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# THE DISTRIBUTION, MINERALOGY AND PARAGENESIS OF THE HELLYER BARITIC AND SILICEOUS CAPS

Robina Sharpe B.Sc.

A thesis submitted in partial fulfilment of the requirements for the degree of Bachelor of Science with Honours



Geology Department University of Tasmania November, 1991

life is earnest, life is real, life is but an empty dream, for the soul is dead that slumbers, and things are not what they seem.

W. Shakespeare (A Midsummer Nights Dream)

# Abstract

Baritic and siliceous caps are a feature of many volcanic-hosted massive sulphide deposits. Their distribution, mineralogy and geochemistry are important to the understanding of the genesis of these deposits.

The baritic and siliceous caps overlying the Hellyer volcanic-hosted massive sulphide deposit, western Tasmania, show a spatial affinity to the centres of hydrothermal activity, identified previously from copper contents of the ore. Mineralogical and textural investigations identified barite as a precursor to formation of the siliceous cap. In both caps intricate sulphide textures, including pristine colloforn pyrites, are present. Mineralogical and spatial relationships suggest an interdigitation of the baritic and siliceous caps.

Sulphur isotope studies of barite (with  $\delta^{34}$ S values between +38 and +50 per mil) and pyrite (with  $\delta^{34}$ S values between +6 and +18 per mil) revealed a duality in the source of sulphur during formation of the caps; incompletely reduced seawater sulphur, and magmatic sulphur. The wide range of  $\delta^{34}$ S values are thought to be the result of fluctuating contributions from these two sulphur sources.

Metal zonation and mineral geochemical studies show that base and precious metal contents of both caps are enriched proximal to underlying massive sulphides. In such zones, textural evidence supports hydrothermal overprinting and porosity infill by paragenetically late sulphides.

Formation of the barite cap at or above the seawater interface is interpreted to be the result of oxygenated seawater mixing with spent hydrothermal fluids enriched in barium, during periods of low hydrothermal flux, at temperatures between 230 and 250°C. By contrast, silica cap precipitation requires the local dominance of  $H_2S$  and a combination of conductive cooling and mixing. This is evidenced by the presence of arsenopyrite, and the absence of hematite.

The interdigitating spatial affinity combined with mineralogical and textural evidence suggests that formation of the baritic and siliceous caps at Hellyer was an integral part of orebody formation. Thus these facies evolved with the growing sulphide mound, in a manner consistent with the zone refining model proposed by Eldridge et al. (1983), for the growth of seafloor sulphide deposits.

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In conclusion, the loving support provided by my father, Stan, who provides his daughter with a place to call home no matter how far she may stray; the endless words of wisdom of my brother, Ian, and the patience and guidance of Annie McEntee; I cannot thank them enough.

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# Chapter One Introduction

Barite and hydrothermal cherts form principal accessory components in many volcanichosted massive sulphide (VHMS) deposits. They often occur as distinct horizons or as gangue constituents in the upper regions of VHMS accumulations. Their concomitant association with massive sulphide mineralisation is an indication that they are products of the same hydrothermal activity which formed the mineralisation. The geological environment and geochemical signature of stratiform baritic and siliceous zones associated with massive sulphide mineralisation are significant for the following reasons:-

- i) They serve as hydrothermal tracers or indicators of nearby mineralisation in the exploration for VHMS deposits.
- ii) They provide a means to evaluate the genesis and evolution of mineralising fluids.

iii) The barite is often a mineable resource, frequently enriched in precious metals.The following investigation documents the distribution, mineralogy, paragenesis and geochemical characteristics of the baritic and siliceous caps which overlie the Hellyer VHMS deposit.

The Hellyer deposit is located in the Cambrian Mount Read Volcanic Belt in Western Tasmania (Figure 1.1) and represents a resource of 16 million tonnes which is currently being mined by Aberfoyle Resources Limited. It is a well preserved example of a volcanichosted sea floor vent deposit (McArthur and Dronseika, 1990).

# 1.1 Aims

This study will:

- Define the spatial distribution of the baritic and siliceous caps overlying the Hellyer deposit.
- 2) Describe mineralogical and textural variations within the baritic and siliceous caps.
- Deduce the geological association of the baritic and siliceous caps to underlying mineralisation.
- 4) Investigate the geochemical characteristics of the baritic and siliceous caps by means of; sulphur isotope geochemistry, mineral and whole rock geochemistry, fluid inclusion studies and metal zonation studies.
- 5) Propose a genetic model for formation of the baritic and siliceous caps at Hellyer.

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Figure 1.1: The location of the Hellyer deposit and other major volcanic-hosted massive sulphide deposits within the Cambrian Mt. Read Volcanic Belt in western Tasmania (from Gemmell and Large, in press)

# 1.2 Previous Research

The Kuroko deposits in Japan, are unmetamorphosed examples of volcanic-hosted massive sulphide deposits (Eldridge et al., 1983). In these deposits barite occurs as distinct horizons, lateral to or overlying mineralisation, and/or as an interstitial gangue mineral within the massive sulphides. In the former, barite is often a mineable resource. Geochemical studies on baritic and siliceous/ferruginous chert (tetsusekiei) horizons of these deposits are recorded by; Igarashi et al. (1981), Kusakabe and Chiba (1983), Kalogeropoulous and Scott (1983) and Eldridge et al. (1983). A paucity of information however, exists on the nature of equivalent zones in Phanerozoic polymetallic VHMS deposits.

Several recent studies have focussed on the venting of hydrothermal solutions to the sea floor (for example: Bluth and Ohmoto, 1988; Herzig et al., 1988; Fouquet et al., 1991). The

venting of hydrothermal fluids is often associated with active deposition of sulphides, sulphates and hydrothermal cherts. Processes operating within modern hydrothermal environments are thought to be analogous to those processes which formed ancient volcanichosted massive sulphide accumulations. Investigation of these modern centres of hydrothermal activity have made possible the documentation of hydrothermal fluid compositions, pristine mineralogies, textures and geochemical signatures with which existing massive sulphide deposits can be compared. In addition, these studies have shown that barite and hydrothermal cherts are often an integral part of the ore forming processes.

This study is the first to document the mineralogical and geochemical characteristics of the baritic and siliceous horizons overlying the Hellyer massive sulphide deposit. Previous studies on the Hellyer deposit have described the geophysical discovery (Eadie, Silic and Jack, 1985; Sise and Jack, 1984), the regional geology and orebody setting (McArthur, 1986; McArthur and Dronseika, 1990; Staff, Aberfoyle Resources, 1990), the metal zonation (McArthur, 1990), mineralogical variations (Ramsden et al., 1990) and the geochemical characteristics of host rock alteration (Jack, 1989). A number of reports also exist on the deformational style of the Hellyer deposit (Drown and Downs, 1990) and isotopic geochemistry (Whitford et al., 1984; 1985). Other investigations include the alteration geochemistry and metal zonation in the underlying stringer system (Gemmell, 1988; 1989; 1990; Gemmell and Large, in press), as well as ongoing documentation by Hellyer geologists.

# 1.3 Terminology and Definitions

Baritic and siliceous occurrences are often referred to as exhalative products. Strictly an "exhalation" is defined as a gaseous emanation (A.G.I. Glossary, 2nd ed., 1980), however the term is often used broadly to incorporate all localised expulsion of fluids and gases accompanying volcanism (Ridler and Shilts, 1974). Due to its genetic connotation, the term exhalative will not be used further.

A series of logging and mapping codes (Appendix 1.1) are employed by the geologists at the Hellyer deposit. The logging and mapping codes have been adopted throughout the course of this study, as they are an effective and coherent means to describe mineralogy, texture and alteration.

The barite cap at the Hellyer deposit is defined as that unit which stratigraphically overlies massive sulphide mineralisation and is predominantly composed of barite. The siliceous cap

at Hellyer is a hydrothermal chert horizon, which may overlie massive sulphide mineralisation and/or the barite horizon. This siliceous unit is defined by distinctive pyritic textures in a grey, glassy siliceous matrix. It is consequently termed glassy silica pyrite (GSP).

# 1.4 The Hellyer Deposit

The Hellyer orebody is an elongate, faulted massive sulphide lens hosted in the Que-Hellyer volcanics of the Dundas Group, Mount Read Volcanics (Corbett, 1989). For the purpose of this study the regional geology of the Hellyer area will not be detailed. Instead, the reader is referred to Corbett and Solomon (1989) and references cited therein.

The location of the Hellyer orebody and immediate stratigraphy is shown in Figure 1.2a and 1.2b. The footwall Feldspar Phyric Sequence, of massive lavas and volcaniclastics, is dominantly andestic in composition and forms the basal unit at Hellyer (McArthur, 1986). The top of this unit represents the time equivalent horizon, to hydrothermal mineralisation (McArthur and Dronseika, 1990). Overlying the Feldspar Phyric Sequence is the Hangingwall Volcaniclastic Sequence (HVS). Two interbedded lithologies constitute the HVS; a poorly sorted volcanic breccia and a well sorted, finely laminated ash unit (Staff, Aberfoyle Resources Limited, 1990). The former onlaps the sulphide deposit (McArthur, 1989). In the central part of the orebody, where massive sulphides attain their greatest thickness, the HVS is absent. In these areas, the massive sulphide mineralisation, including the barite and siliceous caps, is in direct contact with overlying basalts of the Pillow Lava Sequence (PLS). The PLS consists predominantly of pillowed and arnygdaloidal basalt with pyritic chert, cherty shale or hyaloclastic interpillow margins (McArthur, 1989). Conformably overlying the PLS is the Que River Shale, which is in turn overlain by the Upper Rhyolitic Sequence (Staff, Aberfoyle Resources Limited, 1990).

The Hellyer massive sulphide deposit displays metal, mineral and textural zonation typical of many Kuroko style deposits (McArthur, 1990). Grades for the massive sulphide, baritic and siliceous caps are given in Table 1.1. The deposit averages 45 metres true thickness, with variable dip and strike and sharp geological contacts (McArthur, 1990).

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Figure 1.2: a) Plan view of the surface geology surrounding the Hellyer deposit (after Gemmell and Large, in press). b) Schematic cross section of the Hellyer deposit stratigraphy (after McArthur, 1989).

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|                           | Cu (%)     | Pb (%)     | Zn (%)      | Ag (ppm)   | Au (ppm)   | Ba (%)      | As(%)      | Fe(%) | S (%) | S.G        |
|---------------------------|------------|------------|-------------|------------|------------|-------------|------------|-------|-------|------------|
| Ore Body*<br>Barite Cap** | 0.3<br>0.2 | 6.8<br>3.2 | 13.0<br>4.9 | 160<br>116 | 2.3<br>1.9 | 3.0<br>26.4 | 1.0<br>0.2 | 13.0  | 16.3  | 4.6<br>4.2 |
| Siliceous Cap*            | * 0.2      | 4.4        | 7.3         | 140        | 3.0        | 3.7         | 0.5        | 19.1  | 22.9  | 3.8        |

\* Gemmell and Large, in press.

\*\* G.J. McArthur, pers. com., 1991

Table 1.1: Ore reserve grades for the massive sulphide mineralisation, barite cap and GSP at the Hellyer deposit.

The footwall rocks host a well preserved stringer vein system and encompassing hydrothermal alteration zones (Gemmell et al., 1990). The alteration zones show a mineralogical zonation from an outer shell of sericite-quartz through chlorite-sericite to a highly siliceous core (Gemmell and Large, in press). Syn-mineralising veins, representing conduits for the passage of hydrothermal solutions through the alteration zones to the sea floor, are a feature of the stringer zone. The alteration associated with the siliceous core hosts the strongest development of stringer vein mineralisation and represents the central feeder system. Footwall alteration textures and mineralogies at Hellyer are similar to those present at several Kuroko style deposits (Gemmell and Large, in press).

The PLS exhibit calcite-fuchsite alteration, indicating the continuation of the hydrothermal system after the extrusion of the basalts (Jack, 1990). The result is a plume shaped alteration zone directly over the central feeder of the stringer zone (Jack, 1989).

The well preserved stratigraphic sequence at Hellyer is the result of low metamorphic grade with minimal deformation (McArthur, 1990). The regional metamorphic facies is prehnitepumpellyite and the regional metamorphism is the result of the Tabberabberan (Middle Devonian) Orogeny (Whitford et al., 1982). Deformation of the Hellyer orebody encompasses open folding and wrench faulting. The Hellyer deposit, which lies proximal to the axial plane of a broad anticline, is transected by a major north-south structure; the Jack Fault. The Jack Fault divides the deposit into an eastern and western ore block. Post mineralisation movement on the Jack Fault has resulted in a sinistral displacement of 130 metres east block north and 30 metres up (McArthur, 1986). Sub-vertical faults with minor movements strike east-west and are commonly developed as dextral conjugates to the Jack Fault (Drown and Downs, 1990; McArthur and Dronseika, 1990).

# 1.5 Study Outline

The first consideration in this study has been to record the spatial distribution of the baritic and siliceous caps (Chapter Two). It has been necessary to define the association of the cap zones to underlying mineralisation, to each other and to the hangingwall stratigraphy. This was achieved by examining a range of existing diamond drill core from the cap zones. Two Sections, namely 10790 N and 10630 N on the eastern and western ore blocks respectively, were investigated in detail. These two Sections were chosen in order to remove the effect of the sinistral offset along the Jack Fault. During drill core logging, particular attention was paid to mineralogy, texture and the nature of the contacts. Where possible, underground exposures of the baritic and siliceous horizons were studied . In association with core logging and underground mapping, samples were collected for later petrological and geochemical investigations.

Polished thin sections for microscopic mineralogical and textural investigations were prepared at the University of Tasmania. Further textural evaluation was completed on the Scanning Electron Microscope (SEM) at the Central Science Laboratory (CSL) of the University of Tasmania. The results are presented in Chapter Three. Mineral and whole rock geochemistry (Chapter Four) were determined using microprobe facilities at the CSL and X-ray fluoresence analyses available in the Geology Department, University of Tasmania . The former included the chemical and submicroscopic constituents as well as chemical variation of the mineralogy within the siliceous and baritic horizons. In total eleven samples were analysed for whole rock geochemistry using X-ray fluoresence.

Metal zonation studies (Chapter Five) determined the lateral and vertical associations of metals in the cap zones. This study is based on Aberfoyles' routine 1 to 2 metre drill core assays for grade control and ore reserve calculations. Assay data, stored on a DATAMINE database was used in this study to prepare plan projections of metal distributions for zonation studies. The DATAMINE database was also used in the generation of orebody sections and hangingwall structure contours.

Sulphur isotope analyses (Chapter Six) were performed at the CSL stable isotope facilities. Sulphide and sulphate species were either hand picked or drilled and analysed using standard techniques. Fluid inclusions (Chapter Seven) were investigated from a limited number of barite samples, using the Fluid Inc heating/freezing stage in the geology department. Difficulty was experienced in the identification of primary fluid inclusions and consequently this portion of the study formed a minor component of the geochemical investigation.

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# Chapter Two Spatial Distribution of the Baritic and Siliceous Caps

### Introduction

Over six hundred diamond drill holes intersect the Hellyer massive sulphide deposit. A large number of these drill holes were scrutinised to define the spatial associations between:

1) the barite cap and GSP

- 2) the cap zones and underlying massive sulphides
- 3) the cap zones and overlying HVS and/or PLS

In total, forty relevant portions of existing diamond drill core, intersecting the barite and/or GSP mineralisation, were examined during field work at the Hellyer mine site. In addition, six underground exposures of the barite cap, GSP and/or baritic veining through the massive sulphides were mapped. Barite veins within the overlying PLS were also examined, however this outcrop is obscured by the mine infrastructure. Defining the spatial distribution of the barite cap and GSP relied heavily on previous work by geologists at the Hellyer deposit.

Two Sections, namely 10630 N and 10790 N, were chosen for detailed investigation, because they correspond to the sinstral movement on the Jack Fault. Thus if the movement on the Jack Fault is restored, the two Sections approximately become one. Simultaneously, these two Sections correspond to regions where the baritic and siliceous caps attain their greatest thickness and overly the central feeder of the stringer system as defined by Gemmell (1989; 1990). The remainder of drill core examined, formed a range over the lateral extension of the cap zones. This also provided the means by which a relatively even distribution of samples for geochemical work were collected. All samples and locations are listed in Appendix 2.1.

