAL DETAIL

The Mount Isa area is the only area containing deposits of this type for which the author has access to comprehensive regional aeromagnetic and gravity coverage. An initial inspection of these data indicates the classic regional gravity and magnetic signatures expected for well developed rift systems i.e.linear gravity highs which appear to be due to crustal thinning beneath the rift systems and outlines of the rifts delineated by irregular magnetic anomalies due to extensive tholeiitic basalts. Gunn (1984) and Wellman (1992) have published overviews of these data. It should however be appreciated that the above simple interpretation may however not be correct in detail because at least three superimposed cycles of rifting now recognised in the area (Derrick, 1992).

6.8 MAGNETIC SIGNATURES

Dugald River and Mount Isa (Section 6.9.1.9) give magnetic anomalies by virtue of their pyrrhotite responses. The ore in the Hilton deposit has been reported as being magnetic but no magnetic data of sufficient detail has been published over this mine to determine if it gives a magnetic response.

The Mount Isa deposit gives a 30 nanotesla airbourne anomaly. Dugald River gives a 400 nanotesla ground magnetic anomaly.

Many of the faults which appear to control the location of the deposits are evident in aeromagnetic data. Such responses are due to the faults displacing underlying basalts.

6.9 DETAILS OF INDIVIDUAL DEPOSITS

6.9.1 The Mount Isa-McArthur Basin Region, Northern Australia

6.9.1.3 Introduction

The Mount Isa region of Queensland, Australia (Blake et al., 1992) is an assemblage of Proterozoic lithologies whose outcropping portions are known by various appellations such as the Mount Isa Inlier or Mount Isa Block. The area contains the Mount Isa, Hilton, Lady Loretta, Dugald River, Century and Walford Creek deposits (Figure 5.3).

The McArthur Basin (Plumb et al., 1990) is a contemporaneous rock sequence in the Northern Territory whose origin is probably related to some of the same tectonic processes as controlled the development of the Mount Isa area. The McArthur Basin contains the HYC deposit plus several other smaller similar deposits.

All of these deposits contain significant zinc-lead and silver and, with the exception of Mount Isa, have only minor copper contents. As discussed below copper mineralization at Mount Isa is apparently unrelated to the original formation of the zinc-lead deposit. All the deposits are hosted by pyritic and/or carbonaceous shales and occur in sections with significant calcareous components.

6.9.1.2 Setting of the Deposits

The north south trending geology of the Mount Isa area can be subdivided into a Western Fold Belt, a central basement block and an Eastern Fold Belt. These eastern and western fold belts contain deformed and metamorphosed sediments that apparently originated in separate but contemporaneous rifts. As described by Blake et al. (1990) and Derrick (1991) the Mount Isa area has undergone at least three and possibly four periods of crustal extension which resulted in rift like structures with associated post-rift sag components. A continental margin setting has been proposed by various authors (listed by Blake et al. 1990), however Wybourne and Blake (1992) and Blake (1987) interpret an intracratonic rift setting and cite the absence of lithologies typically associated with subduction as support for their case.

The Corella Formation sediments of the Eastern succession which host the Dugald River deposit are interpreted as being deposited during the sag (post-rift subsidence) phase of a period of extension which occurred between 1790 and 1760 Ma. The Mount Isa Group and the contemporaneous McNamara Group sediments which host the Mount Isa, Hilton, Lady Loretta and Century deposits are interpreted as occuring in the sag phase of a later extensional episode which occurred between 1680 and 1650 Ma. Webb and Rohriach (1992) identify a sag phase origin for the Fickling Group sediments which host the Walford Creek deposit. The Fickling Group is contemporaneous with the Mount Isa Group and which also has the characteristics of a sag phase origin. Mount Isa, HYC and Dugald river are interpreted to have formed in shallow water environments.

6.9.1.3 Stratigraphic Associations

All deposits occur in sequences of pyritic and/or carbonaceous shales with calcareous components. The calcareous members all appear to be predominantly dolomitic.

6.9.1.4 Mineralization

Mineralization is typically massive pyrite-sphalerite-galena in extensive conformable sheets. The Dugald River mineralization has a strike length of 2200 m, a down dip extent of at least 1000 m and thicknesses up to 21 m. Copper contents are low. Numerous multiple sheets occur in the Mount Isa and Hilton deposits. Dugald River, Lady Loretta and HYC are essentially single sheets with occasional double branches. Century appears to consist of two sheets. No systematic image of mineral zoning is evident from published descriptions. Both "massive" and banded mineralization is reported.

Copper rich feeder zones have been interpreted for some McArthur River deposits.

Pyrrhotite is the dominant sulphide in Dugald River and appears to occur in significant concentrations in Mφunt Isa and Hilton. None of the other deposits appear to have more than trace amounts of pyrrhotite. None of the deposits have more than trace amounts of magnetite.

Lady Loretta has a barite component.

6.9.1.5 Mineralization Associations

All deposits occur adjacent to or close to major faults. Some deposits, notably Lady Loretta and HYC, occur at the intersection of major faults with cross faults.

6.9.1.6 Origin of the Mineralization

The deposits are generally considered to be syngenetic or early diagenetic. No clear consensus appears to exist between various publications. The exhalative model with metal ascent along fault systems has been suggested for some deposits. Restricted depositional basins are required for some of the published models. The McArthur River deposits are the only ones where the existence of feeder pipes has been interpreted.

6.9.1.7 Additional Regional Detail

Discussed in Section 6.7

6.9.1.8 Magnetic Signatures

Mount Isa and Dugald River give aeromagnetic anomalies due to their pyrrhotite contents. The Hilton deposit contains monoclinic pyrrhotite and could be expected to give a magnetic response. None of the other deposits contain magnetic minerals. The Mount Isa, Hilton and Dugald River deposits appear to have undergone higher metamorphism than the other deposits. It is not clear if their pyrrhotite contents have resulted from metamorphic conversion of pyrite.

Intersecting fault systems which apparently control the location of the HYC and Lady Loretta deposits are clearly visible in aeromagnetic data. Major faults flanking other deposits are clearly visible in aeromagnetic data. The magnetic responses of these features appear to originate from underlying basalts.

6.9.1.9 Details of Individual Deposits

Mount Isa Mine

Principal references: Mathias and Clarke (1975), Forrestal (1990), Perkins (1990).

The Mount Isa deposit contains zinc-lead-silver bodies and copper rich bodies. The copper mineralization is believed to be significantly younger than the zinc-lead mineralization and to have formed as a result of a separate mineralizing process. The copper mineralization interdigitates with the lead zinc mineralization and many workers believe that the copper deposit resulted from leaching from the Eastern Creek Volcanic which it abuts.

Host Rocks: the Urquart Shale, a unit of dolomitic and variably carbonaceous siltstone, rich in fine grained pyrite. The Urquart Shale contains numerous thin potassium rich beds identified as tuffs.

The Copper orebodies are hosted in a silica dolomite body which is a zone of brecciated shale in which reconstitution of quartz, carbonates and sulphides has taken place.

The metamorphic grade of the area is believed to have attained greenschist facies.

Form of the Mineralization: the lead-zinc mineralization occurs as beds of sulphides 1mm to 1 metre thick within the Urquart Shale. When these bands are sufficiently concentrated they form orebodies. Approximately 30 such orebody sheets occur which have varying lengths and thicknesses. These are confined to the upper 650 m of the Urquart Shale in a zone measuring 1.6 km along strike and 1.2 km down dip. The copper orebodies appear to occur as discrete tabular bodies in published sections but the different lenses have considerable thicknesses (up to several hundred metres) and appear to be interconnected.

Mineralization: zinc-lead orebodies contain pyrite sphalerite and galena. Pyrrhotite is locally common and in places constitutes the major sulphide phase. Chalcopyrite is a very minor constituent.

Copper orebodies: chalcopyrite, pyrite and lesser amounts of pyrrhotite.

Deposit Size: The zinc-lead orebody had an approximate original size of 150 mt, 7%Zn, 5-6%Pb and 140g/t Ag.

The copper orebody has been estimated at 255 mt of 3.3%Cu.

Structural Setting: the zinc-lead orebodies are conformable to the bedding. The mineralization is within 1km of a major fault (the Mount Isa Fault Zone) and the area of the deposit is cut by major shears.

The copper orebody is in faulted contact with tholeiitic Easter Creek Basalts.