#### 2.1 Stratigraphic Position

The contacts between the barite cap, GSP and massive sulphides were often difficult to identify and extremely variable. The barite cap, predominantly composed of barite, often contains a significant proportion of glassy silica pyrite or massive sulphide mineralisation. Similarly, the GSP may contain significant proportions of barite or massive sulphides. In such occurrences, the barite cap and GSP are occasionally fragmental (Plate 2.1), however more often they are pristine.

Plate 2.1: Fragmental barite and GSP:- a) RS005:- The GSP is a milky grey chert that shows minor pyrite and barite veins. Barite laths are themselves fractured and form nodules of fragmental barite. b) RS75:- Fragmental GSP which contains minor pyrite and barite filled cavities and veins. The apparent banding of siliceous fragments is due to fine grained disseminations of pyrite.

Plate 2.2: Underground development exposure (89-77WXC, 450 Level) of a sharp contact between the massive sulphide and GSP. The GSP contains a significant proportion of barite as veins, but is dominated by the presence of silica and pyrite (Photo courtesy of B. Gemmell).

Plate 2.3: Underground development (450 Level) exposure of a sharp contact between the massive sulphide and barite cap. The barite cap contains a significant proportion of GSP, but is dominated by the presence of barite (Photo courtesy of B. Gemmell).

Plate 2.4: RS70:- A sharp contact between high grade massive sulphides and the barite cap. The barite cap contains 1 to 2 cm barite laths in a fine grained pyritic and baritic matrix. Cross cutting the massive sulphides, is a pyrite and barite vein that contains small (3 to 4 mm) laths of barite.

Plate 2.5: Contacts between the massive sulphides and barite cap. a) RS83:- A sharp contact between high grade ore, predominantly sphalerite and galena, and the barite cap. At the contact, fine grained colloform pyrites are well developed. The massive barite consists of fragmented and rounded laths in a fine grained baritic matric, with colloform and disseminated pyrite. b) RS89:- A gradational contact between massive sulphides and the barite cap. The barite is dominantly fine grained and contains colloform to recrystallised pyrite.

**Plate 2.6:** Baritic veining of underlying massive sulphides. a) RS56:- Intense barite veining within massive sulphide. Barite is predominantly fined grained. b) RS17:- Fine grained banded sulphides; including pyrite, galena and sphalerite, with coarse to fine grained barite and pyrite veins.

Plate 2.7: Underground development exposure of a sharp contact between the barite cap and HVS (450 Level; Photo courtesy of B. Gemmell).

Plate 2.8: Contact between the HVS and barite cap. a) RS92:- Rounded barite fragments hosted in a sericite altered fine grained volcaniclastic. The rounded barite clasts show large tabular barite laths in a fine grained baritic groundmass, and minor disseminated pyrite. b) RS129:- Fragmental HVS and barite. The barite is dominantly fine grained, with occasional tabular laths.



HL414 (Figure 2.1a) shows an interdigitating relationship between the barite cap and GSP. The contact between the GSP and barite is commonly sharp, but irregular. Frequently, the barite cap, which overlies massive sulphide mineralisation, is itself overlain by the GSP. This is however, not always observed. Section 10790 N (Figure 2.1b and 2.2b) shows the GSP to occur within the barite cap (HL326), underlie the barite cap (HL329) or occur in regions where the barite cap is absent; such that the GSP is in direct contact with underlying massive sulphides (HL331 and Plate 2.2). The GSP frequently contains nodules of fragmental barite. These are thought to represent early barite formation, followed by fragmentation, which was subsequently followed by GSP formation (Figure 2.1b and 2.2a).

The contacts between the barite cap and massive sulphides vary from sharp and irregular, to diffuse (Plates 2.3, 2.4 and 2.5). In the former instance, barite occurs as tabular laths in a fine grained granular baritic matrix (Plate 2.4) or as massive barite of highly variable grain size. In barite peripheral to massive sulphides, occasional bedding has been observed. Diffuse contacts between the barite cap and massive sulphide may be gradational from centimetres to meters (HL326, HL413 and Plate 2.1), where the proportion of barite in the massive sulphides increases toward the hangingwall or contact with the barite cap. Barite in the massive sulphides also occurs as veining (Plate 2.6) or as nodules filled by tabular barite and carbonate. The width of the barite veins is variable from between 1 to 2 mm to 10 to 30 cm zones of banded massive sulphide/barite or crustiform barite veins.

Where the HVS is present, its contact with either the GSP or barite cap is sharp (HL331, HL413, HL417 and Plate 2.7). The HVS, a fine grained, polymict volcaniclastic, is strongly altered by sericite proximal to the contact with either the barite cap or GSP. Commonly, subrounded to angular fragments of barite are incorporated within the HVS (Plate 2.8). No fragments of GSP were observed in the HVS.

Predominantly, the contact of the barite cap or GSP with the PLS is faulted. Drown and Downs (1990) conclude that faulting and shearing at the orebody-hangingwall contact is the result of strain partitioning between ductile and brittle lithologies. The PLS shows variable intensities of sericite and fuchsite alteration, commonly associated with cleavage development. Interpillow margins, consisting of a dark chert, in places display carbonate and/or minor baritic veining.

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KEY: Ba = barite, BMS = banded massive sulphide, Bn = banded, Ds = disseminated, Fmb = framboidal, Fu = fuchsite, Gn = galena, GSP = glassy silica pyrite, HVS = Hanging Wall Volcaniclastic Sequence, Ma = massive, PLS = Pillow Lava Sequence, Py = pyrite, Rw = reworked, Rx = recrystallised, Se = sevicite, Sp = sphalerite Distance down drill hole (metres) given on the left of each diagram.

### Figure 2.1a

Stratigraphy of drill holes HL414, HL413 and HL417 intersecting the barite cap and/or GSP; from section 10630 North.



KEY: Ba = barite, BMS = banded massive sulphide, Fmb = framboidal, Gn = galena, GSP = glassy silica pyrite, HVS = Hanging Wall Volcaniclastic Sequence, Ma = massive, PLS = Pillow Lava Sequence, Py = pyrite, Rx = recrystallised, Se = sevicite. Distance down drill hole (metres) given on the left of each diagram.

### Figure 2.1b

Stratigraphy of drill holes HL326, HL329 and HL331 intersecting the barite cap and/or GSP; from section 10790 North.



Figure 2.2: Cross sections a) 10630 North and b) 10790 North, which show the stratigraphic position of the cap zones and immediate stratigraphy

#### 2.1.2 The Observed Relation Between the Barite Cap and GSP

The interdigitating contacts between the GSP suggest that the formation of the caps were near contemporaneous. Siliceous veins transecting the barite cap would indicate barite to the an earlier phase. The common occurrence of nodules of fragmental barite, encompassed in pristine GSP, would support this.

## 2.2 Lateral distribution of the Caps

As it was not feasible to consider each hole intersecting barite and/or GSP mineralisation, the lateral distribution of the cap zones were largely derived from existing mine section interpretations. The coordinates used in the construction of the plan projection for barite cap and GSP were derived from mine section interpretations (Appendix 2.2). Where applicable core logging from this study was integrated.

#### 2.2.1 The Barite Cap

The baritic cap, bounded by the orebody extremities, forms an elongate lens with a northnortheast to south-southwest trend (Figure 2.3a). The barite cap does not form a continuous sheet over the orebody, but is rather an irregular cap that shows continuity. The barite cap extends from 10950 N to 10330 N, with a small lens located at 11030 N.

# 2.2.2 The GSP

The GSP forms a discontinuous and irregular cap (Figure 2.3b). The main occurrence is from 10670 N to 10850 N. Small irregular lenses of GSP occur on the western ore block at 10750 N north, 10800 N and 10700 N. These lenses of GSP are in direct contact with underlying mineralisation, in the absence of the barite cap. With these exceptions, the occurrences of the GSP correlate to the that of the barite cap, shown in Figure 2.4.

## 2.2.3 The Hellyer Stringer System

Gemmell (1988; 1989) and Gemmell and Large (in press) have defined three main feeder systems within the stringer system underlying the Hellyer massive sulphide deposit. The three feeder systems are outlined by centres of pyrite concentration in the stringer system and indicate the hottest parts of the mineralising system. The central feeder is best developed, while the northern and southern feeders are thought to represent secondary systems. The locations of each of the three feeders is shown Table 2.1.

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Figure 2.3: Plan projection of a) the barite cap and b) the GSP, relative to massive sulphide mineralisation. The barite cap is an irregular, but continuous sheet from 10330 N to 10950 N. The GSP forms an irregular, thin discontinuous cap, which is most developed between 10670 N and 10850 N.

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Figure 2.4: Plan projection of the barite cap and GSP superimposed over massive sulphide mineralisation. The main occurrence of the GSP correlates with that of the barite, circumferential to the Jack Fault.

| Feeder                            | eastern ore block | western ore block  |
|-----------------------------------|-------------------|--------------------|
| northern feeder                   | 10950 N           | -                  |
| central feeder<br>southern feeder | 10850 N<br>-      | 10700 N<br>10500 N |

Table 2.1: The location of the three feeder systems in the stringer zone as defined by Gemmell (1988; 1989) and Gemmell and Large (in press).

The occurrence of the barite cap correlates well to the location of the central and southern feeders. The small lens of barite at 11030 N overlies the northern feeder. Similarly the GSP is best developed over the position of the central feeder, but is absent from the vicinity of the southern and northern feeders.

Gemmell and Large (in press) showed the three feeders, after reconstruction of the movement on the Jack Fault, align in a northeast-southwest trend that is oblique to the Jack Fault. The intersection between the feeder system trend and the Jack Fault, is the location of the central feeder (Figure 2.5). The authors suggest that intersection of the feeder system trend and the Jack Fault provided a structural control on hydrothermal discharge sites. The trend of the barite cap (Figure 2.3a) is observed to be subparallel to the feeder trend, which would support this.



Figure 2.5: Location and distribution of the feeders in a pre-Jack Fault reconstruction of the stringer zone (at approximately 400 metres R.L.). The three feeders are aligned on a trend that is acute to the trend of the Jack Fault, however the central feeder is located where the two structural trends cross (from Gemmell and Large, in press).

#### 2.3 Thickness

Contours of the thickness of the barite cap and GSP are shown in Figure 2.6. The contoured plan projection of cap thickness is derived from the Hellyer DATAMINE database using linear block kriging (refer McArthur and Kuipers, 1990). Due to the irregular and infrequent occurrence of the GSP, the two cap zones were combined. The contoured plan (Figure 2.6) is based on the 1990 ore reserves and, as a consequence, the cap distribution is slightly different from that previously derived by mapping and logging (Figure 2.4).

The cap zones show highly variable thickness and consequently a longitudinal projection of the cap zones was not attempted. Maximum cap thickness, of 15 metres, is attained at 10790 N, between 10590 N and 10700 N and at 10470 N. North of 10800 N, the cap thickness is less than 8 metres. The thickness of the caps is therefore greatest over the hydrothermal feeders, which also correspond to regions where both the barite cap and GSP are present.

### 2.4 Faulting

Figures 2.7a and 2.7b show the position of the main faults intersecting the barite cap and GSP respectively. The location of faults were derived from the orebody model, as proposed by the geologists at the Hellyer deposit.

The orebody, and consequently the barite cap and the GSP, are offset by a number of sinstral faults. The barite cap and GSP are well developed circumferential to the Jack Fault. The lateral distribution of the barite cap would indicate a close spatial affinity to the faults (Figure 2.7a), whilst the GSP shows no obvious correlation, except in regions proximal to the Jack Fault (Figure 2.7b). The faults presently transecting the orebody are thought to be the result of strain partitioning during deformation (Drown and Downs, 1990). McArthur (1989) suggested there to be no structural control on the depositional sites of the barite cap and GSP. There would however, appear to be a spatial association between the barite cap and the location of the orebody faults, in particular that of the Jack Fault.

## 2.5 Conclusions

The barite cap and GSP are most developed between 10670 N and 10790 N. In these regions, the cap zones attain maximum thickness and overly position of the central feeder, proximal to the present Jack Fault. A Cambrian structure (pre-Jack Fault) is believed to have existed at the time of mineralisation (R.C. Downs, pers. comm.). The distribution of the barite cap is an irregular, but continuous lens, which is subparallel to the trend of the feeder.



Figure 2.6: Contours of thickness of the barite cap and GSP (combined). Greatest thickness of approximately 15 metres, occurs at 10470 N, between 10590 N and 10700 N, and at 10790 N.

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Figure 2.7: The location of the main faults which intersect the a) barite cap and b) GSP.

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The GSP, however is thin, irregular and discontinuous. The barite cap and GSP show gradational to sharp contacts with massive sulphide mineralisation. Barite veining in the massive sulphides is a common feature of the gradational contacts. An interdigitating relationship exists between the barite cap and GSP, however the genetic relation of the caps to one another remains obscure and is addressed in mineralogical and textural studies (Chapter Three).

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# Chapter Three Mineral and Textural Paragenesis

## 3.1 Introduction

Barite and quartz are the predominant minerals in the barite and silica caps of the Hellyer deposit. Sulphides present in both of the cap zones include; pyrite, sphalerite, galena, tetrahedrite-tennantite and chalcopyrite, in the stated order of abundance. Arsenopyrite is abundant in the GSP, however it is totally absent from the barite. Other minerals observed include calcite, sericite and chlorite. The sulphides form texturally intricate, fine grained intergrowths and overgrowths. As a result, is is useful to describe the characteristics of each mineral phase below, in order to broadly define textural and mineral paragenesis. This necessitates a range of samples to be considered, in order to assess the environment of formation.

In addition to routine microscopy, twelve samples from the the barite cap and GSP were investigated under a Phillips Model 505 SEM. The samples, in the form of small chips, were initially etched in hydrofluoric acid for 10 minutes (refer Duhig, 1991), and then washed thoroughly in distilled water. They were dried at 100°C for 24 hours prior to mounting on to a suitable holder. Prepared samples were submitted to the CSL for gold coating prior to examination.

## 3.2 Barite

Barite (BaSO<sub>4</sub>) has a hardness of 3 to 3.5 and a specific gravity of 4.5 (Dana 1944). Its high specific gravity and soft brittle nature are distinguishing features. Barite is the predominant mineral in baritic mineralisation and present, to a lesser extent, in the GSP.

Barite from the barite cap ranges in occurrence from massive interlocking subhedral to euhedral grains, (measuring up to 1cm in size, Plate 3.1 and 3.2), to well formed crystalline tabular laths (Plate 3.3) measuring up to 10 cm in size. In these zones, sulphides occur as minor component. In hand specimen well crystalised barite had a pink colouration, which may be the result of very fine grained disseminations of hematite. Since the barite often displayed a yellow fluorescence, it is likely that iron or other impurities exist in the crystal structure. Tabular barite laths occasionally exhibit zonation and in general contain numerous

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Plate 3.1: Massive barite which forms subhedral to euhedral interlocking grains. A pink colouration would indicate the presence of finely disseminated hematite impurities. Minor sulphides, predominantly pyrite, are best developed along the grain boundaries of the barite (Sample 525 7482 WXC).

**Plate 3.2:** Massive barite showing well formed networks tabular barite laths. Tabular barite is variable in size from 1 to 2 cm to less than 2 mm. The matrix interstitial to the tabular barites is a combination of granular barite and massive sulphides including pyrite, sphalerite and galena in order of abundance (Sample 7377).

Plate 3.3: Large acicular needles of barite, up to 4 cm in length, in a milky grey chert of the GSP. These needles of barite are often fractured. A zone of recrystallised pyrite and coarse grained galena is present (Sample RS67).

**Plate 3.4:** Barite rosette showing radiating laths from a centre composed of smal subhedral barite and calcite. At the top left, the rosette of barite is being replaced by pyrite. The opaque minerals are pyrite, with minor sphalerite and galena (Sample RS93, longest dimension = 2 mm).

**Plate 3.5**: Barite deposition in open space. Tabular laths of barite show pyrite rims and the minor occurrence of colloform pyrite along cleavage is evident. The background mineral is calcite. The pyrite overgrowth varies from recrystallised pyrite, close to the barite grain to colloform or framboidal pyrite (Sample RS70, longest dimension = 4 mm).

**Plate 3.6:** Large barite grain displaying dissolution along grain boundaries. Fracturing and replacement by sphalerite along cleavage is evident. The matrix contains a high proportions of sulphide, predominantly pyrite and sphalerite, and granular barite indicative of a hydrothermal overprint zone (Sample RS95, longest dimension = 4 mm).

**Plane 3.7:** a) Fine grained massive barite composed of granular (less than 1 mm in size) subhedral barite grains. Sulphides present are fine grained pyrite and sphalerite (Sample RS13). b) Fragmental barite hosted in a granular barite and sulphide matrix. Larger barite grains are rounded to angular, showing evidence of reworking (Sample RS59).

Plate 3.8: Barite deposition in open space forming network barite. These randomly orientate laths show evidence of intergrowths and overgrowth, with carbonate filling interstices (Sample RS93, longest dimension = 4 mm).



fluid inclusions. Intergrowths of barite are common and radiating "rosette" barite aggregates have been observed (Plate 3.4).

Barite grains, in zones with a high sulphide content, were often rounded and fractured. This would suggest that the barite has been reworked and suffered dissolution. Sulphide deposition along barite grain boundaries is a common feature (Plate 3.5). As barite has three cleavage planes, later sulphides deposit in and/or replace barite along cleavage planes or fractures (Plate 3.6). Fine grained or granular (Plate 3.7a) consists of 0.5 to 1 mm rounded subhedral barite grains which often form a groundmass. The nature of fragmented barite (Plate 3.7b) has been interpreted to be the result of reworking of the barite. The reworked areas are often associated with a large proportion of sulphides. Large tabular barite laths are frequently hosted granular barite. Barite deposition in open space (Plate 3.8) can be concluded from the random deposition of tabular barite laths (or network barite) with subsequent late infilling by carbonate and/or silica and/or granular barite.

In the GSP, barite may occur as either barite cap fragments or zones of network laths, which have been encompassed by silica. The latter is interpreted to indicate influx of silica (GSP deposition) after precipitation of the tabular barite. Barite cap fragments in the GSP are indicative of reworking processes, which see clasts of massive barite incorporated into the GSP, during GSP deposition. Minor occurrences of late barite have been identified from vug linings and cross cutting veinlets. Late barite veins in underlying massive sulphides are either crustiform (Plates 3.9 and 3.10) or granular in nature (refer Chapter 2, Plate 2.6). Crustiform veins are composed of acicular barite laths, of variable size.

Paragenetically, broad stages of barite precipitation can be determined. Numerous overgrowths of small barite grains by larger barite grains indicates differential stages of barite growth. The earliest identifiable phase is that exhibited by the well formed acicular and tabular laths and the crystalline massive barite. Granular barite appears to be paragenetically late, as are the crosscutting barite (and/or carbonate) veinlets and vug linings, and crustiform veins within massive sulphides.

#### 3.3 Quartz

The GSP is predominantly a quartz-iron horizon. The textural classification used to classify the GSP is derived from Kneller et al. (1986) and Duhig (1991).

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Plate 3.9: Crustiform barite veining from within the massive sulphides. The vein contains large tabular barite laths with a pyrite/chlorite centre (Sample 7377 SD).

Plate 3.10: Barite veining through massive sulphides. The sulphides, predominantly pyrite, are fractured and healed by granular barite. The crustiform vein (bottom right) is composed of small barite laths (less than 1 mm) to small subhedral barite grains (Sample 5976 WXC).

Plate 3.11: Contact between the barite cap and the GSP. The apparent banding in the milky grey chert is the result of finely disseminated pyrite. The fine grained granular barite of the barite cap shows a transecting siliceous vein, that is rimmed by crystalline pyrite in the GSP (Sample 450E).

**Plate 3.12:** GSP with barite. The GSP is a milky grey chert exhibiting banding due to finely disseminated pyrite. The barite at the edge of the GSP is of a different stage (either later or earlier?) than the GSP. The large barite lath (centre) is encompassed by the GSP and shows a rim of calcite (Sample 7377).

Plate 3.13: Typical GSP a) Top - The GSP has a high sulphide content which is predominantly pyrite. These sulphides are colloform in nature and encompassed by microcrystalline quartz. The microcrystalline quartz has a high content of disseminated pyrite, which causes the chert to exhibit a dark grey colouration (Sample RS106). b) Bottom - Grey chert with nodules of recrystallised pyrite. The chert, composed of microcrystalline quartz, has a high content of disseminated pyrite. Sphalerite and galena are present in minor amounts in the chert (Sample RS42).

Plate 3.14: An infilling of open space by large equant megaquartz grains. The background matrix is microcrystalline quartz that contains a significant proportion of pyrite. The cavity shows a rim of microcrystalline quartz and a terminal filling of calcite in the centre (Sample RS32, longest dimension = 2 mm).







Broadly the GSP can be classified into two different silica polymorphs. These silica polymorphs are:

| Microcrystalline Quartz: | Equidimensional grains from 0.01 to 0.001 mm size,             |
|--------------------------|--|
|                          | with undulatory extinction and pinpoint birefringence.         |
| Megaquartz:              | Distinguished by equant to elongate grains larger than 0.02mm. |

## 3.3.1 Microcrystalline Quartz

Microcrystalline quartz is the main silica polymorph component of the GSP. In undeformed samples (Plates 3.11 and 3.12 respectively) the GSP is a light milky grey, with finely laminated bands. In thin section, banding appears to be the result of widely disseminated euhedral and framboidal pyrite. The differences in pyrite contents delineate an apparent primary banding. No delineation of banding by differential quartz sizes is evident.

In more typical GSP samples (Plates 3.13) the chert of the GSP is a dark grey. The dark grey colouration of the chert is probably due to the large proportion of pyrite observed in microcrystalline quartz. The variation in the colour of the GSP, from milky grey to dark grey, is likely the result of an increase in pyrite within microcrystalline quartz aggregates.

The GSP contains numerous cavities and is thus highly porous. Cavities are typically round to elongate in nature, some being as large as 20 cm in size. These open spaces are infilled by, firstly a microcrystalline chert lining and secondly by subhedral equant megaquartz  $\pm$  barite and/or carbonate (Plate 3.14).

SEM examination of chert from the GSP at Hellyer showed that the microcrystalline chert was composed of subhedral silica grains, with no evidence to suggest that bacterial filaments were present (Figure 3.15). Submarine thermal vent sites are typically colonized by sulphuroxidising bacteria, as noted by other workers (Zirenber and Schiffman, 1990; Duhig, 1991). It is therefore possible that bacterial filaments at Hellyer, have been masked or completely replaced by the sulphide phases if they were present.

## 3.3.2 Megaquartz

The deposition of megaquartz is paragenetically late within the cap systems. Its occurs as equant grains which fill cavities in both baritic and GSP mineralisation (Plate 3.14).

### Plate 3.15: SEM micrographs

a) Barite being replaced by megaquartz in the GSP (Sample RS202, scale bar = 10 microns).

b) Close up of the nature of the contact between the barite and megaquartz in a). (Sample RS202, scale bar = 10 microns).

- c) Isolated barite lath in microcrystalline quartz (Sample RS32, scale bar = 10 microns).
- d) Texture of elongate megaquartz within the GSP (Sample RS32, scale bar = 10 microns).
- e) Texture of meqaquartz of the GSP (Sample RS32, scale bar = 10 microns).
- f) Texture of microcrystalline quartz with pyrite framboid. Shows a distinctive grannular nature (Sample RS32, scale bar = 10 microns).
- g) Microcrystalline quartz aggregates in the GSP (Sample RS67, scale bar = 10 microns).
- h) Microcrystalline quartz aggregates in the GSP (Sample RS67, scale bar = 10 microns).

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Megaquartz is also present within late stage carbonate  $\pm$  barite crosscutting veinlets. An elongate megaquartz form, is commonly observed in pressure solution shadows around pyritic aggregates (associated with sericite and chlorite development). Essentially, the megaquartz appears to fill interstices between sulphides, barite accretions and open spaces in the microcrystalline chert.

## 3.3.3 Silica Pseudomorphs

The genetic association of the barite cap to the GSP is enhanced by the presence of silica pseudomorphs. Sample RS32 highlights this relationship in particular. Here, well formed laths of barite occur in fine grained microcrystalline chert. The tabular barite grains are pseudomorphed, either completely or partially by quartz (Plates 3.16 to 3.20). The occurrence of tabular barite laths in GSP appears to be the result of either; fragmental barite incorporated into the GSP from reworked or collapsed structures; or low temperature silica polymorph deposition in a network of open space network barite laths. Quartz pseudomorphs are composed of 0.04 to 0.08 mm megaquartz grains, which are smaller in grain size than that megaquartz contained in cavities. Where barite replacement has been complete, quartz pseudomorphs form tabular ghosts. These ghosts may have either an isolated occurrence (Plates 3.16 and 3.17) or constitute an array or network of interlocking pseudomorphs (Plates 3.19, 3.29 and 3.20). This pseudomorph style is frequently observed throughout the GSP and represents the dissolution of barite and its movement out of the GSP.

## 3.4 Pyrite

Pyrite is the most abundant sulphide mineral in the barite and GSP caps and occurs as framboids, framboidal aggregates, spongy aggregates, concentric growths, colloform intergrowths, crystalline pyrite and recrystalised pyrite. Pyrite shows a wider textural variation in the GSP than observed in the barite cap.

## 3.4.1 Pyritic Textures in the GSP

Concentric pyrites are intergrown by galena and/or sphalerite (Plate 3.21). These textures may either represent contemporaneous intergrowths of pyrite, sphalerite and galena or the deposition of sphalerite and galena into porous colloform pyritic bands (Craig and Vaughn, 1981). If the latter is true, then sphalerite and galena are paragenetically later than the colloform pyrite bands.

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Plate 3.16: A single barite lath in microcrystalline quartz of the GSP, being pseudomorphed by megaquartz (of dimensions 0.04 mm to 0.08 mm). The microcrystalline quartz contains framboidal pyrite. Plane polarised light (Sample RS32, longest dimension = 2 mm).

Plate 3.17: As for plate 3.16 under crossed nicols (Sample RS32, longest dimension = 2 mm).

**Plate 3.18:** Network silica pseudomorphs in a pyritic microcrystalline matrix. The pseudomorphs show occasional relict barite cores. The silica pseudomorphs or ghosts retain a tabular outline and are a frequent occurrence in the GSP. Plane polarised light (Sample RS32, longest dimension = 2 mm).

Plate 3.19: As for Plate 3.18 under crossed nicols (sample RS32, longest dimension = 2 mm).

**Plate 3.20:** Incompletely replaced barite forming network silica pseudomorphs. The barite laths retains much of their tabular habit, showing megaquartz rims. These incompletely replace barite laths are a likely precursor to Plates 3.18 and 3.19. Crossed nicols (Sample RS202, longest dimension = 4 mm).







Plate 3.21: Concentric pyrites in microscrystalline quartz. The pyrite appears to be intergrown with sphalerite (light grey) and galena (pale grey). The core of each of the concentric pyrites/sphalerite/galena intergrowths is pyrite (Sample RS42, largest dimension = 250 microns).

**Plate 3.22:** Concentric overgrowths of framboids in megaquartz. The framboids are overgrown by two stages of galena deposition, intermittent to spongy pyrite formation. These galena rims are host to well formed arsenopyrite grains. (Sample RS27, longest dimension = 4 mm).

Plate 3.23: Colloform pyrites rythmically deposited in open space, possibly relict of a fluid conduit, now filled by megaquartz. Chalcopyrite is evident to fill fractures in the colloform pyrite (Sample RS106, longest dimension = 1 mm).

**Plate 3.24:** Colloform pyrite encompassing a tabular barite lath in late stage galena and sphalerite (RS27, longest dimension = 4 mm).

**Plate 3.25:** Rhythmically deposited spongy pyrite in sphalerite. The spongy pyrite is fractured, infilled by galena and sphalerite. The spahlerite shows chalcopyrite disease (Sample RS70, longest dimension = 2 mm).

**Plate 3.26:** Colloform pyrite with fine intermittent galena banding. The colloform pyrite shows later chalcopyrite, which infilled fractures in the pyrite. The dark grey back ground (top right) is microcrystalline quartz of the GSP (Sample RS32, longest dimension = 2 mm).







Colloform pyrites (Plate 3.22 to 3.26) are suggestive of rhythmic deposition of pyrite (and/or galena and sphalerite) into vugs at low temperatures as discussed by Craig and Vaughn (1981) and Ineson (1989). Colloform pyrites (Plate 3.22) show at least two stages of galena overgrowths, with a later overgrowth by spongy pyrite. This feature is also seen associated with euhedral pyrites (Plate 3.27), where pyrite euhedra are overgrown by at least two stages of galena precipitation and subsequently by pyrite. These intermittent galena rims are host to well formed arsenopyrite grains. Pyrite atoll textures, caused by the replacement of pyrite euhedras by sphalerite, would suggest that sphalerite has precipitated after the precipitation of euhedral pyrite. Rounding and corrosion of euhedral pyrite grains has also been observed.

Pyrite, as isolated framboids (Plates 3.28 and 3.33 a, b, c, h) to extensive arrays of framboidal aggregates (Plates 3.33 e, f, g and 3.29) are common textures of microcrystalline quartz in the GSP. The framboidal aggregates consist of numerous pyrite framboids deposited in very close proximity and form a spongy pyrite texture. The aggregates may display tabular holes (Plate 3.30), which are observed to be tabular barite laths that are engulfed by an array of micron to submicron pyrite framboids. In these instances, tabular barite may either be replaced completely or partially by megaquartz. This is true for colloform pyrites (Plate 3.24) where barite laths have been overgrown by colloform pyrite. These textures are indicative of sulphate deposition prior to an influx of sulphide. Pyrite may also occur framboidal pyrites in association with small, subhedral to euhedral, cubic crystals which are less than 0.05 mm in size (Plates 3.33 c, d).

#### Pyrite Pseudomorphs

Pyrite pseudomorphs are a feature of pyritic aggregates and subhedral crystalline pyritic masses in the GSP. These textures of these pseudomorphs are variable and their interpretation is problematic due to the complete replacement of the previous phase. The textures form spongy pyrite overgrowths on a crystalline pyrite and/or galena and/or sphalerite core and can be described as acicular pyrite pseudomorphs (Plates 3.34 to 3.38). Acicular pyrite pseudomorphs in Plate 3.38 show a dendritic texture, outlined by pyrite. Acicular textures in the GSP vary between bladed acicular and tabular relicts. SEM investigations (Plate 3.40) demonstrate the spongy nature of the pyrite and fine grained galena overgrowths.

Plate 3.27: Euhedral pyrite overgrown by galena, followed by crystalline pyrite. The galena overgrowths are host to well formed arsenopyrite grains. The sample is from the GSP (Sample 106, longest dimension = 1 mm).

**Plate 3.28:** Isolated pyrite framboids and euhedras in the microcrystalline quartz of the GSP. The presence of pyrite in the GSP causes the dark colouration of the chert (Sample RS57, longest dimension = 0.5 mm).

**Plate 3.29:** Pyrite framboids and occasional pyrite euhedras deposited in close proximity within microcrystalline quartz (Sample 57, longest dimension = 0.5 mm).

**Plate 3.30:** Spongy pyrite in the microcrystalline chert of the GSP. The tabular 'holes' are relict of barite, which in most cases is replaced by megaquartz (Sample RS32, longest dimension = 2 mm).

Plate 3.31: Recrystallised pyrite containing fragments of colloform pyrite and inclusions of framboids (Sample RS42, longest dimension = 0.5 mm).

**Plate 3.32:** Tabular outline by recrystallised pyrite, infilled by galena, chalcopyrite and minor tetrahedrite in the GSP (Sample RS12, longest dimension = 1 mm).







Plate 3.33: SEM Micrographs

a) Framboidal pyrite in microcrystalline chert (Sample RS32, scale bar = 10 microns).

b) Close up of large pyrite framboid in a), showing a pyrite framboid and euhedra to be deposited at the surface of large pyrite framboid observed in a). (Sample RS32, scale bar = 10 microns).

c) Pyrite framboids and euhedras in microcrystalline chert (Sample RS26, scale bar = 10 microns).

d) Cluster of euhedral pyrite in microcrystalline chert (Sample RS26, scale bar = 10 microns).

e) Pyrite framboids in megaquartz. The cubes which constitute the framboids are evident (Sample RS202, scale bar = 10 microns).

f) Close up of e)

g) Close up of e)

h) Framboidal pyrite in microcrystalline chert (Sample RS32, scale bar = 10 microns).