Magnetic Signatures: Leaman (1991b) reports that the zinc-lead mineralization in the Mount Isa mine has a susceptibility of 0.012 SI units. This is apparently due to its pyrrhotite content which Fallon and Busuttil (1992) report to be monoclinic. Although this pyrrhotite has a Koenigsberger ratio of 2 its NRM direction appears to be random. Aeromagnetic results over the mine site are presented by Fallon and Busuttil (1992). Extensive filtering indicates that an observed 30 nanotesla the anomaly arises from the mineralization rather than cultural features associated with the mine workings. The small scale of the maps of this data has precluded their reproduction.

Leaman (1991a) reports "pyrrhotite is associated with both ore types (meaning Zn-Pb and Cu ores) but small magnetic anomalies are only pronounced in the region of the lead-zinc mineralization. It is possible that the younger higher temperature copper mineralization has introduced another or varied form of pyrrhotite". Leaman (1991b) on the basis of detailed magnetic modelling has detected a significant decrease in the susceptibility of the underlying Eastern Creek Volcanic at the Mount Isa mine site. He ascribes this to the destruction of magnetite resulting from the passage of mineralizing solutions. Magnetic maps published by Fallon and Busuttil (1992) demonstrate how magnetic data in the vicinity of the Mount Isa mine maps faults affecting the Eastern Creek volcanics.

Hilton Mine

Principal reference: Forrestal (1990)

The Hilton Mine occurs 20 km north due of the Mount Isa Mine in a very similar geological setting to the Mount Isa Mine. Similar distributions of multiple lenses of zinc-lead rich mineralization occur at Hilton as at Mount Isa. The significant difference between the deposits however is the absence of major copper mineralization although chalcopyrite has been reported as an important accessory mineral in brecciated hangingwall bodies. The published reserves are: 49 mt, 9.3%Zn, 6.5%Pb, 151g/t Ag with further 23 mt of probable 12.1%Zn, 6.4%Pb and 110g/t Ag in a northern deposit.

No magnetic survey data has been published for Hilton however the deposit contains pyrrhotite. Leaman (1991b) implies that the Hilton ores have the same susceptibility as the Mt Isa Zn-Pb ores (i.e. 0.012 SI units). The deposit could thus be expected to give a magnetic response.

Dugald River

Principal references: Witchter (1972), Connor et al. (1982), Connor (1990), Johnson (1990)

Host Rocks: black, commonly carbonaceous slates of the Dugald River Shale Member of the Mid Proterozoic Corella Formation. The hangingwall for the lode consists of highly carbonaceous slate and spotted slate. The mineralization occurs in a fine grained black slate with abundant sulphides. These are underlain by a spotted graphitic limey slate and a limestone unit.

The area of the deposit has been metamorphosed to greenschist facies.

Form of the Mineralization: Steeply dipping sheet, 2200 m long, 5-21 m wide with a down dip extent of at least 1000 m.

Mineralization: in decreasing order of abundance the main sulphide minerals are pyrrhotite, sphalerite, pyrite and galena with only traces of chalcopyrite. A central massive sulphide zone is flanked by "banded ore". A discontinuous weaker horizon of zinc-lead mineralization is developed in carbonaceous slates 60-90 m stratigraphically above the main deposit. The gangue consists of graphitic shale and slate, quartz and carbonates.

Deposit Size: 60mt, 10%Zn, 1%Pb and 30g/t Ag.

Structural Setting: the mineralization occurs in what was originally a shallow water clastic basin. The mineralization is presently steeply dipping, conformable to the bedding and is located approximately 3 km west of a major fault.

Magnetic Signature: Connor et al. (1982) have published a profile of ground magnetic data which shows that the mineralization gives a 400 nanotesla anomaly.

Other Deposits in the Mt Isa Area

Several significant sphalerite-galena-pyrite deposits are located north and west of Mount Isa in sedimentary sequences developed during rifting events which were contemporaneous with the rifting processes occuring in the Mount Isa area.

All of these deposits are stratiform and conformable and occur in shale-siltstone-carcareous sequences where the shales are frequently calcareous and/or pyritic and the calcareous sections are frequently dolomitic. None of these deposits appear to give a magnetic response and none are reported to contain pyrrhotite or magnetite.

All these deposits appear to be located adjacent or close to major faults and in some cases they are located at the intersection of major faults with cross faults. Some of these fault systems are visible in regional aeromagnetic data.

These deposits are:

Lady Loretta (Hancock and Purvis, 1992)
with 12%Zn cut off, 8.3mt, 18.4%Zn, 8.5%Pb, 125g/t Ag.

Barite-chert-sulphide mineralization occurs on one flank of the deposit.

The mineralization is confined to a section including carbonaceous shales, pyritic shales and sideritic and dolomitic units. The presence of pyrrhotite is not reported and no aeromagnetic signature is apparent for the deposit.

The deposit is located at the intersection of a major NE trending fault (the Carlton Fault) and a NNE trending cross fault. These faults are evident in regional government aeromagnetic data of the area.

Century (Broadbent, 1993, Thomas et al., 1992)

116mt, 10.3Zn, 1.5%Pb, 35g/t Ag

The deposit is hosted by siderite rich siltstones and finely laminated black carbonaceous shales. Thomas et al. (1992) report that "the Century deposit does not produce a clearly defined airbourne anomaly". Notwithstanding this comment a single aeromagnetic profile across the deposit which is included in their paper shows a minor anomaly of 2 nanoteslas amplitude in the vicinity of the orebody. Pyrrhotite has not been recorded in any published description of the deposit.

The deposit is adjacent to the major Termite Range Fault. Cross faults are mapped as affecting the mineralization.

Walford Creek (Webb and Rohriach, 1992)

Zn, Pb, Cu, Ag (presently sub economic, grades and tonnages not published)

The deposit is hosted by a sequence of dolomitic siltstone and carbonaceous pyritic argillites. The base metal occurrences are associated with a much larger body of stratiform massive pyrite. Magnetic data in the area has been interpreted as defining an adjacent fault system (the Fish River Fault) which may have controlled the location of the deposit. No mention is made of a magnetic response due to the mineralization or to the presence of pyrrhotite.

HYC-McArthur River Basin Area (Lambert, 1976; Logan et al., 1992)

HYC 227mt, 9.2%Zn, 4.1%Pb, 0.2%Cu, 41g/t Ag

The deposit is hosted by a pyritic dolomitic shale unit with elevated lead and zinc values. Geophysical responses have been published by Shalley and Harvey (1992). Although they report that the deposit has no magnetic signature regional aeromagnetic data published by these authors appears to be outlining the major faults in the area. The deposit lies close to the intersection of the Emu Fault and a cross fault. A zone of coarse grained copper-silver-lead mineralization is interpreted as a feeder zone for the HYC deposit.

Several smaller similar deposits are known in the McArthur Basin.

6.9.2 The Irish Pb-Zn-Cu Deposits

Principal references: Morrisey et al. (1971), Andrew et al. (1986), Hitzman and Large (1986)

Ireland has several significant Pb-Zn deposits which are hosted by predominantly calcareous lower Carboniferous sediments deposited in shallow platform shelf environments. The deposits include:

Navan	70 mt	10.1%Zn	2.6%Pb
Tynagh	9 mt	3.2%Zn	3.0%Pb
Silvermines (two zones):			
	9 mt	9.2%Zn	2.4%Pb
	2 mt	3.4%Zn	4.5%Pb
Gortdrum	4 mt	1.2%Cu	23.1g/t Ag

The actual host lithologies of the deposits include shales, dolomites, argillaceous limestones, siltstones and sandstones. The mineralization consists of pyrite, sphalerite, galena and chalcopyrite. Pyrrhotite and magnetite appear to be completely absent from most deposits. Minor occurrences of pyrrhotite have been recorded at Silvermines.

All deposits are located adjacent to major north east trending faults. Some authors including Deeny (1981) have postulated that these faults developed during early Carboniferous rifting processes. Various authors have concluded that many of the mineral occurrences are located at the intersection of north east trending faults and north south trending faults.

Exhalitive origins with metal bearing solutions rising via the fault systems flanking the deposits are accepted by many workers on these deposits. A brecciated feeder zone is clearly recognised at Silvermines (Sampson and Russell, 1983).