**Plate 3.34:** Acicular pyrite pseudomorphs with spongy pyrite outlines, contained in crystalline pyrite (Sample RS106, longest dimension = 2 mm).

Plate 3.35: Radiating acicular pyrite pseudomorph in sphalerite (Sample RS70, longest dimension = 0.5 mm).

**Plate 3.36:** Network type acicular pyrite with spongy pyrite overgrowths in association to galena, sphalerite, tetrahedrite and chalcopyrite (Sample RS12, longest dimension = 1 mm).

Plate 3.37: Framboidal and acicular spongy pryites in sphalerite (Sample RS70, longest dimension = 0.5 mm).

**Plate 3.38:** Dendritic or frondescent pyrite in a spongy to crystalline pyrite (Sample RS32, longest dimension = 1 mm).

**Plate 3.39:** Boundary between colloform pyrite and microcrystalline quartz of the GSP. Arsenopyrite grains are well formed but show evidence of replacement by sphalerite. The edge of the colloform pyrite is composed of framboidal pyrite (Sample RS106, longest dimension = 0.5 mm).

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Plate 3.40: SEM micrographs from sample RS106

a) Pyritic pseudomorphs with galena (light grey) overgrowths (scale bar = 10 microns).

b) Tabular pyrite pseudomorphs with galena overgrowths (Scale bar = 10 microns).

c) Shows a spongy pyrite (dark grey) with two overgrowths of galena (light grey). Scale bar = 10 microns.

d) Close up of c).

e) Close up of a single pseudomorph which show two distinct overgrowths of galena followed by pyrite (Scale bar = 10 microns).

f) Close up of the pseudomorph in e).







Similar occurrences of pyrite pseudomorphs are observed in the Escanaba Trough, southern Gorda Ridge where barite tablets, measuring up to 2.5 mm in length, occur as radiating clusters or dendrites that extend outward from a sulphide substrate (Koski et al., 1988). Acicular pyrite textures have also been documented by Grenne and Vokes (1989), in massive sulphides of the Hoydal volcanogenic deposit in the New Caledonies. The authors observations would support a sulphate precursor for the observed acicular and tabular pyrite pseudomorphs (for example compare Plates 3.40 and 3.32). As pseudomorphism is complete, the previous composition can only be postulated. Pyrite pseudomorphs would however appear to represent some phase which existed prior to the deposition of the GSP and influx of sulphides.

Crystalline pyrite appears to have formed late and often encompasses fragments of relict colloform or framboidal pyrites (Plate 3.31). Crystalline pyrite is the dominant form of pyrite present in the GSP, and occurs in rounded nodular masses. It may represent recrystalisation of framboidal aggregates as annealing is occasionally observed. Microfolding of recrystalised pyrite bands has been observed in the GSP.

## 3.4.2 Pyrite Textures of Barite

Pyrite textures observed in massive barite are similar to some textures observed in the GSP. Pyrite as framboids or colloform structures, may be found in granular barite and is observed around barite lath boundaries (Plate 3.6) and along cleavage planes and fractures within tabular barites (Plate 3.5). Pyrite may form a dominant phase associated with granular barite. The crystalline nature of pyrite in these zones, indicate that the pyrite is late stage.

#### 3.5 Sphalerite

Two distinct sphalerite phases have been identified. Early low iron sphalerite in the GSP forms irregular to hexagonal grains which are interpreted as a syn-precipitate to microcrystalline quartz (Plate 3.39). This early phase of sphalerite often exhibits hexagonal outlines (Plate 3.41) which are delineated by zones of fine grained chalcopyrite as chalcopyrite disease. The hexagonal nature of the grains would suggest wurtzite to be the sphalerite form indicating primary deposition of sphalerite (Hekinian et al., 1980).

Late stage sphalerite occurs as irregular masses in both the barite cap and GSP. In barite grains it may form along cleavage planes (Plate 3.5). In the GSP, late sphalerite is

commonly found in association with pressure solution shadows that surround crystalline pyrite or which replace euhedral pyrite. Chalcopyrite disease in this sphalerite is variable in intensity (for example Plate 3.42) and often absent. Exsolution of chalcopyrite with in sphalerite has also been observed (Plate 3.43).

#### 3.6 Arsenopyrite

Arsenopyrite has only been observed in the GSP. In general, it forms euhedral grains as isolated islands in a microcrystalline quartz matrix, although it has been observed at the perimeters of colloform pyrites (Plate 3.39). Arsenopyrite is often well developed in sphalerite masses (Plate 3.44), and has been observed to form atoll structure from its replacement by sphalerite. Ramsden et al. (1990) found arsenopyrite grains to exhibit zoning in the Hellyer massive sulphide mineralisation. No apparent zoning in arsenopyrite euhedras from the silica cap is seen.

# 3.7 Galena

Galena is present in the barite cap and GSP as intergrowths with concentric and colloform pyrites (Plates 3.21, 3.22 and 3.26) and is considered to be paragenetically early. Galena also occurs as overgrowths on euhedral pyrite and framboids (Plates 3.27 and 3.30 respectively). Most commonly, in the barite cap and GSP, galena is a late stage mineral observed in association with tetrahedrite-tennantite, infilling cavities and in the fractures of large crystalline pyrites or colloform pyrites (Plates 3.24, 3.25, 3.26, 3.29 and 3.36). Galena in the barite cap may replace barite along fractures or cleavage.

## 3.8 Tetrahedrite-Tennantite

Tetrahedrite-tennantite is predominantly found in association with late stage galena and chalcopyrite (Plates 3.32 and 3.36). Grains are observed to be irregular irregular and variable in size.

## 3.8 Chalcopyrite

Chalcopyrite is considered to be a late stage mineral and occurs as irregular grains which are variable in size. Commonly it fills cracks in colloform or crystalline pyrite (Plates 3.23 and 3.26). Chalcopyrite disease in sphalerite is variable and may show exsolution textures in sphalerite (Plate 3.44). Chalcopyrite disease is most frequently observed in early hexagonal

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Plate 3.41: Hexagonal sphalerite showing low iron concentrations. The hexagonal outlines are the result of chalcopyrite disease. This type of sphalerite indicates wurtzite (Sample RS25, longest dimension = 1 mm).

Plate 3.42: Chalcopyrite replacing sphalerite in the GSP. Zones showing such intensity of chalcopyrite in sphalerite are uncommon (Sample RS006, longest dimension = 1 mm).

Plate 3.43: Chalcopyrite replacing sphalerite in an exsolution texture. The euhedral pyrite is being replaced by the sphalerite (Sample RS35, longest dimension = 0.5 mm).

**Plate 3.44:** Arsenopyrite and spongy pyrite with chalcopyrite in a large sphalerite grain of the GSP (Sample RS12, longest dimension = 0.5 mm).

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Plate 3.45: Isolated occurrence of electrum in a crystalline pyrite (Sample RS001, longest dimension = 250 microns).

Plate 3.46: Electrum grain hosted in a fracture in crystalline pyrite (Sample RS001, longest dimension = 250 microns).







sphalerite. Chalcopyrite is dominant in those regions which show a large proportion of sulphide minerals.

#### 3.9 Electrum

Electrum has been observed for two samples from the barite cap (RS001 and RS35). The occurrence of electrum is as isolated grains nested in recrystalised or euhedral pyrite (Plates 3.45 and 3.46) or as grains which are hosted in fractures of the aforesaid pyrites (refer Chapter Four). In the former, electrum grains are relatively small (largest dimension of 10 microns), whilst electrum hosted in fractures form relatively larger grains, up to 25 in size. Electrum was not observed in GSP mineralisation.

#### 3.10 Carbonate

In the GSP, calcite occurs as subhedral grains which are interstitial to, or replace, tabular barite laths (Plate 3.8). Calcite also occurs as veinlets and vug linings and has a frequent occurrence in barite. In the barite former carbonate has been observed to replace barite along cleavage planes or fractures.

## 3.11 Sericite and Chlorite

Sericite alteration is concomitant to chloritic alteration. These minerals are associated with megaquartz and crystalline pyritic aggregates, but may also occur as disseminations throughout the microcrystalline quartz groundmass. Chlorite is frequently associated with megaquartz, being found in pressure solution shadows surrounding crystalline pyrite masses. The sericite and chlorite minerals correspond to zones of high hydrothermal alteration, concomitant to zones containing a large proportion of paragenetically late sulphides. Sericite commonly occurs as fine grained platy needles measuring less than 0.2 mm in size. Chlorite occurs as fine dustings in barite or microcrystalline quartz and occasionally as radiating fans of platy needles.

## 3.12 Paragenesis

#### 3.12.1 Stage 1 : Primary Textures

Textures which indicate open space deposition as described by Schwartz (1951), Freund (1966) and Craig and Vaughn (1981), are the first recognisable event in precipitation of the barite cap and GSP. In the barite cap, these textures show network barite laths and colloform and concentric pyrites to be the earliest precipitates. Concentric intergrowths and colloform

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textures observed in both the barite cap and GSP, are the result of the unobstructed growth of minerals into fluid filled voids (Craig and Vaughn, 1981). The development of the barite cap is therefore suggested to be largely derived from networks barite laths and colloform or concentric pyrite.

The relative timing of the network barite to the colloform or concentric pyrite/sphalerite/galena intergrowths is suggested to be barite followed by pyrite. Evidence to suggest that barite was the first precipitant is indicated by barite laths encompassed by colloform pyrites (Plates 3.24 to 3.30).

Textural interpretations are made difficult by the recognition of replacement phases when no vestige of the replaced phase remains. Pyrite pseudomorphs hosted in colloform to recrystalised pyrite (Plates 3.34 to 3.39) are suggested by Grenne and Vokes (1989) to have provided a substrate upon which ore deposition took place. In the cap zones at Hellyer, the observed acicular pyrite pseudomorphs may indicate a precursor of sulphate origin. Studies of recent hydrothermal activity from the Juan de Fuca Ridge (Davis et al., 1987) and 13°N East Pacific Rise (Hekinian and Fouquet, 1985) have found similar textures. These authors postulate the origin of acicular pyrite textures to be a sulphate, likely anhydrite or gypsum. No anhydrite or gypsum from the Hellyer baritic or siliceous caps was observed.

The cleavages of barite provides a prime site for the initiation of replacement processes. A chemical control of replacement is demonstrated between pyrite and barite as pyrite forms rims around tabular barite (Plate 3.6). Replacement of barite may therefore occur selectively.

The deposition of microcrystalline quartz appears to postdate that of barite formation. Observations of microcrystalline quartz engulfing network barite, causing dissolution and pseudomorphism of barite, would support this. In addition to silica psedomorphs (Plates 3.16 to 3.20) are silica veins (Plate 3.11) observed to transect the barite cap. The relative timing of colloform pyrite to microcrystalline quartz is unclear. Pyritic nodules of colloform pyrite in GSP may indicate formation prior the microcrystalline deposition or alternatively the growth of colloform pyrites in cavities within the GSP. The open framework of the GSP may also induce the precipitation of barite laths in cavities, during times of minor sulphide deposition.

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The deposition of microcrystalline chert is closely associated with the precipitation of pyrite framboids and euhedras, sphalerite and arsenopyrite. These sulphides are encompassed within the microcrystalline quartz matrix and are thought to be contemporaneous to microcrystalline quartz formation. Early formed sphalerite occurring as colloform bands is sometimes affected by chalcopyrite disease. Copper bearing solutions may have gained access to sphalerite along cracks or grain boundaries, initiating chalcopyrite disease along crystallographic planes or growth zones of sphalerite (Craig and Vaughn, 1981). Hekinian et al. (1980) suggested wurtzite to occur as hexagonal crystals which may have precipitated out of a gel-like material.

## 3.12.2 Stage 2 : Main Sulphide Deposition Phase

Following the formation of early precipitates is a period of predominantly sulphide deposition. The porous substrate, provided by the existing barite and silica precipitants, is filled and overprinted by sulphides. Increased sulphide precipitation is a likely response of increasing hydrothermal activity associated with increasing temperatures (Eldridge et al., 1983; Ohmoto et al., 1983). The paragenetic sequence of these sulphide phases is not definitive. Crystalline pyrites may be either directly precipitated or the recrystalisation of framboidal aggregates precipitated during Stage 1. Euhedral pyrite may indicate recrystalisation of colloform or framboidal pyrite in response to higher temperatures (Heinikan et al., 1980). Recrystalised pyrite however lacks any evidence of the galena intergrowths, associated with framboidal pyrite deposition during Stage 1 and are thus thought to be deposited during Stage 2. Recrystalised pyrite often contain fragments of colloform pyrite, framboidal pyrite (Plate 3.32) and/or euhedral pyrite. It is therefore suggested that during Stage 2 the order of pyrite precipitation was euhedral pyrite followed by well crystalised pyrite masses.

The order of deposition of late stage sphalerite, galena, tetrahedrite-tennantite and chalcopyrite in the barite and GSP is unclear. In some samples, these sulphide phases are dominant, and replacement or infilling of open space has been pervasive. These later sulphide phases occur in fractures and along grain boundaries of pre-existing phases.

#### 3.12.3 Hydrothermal Alteration and fill of Open Space

The presence of sericite and chlorite in the GSP and barite cap are most likely the products of hydrothermal alteration associated with the passage of hydrothermal solutions. These

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alteration products are associated with megaquartz and are often pervasive in the barite cap. Megaquartz deposition, as observed in cavities (Plate 3.14) are late stage fill of open space. Crustiform barite veining, as observed in the underlying massive sulphides, may indicate a sealing of fissures (Craig and Vaughn, 1981). Crustiform barite veins, sealed during the waning of hydrothermal activity, may represent conduits through which mineralising hydrothermal solutions passed to the sea floor.

## 3.13 Conclusion

It is difficult to detail a growth history for the barite cap and GSP. The diverse mineralogical and textural affinities of the samples examined reflect the growth history for that particular site in the cap zone from which the sample was collected. Variable conditions under which mineral phases precipitated are observed as hydrothermal overprinting processes. The effects hydrothermal overprinting, dominated by sulphide phases, masks a definitive paragenetic sequence. The broad paragenetic sequence derived for the formation of the baritic and siliceous caps is schematically presented in Figure 3.1. Indicated, is a chaotic and fluctuating system where the paragenetic order of mineral precipitation is controlled by proximal temperature and chemical conditions of formation. It is likely that Stages 1 and 2 have been recurrent during the growth of the barite cap and GSP, with the underlying sulphide mound.

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Figure 3.1: The relative paragenetic order of mineral deposition within the barite cap and GSP. Stage 1 and 2 may be recurrent stages indicating a fluctuating and chaotic system of precipitation.

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# Chapter Four Mineral and Whole Rock Geochemistry

## 4.1 Introduction

Mineral and whole rock geochemistry are complementary geochemical techniques. Whole rock analyses broadly define chemical compositions, whereas mineral geochemistry characterises the chemical constituents of mineral phases. As a result, chemical constituents may be ascribed to particular mineral phases.

The geochemical methods of investigation were XRF and microprobe analysis. Analyses by XRF were undertaken with the following aims:

- 1) To determine if the GSP is of hydrothermal origin.
- 2) To identify barium alteration of immediate hangingwall basalts and volcaniclastics.
- To compare signatures of the barite cap and GSP to similar horizons in other deposits.

As the cap zones at Hellyer are enriched in precious metals, it is of metallurgical interest to determine the residence of precious metals. Microprobe analyses were therefore undertaken with the following aim:

1) To determine the mineralogic residence and elemental associations of base and

precious metals to explain the distribution of metals from whole rock

analyses (this chapter) and metal zonation (Chapter Five). All sample locations are given in Appendix 2.1.