A section published by Morrissey et al. (1981) is of particular significance as it shows a hematite chert ironstone bed approximately 50 m thick which is stratigraphically equivalent to the ore and continues for at least 1000 m away from the deposit. This formation has all the characteristics of an iron rich "ore equivalent horizon". Such iron rich facies equivalents do not appear to occur at the other deposits.

The Irish deposits themselves will not give magnetic responses but it is possible that "hematitic ore equivalent horizons" such as the ore at Tynagh could give weak but diagnostic magnetic signatures. The fault systems controlling the locations of these deposits are commonly identifiable in regional magnetic data.

6.10 EXPLORATION GUIDELINES

1. Deposits of this type are most likely to be of the Pb-Zn-Ag variety and in their unmetamorphosed forms to be most probably associated with pyrite and effectively devoid of pyrrhotite and magnetite.

2. Identify a late syn-rift early post-rift sedimentary section containing pyritic/carbonaceous/calcareous shales. These may occur in platform areas.

3. Consider linear zones adjacent to major fault systems to be prospective. A maximum distance of approximately 2km from the fault is a reasonable target width.

4. Regional magnetic data may help identify major faults.

5. Intersection of major faults (parallelling the rift axis) with cross faults define particularly prospective areas. These cross faults may be evident on regional aeromagnetic data.

6. In unmetamorphosed terrain the mineralization is unlikely to be magnetic and only two effects related to the mineralization are likely to create magnetic phenomena:

   (a) destruction of magnetite may occur by alteration processes as fluids rise through underlying rocks to the site of precipitation. These effects may produce quiet magnetic zones or magnetic lows in the country rock. As faults appear to be fluid conduits for many of these deposits these effects should be looked for along fault zones.

   (b) it is possible that hematitic ore equivalent horizons are developed at the same stratigraphic levels as the mineralization. These may give weak magnetic effects albeit either above or lateral to the mineralization (c.f. Tynagh, Section 6.9.2).

7. With increasing metamorphic grade it is expected that pyrite within the deposit and in enclosing sediments will be progressively transformed to pyrrhotite so magnetic data will have the possibility of defining host horizons and the massive mineral accumulations (c.f. Dugald River, Mount Isa). It should be noted that the unmetamorphosed forms of these deposits may have pyritic "ore equivalent horizons".

8. Such types of mineralization are typically concordant with bedding so an appreciation of structural dip in any exploration area is essential.

CHAPTER 7
CYPRUS TYPE MASSIVE SULPHIDE DEPOSITS

Principal References: Franklin et al. (1981), Sawkins (1990)

7.1 INTRODUCTION

The Cyprus type Cu-Zn massive sulphide deposits are massive sulphides emplaced into basaltic oceanic crust formed in oceanic settings. They tend to be of relatively small size (less than 2 mt). The following brief account is a summary from several well documented descriptions of such deposits with emphasis on their magnetic responses.

A particular significance of the deposits is that they appear to be an end member of the hydrothermal mineralizing process which results in massive sulphide mineralization in rifting environments and as such they provide significant insights into the characteristics of such mineralization.

7.2 SETTING OF THE DEPOSITS

When a rifting process causes complete rupture of the continental crust basic igneous oceanic crust capped by tholeiitic pillow basalt lavas is emplaced. Massive sulphide deposits of the Cyprus type may occur in the pillow basalts. These deposits become exposed when sea floor fragments (ophiolites) are incorporated into continental crust by compressive processes such as thrusting.

It has been suggested that the majority of the known deposits of this type are hosted by ophiolites which formed in backarc or marginal basin settings. If this observation is true it may be a result of the fact that backarc settings are probably more prone to be incorporated into continental crust during orogenic processes than oceanic crust formed in true oceanic basins.

7.3 STRATIGRAPHIC ASSOCIATIONS

A complete section of oceanic crust, from top to bottom , consists of:

- sediments, typically deepwater black shales
- tholeiitic basic volcanics, typically pillowed, which merge at depth into a basic sheeted dyke complex.
- high level intrusives such as gabbros
- layered cumulates such as olivine gabbros, pyroxenites and peridotites
- upper mantle rocks such as harzburgite commonly serpentinized +/- lehrzolite, and dunite.

The Cyprus type massive sulphides occur at the top of, or within, the basic volcanic section.

7.4 MINERALIZATION

Chalcopyrite and lesser amounts of sphalerite occur in massive pyrite lenses capping a frequently siliceous feeder zone through which ore bearing fluids have risen. This comparatively simple geometry appears to be commonly overlain by chemical sediments whose relationship to the mineralization appears similar to that of the "ore equivalent horizon" noted for the VHMS and other deposits . For example, ores in Cyprus are sometimes overlain by ochres up to 5 m thick which contain hematite, goethite and maghemite. Deposits in Norway have been reported as being overlain by jaspers, sulphidic black chert and quartz magnetite.

The presence of magnetite has been reported in some deposits. Pyrrhotite hardly rates a mention in any deposit description and pyrite appears to always be the major non-economic sulphide component. It is not clear if exceptions to this situation occur. Although Cyprus type deposits are commonly perceived as being small and as almost exclusively copper deposits, they can have large tonnages (e.g. the 16 mt Limni deposit in Cyprus) and can contain significant zinc concentrations (e.g. 3.4% in Kinousa in Cyprus and 1.9% in the 25 mt deposit at Lokken in Norway which also contains 2.1% Cu). The Turner Albright deposit in Oregon USA contains 3.3 mt of ore with average grades of 1.5%Cu, 3.3%Zn, 0.4%Ag and 2.8g/t Au.

The general form of mineral zoning in the Cyprus-type deposits is consistent with the generalized model for exhalative massive sulphide deposits shown in Figure 3.1 with notable lack of any galena component and a normally minor sphalerite component.

7.5 MINERALIZATION ASSOCIATIONS

As described above, the mineralization occurs in the pillow basalt sections of ophiolite sequences. Deposits often occur in close proximity to each other. It has been suggested that fault systems control the ascent of hydrothermal solutions which are thought to form such mineral deposits.

7.6 ORIGIN OF THE MINERALIZATION

The geometry of the Cyprus type massive sulphides with their underlying stringer zones is strongly suggestive of a hydrothermal origin.

As reported by Sawkins (1990) and many others such processes have now been observed to be occurring in present day oceans along mid oceanic ridges where the pillow basalts which host the Cyprus type deposits are presently being formed.

7.7 ADDITIONAL REGIONAL DETAIL

Ophiolite assemblages will only be produced in rift settings where crustal separation has reached the stage of true crustal splitting with the generation of oceanic crust at a spreading centre. As oceanic crust is significantly thinner than continental crust such areas will correspond to positive Bouguer gravity anomalies.

The ophiolite assemblages accessible to mineral exploration normally occur as sheets or slices of ophiolitic material incorporated into fold belts as a result of compressive processes. Such assemblages may have dimensions up to several hundred kilometres in length. The widths of such zones are normally significantly less than their lengths.

Such linear zones often indicate the boundaries of ancient marginal basins and form useful tectono-stratigraphic markers for controlling exploration for other massive sulphide deposit types.

7.8 MAGNETIC SIGNATURES

On a regional scale ophiolite complexes may be magnetically mapped by virtue of the generally strong magnetic response of their igneous components. With geological control and with attention to detail it is sometimes possible to discriminate the igneous zoning of these complexes. For example, the basic cumulate portions will tend to produce zones of continuous linear anomalies. Sheeted dyke complexes give more uniform magnetic response than pillow basalts. This is due to the semi-random flow composition of the basalts plus a more variable cooling history for the extrusive rocks.

While it is thus possible to use magnetics to identify and map the host rocks for Cyprus type deposits the actual detection of such bodies within the pillow basalts by magnetic methods is problematical. This is a result of the envelope of variable magnetic responses associated with the basalts and the (apparent) low proportion of Cyprus type mineral deposits containing significant amounts of magnetic minerals. Magnetite quartzites associated with any ore equivalent horizon could be identifiable in such an environment due to their high amplitudes and linear character. The development of such formations may however require metamorphism to develop magnetite from sulphur facies iron minerals.

Although no actual examples have been identified in the literature it may be possible to use magnetic data to locate the siliceous alteration pipes which are associated with many such deposits. Such features may correspond to magnetic lows or magnetic quiet zone where they have resulted in magnetite destruction.

7.9 DETAILS OF INDIVIDUAL DEPOSITS

The Cyprus Deposits

Principal Reference: Franklin et al (1981)

Host Rocks

The upper pillow basalt portion of the Troodos ophiolite massif in Cyprus hosts the deposits. The pillow lava sequence consists of three units; the Upper Pillow Lavas composed dominantly of olivine basalt, the Lower Pillow Lavas composed of oversaturated basalt and the Basalt Group consisting of altered and metamorphosed basalts with more than 50% dyke content.

Waterlain volcanic derived sedimentary rocks occur as discontinuous layers in the upper lava sequence. The volcanic rocks are overlain by maganiferous iron rich sediments, marls and argillites. Ore bodies occur at the top of all lava sequences.

Form of the Mineralization

A typical orebody consists of an upper massive zone underlain by a stringer zone that may extend for hundreds of metres below the deposit. The upper massive portions of the bodies are inferred to have subcircular shapes, concave bases and approximately flat tops.

Mineralization

The massive ore is composed primarily of pyritic chalcopyrite and lesser amounts of sphalerite. Pyrrhotite only occurs in trace amounts. A basal siliceous ore consisting mostly of pyrite and chalcopyrite in a quartz matrix underlies some ore bodies. The stringer zone which underlies both these zones contains veins and disseminations of pyrite and quartz with some chalcopyrite and sphalerite. "Ochre" sedimentary cappings occur above most ore bodies and variably contain goethite, quartz hematite and maghemite. These have been interpreted to be exhalative products representing and an "ore equivalent horizon".

Deposit Size

Although the general image is that Cyprus type deposits are small in tonnage and poor in zinc significant exceptions to these generalizations occur e.g.

Marrouvouni	15mt	4.0%Cu	0.5%Zn
Skouriotissa	6mt	2.2%Cu	
Knousa Underground	300000t	2.4%Cu	3.4%Zn

Structural Setting

The Troodos Massif is a domal uplift variably interpreted as an off-axis part of an oceanic ridge or a relic of an island arc marginal basin floor. Deposits at the tops of pillow basalt sections of this ophiolite complex tend to occur in clusters and to be located adjacent to steep normal faults which appear to have channelled mineralizing solution.

Other Deposits of the Cyprus Type

As detailed by Franklin (1981) and Sawkins (1990) deposits of the Cyprus type are known in Newfoundland, the Solomon Islands, the Phillipines, Turkey, Oman, Norway and the United States.

7.10 EXPLORATION GUIDE LINES

1. Locate an ophiolite rock association

   These may be obvious on geological maps. They are typically located:

   (i) along subduction zones
   (ii) along suture zones
   (iii) on the boundaries of marginal basins which have undergone compression.

   Ophiolite zones give strong magnetic responses which vary in detail according to whether the ophiolites occur as a flat obducted sheet or a narrow linear slice in a zone of compression.

2. Attempt to determine what sections of the ophiolite are exposed and to identify the pillow basalt portions of the ophiolite.

   The lower cumulate portions of ophiolites may be evident as linear magnetic anomalies. The gabbro and sheeted dyke portions may give relatively uniform magnetic responses. The pillow basalt portions may give more erratic and variable response than the other sections of the ophiolite.

3. Concentrate on portions of the ophiolite which are known to contain Cyprus type mineral deposits as the deposits tend to occur in clusters

4. Attempt to define a stratigraphy within the pillow basalts.

   Cyprus type deposits tend to occur at the tops of sections of lava flows with internally constant petrology but whose mineral compositions differ from earlier and later flows. Such lava sequences may show different magnetic characteristics. The tops of each sequence should be regarded as prospective.

5. Fault zones may be evident in the magnetic data from the pillow basalt sections.

   Faults are known to localize Cyprus type deposits and locations along fault zones should be regarded as prospective.

6. Alteration zones which underlie ore bodies may result in the destruction of magnetic minerals in the basalts. These may be recognisable as magnetic quiet zones or magnetic lows.

7. The Cyprus type massive sulphide deposits typically do not contain significant amounts of magnetic minerals but exceptions may occur. Metamorphic effects may however significantly increase pyrrhotite and magnetite contents. The deposits could give discrete magnetic highs.

   A large accumulation of non-magnetic massive sulphide ore in a magnetic pillow basalt section may be obvious as a magnetic low or magnetic quiet zones.

8. The "ore equivalent horizon" i.e. the exhalitive sediments occurring immediately above the ore and extending laterally from it may be evident as a linear magnetic anomaly if it contains magnetic minerals such as magnetite or pyrrhotite.

9. The coincidence of the top of a basalt sequence, a fault zones and a magnetic quiet zone in the data should be considered as a possible locality of a Cyprus type mineral deposit.

10. In all these interpretations it is important to appreciate whether the ophiolite is exposed in section or plan view.

    A section view would expose the stringer zone as well as the massive sulphides and favour identification of basalt flow boundaries. A plan view would favour delineation of faults but would only present horizontal slices of the ore bodies.

CHAPTER 8
THE ABRA DEPOSIT, BANGEMALL BASIN, WESTERN AUSTRALIA : A DEPOSIT IN AN EARLY RIFT SETTING?

8.1 INTRODUCTION

The Bangemall Basin of Western Australia hosts the Abra massive sulphide deposit which contains the 200 mt of 1.8%Pb, 6g/t Ag, 0.18%Cu and 6% barium including 150 mt at 0.13g/t Au. The Abra deposit is apparently the only one of its type in the region and in fact is possibly a distinct deposit type by virtue of its elevated magnetite content, its distinctive shallow water depositional environment and the fact of its apparent formation during the early stages (pre-rift or early syn-rift) of a non-volcanic rifting process.

No exploration guidelines are offered for this unique deposit other than to note its distinct high amplitude elliptical magnetic response relative to its effectively non-magnetic sediment host.

8.2 SETTING OF THE DEPOSIT

The Proterozoic Bangemall Basin (Blockley and Myers, 1990), overlies a suture zone between the Archean Pilbara and Yilgarn Cratons. It is an elongated intracratonic depression whose development appears related to crustal extension (rifting).

The Abra mineralization is hosted by the earliest sediments in the Bangemall Basin and is located in the narrow Jillawarra Graben which is 60 km long and 1.5-9 km wide. The Jillawarra Graben is located in the axis of the Bangemall Basin and was developed as the rifting which gave rise to the Bangemall Basin commenced.

Although the Jillawarra Graben has been squeezed in a tectonic episode the rocks in it are only moderately deformed and in the vicinity of the Abra deposits the structure is dominated by the major Coolina Anticline. The area has been metamorphosed to greenschist facies.

8.3 STRATIGRAPHIC ASSOCIATIONS

The Abra Deposit is hosted by the upper part of the Gap Well Formation of the Middle Proterozoic Bangemall Group. The Gap Well Formation is the earliest unit of the Bangemall Group and it directly overlies the basement in the area. In the vicinity of the deposit it contains interbedded lutite-siltstone which is locally carbonaceous, dolomitic and pyritic which is associated with subordinate amounts of quartz arenite.

8.4 MINERALIZATION

See section 8.9

8.5 ORE ASSOCIATIONS

Not obvious.

8.6 ORIGIN OF THE MINERALIZATION

The deposit has been interpreted to be the result of hydrothermal fluids ascending fracture systems to reach the seafloor where they precipitated. A well developed stringer zone at the base of the deposit is taken as evidence of the ascent of the mineralizing solutions. A shallow water origin has been interpreted from the mineral assemblages, the oxidation of sulphides at the top of the orebody and the presence of stromatolites. The mineralizing process is thought to have been coeval with deposition of the sedimentary host.

8.7 ADDITIONAL REGIONAL DATA

None noted.

8.8 MAGNETIC SIGNATURE

The body is magnetic - See Section 8.9.

8.9 DETAILS OF THE ABRA DEPOSIT

Principal References: Boddington (1987), Mutton and McInerney (1987), Boddington (1990)

Host Rocks: Interbedded lutite-siltstone locally carbonaceous, dolomitic and pyritic with subordinate quartz arenite.

Form of the Mineralization: An inverted cone tilted to the south. An irregular saucer shaped area of stratabound mineralization overlies a stringer zone with a radius of approximately 400 m and a height of 330 m. The stratabound mineralization has been subdivided into 4 units (see below).

Mineralization (bottom to top):
Stringer Zone: veins, breccias and replacement zones (Cu 0.19%, Pb 1.45%). The stringer zone is pervasively chloritized with local silicification, carbonatization and baritization. Magnetite is associated with chalcopyrite in this zone.