#### 4.2 XRF Sample Preparation

Samples analysed were core splits from the baritic cap, the GSP, and the overlying basalt and HVS. The samples were initially crushed to 1-3 mm pieces using a jaw crusher, and then 50 grams were ground in a tungsten-carbide ring mill. The ignition loss was determined by heating 1-2 grams of each sample at 1000°C overnight. Owing to the high sulphide content in many samples, the ignition loss was high. The ignited materials were made into fused glass discs for major element analyses (SiO<sub>2</sub>, TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, MnO, CaO, Na<sub>2</sub>O and K<sub>2</sub>O). Analysis of internal standards and replicate samples were made to assure quality of the analyses. Barium-rich samples were diluted with acid washed silica owing to barium interference. Pressed powder pills for trace element determinations were prepared from 5-6 grams of non-ignited sample powder. Silica-rich samples were bound using 0.3-0.5 grams of PVA solution. In total 11 samples were analysed.

## 4.3 Analytical Techniques

Major element oxides and trace elements (Ba, Cu, Pb, Zn, Bi, As, Cd, Ni, Nb, Zr, Y, Sr, Rb, V) were analysed for using a Phillips 1410 automated XRF under the guidance of

P.Robinson. Several elements were corrected due to interference of high barium levels, and tungsten was analysed to correct for As interference. Complete analytical results are listed in Appendix 3.1

Microprobe analyses, from carbon coated polished thin sections, were determined using the Cameca SX50 at the CSL under the guidance of operator W. Jabolaski. The minerals examined for major and trace elements included barite, calcite, pyrite, sphalerite, galena, arsenopyrite and tetrahedrite.

#### 4.4 The Composition of the Barite Cap

## 4.4.1 Whole Rock Geochemistry of Barite Samples

Three samples from the northern, central and southern parts of the barite cap (RS95, RS18 and RS228 respectively) were analysed by XRF. In all samples <u>Ba (as BaSO4)</u> was high (Appendix 3.1), between 40.77% and 51.98% Ba. Sr contents were similarly high ranging from 0.49% to 1.06% The majority of major oxides were low to non-detectable, as were most trace elements. High Cu, Pb, Zn values however, reflect differential proportions of sulphides within the barite cap samples.

Figure 4.1 shows the abundances of major oxides and the trace elements Pb, Zn, Cu, Sr and As. All other trace elements were below detection. The fluctuations of SiO<sub>2</sub>, Fe<sub>2</sub>O<sub>3</sub> and CaO are the result of differential quartz, pyrite and carbonate contents. Similarly, variations in Cu, Pb, Zn, Cu and As correspond to variable sulphide concentrations in massive barite. TiO<sub>2</sub> is constant throughout at approximately 0.3% and Al<sub>2</sub>O<sub>3</sub> at approximately 2%. Na<sub>2</sub>O, P<sub>2</sub>O<sub>5</sub> and MnO are less than 0.2%.



Figure 4.1: Comparison of whole rock analyses from massive barite of the barite cap at Hellyer. The three samples are distributed over the length of the barite cap, with RS95 from the northern portion of the cap, RS18 from the central area and RS228 from the southern portion of the barite cap.

# 4.4.2 Barium and Strontium Concentrations in Barite

Samples which contained barite that were analysed by microprobe included RS18 and RS70 from the barite cap and RS32, RS57 and RS63 from the GSP (Appendix 3.2). In all analyses Mg, Ca, Fe and Pb were below detection limits. Si occurred as impurities of microcrystalline quartz. Significant levels of Sr were present in nearly all barites analysed. Sr levels ranged from below the detection limit (0.1%) to a maximum of 2%, with an average of 0.7%. The barium content of barite ranged from 53.6% to 59.8 %, with an average of 58.1%.

A tightly constrained inverse relationship between Ba and Sr exists for barites in both the GSP and barite cap (Figure 4.2). High Ba levels correspond to low Sr levels and vice versa. In a traverse across and along a tabular barite lath (RS70) the relationship of Sr and Ba in barite is shown (Figure 4.3a and 4.3b). The central cores of the barite laths are enriched in Sr and relatively depleted in Ba, whilst the margins of the lath are depleted in Sr and enriched in Ba. This zonation was observed in a number of analysed grains (Appendix 3.2). Consequently the variations between Sr and Ba within barite appear systematic. Barite laths undergoing pseudomorphism by microcrystalline chert however, have below detection limit levels of Sr, which accounts for the outliers from the main Ba-Sr trend in Figure 4.2. A lack of metamorphic textures would indicate that the zonation of barite grains is a primary feature rather than a metamorphic induced feature.







Figure 4.3: A) Traverse across a barite grain (RS70). The microprobe results show an inverse relationship between Sr and Ba. When Ba is high, Sr is low and vice versa. A zonation of strontium is evident, with depletion of Sr at the edges of the grain and enrichment of Sr in the central portions of the grain. B) Traverse along the length of the same barite grain. No zonation along the length of the grain is evident, however the inverse relationship between Sr and Ba is present.

Whole rock analyses of the barite from the barite cap (Appendix 3.1) show Sr levels to be as high as 1%. A marked increase in Sr content from the north to south end of the barite cap is also observed (Appendix 3.1). Under the assumption that all Sr is dominantly contained within barite (refer section 4.5), then the substitution of Sr for Ba must also increase toward the south end of the cap zone. In view of this, a change in either the availability of Sr or the chemical conditions of barite precipitation is inferred.

Ba can be replaced by Sr in a continuous solid solution series from barite (BaSO<sub>4</sub>) to celestine (SrSO<sub>4</sub>). In the same solution series, the replacement of Ba by Pb (to anglesite) is reported to be uncommon. Pb levels in barite at Hellyer are below detection, indicating a Pb-Ba substitution did not occur. Members of the BaSO<sub>4</sub>-SrSO<sub>4</sub> series with a preponderance of the Ba molecule are called strontiobarites (Deer et al., 1962). Microprobe analyses of Sr levels in Hellyer barites indicate that they should be classified as strontian barite. Studies of the system  $CaSO_4$ -BaSO<sub>4</sub> show that BaSO<sub>4</sub> is the limit of the solid solution series of Ba in anhydrite (Phillips and Griffen, 1981). Slightly more Ca however can be accepted into strontiobarites than barites (Deer et al., 1962). Ca is in very low concentrations in the barites at Hellyer and consequently, Ca must be present in the cap zones in the form of calcite species as anhydrite has not been observed.

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One possible source of Sr is Cambrian seawater (refer Burke et al, 198?). Sr isotope studies at Que River and Hellyer however (Whitford and Craven, 1986), show barites to fall outside the range defined by Cambrian host rocks and coeval seawater . Whitford and Craven (1986) suggest the mineralising fluids derived Sr from an additional radiogenic source. Sr contents may therefore be the result of partitioning of Sr between the hydrothermal fluid and barite however, Sr isotopes on barite of the barite cap would be required to confirm this. At present, a total of twenty samples from the barite cap and barite veins in the stringer zone have been submitted to D. Whitford at the CSIRO, Sydney, for <sup>87</sup>Sr/<sup>86</sup>Sr isotopic analysis. The results of this investigation are not presently available.

# 4.4.3 Hangingwall Barium Alteration

Jack (1989; 1990) showed a major alteration zone in the hanging wall basalt to be the hanging wall plume. This zone overlies the siliceous core of the stringer zone and is defined by enrichments in CaO,  $K_2O$ ,  $Al_2O_3$  and Ba, and depleted with respect to Fe<sub>2</sub>O<sub>3</sub>, MgO and SiO<sub>2</sub> (Jack, 1989). Samples RS112 and RS117 from the PLS directly overlying the barite cap show enriched levels of Ca (mean of 18%),  $K_2O$  (mean of 4%) and  $Al_2O_3$  (mean of 16%). Barium levels reach a maximum of 0.3%, whilst depletions in Fe<sub>2</sub>O<sub>3</sub>, MgO and SiO<sub>2</sub> are observed (refer Appendix 3.1). The hanging wall basaltic samples analysed therefore, correlate to those analysed by Jack (1989) and are part of the hanging wall alteration plume.

# 4.5 GSP - A Classification

Two representative samples from the GSP (RS20 and RS64, from cross Sections 10630 N and 10790 N respectively) were analysed using whole rock geochemistry (Appendix 3.1). RS20 is a dark siliceous chert with minor pyrite and RS64 is contains a significant proportion of pyrite.

#### 4.5.1 Whole Rock Analyses of GSP

Whole rock analyses are dominated by concentrations of  $SiO_2$  and/or  $Fe_2O_3$ . RS20 contains high  $SiO_2$  and low  $Fe_2O_3$ . By comparison the  $SiO_2$  content of RS64 was significantly lower and, as expected, the  $Fe_2O_3$  content very high. RS64 also showed enrichment of Pb, Zn, Cu, Sb, Cu, Ag, whereas these elements are significantly lower in RS20. Enrichment of base and precious metal therefore relates to high sulphide content. The oxide distribution of both samples is shown in Figure 4.4a. Low Zr, Y, Nb, Rb and Sr values indicate that the GSP does not contain a significant detrital component (Duhig, 1991).

Adachi et al. (1986) used an Fe-Al-Mn plot to discriminate between hydrothermal and nonhydrothermal cherts. Samples analysed from the GSP lie within the hydrothermal chert field (Figure 4.5). For comparison, the tetsusekiei and Noranda chemical and clastic cherts have also been plotted (Figure 4.5), as has an interpillow chert from the PLS at Hellyer (RS118). The interpillow chert shows an identical signature to the clastic cherts at Noranda and is also

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Figure 4.4: Comparison of iron formations. a) A spiderdiagram distribution of the major oxides in the GSP at Hellyer b) Distribution of the major oxides for the tetsusekiei and Noranda (Main contact tuff) chemical and clastic layers (from Kalogeropoulos and Scott, 1983).



Figure 4.5: Chert Classification

**Figure 4.5:** A-F-M chert classification of Adachai et al. (1989). The GSP lies well within the hydorthermal chert field. Plotted also is a chert of the interpillow margin from the PLS at Hellyer. This chert is classified as a non-hydorthermal chert and is comparable to the clastic components of the Noranda and Tetsusekiei cherts (data from Ohmoto et al., 1983).

similar to the clastic component of the Tetsusekiei. Interpillow chert from basalts overlying Hellyer are thus not hydrothermal cherts.

Sample RS64 shows distinct similarity to the Tetsusekiei chemical component. Both samples analysed fall in the hydrothermal chert group. Spiderdiagrams from the GSP are similar to those of the tetsusekiei and Noranda cherts (shown in Figure 4.4b).

The hydrothermal chert signature and enriched levels of precious and base metals are a feature of siliceous horizons associated with VHMS deposits (Kalogeropoulos and Scott, 1983; Duhig, 1991). The issue of varying metal contents with stratigraphic position within the GSP is discussed in Chapter Five.

#### 4.6 Carbonates

Carbonate analyses from this study and from other studies by Aberfoyle geologists reveal that the carbonates are nearly pure calcite with only minor Mg (0.1%), Mn (0.1%) and Fe (0.6%). The calcites average 38.6% Ca (Appendix 3.3). Ba levels in most carbonates were low, as was the Sr content. Microprobe analysis of carbonate confirms that the Ca present in the cap zones resides in calcite and that Ba and Sr reside in barite.

#### 4.7 Iron content of sphalerite

The Fe content of sphalerite from the barite cap (samples RS83 and RS75) and GSP (samples RS42 and RS106) is similar (mean of approximately 2.3%; Appendix 3.4). This result is close to the average of 2.7% for the Hellyer deposit obtained by Ramsden et al. (1990). No broad differences in the Fe content of sphalerite was observed in the baritic cap or the GSP. Minor zones of high Fe sphalerite (orange in plane polarised light) appear to be the result of microscopic to submicroscopic chalcopyrite disease. In these cases an enhancement of hexagonal growth is present. Iron poor sphalerite suggests that oxygen fugacity was elevated in this locality (Jack, 1989) which is consistent with oxygenated seawater mixing with hydrothermal solutions.

# 4.8 Mineralogic Residence of Arsenic

As previously indicated (Chapter Three), arsenopyrite was not observed in massive barite of the barite cap. At Rosebery the absence of arsenopyrite in barite is a feature of the baritic ore lens (Braithwaite, 1969). The As content of the Hellyer barites is low, ranging between 21 ppm and 49 ppm (refer section 4.4.1). The absence of arsenopyrite in massive barite can be ascribed to the differing redox conditions under which the two minerals are stable (Huston, 1988). Arsenopyrite is not stable under the oxidising conditions required to precipitate barite but is, however, stable where reducing conditions prevail (Henrich and Eadington, 1986). Therefore due to the stability of barite and arsenopyrite, barite mineralisation cannot contain

significant arsenopyrite and consequently As must be present in either tetrahedrite-tennantite or in As bearing pyrite (Huston, 1988).

In the GSP, arsenic impurities in framboidal pyrite were as high as 2.8%. Pyrite euhedras contained low levels of As. Framboids appear to be relatively depleted with respect to As in the cores and enriched in As in the rims (Appendix 3.5). The barite cap shows framboidal pyrite to contain up to 4.4% As at the cores. Pyrite euhedras in the barite cap also display elevated levels of As. The average content of As in pyrite for the barite cap is 1.5%, whilst the average for the GSP is 0.8%. Arsenic in the GSP occurs mostly in arsenopyrite (Appendix 3.6), whereas in the barite cap it is present in pyrite. Arsenopyrite from the GSP averages 43.3% As.

#### 4.9 Mineralogic residence of silver

Microprobe analyses of galena (samples RS42, RS106, RS83 and RS75; Appendix 3.7) show galena to be devoid of Ag in both the barite cap and GSP. Tetrahedrite were found to contain 2 to 3% Ag with approximately 20% Sb and 30% Cu (Appendix 3.8). The limited number of analyses would confirm the majority of Ag resides in tetrahedrite, as suggested by Ramsden et al. (1990).

The silver content of pyrite in the GSP reaches a maximum of 0.25% and is correlated with high As and Au levels. In most cases the Ag content of pyrite in the GSP was low. Unlike the As and Au, high Ag values were measured in both framboidal and euhedral pyrite. High Ag values commonly, but not always, corresponded to elevated As levels. In the barite cap, the content of Ag in pyrite is commonly low.

Sphalerite from the GSP shows low levels of Ag. Sphalerite in the barite cap however, displayed high Ag contents (up to 2390 ppm, averaging 320 ppm). In the latter where Ag was present, Hg was also present in sphalerite.

## 4.10 Mineralogic Residence of Gold

The baritic and siliceous caps are enriched in Au (McArthur 1986). Previously reported occurrences of gold at Hellyer suggest the gold in the GSP resides in pyrite and arsenopyrite (Gemmell, 1990; Ramsden et al., 1990). No free grains of electrum have been observed in the GSP. In the barite cap, gold may occur either as free electrum grains or as low levels of Au in pyrite (McArthur, 1986).

## 4.10.1 Electrum

Electrum is relatively rare at Hellyer, with only six grains previously identified (Gemmell, 1990). This study has further identified another 19 grains of electrum (Table 4.1).