Unit 1 (overlies the stringer zone) a colloform unit of alternate bands of magnetite (jaspilite)-hematite, barite-silica (jaspilite)-carbonate and barite-carbonate-silica +/- galena-pyrite-chalcopyrite.

Unit 2 and 3 massive jaspilite with hematite, magnetite, barite, carbonate and silica +\- banded galena, chalcopyrite and pyrite. These units have been extensively veined and brecciated.

Unit 4 is a quartz arenite of limited distribution with minor disseminated pyrite and very minor galena, sphalerite and chalcopyrite.

Deposit Size: 200 mt of 1.8%Pb, 6g/t Ag, 0.18%Cu and 6% barium including 150 mt at 0.13g/t gold.

Structural Setting: In its present form the Abra body is on the south limb of an anticline. The deposit is immediately adjacent to several major faults which appear to have developed as a result of early tension in the Bangemall Basin and which appear to have existed at the time of formation of the mineralization.

Magnetic Response: (Boddington,(1987); Mutton and McInerney (1987))

The Abra deposit gives a distinctive "bulls-eye" magnetic anomaly (Figure 8.1) which arises from its magnetite content. The results of magnetic susceptibility measurements are:

Rock Unit	**Susceptibility SI Units**
Hanging wall sediments	.0001
Stratabound zone	.1024
Stringer zone	.0398
Footwall sediments	.0027

The deposit is not obviously associated with a magnetic "ore equivalent horizon" however bulges in the contours of Figure 8.1 west and north of the deposit could be due to disseminations of magnetic minerals in sediments.

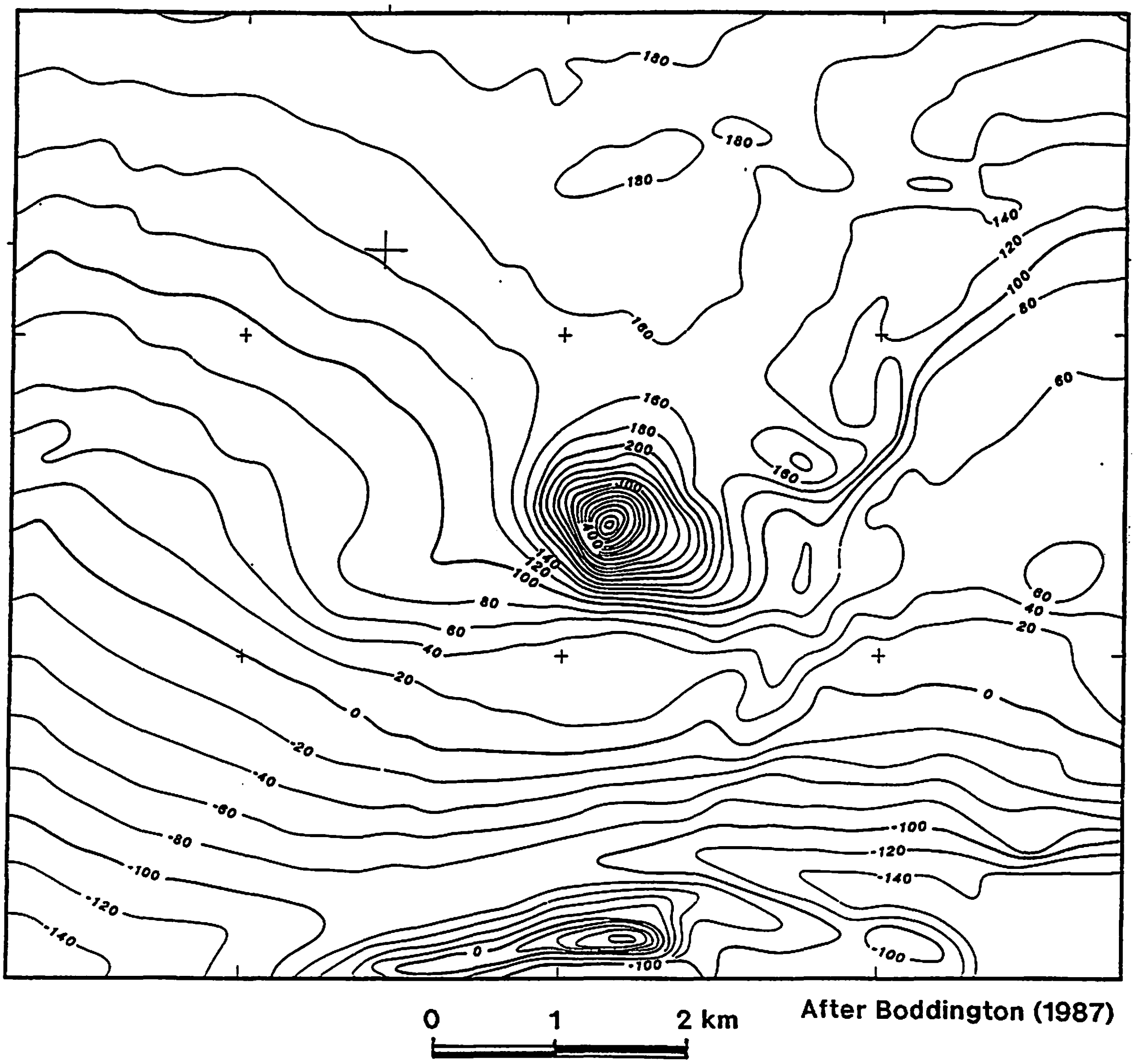


Figure 8.1 Aeromagnetic response of the Abra deposit (line spacing 200 m, ground clearance 80m). The deposit is hosted by nonmagnetic sediments. The magnetic peturbations east and south of the deposit appear to be due to younger dolerite sills.

CHAPTER 9
TENNANT CREEK AREA, NORTHERN TERRITORY, AUSTRALIA: DEPOSITS WHERE IRON OXIDES DOMINATE

9.1 INTRODUCTION

The Tennant Creek area of the Northern Territory of Australia contains numerous magnetite rich copper-gold-bismuth orebodies which vary in size from a few tonnes to over 15 mt in the case of the Warrego Mine (which contains 5 mt, 7g/t Au, 2.6%Cu and 0.3% bismuth). These deposits are hosted in turbidites but have significant differences to the massive sulphide deposits described in the previous sections, notably the general subordinate nature of the sulphide facies, the virtual absence of Zn and Pb and economic concentrations of bismuth. Bismuth does however commonly occur as a minor mineral in the Cu rich portions of VHMS deposits (Large, 1992; Table 6) so the contents of this metal may not be a diagnostic difference. It is not clear if the hosts sediments were deposited in an extensional tectonic setting.

The following condensed summary of the characteristics of these deposits, which at first sight appear to be in a class apart from any previously mentioned in this study, was initially included for the sake of completeness and for the possible insights they may add to the general understanding of other magnetic basemetal-gold deposits hosted by sedimentary sequences. Closer consideration of their characteristics suggests that they may be a variant of the turbidite hosted deposits described in Chapter 4.

9.2 SETTING OF THE DEPOSITS

Principal References: Crohn (1975), Lemessurier et al. (1990)

The host Warramunga Group sediments are a sequence of turbiditic greywacke, siltstone and shale with interbedded felsic volcanics. A deep water depositional environment is probable. A maximum sediment thickness of about 6000 m is indicated. The tectonic setting of the area is not clear but the above characteristics are consistent with those of an extensional rift-like trough. The rocks have been tightly folded and cleaved along east-west axes. Metamorphism in the area has attained greenschist facies. The sediments have been intruded by younger granites and dolerites.

9.3 STRATIGRAPHIC SETTING

The economically important deposits in the area occur in the Carraman Formation of the Warramunga Group.

9.4 MINERALIZATION

Chalcopyrite, native gold, bismuthite and a variety of bismuth sulphosalts are associated with magnetite, quartz, chlorite, talc, hematite, jasper, pyrite and pyrrhotite in generally ellipsoidal masses. The long axes of these bodies are normally near vertical or near horizontal. Although these bodies are typically pipe like in a vertical perspective there is a tendency for them to be wider in the east west direction than in the north south direction.

Chlorite alteration occurs both around and above the bodies and stringer zones have been found below some deposits.

Sulphides facies are rarely dominant in the deposits in which iron usually occurs as oxides. Shallow weathered deposits contain hematite but magnetite appears to be the main constituent of fresh mineralization.