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| Grain No. | Sample         | **Size (µ) | Fineness | Description  |
|-----------|----------------|------------|----------|--|
|           |                |            |          |  |
| 1         | RS001          | 12.5       | 558*     | Electrum grain at the edge of recrystallised pyrite, in the massive      |
|           |                |            |          | barite zone. The grain is an irregular shape, with high reflectivity.    |
| 2         | RS001          | 9.5        | 808      | Electrum hosted at the contact between two euhedral pyrite grains,       |
|           |                |            |          | in a fracture. Occurs with chalcopyrite as an infilling of the fracture. |
| 3         | RS001          | 5.5        | 796      | Electrum grain hosted in chalcopyrite inbetween two pyrite euhedras,     |
|           |                |            |          | at the grain boundaries. Occurs near the contact between                 |
|           |                |            |          | massive sulphide mineralisation/baritic zone.                            |
| 4         | RS001          | 4.5        | 796      | Electrum hosted in euhedral pyrite, not associated with fractures        |
|           |                |            |          | or chalcopyrite. Occurs near the contact between massive sulphide        |
|           |                |            |          | and the baritic zone.  |
| 5         | RS001          | 4.5        | 901      | Electrum hosted in chalcopyrite against a euhedral pyrite grain. The     |
|           |                |            |          | chalcopyrite has infilled a fracture in the pyrite grain. Massive        |
|           |                |            |          | sulphide zone, close to the baritic contact.                             |
| 6         | RS001          | 10.5       | 785      | Elongate electrum in a fracture through a euhedral pyrite grain.         |
|           |                |            |          | Proximal to the massive sulphide/baritic contact.                        |
| 7         | RS001          | 2          | NA       | Continuation of the same fracture as in (6). A small electrum bleb       |
|           |                |            |          | isolated in a fracture cross cutting pyrite. Massive sulphide zone.      |
| 8         | RS001          | 3          | 902      | Small bleb of electrum occurring with chalcopyrite in a large            |
|           |                |            |          | recrystallised pyrite grain. Massive sulphide zone                       |
| 9         | RS001          | 2          | 791      | Small electrum grain occurring in pyrite in association with             |
|           | -              | ~          |          | chalcopyrite. Not associated with fractures. Massive sulphide zone.      |
| 10        | RS001          | 6          | 785*     | Kounded electrum grain, occuring in a cavity in chalcopyrite,            |
|           | Desse          | 05         | 000+     | nosted in a large irregular recrystallised pyrite grain.                 |
| 11        | RS001          | 25         | 808*     | Large rounded electrum grain, nosted in chalcopyrite, amongst            |
|           |                |            |          | ractured recrystallised pyrite. Note that the AU is not in contact       |
|           | D COOT         | -          | 000      | with the pyrite. Massive sulphide zone, close to barite contact.         |
| 12        | K2001          | /          | 902      | counded electrum grain nosice in pyrite, not associated with fractures   |
|           |                |            |          | or charcopyrite, occurring at the margin of the pyrite grain. Massive    |
| 10        | DCOOT          | 20         | 800      | Sulphice 2006.   |
| 13        | K2001          | 20         | 009      | Large rounded electrum grain located on the edge of a recrystallised     |
| 14        | D C001         | 2          | NIA      | Council at pyrite grain, with charcopyrite. Massive sulpride Zone.       |
| 14        | K2001          | 2          | MА       | large purite grains Massive sulphide zone/baritic zone                   |
| 15        | <b>P</b> \$001 | 65         | 172      | Flongate gold arsin occurring interstitual between two larger purities   |
| 15        | V2001          | 0.5        | 422      | with barite having a high reflectivity. Contest zone                     |
| 16        | 0001           | 5          | 797      | Isolated rounded electrum grain hosted in purity provimal to cold        |
| 10        | 10057          | 5          | /0/      | grain (15) Exhibits high reflectivity Sulphide/beritic contact           |
| 17        | 0001           | 6          | 804      | Flattrum with chalconverte, as an inclusion in subsided avoits           |
| 1         | 10067          | 0          | 074      | Massive subbide zone   |
| 10        | D 0001         | 4          | NT A     | Pleatrum in a fracture in purity not in contact with shelconverts        |
| 18        | 10067          | 4          | NA       | Massive subhide zone   |
| 10        | DCOF           | 6          | NT A     | Pressive sulpline 2010.  |
| 19        | 1000           | 0          | NA       | Electron grain nosied in chalcopyrite associated with gatena and         |
| 1         |                |            |          |  |

\* average fineness: [1000\*Au (wt%)]/[Au(wt%)+Ag(wt%)]

NA = not analysed

\*\*size = average grainsize: (longest dimension+shortest dimension)/2

 Table 4.1:
 Electrum grain descriptions

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### Occurrence of Electrum

Eighteen of the nineteen grains observed occur on the sharp contact between the barite and massive sulphide mineralisation at 10670 north (RS001). Electrum is observed to have three broad occurrences; in the barite horizon associated with pyrite and galena; at the massive sulphide contact, either nested in fractures in pyrite with or without chalcopyrite; or as isolated inclusions in pyrite. The grain size of electrum ranges between 2 and 25 microns, averaging 7.5 microns, however the electrum grains are often irregular in shape (Figure 4.6).

## Electrum Composition

Microprobe analyses of electrum grains reveal that they are composed of Au, Ag, and Hg. Analytical data is given Appendix 3.9. The total gold fineness (1000Au/Au+Ag) ranges between 422 to 902, with an average of 758 (Figure 4.7). Mercury content varied between the detection limit and 9.8%. The results are divided into two groups, corresponding to grains hosted within baritic mineralisation and those associated with massive sulphide mineralisation.

#### Baritic associated electrum

Gold occurring in the baritic horizon has a low fineness, with significantly elevated Hg contents (Appendix 3.9). A traverse across a grain of electrum (Figure 4.8 a, b, c) shows the core of the electrum grain to be high in Au (corresponding to higher fineness), with depleted Au rims (lower fineness) and enrichment in Hg. Silver-rich rims have been observed in a number of other VHMS deposits (Huston, 1988; Huston et al., in press).

#### Massive sulphide associated electrum

Most electrum grains occur in the massive sulphide proximal to the contact with the baritic horizon. Characteristically, these electrum grains display high Au and low Ag and Hg contents. The grainsize distribution is irregular. Two traverses across different grains (11 and 13; Table 4.1) indicate relatively constant high fineness and low Hg content (Figures, 4.9 a, b, c, d).

## 4.10.2 Gold content of Pyrite

Pyrites from three GSP samples (RS57, RS42, RS106) and two barite cap samples (RS83, RS75) were analysed (Appendix 3.5). In the GSP, framboids and spongy pyrite contain the highest levels of gold, up to 0.46%. No zonation of Au from rim to core of the framboids was apparent. Similarly, framboidal pyrites in the barite cap contain the only detectable levels of Au, which are generally low. Framboidal pyrites of the GSP show higher levels of Au than pyrite the barite cap. Euhedral pyrite was found to contain no significant Au in either the barite cap or the GSP. Colloform pyrites were not extensively examined and may contain significant levels of Au (D. Huston pers. comm.). Recent work by Huston (pers. comm.) has correlated high gold in colloform pyrite with elevated As levels at other VHMS deposits.



Figure 4.6: Electrum Grain Size Distribution

Figure 4.7: Electrum Fineness Distribution







Figure 4.8: Core-rim-core analytical traverse across electrum grain 1 (Sample RS001). A) Location of traverse and sample points on the electrum grain. The grain shows high reflectivity and is located along the boundary between pyrite and barite (dark grey). B) Distribution of the fineness values. C) Distribution of Hg (wt %) concentrations. The fineness values are higher and Hg values higher near the cores compared to the rims.



## 4.10.3. Gold content of arsenopyrite

Arsenopyrite from 2 samples of GSP (RS42, RS106) were analysed (Appendix 3.6). Significant levels of Au, up to 0.1%, were found in a number of analyses. No zonation was noted.

## 4.11 Discussion

### ¥ 4.11.1 Barite Solubility and Precipitation

The solubility of pure barite is low (Deer et al., 1962) and barites containing Sr show incongurent solubility (Blount, 1977). Trace contents of elements can modify the crystallisation of barite from solution, inducing changes in either crystal nucleation, growth and crystal morphology (Fernandez-Diaz et al., 1990). As barite is a sulphate mineral, it is only stable near or above the boundary between oxidised and reduced sulphur species (Ohmoto et al., 1983). Consequently, barite may be a dominant phase in the upper regions of VHMS systems where oxidising conditions prevail (Large, 1977). The low solubility of barite precludes effective transport of barium in large quantities in oxidised fluids. Therefore the deposition of barite results from the mixing of two different solutions. At Hellyer these are interpreted to be upwelling relatively reduced hydrothermal fluids which carry Ba<sup>2+</sup> and Cambrian seawater, which contains  $SO_4^{2-}$ . Oxygenated seawater may either supply  $SO_4^{2-}$ directly, or oxidise H2S in the hydrothermal fluid to  $SO_4^{2-}$ . Estimated temperatures of barite precipitation is between 100°C to 250°C, where barite is stable at high oxygen fugacity ( $fO_2$ ) (Green et al., 1981).

#### 4.11.2 Silica Solubility

Williams and Crear (1985) and Williams et al. (1985) review controls and mechanisms of silica solubility and precipitation. The interpretation of different forms of silica can establish the physiochemical environment of precipitation (Duhig, 1991).

Silica solubility depends on temperature, surface area, pH, pressure and dissolved ionic species. The predominant controls are however, temperature and surface area. Silica will only precipitate from a solution containing pure dissolved silica if the solution is supersaturated with respect to silica. The kinetics of different silica polymorph mechanisms, favour amorphous silica (opal-A) precipitation at temperatures less than 300°C. Duhig (1991) concluded microcrystalline chert was the result of the inversion of amorphous silica (opal-A) to more stable polymorphs. Co-exisitng megaquartz and microcrystalline quartz may be explained in terms of surface area and timing. Amorphous silica has much greater surface area and it transforms more easily to stable polymorphs (Williams and Crear, 1985; Williams et al., 1985). In the GSP there is no indication of pre-exisitng amorphous silica in

the form of chalcedonic spherules, however observed microcrystalline chert may represent an inverted phase of amorphous silica.

# 4.11.3 Gold depositional and transport mechanisms

In the upper regions of VHMS deposits, the transportation of gold is as thiocomplex  $(Au(HS)_2)$ , due to low temperatures (<300°C), high  $aH_2S$ , neutral to alkaline pH (Huston and Large, 1989). In these areas oxygenated seawater, mixing with upwelling hydrothermal fluids causes gold deposition (Huston et al., in press). This is confirmed by the presence of the majority of electrum grains, observed in this study, in close proximity (±3cm) to a sharp contact between the massive sulphide and barite cap (RS001). The boundary between the massive sulphide and baritic cap (RS001). The boundary between the massive sulphide and barite cap (RS001). The boundary between the massive sulphide and barite cap (RS001). The sundary between the massive sulphide and barite cap (RS001). This is consistent with work by Huston and Zaw (1988) who report a large variation in fineness from massive sulphide deposits. Larger electrum grain sizes, their rounded nature and occurrence with chalcopyrite (for example grain 11) would indicate the occurrence of electrum to be the result of remobilised Au.

Huston et al. (in press) proposes that higher oxygen fugacity  $(fO_2)$  conditions, due to oxygenated seawater mixing with upwelling hydrothermal solutions, result in electrum and pyrite being the major gold repositories. Gold and silver precipitate as electrum due to dilution and/or oxidation of H<sub>2</sub>S, caused by the mixing of seawater with hydrothermal fluids. Silver also precipitates in electrum owing to the rapid decrease in temperature and increase in pH, associated with mixing of seawater.

Previous low level gold analyses of the GSP found arsenopyrite to contain significantly more gold than pyrite (Gemmell, 1990). In the present study, a major limitation was the high detection limits (of approximately 600 ppm) of Au. As a consequence, low levels of gold were not determined, with only anomalously high gold contents documented. The somewhat anomalous values however, confirm Au to reside in pyrite and arsenopyrite in the silica cap. The precipitation of gold in pyrite as evidenced in the GSP, may occur by co-precipitation of submicroscopic gold grains caused by decreasing  $aH_2S$  in the micro-environment surrounding a growing pyrite grain. Graham et al. (1989) suggests arsenopyrite concentrates Au from the hydrothermal fluid in preference to pyrite.

## 4.11 Conclusions

Barite precipitation, which occurred when oxidised seawater mixed with upwelling hydrothermal fluids, shows Ba-Sr substitution which is the result of partitioning of Sr from the hydrothermal fluid into barite during deposition. The GSP is a ferruginous chert of hydrothermal origin, which precipitated as amorphous silica and reverted to microcrystalline

quartz. As indicated by the presence of arsenopyrite and pyrite, and the absence of hematite, GSP precipitation occurs under more reducing conditions than that of barite. Low iron content of sphalerite, in both the barite cap and GSP would however indicate a relatively oxygenated hydrothermal fluid-seawater mixing environment. The major repositories of precious metals varies between the two caps, reflecting the differing physiochemical conditions under which each cap formed.

# Chapter Five Metal Zonation

#### 5.1 Introduction

Textural and mineralogical associations reflect physiochemical conditions under which mineral phases formed (Leblanc and Billaud, 1990). Metal zonation is an analogue of mineralogic zonation, which can be used to study spatial element affinities on a broader scale. In a hydrothermal system, the zonation of metals are indicative of changes in temperature, solubility and/or chemistry of the ore fluids in space and time (Large, 1977). If metal and mineral associations are recognised, for example the concentration of barium is dominantly controlled by the presence or absence of barite, then metal zonation can be used to simultaneously infer a mineralogical zonation.

# 5.1.1 Aims

This chapter investigates metal zonation within the barite cap and GSP. The objectives are to correlate metal zonation in the cap zones with zonation in the underlying massive sulphide and stringer system. In addition, the depositional sites of the cap zones and their spatial affinity to the hottest parts of the hydrothermal system will be considered. Metal zonation in the cap zones extends previously developed mineralogical associations (refer Chapter 4) and is based on Aberfoyles' 1 to 2 metre diamond drill core assay results.

#### 5.1.2 Metal Zonation in VHMS Deposits

There have been many contributions to zonational models of VHMS systems (for example: Large, 1977; Franklin et al., 1981; Eldridge, 1983; Pisutha-Arnond and Ohmoto, 1983; Huston and Large, 1988). Polymetallic mineralisation at Hellyer shows characteristic VHMS style metal zonation (McArthur, 1990). The Hellyer deposit exhibits a central Fe, Cu rich core, overlying the footwall stringer system (Gemmell and Large, in press). Within the central core chalcopyrite and pyrite dominate the mineralogy (Gemmell, 1988; McArthur, 1989). The upper and outer regions of the massive sulphide body are enriched in Pb, Zn, Ag, Au , As and Ba (McArthur, 1990). These regions of the Hellyer deposit correspond to hangingwall enriched zones, where metals leached from the footwall, were deposited . The process of continual leaching and re-deposition during the life of the hydrothermal system is termed a zone refining process (Pisutha-Arnond and Ohmoto, 1983; Large, 1991). The following conceptual mineral zonation from footwall to hangingwall in VHMS deposits has been postulated (Eldridge et al., 1983):

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footwall hangingwall Fe --> Cu (Au) --> Cu --> Pb, Zn --> Au, Ag -->Ba ----->> decreasing temperature

As a consequence, the upper regions of VHMS deposits often display enrichment in barium and precious metals.

## 5.2 Lateral Zonation

Plan projections of the cap zones were derived from the Hellyer DATAMINE database using linear block kriging (refer McArthur and Kuipers, 1990). Due to the discontinuity and variable thickness of the GSP (less than 6 metres), the GSP was combined with the results for the barite cap. Plan projections therefore represent metal zonation in both the barite cap and GSP. The results of the lateral zonation studies are presented as five percentile levels and each percentile level records twenty percent of the total range of assay values. Plan projections of lateral zonation, based upon 1990 ore reserve data, vary slightly from the cap outline as defined in Chapter Two. The plan projections of lateral zonation for Ba, Fe, Pb, Zn, Au, Ag, As, Cu in the cap zones are schematically presented in Figures 5.1 to 5.8.

*Barium* (Figure 5.1) is concentrated on 10750 N on the eastern ore block and 10710 N on the western ore block. This concentration corresponds to the area above the central feeder system. A second zone of Ba enrichment occurs at 10890 N on the eastern ore block. This Ba enrichment overlays the northern portion of the central feeder. The southern and northern feeders are not defined by Ba zonation.

*Pyrite* (Figure 5.2) or calculated Fe concentrations show broad highs that correlate well with the location of the central feeder system, and occur on 10800 N on the eastern ore block. Elsewhere, Fe contents are relatively depleted.

Lead and zinc (Figures 5.3 and 5.4 respectively) show distinct zonal similarities on the east and west ore blocks. High Pb and Zn concentrations occur at 10800 N and 11010 N. The highest concentrations of Pb and Zn are best developed on the eastern ore block, concurrent with the northern portion of the central feeder and the northern feeder. Zinc, however, differs from lead at 10470 N where a small high, coinciding with the location of the southern feeder, is present.

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*Gold* enrichment (Figure 5.5) occurs at 10850 N on the eastern ore block with relatively high levels of Au overlying the central feeder. Low levels of Au exist over the northern and southern feeder regions.

*Silver* zonation (Figure 5.6) is similar to that of Pb and Zn, in that zones with high Ag concentrations outline the central feeder on the eastern ore block. In addition, high Ag values also outline the location of the northern feeder and to a lesser extent the southern feeder.

*Copper* zonation (Figure 5.7) distinctly outlines the southern feeder. High Cu values occur over the northern and northern part of the central feeder systems. The southern part of the central feeder is depleted however, as is the southern end of the cap zone.

*Arsenic* distribution (Figure 5.8) shows a high over the central feeder on the eastern ore block. Arsenic is significantly less developed on the eastern ore block. An As high is centred on 10630 N, and corresponds to an isolated occurrence of the GSP.

#### 5.2.1 Interpretation

The contribution of either the barite cap or GSP to the observed metal zonation patterns only is inferred from qualitative and quantitative work on mineral associations (refer Chapter Three and Four). The dominant As distribution is derived largely from the GSP, and in particular, the As high on the eastern ore block (Figure 5.8) corresponds definitively to the GSP. Gold in the GSP is contained either in pyrite or arsenopyrite (refer Chapter Four) and a positive correlation between As, Au and Fe is evident, particularly on the eastern ore block in the vicinity of the central feeder. Since As occurs within pyrite in the barite cap, this trend is enhanced. Ag as tetrahedrite-tennantite series of minerals, displays a distinct zonal distribution around the central feeder. A similarity in solubility and temperature for Pb and Zn (Huston and Large, 1987) is indicated by their close zonal affinities, and may be attributed to similarities is transport and deposition systematics.

The enrichment of metals in the cap zones is best developed over the central feeder on the eastern ore block. The northern feeder is outlined by Pb, Zn, Cu, Ag, whilst the southern feeder is only outlined by Zn and Cu, and to a lesser extent Ag. Zones of Ba enrichment correlate with regions where the barite cap attains its greatest thickness (Figure 2.6), and with zones of Pb, Zn, Fe, As, Ag, Au enrichment.

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As stated previously (Chapter Two) the trend of the barite cap and GSP parallels with the alignment of the feeder systems (Figure 2.5). The oblique intersection of this northeast-southwest structure with the Jack Fault, corresponds to the central feeder and is the location where the caps show maximum thickness and enrichment in base and precious metals. As a result, enrichment of the cap zones would appear structurally controlled, and correspond to the hottest regions of the hydrothermal system. Thus they indicate the sites of maximum fluid discharge.

## 5.3 Vertical Zonation

In order to enhance zonation studies and to present a three dimensional perspective, zonation studies on Sections 10630 N and 10790 N were completed (Figures 5.9 and 5.10 respectively). The contoured sections record vertical metal associations within and between the barite cap and GSP. Metal zonation contours through the cap zones for Sections 10630 N and 10790 N were hand contoured from assay data.

The distribution of barium throughout the underlying massive sulphide was also examined. The percentile levels used in the construction of Ba contours were derived from the spectrum of assay results of 10630 N and 10790 N.

### 5.3.1 Section 10630 N

From Section 10630 N (Figure 5.9 a, b, c, d, e, f, g) it can be seen that the GSP contains enriched levels of Au and As. A central core within the GSP is enriched in Ag, Zn, Pb and to a lesser extent Cu. Barium levels are low in the GSP.

As expected the barite cap is enriched with respect to Ba, to levels greater than 27.3 weight % Ba). Au values are elevated along the barite/massive sulphide contact and decrease with increasing distance distance from the contact. In stratigraphically higher regions of the barite cap, Au is depleted. A similar pattern exists for Cu, Pb and Zn, which exhibit lower concentrations further from the massive sulphide contact. Zn values are elevated directly over the massive sulphide, proximal to the Jack fault. Ag levels are low throughout the entire barite horizon. As contours for the barite cap record intermediate to low As levels. An elevated As zone in the massive barite corresponds to a zone of massive barite, that contains a significant proportion of GSP (for example sample RS12).

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#### 5.3.2 Section 10790 North

The GSP has a low concentration of Ba and Cu, and is elevated in As, Au, Ag, Zn and Pb (Figure 5.10 a, b, c, d, e, f, g). The barite cap exhibits a variation in Ba levels and an enrichment of Au, Ag, and to a lesser extent As. The zonation of Pb and Zn are similar, being anomalously high near the barite cap/massive sulphide contact, and grade to relatively lower values near the HVS/barite cap contact. Cu is enriched proximal to the massive barite cap/sulphide contact and relatively depleted in the upper portions of the barite cap. The GSP and barite caps are not nearly so identifiable by their metal zonation patterns as previously observed in Section 10630 N.

## 5.3.3 Barium Zonation In The Massive Sulphide

The genetic association of the cap zones to underlying massive sulphide mineralisation is considered in the schematic diagrams (Figure 5.11 and 5.12) of Ba distribution through the massive sulphides, barite cap and GSP.

## Section 10630 N

Section 10630 N through the western ore block, displays a distinct Ba zonation proximal to the Jack Fault (Figure 5.11). Ba shows a plume style enrichment, broadening upwards and outwards toward the top of the mound. Zones of Ba enrichment at the base of the sulphide mound do not appear to be associated with elevated Ba levels proximal to the Jack Fault. Intermediate Ba levels are associated with the Gillian Fault, but broaden to a thin barite cap on the western flank of the massive sulphide. Remainder massive sulphides show anomalously low levels of Ba.

#### Section 10790 N

Section 10790 N (Figure 5.12) shows similar metal zonation patterns to that of Section 10630 N. A similar plume of Ba enrichment is localised against the Jack Fault. In the lower eastern portions of the sulphide mound, anomalous barium highs occur. These zones appear quite separate to the observed zonation proximal to the Jack Fault and are thought to be the result of barite veining in the massive sulphide. The central portions of the massive sulphides are anomalously low in Ba.

## 5.3.4 Interpretation

The metal zonation patterns in the cap zones of Section 10630 N are quite different from those in Section 10790 N. The lateral distributions of metals (section 5.1) showed the central feeder on the eastern ore block to be a locus of hydrothermal activity, due to high base and

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Figure 5.11: Section 10630 N showing barium zonation through massive sulphides and cap zones. When movement of the Jack Fault is restored the section approximates that of Section 10790 N. Assay data from Aberfoyle Resources Limited.

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Figure 5.12: Section 10790 N showing barium zonation through massive sulphides and cap zones. When movement of the Jack Fault is restored the section approximates that of Section 10630 N. Assay data from Aberfoyle Resources Limited.

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precious metal concentrations in the cap zones. It is postulated that the distribution of metals in the cap zones, particularly on Section 10790 N is the result of hydrothermal redistribution of metals from the underlying sulphides to the cap zones. Petrological evidence (Chapter Three) suggests that many sulphide phases in the barite cap and GSP are later, and consequently the products of later hydrothermal activity during the same mineralising phase. The complex metal zonation patterns and the interfingering nature of the barite cap and GSP on Section 10790 would support this. Section 10630 N also occurs within the central feeder region. The location of this Section on the western ore block, indicates it to that it is spatially removed from regions of intense hydrothermal activity.

In general the metal distributions show the GSP to be enriched in Au, Ag, Pb, As, Zn and to a lesser extent Cu. The barite cap is locally enriched in Au, Ag, Pb and Zn proximal to the massive sulphide contact and the Jack Fault. The metal distributions may be interpreted as either the result of the passage of hydrothermal fluids through the barite cap, or as a consequence of dynamic chemical transition from the massive sulphide regime (reducing) to the barite cap regime (oxidising). Alternatively, the zonation patterns may be an expression of both. A low Ba content of the GSP would suggest a similar transition of Ba from the barite cap (oxidising) to the GSP (reducing). In the upper portions of the barite cap, the development of metals other than Ba is poor.

When Devonian movement on the Jack Fault is restored Sections 10630 N and 10790 N approximately align. Ba contours for the massive sulphide and cap zones indicate a plume of Ba developed around the Jack Fault. The plume appears to broaden toward the upper portions of the massive sulphides, attaining maximum development in the cap zones. The distribution of Ba as indicated from Ba zonation may be the result of an increased component of seawater and hydrothermal fluid interaction toward the upper regions of the sulphide mound. The distinctive zonation around the Jack fault on Sections 10630 N and 10790 N are suggestive of fluid pathways for the precipitation of barium due to the cooling of upwelling hydrothermal solutions. Cooling hydrothermal solutions, appear to have moved upwards and outwards from what is now the Jack fault. To a lesser extent this is true for smaller faults such as the Gillian fault. Evidence of similar Ba zonation has been observed in underground exposures (R.C. Downs pers. comm.). Barium highs in the lower eastern portions of Sections 10630 N and 10790 N appear to be isolated. These anomalous Ba highs may be related to baritic veining in the massive sulphides, and could be the result of late stage open space fill.

Barium zonation through the massive sulphide is therefore centred on the hottest parts of the feeder system. The observed plume of Ba within the massive sulphide may be either the result of the central feeder, which was later transected by the Devonian Jack Fault, or the result of a pre-existing structure which acted as a conduit for hydrothermal solutions passing to the sea floor.

#### 5.4 Hangingwall Barium Zonation

Hangingwall basalt shows a plume enriched in Ba (Jack, 1989),. The alteration zone is localised along the plane of the Jack Fault in the central area above the Hellyer deposit. This zone correlates with those areas of maximum thickness of the orebody and cap zones, as well as to zones of Ba enrichment in the barite cap. Jack (1990) concluded that the deposition of the overlying basalts occurred during the Cambrian, prior to the termination of the hydrothermal system (Jack, 1990). Jack (1989;1990) and McArthur (1990) concluded that the baritic alteration of overlying basalts is the result of the waning hydrothermal system .

## 5.5 Discussion

An important assumption, which has previously been addressed, is the later remobilisation and recrystallisation of minerals due to metamorphism. Gemmell (1989) suggested that low grade metamorphism and structural deformation has preserved the hydrothermal effect associated with the mineralising system. From this, it has been assumed that the distribution of metals is the direct result of the hydrothermal system.

Hydrothermal overprinting of the barite cap and GSP causes difficulty in the interpreting of metal zonation patterns. Textural evidence (refer Chapter Three) suggests that many of the sulphide phases are the result of hydrothermal activity, which post dates the deposition of both the barite cap and GSP. In particular much of the sphalerite, galena, pyrite, tetrahedrite-tennantite and chalcopyrite are thought to be the products of late stage hydrothermal activity. Assuming this to be the case, then zonal distribution of Zn, Pb, Fe, Ag, Au and Cu will largely represent those sites where hydrothermal overprinting of the cap zones has occurred. From lateral zonation studies the effects of hydrothermal overprinting were best developed over the central feeder system, proximal to the intersection of the feeder trend and Jack Fault. The somewhat irregular distribution of metals through the interfingering cap zones on Section 10790 N would support this. The zone refining model of Eldridge et al (1983) would suggest that metals from underlying massive sulphides have redistributed into the upper portions of the mound, including the barite cap and GSP. Evidence of Au, Ag, Pb, Zn

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to be the most affected. The zone refining process is closely linked to growth of the mound (Lyddon, 1988). It is envisaged that as the lower portions of the cap zones become overprinted by sulphide phases, the caps zones effectively become part of the underlying massive sulphide. In a similar style, the barite cap and GSP are thought to be replaced. The GSP and barite caps are dominated by a porous open framework array, indicating that open space precipitation is likely to occur in the upper regions of the cap zones. This feature is present on Section 10630 N, where the upper portions of the barite cap and GSP may therefore be predominantly where hydrothermal fluids were in direct contact with the seawater. The deposition of barite or silica on the outer surface of the mound may have assisted growth (Ohmoto et al, 1983), with barite and silica continually being replaced by sulphides lower in the cap zones during mound growth. The growth of the sulphide mound and caps zones is envisaged to have occurred in a similar fashion.

The waning period of the hydrothermal system is indicated by the presence of late barite veins in the massive sulphide and as the hangingwall alteration zone. The plume of barium enrichment, observed in the massive sulphide and localised against the Jack Fault and central feeder system, would indicate the sites of the likely passage of mineralising hydrothermal fluids up to the sea floor.

## 5.6 Conclusion

Previous studies of metal zonation in the Hellyer orebody have revealed a distinct spatial relation between the core of the feeder system and metal distribution within the ore (McArthur and Dronseika, 1990). Metal zonation studies for the barite cap and GSP would confirm this. These studies also suggest that the barite cap and GSP are due to progressive replacement associated with mound growth.

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# Chapter Six Sulphur Isotope Geochemistry

## 6.1 Introduction

A sulphur isotope study was carried out to examine the sulphur isotopic compositions of sulphate and sulphide species of the barite cap and GSP. Sulphur isotopes can be used to constrain the physiochemical conditions and/or mechanisms of mineral precipitation, providing information on the sources of sulphur and temperatures of formation (Ohmoto and Rye, 1979). Examination of the spatial distribution of sulphur isotopes values may provide valuable information on the evolution of mineralising fluids (Ohmoto, 1986).

Variations in sulphur isotopic compositions of sulphide and sulphate species is an indication of variations in the source of sulphur. In hydrothermal systems there exist three main contributors to the isotopic signature; seawater, magmatic and biogenic sulphur (Ohmoto, 1986). Magmatic sulphur may result from direct contribution by the hydrothermal fluid or the leaching of sulphur from rocks.

Sulphur isotopic analyses of 100 mineral separates from the barite cap and GSP are presented. Samples were predominantly barite and pyrite. Barite separates numbered forty six and sulphide species, including pyrite, sphalerite and galena formed the remainder.

The equilibrium fractionation of sulphur, between co-existing sulphide minerals, can be used as a geothermometer. Difficulties however, in proving co-precipitation under equilibrium conditions, and in obtaining pure mineral separates, limit the application of sulphur isotopes as indicators of temperatures of formation. Isotopic fractionation factors of sulphate species are sensitive to temperature (Ohmoto, 1986). The observed fractionation between sulphates and sulphides would not be equivalent to the equilibration values at the time of deposition due to temperature induced modification. Consequently sulphate-sulphide pairs are not suitable geothermometers (Ohmoto, 1986). For this reason, no attempt was made to derive temperatures from the observed fractionation of co-existing mineral pairs.

#### 6.2 Analytical Procedure

The sulphur isotopic compositions ( $\delta^{34}$ S) were determined using standard analytical techniques (refer to Ohmoto and Rye, 1979) at the Central Science Laboratory of the

University of Tasmania. A number of duplicate samples were analysed, with the result that the  $\delta^{34}$ S values are accurate to  $\pm 0.1$  per mil and  $\pm 1.0$  per mil for sulphide and sulphate species respectively. All  $\delta^{34}$ S values are quoted relative to the CDT standard.

Separates for isotopic analyses were either drilled or hand picked. Drilled samples were accompanied by polished thin sections for purity checks. Minor impurities were caused by the fine grained nature and often complex intergrowths of sulphide and/or sulphate phases.

### 6.3 Results

#### 6.3.1 Isotope Distributions

The sulphur isotope distributions for the barite cap, GSP and HVS are shown in Figure 6.1, 6.2 and 6.3 respectively. Isotopic values and sample locations are tabulated in Appendix 4.1, 4.2 and 4.3 respectively.

Analysis of sulphate samples (barite) from the barite cap show isotopic compositions which range from +26.0 to +44.9 per mil (mean of 39.6 per mil). Sulphide separates range between +6.4 to +16.1 per mil for pyrite (mean of +9.7 per mil), +6.1 to +8.2 per mil for sphalerite (mean of +7.5 per mil) and 6.4 to 7.1 per mil for galena (mean of +6.8 per mil).

The  $\delta^{34}$ S values for barite in the GSP are between +38.2 and +49.6 per mil (mean of 43.7 per mil). Pyrite  $\delta^{34}$ S values show a wide range from +8.3 per mil to +36.9 per mil (mean of +14.5 per mil). Sphalerite  $\delta^{34}$ S values show a narrow range of +6.0 to +10.4 per mil (mean of +7.7 per mil). A single determination for galena shows a  $\delta^{34}$ S value of +5.5 per mil.

Six  $\delta^{34}$ S values were determined for barite in the HVS (Figure 6.3). The range of  $\delta^{34}$ S was from +36.5 to +41.8 per mil, with a mean of +40.3 per mil.

Two isotopic analyses from barite veining in outcropping Pillow Lava Sequence (PLS) were determined. The  $\delta^{34}$ S values were +29.6 and +28.3 per mil.