The deposits exhibit considerable zoning.

9.5 MINERALIZATION ASSOCIATIONS

The Carraman Formation contains broad stratabound zones of disseminated magnetite which can be recognised in aeromagnetic data. One particular iron rich unit, the Black Eye Member, contains the mineral deposits. This unit also exclusively contains thin discontinuous argillaceous banded iron formations known locally as hematite shale. The juxtaposition of ore grade mineralization and these iron formations is common. The favourable host beds are mudstones.

The magnetite rich copper-gold-bismuth deposits and mineralogically equivalent but economically barren magnetite masses have been preferentially developed at the intersection of major shear zones. Fold axes are favourable loci for emplacement.

The ores generally cross cut stratigraphic layering although a few appear to be concordant. The ores have sharp contacts with the sediments.

Some ores occur in the vicinity of felsic porphyrite particularly those in the proximity of the hematite shale marker beds.

9.6 ORIGIN OF THE MINERALIZATION

There is a general concurrence that diagenetic processes were responsible for the emplacement of the ores at Tennant Creek. A typical model has been proposed by Wedekind and Love (1990) which invokes the precipitation of minerals into favourable structural locations after leaching from the sediment mass.

It could be argued that these deposits have many similarities with the remobilized deposits of the Cobar area (Section 4.9.1) with the main difference being that iron occurs in the host rocks and the deposits mainly as oxide instead of sulphide. It may be the case the the metals in the Tennant Creek area had their origins in hydrothermal processes. Such a process would imply a contemporaneous exhalative origin for the iron content in the host rocks and the ore bodies. Such an idea may not be universally accepted. For example Rattenbury (1992) has postulated that the mineralization resulted from iron charged solutions rising through the sediment section and being precipitated when they encountered the oxidized iron formations.

9.7 ADDITIONAL REGIONAL DETAIL

See Etheridge et al. (1987)

9.8 MAGNETIC SIGNATURES

The magnetite contents of the orebodies results in them giving distinct, readily identifiable intense dipolar or "bulls-eye" type magnetic anomalies. Mineralogically similar, but economically barren, magnetite masses in the area give identical magnetic anomalies. Examples of magnetic responses due to such bodies have been published by Daly (1957), Gunn (1979), Farrar (1979), Hoschke (1985, 1988), Edwards et al. (1990) and Hill (1990). Important conclusions resulting from these reports are that while it is possible to accurately model the sources of these anomalies with triaxial ellipsoids, it is normally necessary to account for demagnetization which can have a significant effect due to the intense magnetization of the bodies and for the influence of remanence which is frequently an important component of the magnetization vector.

The Carraman Formation contains broad stratabound zones of disseminated magnetite which can be recognised in aeromagnetic data. One particular iron rich unit, the Black Eye Member contains all the known hematite shale lenses and many of the mineral deposits. Magnetic stratigraphy can be an important indicator of favourable host rocks in the area although the Black Eye Member loses its distinctive magnetic response in the north east of the area where it becomes hematitic. The shear systems and faults controlling the location of the deposits can be recognised in aeromagnetic data. Figure 9.1 presents a sample of aeromagnetic data from the Tennant Creek area showing the magnetic anomalies caused by many of the major deposits. It can be noted that the the deposits occur on alignments of magnetic gradients trending in a northwesterly direction. The gradients are an artifact of the inclination of the earths magnetic field in the area (50^0) and would be classical magnetic ridges at higher magnetic latitudes. The magnetite rich sediments causing these anomalies are, in effect, "ore equivalent horizons". Detailed computer modelling by Gunn (1979) has demonstrated the localization of magnetite rich plate-like bodies at fault intersections with one of these magnetic horizons.

9.9 DETAILS OF INDIVIDUAL DEPOSITS

The Tennant Creek Field contains numerous individual orebodies however the median production has been only 3000 t of ore and only three mines produced more than 1 mt. The most significant deposits include:

Warrego (Goulevitch, 1975; Wedekind and Love, 1990) 5mt at 7g/t gold, 2.6%Cu and 0.3% bismuth. Farrar (1979) has published magnetic responses for this deposit.

Juno (Large, 1975) produced 5.8g/t Au from 0.45 mt of ore. Hoschke (1991) has published regional aeromagnetic contours showing the magnetic response of this body.

Nobles Nob (Yales and Robinson, 1990) 2 mt of ore treated with an average recovered grade of 17.3 t. Hoschke (1991) has published regional aeromagnetic contours showing the magnetic response of this body.

Gecko Mine (Main et al, 1990) reported remaining reserves of 4.7mt, 3.8%Cu, 0.7g/t Au.

Small high grade gold deposits occur e.g.

White Devil (Edwards et al, 1990) 276,000 t at 19.9g/t Au. Edwards et al. have published a magnetic map of this deposit.

TC8 (Hill, 1990) 27,100 t, 20.0g/t Au. Hill includes a magnetic map of this deposit in his paper.

9.10 EXPLORATION GUIDELINES

Exploration in the Tennant Creek area is very area specific and ideally involves the identification of discrete magnetic anomalies coincident with lesser more elongate magnetic anomalies due to the favourable "ore equivalent horizons ". The optimal location of such anomalies appears to be where these "ore equivalent horizons " are cut by cross faults. In many respects the exploration methodology is analogous to that applying to the deformed remobilized pyrrhotite rich turbidite hosted deposits of the Cobar region (Chapter 4) with notable difference being the dominance of magnetite as the iron mineral in the Tennant Creek area and the resultant propensity to higher amplitude magnetic anomalies. It is suggested that that exploration guidelines of Section 4.10 have general applicability to Tennant Creek type targets providing it is realized that the Tennant Creek type deposits occur in a magnetite rich system and not a pyrite or pyrrhotite rich system and the the Tennant Creek type bodies have undergone extensive remobilization.

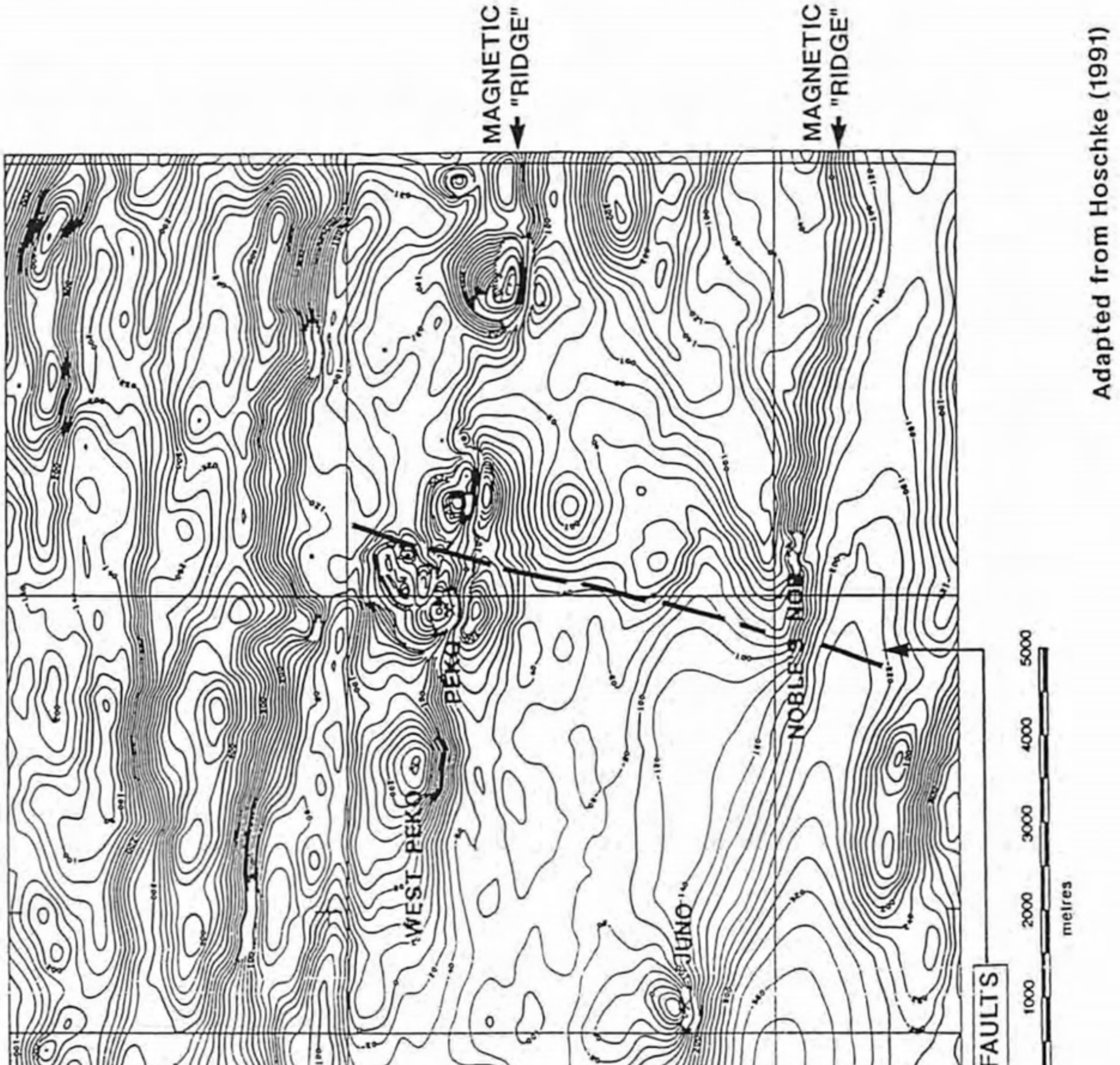


Figure 9.1 Aeromagnetic data from the Tennant Creek area showing responses of several mineral deposits.

CHAPTER 10
OVERVIEW AND CONCLUSIONS

The study has described a series of deposit-types with similarities in geological settings and mineral assemblages and has developed a set of pragmatic exploration guidelines applicable to their location using magnetic data. The deposit types studied were:

(i) Volcanic hosted massive sulphides (Chapter 3).

(ii) Deposits hosted by deepwater turbidite sediments with no obvious association with igneous activity (Chapter 4).

(iii) Massive sulphide deposits associated with banded iron formations / amphibolites / basic igneous activity (Chapter 5).

(iv) Deposits in pyritic/carbonaceous/calcareous shales which have no obvious association with igneous activity (Chapter 6).

(v) Cyprus-type massive sulphide deposits (Chapter 7) i.e. deposits emplaced in oceanic crust.

(vi) The Abra deposit, Western Australia - a deposit in a non-volcanic early rift setting (Chapter 8).

(vii) Deposits in the Tennant Creek area , N.T., Australia - deposits where iron oxides dominate (Chapter 9).

The summaries of the deposit-type characteristics and the exploration guide-lines are described in the relevant chapters and will not be repeated here.

It is however possible to extend the study beyond the above practical observation based approach by synthesizing the facts presented throughout the study to develop a unified approach to the understanding the magnetic responses of base and precious metal massive sulphide deposits in extensional sedimentary basins. In the author's opinion, the key elements for such a global viewpoint are:

(i) an appreciation that these deposits have hydrothermal exhalative origins and have predictable mineral zonations and geometries.

(ii) an appreciation that the deposits form in rift systems whose sedimentary and volcanic components change in a predictable fashion as the rifts evolve. This means that similar mineral deposits will occur in different host rock assemblages.

(iii) a recognition of the fact that the deposits have a tendency to occur as Cu and Cu-Zn or Pb-Zn-Ag types and that these variations are most probably related to the degree of crustal thinning underlying the rift in which the deposits are formed.

(iv) the recognition of the fact that pyrite may be metamorphosed to pyrrhotite and/or magnetite and that pyrrhotite may be metamorphosed to magnetite with consequent significant transformations of the magnetic properties of massive sulphide deposits.

(v) the appreciation that massive sulphide bodies may be deformed by compressive pressure into tabular or pipe-like bodies markedly elongated in the vertical direction and that such deformed bodies may exhibit discordance with the enclosing rocks.

(vi) a knowledge of the typical dimensions and geometries of massive sulphide deposits together with an appreciation of the types and magnitudes of the magnetic responses associated with such deposits.

These factors and their relevance in an exploration context will now be reviewed in greater detail.

10.1 THE EXHALATIVE ORIGIN OF MASSIVE SULPHIDE DEPOSITS

The author believes that the evidence for original synsedimentary exhalative hydrothermal origins for virtually all of the deposits in the study is overwhelming. In many examples direct evidence of such processes, such as the identification of feeder pipes, has been identified. Structuring and metamorphism effects can be invoked to explain many of the cases which it has not. While several of the Pb-Zn-Ag deposits, particularly those in Chapter 6, give the appearance of having been precipitated from sea water without having an obvious hydrothermal source the proximity of such deposits to major faults suggest that the fluid conduits feeding such deposits were faults. In brief, a strong case can be made that the range of mineralizing processes illustrated in Figure 3.2 apply to all the deposits of this study. In the author's opinion the elevated heat flow associated with rifting processes is probably the common driving mechanism.

This conclusion is of more that academic interest because if it is true the model mineral distributions as described Chapter 3 for exhalative deposits in a volcanic context will be expected to have the same form and zonations regardless of the host rocks and tectonic setting of the deposits. This fact is of paramount importance because the well studied volcanic hosted deposits have been shown to have systematic distributions of magnetic minerals and a knowledge of these distributions can provide a basis for their direct detection using magnetic methods. Figure 3.1 illustrates these mineral distributions for an ideal case. Discussions in Sections 3.4 and 4.4 elaborate on how actual mineral compositions may vary from this idealized representation while remaining consistent with the general model.

10.2 THE RIFT SETTINGS OF MASSIVE SULPHIDE DEPOSITS

It appears that all the Cu-Zn-Pb-Ag-Au massive sulphide deposit types described in this study evolve in rift settings. It is also clear that rifts undergo sequential stages of development with consequent variations in host rocks and structural settings. For examples in island arc environments we note the progression:

(i) Development of a volcanic rift. Such rifts may produce tholeiitic volcanism during their early stages, calc-alkaline volcanism during their mature stages and tholeiitic volcanism as crustal extension progresses. These volcanic rifts may host the VHMS deposits of Chapter 3.

(ii) Continued crustal extension. Volcanic rifts may develop into proto-marginal basins as crustal extension progresses. Two situations observed for this stage are:

   (a) Turbidite deposition in a deep trough with no associated igneous activity. Such settings host the deposits of Chapter 4.

   (b) Turbidite deposition associated with basic igneous activity. This setting hosts the deposits of Chapter 5.

   (a) and (b) appear to be variants with (b) being a more advanced stage with the igneous activity indicating incipient or actual crustal splitting.

(iii) The rifts of (ii) may either:

   (a) cease extension and undergo thermal subsidence and infill by post-rift sag stage sediments. The deposits of Chapter 6 may have formed in such sequences.

   (b) progress to complete crustal splitting with the generation of ocean floor basalts. The Cyprus-type deposits of Chapter 7 are formed in this environment.

Intracontinental rifts undergo the same sequential development except for the notable lack of initial tholeiitic and calc-alkaline volcanism. Any volcanic activity associated with the early stages of intracontinental rifting normally has alkaline affinities. It is proposed here that the Abra deposit (Chapter 8) was formed during the initial stages of an intracontinental rifting process. No other deposits in such a setting have been identified.

A logical development of the above processes is to have possible vertical superposition of different deposits formed at different stages during the evolution of a particular rift.

10.3 DIFFERENTIATION INTO CU, CU-ZN AND PB-ZN-AG TYPES

Throughout the study a tendency for the deposits to differentiate into Cu, Cu-Zn and Pb-Zn-Ag types has been apparent. The Cu and Cu-Zn types have been repeatedly linked with high temperatures, tholeiitic igneous activity, gravity highs and oceanic crust generation. All of these factors suggest that such deposits are preferentially located in areas of thinner crust and/or greater crustal extension. The obvious examples to demonstrate this association are the Cyprus-type Cu and Cu-Zn deposits which are actually formed in tholeiitic oceanic crust. No Pb-Zn-Ag deposits are known in such settings.

The Pb-Zn-Ag deposits show affinities with calc-alkaline igneous activity when they are associated with volcanic rocks in volcanic rifts and they are also the dominant variety in post-rift sag phase sequences (Chapter 6). They appear to be products of a distinctly different differentiation process to their Cu and Cu-Zn counterparts.

While the causes of such differences have only been briefly considered in this study the fact that gravity highs can indicate thinned crust and magnetic data can map tholeiitic igneous activity or its metamorphosed counterparts means that gravity and magnetic data may have the potential to indicate the types of mineralization likely to occur in a particular rift.

10.4 METAMORPHISM OF SULPHIDES

Metamorphic transformations of pyrite to pyrrhotite and/or magnetite and pyrrhotite to magnetite are most important processes as they increase the magnetic visibility of massive sulphide deposits. While this phenomenon is predictable (Section 1.4.4) the extent of these transformations do not appear to be fully appreciated. The author finds it difficult to believe that the fact of the best examples of associations of massive sulphide deposits and magnetite quartzites all being in highly metamorphosed terrains, the common association of pyrrhotite and massive sulphides in moderately metamorphosed terrains and the prevalence of pyritic massive sulphide deposits in non-metamorphosed terrains is entirely the result of primary mineral producing processes. This phenomenon is strikingly apparent in the Mount Isa area (Chapters 5 and 6) where a consistent southerly and easterly increase in metamorphic grade appears to be linked with a progressive change from pyritic to pyrrhotitic and eventually magnetic rich mineralization. While some of these variations may reflect original iron mineral facies it appears likely that metamorphism has greatly augmented the pyrrhotite and magnetite contents of many deposits. The subject obviously requires further research however the author strongly suspects that many, if not all, magnetite quartzites associated with hydrothermal exhalative vents originated as pyritic emanations which were subsequently metamorphically transformed to magnetite.

A consequence of such metamorphic processes from an exploration point of view is that the original pyrite and pyrrhotite contents of exhalative deposits as illustrated in

Figure 3.1 may be transformed into pyrrhotite and magnetite with a consequence dramatic change of the magnetic response of the deposits.

10.5 PHYSICAL DEFORMATION OF MASSIVE SULPHIDE DEPOSITS

While massive sulphide deposits are typically sheet like bodies which are conformable with the enclosing country rock this geometry and relationship with local geology may be profoundly changed by compressive forces. Intense folding appears to remobilize sulphide bodies firstly into tabular forms markedly elongate in the vertical direction and finally into cigar like ellipsoidal forms which are also markedly elongate in the vertical direction. Such deformed bodies, of which the Cobar Deposits (Section 4.9.3) appear to provide excellent examples, may undergo processes of mineral remobilization with the result that the mineral assemblages do not have the classical geometrical relationships predicted by the exhalative model. Furthermore, such deposits may exhibit varying degrees of discordance with the enclosing rock units. An appreciation of such variants is important when exploring for massive sulphides in deformed terrains.

10.6 FORM AND MAGNITUDE OF EXPECTED MAGNETIC RESPONSES

The generalized form of an exhalative hydrothermal massive sulphide deposit has been described in Chapter 3 and illustrated in Figure 3.1. Such deposits consist of a sub-circular lens like massive sulphide accumulation underlain by a "stringer" feeder zone and overlain by an extensive "ore equivalent horizon". It is a finding of this study that, with very minor qualifications, the mineral distributions of the generalized exhalative model apply to all the deposits types which have been identified. These deposits show zoned, internally consistent, semi-predictable mineral assemblages. In particular, while not ubiquitously present, magnetic minerals frequently occur in specific portions of these deposits (as per Figure 3.1) and when they do they allow the direct detection of such deposits by magnetic survey techniques. It appears that a significant proportion of unmetamorphosed massive may contain magnetically detectable concentrations of pyrrhotite and magnetite.

Massive sulphide deposits tend to occur as discrete Cu and Cu-Zn or Pb-Zn-Ag variants. Section 3.3 and 4.4 discuss general form of these "end members" which are merely versions of the general form exhibiting different relative developments of the various mineral groupings.
The specific points to note when applying the above generalizations are:

(i) While the form and mineral zoning of exhalative deposits appears to have a general consistency their host rocks and tectonic settings do not. The following environments have been noted:

(a) Volcanic rifts containing various assemblages of tholeiitic and calc-alkaline volcanics, volcaniclastics and sedimentary rocks which host the VHMS deposit of Chapter 3.
(b) Turbidite assemblages devoid of volcanics which host the deposits of Chapter 4.
(c) Turbidite assemblages containing tholeiitic volcanics which host the deposits of Chapter 5.
(d) Pyritic/carbonaceous/calcareous (post-rift?) shales which host the deposits of Chapter 6.
(e) Tholeiitic ocean floor basalts which host the deposits of Chapter 7.
(f) Pre-rift or early syn-rift sediments such as host deposits such as Abra in Chapter 8.

An awareness of the magnetic responses of these different environments as described in the relevant chapters provides a fundamental basis for predetermining the magnetic responses of any mineralization they are likely to contain.

Furthermore all the above environments and the deposits themselves may be metamorphosed with a resultant significant alteration of rock types and magnetic characteristics as per Sections 1.3.3.1 and 1.4.4. The result is that the visibility of massive sulphide deposits depends on:

(a) The enclosing country rock and whether the country rock contains obscuring magnetic rock units such as volcanics and intrusives or magnetic sediments and metamorphics.
(b) The magnetic mineral content of the massive sulphide deposit. As explained in Sections 1.4.1 and 1.4.4 the magnetic minerals pyrrhotite and magnetite may be produced in such deposits by primary differentiation processes or by metamorphism of pyrite and pyrrhotite. Pyritic portions of deposits may become magnetic as a result of metamorphism. For example non-magnetic pyritic "ore equivalent horizons" may be transformed to magnetic pyrrhotite or magnetite marker horizons.

(ii) The deposits may be of the Cu and Cu-Zn or Pb-Zn-Ag types with this variation being apparently linked to the factors discussed in Section 10.3.

(iii) The Cu and Cu-Zn types appear to exhibit extreme flattening in the turbiditic settings. This may be a result of broad diffuse feeder systems in such environments. The Pb-Zn-Ag types in post-rift settings appears to require fault systems as feeder conduits. The resultant deposits consists of flat sheets extending away from the feeder fault.

The study has repeatedly shown examples where massive sulphide deposits are localized by fault systems and that many such fault systems are visible in magnetic data.

Only the largest mineralized bodies described in this study have lengths greater that 1 km. Many economically important deposits have lengths less than 500 m. Deposits which have been subjected to compression and which have been deformed into ellipsoidal shapes with elongated vertical dimensions frequently have strike lengths considerably less than 500 m. Such facts indicate that aeromagnetic survey based on 400 m flight line spacings are the absolute minimum which should be considered. Such surveys however are unlikely to reveal meaningful details the mineral zonings that have been outlined in the preceding chapters. At best such surveys are likely to produce characterless "bulls-eye" anomalies over deposits. Line spacings of 200 m or even 100 m appear optimal.

It is also apparent that high resolution surveys are required if the targets are pyrrhotite zones or subtle alteration features. The case of the 27mt Elura deposit (Section 4.9.3.8) is most illustrative. The deposit has a core of massive pyrrhotite which is approximately 60 m thick. Fresh sulphides occur at 100 m below ground surface. A ground magnetic study of this deposit has indicated that the induced magnetization component due to the mineralization only produces a 15 nanotesla anomaly. Clearly to be sure of detecting pyrrhotite in the massive portions of sulphide bodies or in their associated stringer zones high sensitivity measurement and accurate compilation systems must be used when conducting magnetic surveys.

A most significant finding has been the recognition of "ore equivalent horizions" for virtually all the deposit types and the appreciation that such formations are often magnetic by virtue of pyrrhotite or magnetite contents. These formations which typically have lengths of the order of several kilometres and which are commonly pyrrhotitic in mildly metamorphosed terrains and magnetite rich in highly metamorphosed terrains have the potential to be key indicators of massive sulphide locations.

10.7 CONCLUDING REMARKS

If the conclusions of this study are correct, the application of magnetic survey techniques to the detection of massive sulphide deposits in extensional sedimentary basins is primarily related to the recognition of the general applicability of the simple exhalative model with its semi-regular and semi-predictable mineral assemblages, the appreciation of how the settings of such deposits may vary in accordance with rift evolution and finally understanding the effects of metamorphism which may dramatically change the magnetic visibility of the deposits. In simple terms this reduces to first recognising the target, secondly knowing how the scenery surrounding the target may change and finally understanding how the "colour" of both the target and the scenery may change with metamorphism. Nothing in nature is ever quite so straight forward however and the final recommendation is that this report be read in its entirety in order to fully appreciate the full scope of relevant variables.

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