## 6.3.2 Isotopic Variation

The expected order of  $\delta^{34}$ S fractionation under equilibrium conditions between coprecipitating sulphide phases is :



Figure 6.2 : Siliceous Cap - Sulphur Isotope Distribution







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 $\delta^{34}S_{pyrite} > \delta^{34}S_{sphalerite} > \delta^{34}S_{chalcopyrite} > \delta^{34}S_{galena}$  (Bachinski, 1969) This order of fractionation is shown by the sulphide phases of the Hellyer baritic and siliceous caps. Sulphates displays heavy  $\delta^{34}S$  values, consistent with a seawater derived  $SO_4^{2-}$  component (Ohmoto, 1988), on the assumption that sulphate minerals inherit the  $\delta^{34}S_{SO4}$  of the fluid from which they precipitate.

Seawater at the time of formation of Hellyer (Middle Cambrian) is assumed to have a  $\delta^{34}$ S value approximating +30 per mil (Claypool et al., 1980). Sulphates in the barite cap have  $\delta^{34}$ S values (mean 39.6 per mil) that are higher than contemporaneous seawater. This would indicate that either the Middle Cambrian  $\delta^{34}$ S<sub>SO4</sub> value was heavier than estimated by Claypool et al. (1980) or that some mechanism of isotopic enrichment operated during deposition. The  $\delta^{34}$ S<sub>SO4</sub> values determined for the barite cap are in agreement with those  $\delta^{34}$ S ratios determined by Jack (1989) for the barite cap . Similarly, the GSP displays heavy  $\delta^{34}$ S<sub>SO4</sub> values of +43.7 per mil. Sulphate isotope variation in the GSP is however narrower and isotopically heavier than that observed in the barite cap. The HVS shows similar  $\delta^{34}$ S<sub>SO4</sub> values to those of the barite cap.

Massive sulphides at Hellyer have a mean sulphur isotopic signature of +7.2 per mil (Jack, 1989), refer Figure 6.4. Pyrite in the barite cap is therefore significantly heavier at +9.7 per mil, whilst the GSP contains even heavier pyrite values of +14.5 per mil. The increase in  $\delta^{34}S_{H2S}$  values from the barite cap to the GSP, parallel the isotopic increase of  $\delta^{34}S_{SO4}$  values from the barite cap to GSP. Sphalerite and galena, in both the barite cap and GSP, have  $\delta^{34}S$  values which approximate those values obtained for the Hellyer massive sulphides, as reported by Jack (1989).

Similarities exist between the  $\delta^{34}$ S ratios of the cap zones, the underlying stringer system, and the massive sulphides (Figure 6.4). Barite, from the barite cap and GSP, show  $\delta^{34}$ S ratios comparable to those of the barite-carbonate veins in the stringer system (with a range of +42.1 to +49.5 per mil). Pyrite  $\delta^{34}$ S values in the barite cap have a comparable isotopic composition to the  $\delta^{34}$ S values values obtained for the quartz-pyrite-carbonate stringer veins (with mean +9.9 per mil). Sphalerite and galena from within the barite cap and GSP show comparable  $\delta^{34}$ S values to the base metal stringer veins (with mean of +6.9 per mil) (Gemmell, 1988; 1989). Syn-mineralising stringer veins at Hellyer are thought to represent channelways for hydrothermal solutions venting to the sea floor (Gemmell and Large, in press). Gemmell and Large (in press) suggested variations in  $\delta^{34}$ S values to be the result of Cambrian seawater sulphate mixing with a hydrothermal fluid which contains a significant

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Figure 6.4: Sulphur isotope data for the Hellyer barite and siliceous caps (this study) and nearby mineralisation. The line shows the Cambrian  $\delta^{34}$ S value of +30 per mill (Clayton et al., 1980).

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proportion of igneous sulphur. The correlation of sulphate and sulphide isotopic ratios throughout the massive sulphides, stringer system and barite cap at Hellyer, is an indication that the GSP and barite caps were deposited from the evolution of the same mineralising fluid which formed the massive sulphides.

## 6.4 Sulphur Sources

Barite horizons of the Miocene Kuroko deposits show  $\delta^{34}$ S values close to that of Miocene seawater (Kusakabe and Chiba, 1983). As the  $\delta^{34}$ S values of the Hellyer cap zones are significantly heavier than the  $\delta^{34}$ S of Cambrian seawater, other sources of sulphur must have contributed to the  $\delta^{34}$ S<sub>SO4</sub> signature.

Metals in VHMS deposits are thought have been derived by leaching from underlying rocks by the convecting hydrothermal fluid system (Franklin et al., 1981). At Hellyer, massive sulphides show isotopically light  $\delta^{34}$ S values at +7.2 per mil, (Figure 6.4) which would indicate a large proportion of sulphur was derived from underlying igneous rocks (Gemmell, 1989; Jack, 1989).

Sulphides and sulphates precipitating a reduced Cambrian seawater are expected to have  $\delta^{34}$ S values between +10 and +30 per mil respectively. The  $\delta^{34}$ S values however, depend on temperature and the amount of reduced sulphur in the fluid (Solomon et al., 1988). Shank et al. (1981) reports that due to the chemical conditions associated with VHMS deposits, isotopic equilibrium between reduced and oxidised species of sulphur in the hydrothermal fluid is likely to be achieved. Assuming isotopic equilibrium, Solomon et al. (1988) suggested sulphate reduction may occur as a Rayleigh fractionation process. A progressive increase in the  $\delta^{34}$ S<sub>804</sub> values would therefore be accompanied by an increase in the  $\delta^{34}$ S<sub>H2S</sub> values. The progressive reduction of seawater, as derived by Rayleigh fractionation is shown Figure 6.5. Heavy  $\delta^{34}$ S values of sulphide and sulphate species in the Hellyer cap zones may therefore be explained by the incomplete reduction of seawater.

At the Rosebery deposit, Solomon et al. (1988) envisaged the formation of barite to be the result of incompletely reduced seawater sulphate becoming more abundant in the hydrothermal fluid and eventually dominant. An increased sulphate content of the hot ore forming solutions mixing with cold seawater results in the precipitation of heavy  $\delta^{34}$ S sulphates (Solomon et al., 1988; Gemmell and Large, in press). If the Rayleigh fractionation

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model of Solomon et al. (1988) is applied, then barite from the barite and GSP caps was derived from fluids containing between 35 and 40 percent reduced aqueous sulphate (Figure 6.5). If sulphide species were deposited from the same incompletely reduced systems as the sulphates, then the expected  $\delta^{34}S_{H2S}$  values for the GSP and barite horizons would be 20 to 15 per mil (Figure 6.5). The  $\delta^{34}S_{pyrite}$  ratios of the barite cap (mean of +9.9 per mil) is significantly less than the aforesaid range, and this may corresponds to an increased proportion of reduced sulphur in the hydrothermal solution.



Figure 6.5: Diagram to show the progressive reduction of seawater of  $\delta^{34}S = +30$  per mil at 300°C. The curves are derived by Rayleigh fractionation using +20 per mil for sulphatesulphide fractionation at 300°C (from Shank et al., 1981). The trend of the Rosebery massive sulphide lode is generated by mixing totally reduced seawater sulphate with rock sulphur. The Rosebery barite lode reflects late-stage circulation when only partial reduction of seawater sulphate takes place (data from Green et al., 1981). The Hellyer barite cap and GSP show precipitation under similar conditions. The variation of  $\delta^{34}S$  values is the result of a fluctuating system and consequently fluctuating proportions of partially reduced seawater and reduced rock sulphur, from the upwelling hydrothermal solutions mixing with seawater (after Solomon et al., 1988): ba =barite, py = pyrite, sl =sphalerite).

The observed differences in  $\delta^{34}$ S values for sulphides and sulphates of the barite and GSP caps is therefore attributed to fluctuations in the amount of reduced sulphate present in the hydrothermal solution at the time of deposition. Sulphur source variations may have been induced by temperature fluctuations and/or a change in oxidation state. Janecky and Shanks (1988) suggest chemically similar solutions can have significantly different  $\delta^{34}$ S values. The

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baritic cap and GSP each represent a marked change in the oxidation state of the immediate ore-forming environment. This change is reflected by their sulphur isotopic compositions, which are significantly different to those of the underlying massive sulphide accumulation. Reducing conditions associated with GSP deposition correlate to a higher proportion of reduced sulphur in the hydrothermal fluid.

The barite veining in the overlying basaltic pillow lavas exposed at the surface have a  $\delta^{34}$ S values of +29.6 and +28.3 per mil, which is very close to Cambrian seawater (+30 per mil). The origin of the sulphur may be considered to have been reduced sulphate derived from Cambrian seawater . As the veining in the pillow lavas occurred during the waning phase of the hydrothermal system (McArthur, 1986; Jack, 1989), then the contribution of reduced sulphur from hydrothermal fluids decreased and barite precipitated directly from seawater sulphate. These values are therefore, the best available estimate of the contemporaneous seawater sulphate value at the time of formation of the Hellyer deposit.

# 6.5 Textural Variations

In the barite cap at Hellyer, the isotopically heaviest pyrites, with  $\delta^{34}S$  of +16.1 and +14.6 per mil are related to banded barite-pyrite (samples RS73 and 450E) veins cross cutting massive barite. The textural affinities of the two minerals suggest barite and pyrite to be contemporaneous. The  $\delta^{34}S_{pyrite}$  values support deposition from a fluid containing a large proportion of incompletely reduced sulphur.

Each generation of barite within the crustiform barite veins has an identical  $\delta^{34}S_{SO4}$  value (sample RS 7377SD5A). These veins transect underlying massive sulphides and show no contrast in  $\delta^{34}S_{SO4}$  values from values obtained for barite in the barite cap. The source of sulphur for crustiform barite veining in massive sulphides, is therefore the same for the barite cap. Similarly, no isotopic variation was observed between tabular barite laths and the granular barite matrix which surrounds them (RS18). For all, the source of sulphur appears to be incompletely reduced Cambrian seawater sulphate.

A single sample from the barite cap (RS008) however, exhibits a low  $\delta^{34}$ S value of +26.0 per mil. This sample contains fragmented tabular laths of barite in a sulphide matrix. Gemmell (1988) determined a similar result of +19.1 per mil for a barite sample from barite-carbonate stringer veins (Gemmell and Large, in press). Formation of the barite from

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reduced seawater sulphate is concurrent with these  $\delta^{34}S_{SO4}$  values.

The HVS immediately overlying the barite cap contains fragmental barite laths incorporated in a fine grained polymict matrix and barite that is a later replacement feature. The  $\delta^{34}$ S values for barite in the HVS are similar to  $\delta^{34}$ S values of the barite cap. The source of sulphur is therefore assumed to be the same. The sulphur isotope ratios of fragmental barite in the HVS supports the interpretation of McArthur and Dronseika (1990), that barite fragments in the HVS were derived from the underlying barite cap. Replacement style barites are also derived from similar sulphur sources.

The range of  $\delta^{34}S_{SO4}$  values for barite in the GSP is narrow. It would therefore appear that  $\delta^{34}S_{SO4}$  ratios are independent of textural variation in the GSP.

Sphalerite and galena in the barite cap and GSP are dominantly paragenetically late minerals (refer Chapter Three) and show isotopic compositions comparable to that of the underlying massive sulphides and base metal stringer veins. As a consequence the hydrothermal fluid which deposited these phases is postulated to have been similar to that which deposited the massive sulphides; containing a significant amount of rock sulphur. Sphalerite and galena in the cap zones may therefore be the result of later hydrothermal alteration of the barite and GSP caps.

Two pyrite samples showed elevated  $\delta^{34}$ S values of +32.2 and +39.6 per mil (samples RS21 and RS42 respectively). These pyrites were colloform in nature and indicative of pyrite deposition in open space. The highly porous nature of the GSP and barite cap have been previously identified (refer Chapter Three). The resulting  $\delta^{34}$ S values are derived from a reduced seawater sulphur source. Solomon et al. (1988) suggested that in a closed system, for example a pore space, a higher the water to rock ratio, results in a greater seawater contribution. The results is higher  $\delta^{34}$ S values for precipitating sulphides.

Kusakabe and Chiba (1983) examined sulphur isotope variations and modes of occurrence within the barite horizons of the Fukazawa deposit, Japan. The authors concluded there to be no systematic variation in the  $\delta^{34}$ S barite values with different modes of occurrence. At Hellyer however, a broad systematic variation of isotope ratios is identified. Textural variations represent changes in the sources of sulphur as a consequence of differences in the

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chemical conditions under which the mineral phases precipitated.

# 6.6 Sulphur Isotope Compositions of Other Deposits

At the Rosebery deposit, Green et al. (1981) and Solomon et al. (1988) propose the barite ore lens to have formed from the partial reduction of Cambrian seawater sulphate under equilibrium conditions. The authors suggest the process of sulphate removal or reduction during circulation, is decreased in efficiency owing to the destruction of reductants. The distribution of  $\delta^{34}$ S values within the Rosebery barite lens is very similar to the Hellyer barite cap  $\delta^{34}$ S ratio distribution (Figure 6.4). Que River  $\delta^{34}$ S values similarly correlate to both sulphate and sulphide  $\delta^{34}$ S values of the Hellyer cap zones (Figure 6.4). Mineralisation at Mt Charter however, shows  $\delta^{34}$ S<sub>SO4</sub> values to be generally high (between +40 and +48 per mil), corresponding to either; the high  $\delta^{34}$ S ratios of the barite cap or the distribution of  $\delta^{34}$ S in the GSP (Figure 6.4).  $\delta^{34}$ S<sub>H2S</sub> values are in good agreement with those ratios obtained for Mt Charter, Rosebery and Que River (Figure 6.4).

# 6.7 Conclusions

The  $\delta^{34}$ S values obtained for barite within the barite cap and GSP are indicative of formation of barite from partially reduced seawater sulphur. Fluctuations of the  $\delta^{34}$ S ratios for barite are attributed to variations in the amount of reduced sulphur in the hydrothermal solutions; where sulphur in the hydrothermal solution is a combination of rock sulphur and seawater sulphur (Janecky and Shanks, 1988). Such variations suggest the majority of pyrite has precipitated from the same incompletely reduced, seawater sulphur solutions. The wide variation of  $\delta^{34}$ S values for pyrite are similarly thought to be the result of a fluctuating sulphur source. Sphalerite and galena, with  $\delta^{34}$ S ratios approximating the underlying massive sulphides, are the result of a hydrothermal overprinting process. The  $\delta^{34}$ S values for sulphide and sulphate species within the barite cap and GSP are similar to those reported the Rosebery deposit (Green et al, 1981), Que River deposit (McGoldrick, 1988) and Mt Charter (Rand, 1988).

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# Chapter Seven Fluid Inclusions

### 7.1 Introduction

A fluid inclusion study was undertaken in order to obtain temperature and salinity data from fluid inclusions for the Hellyer baritic cap. The microcrystalline nature of quartz within the GSP, made it an unsuitable medium for fluid inclusion investigations.

Salinity data was obtained through a procedure in which fluid inclusion were initially frozen. During subsequent heating, the temperature at which the first melting of ice occurred was recorded ( $T_m$ ), and from these temperatures the salinity of the fluid phase was calculated (Roedder, 1981;1984). The components of the fluid phase, were identified from salinity/temperature phase diagrams (reference). The minimum filling temperature or homogenisation temperature ( $T_h$ ), was determined by heating inclusions until all the phases present homogenised.

### 7.2 Methodology

Four samples (RS67, RS86, 450E and 7773SD) of transparent to translucent, coarsely crystalline barite from the barite cap were selected for fluid inclusions studies. Two samples were prepared as doubly polished thin sections and two as cleavage chips.

Microthermometry analysis was performed on a Fluid-Inc.-modified U.S.G.S. gas flow heating/freezing stage in the Geology Department at the University of Tasmania. Calibration tests used synthetic fluid inclusion standards of know composition, to determine the accuracy of melt temperatures (Tm) and temperatures of homogenisation (Th). An accuracy of to  $\pm 0.3^{\circ}$ C for Tm and  $\pm 0.5^{\circ}$ C for Th was estimated. All liquid to vapour ratios were estimated by assuming that fluid inclusions was a spherical body (after Roedder, 1981).

### 7.3 Fluid Inclusion Petrography

A critical issue in any fluid inclusion study is the selection criteria used for identifying primary fluid inclusions. Although growth zoning within the barite samples examined was absent, the criteria used to identify primary fluid inclusions was adapted from Hollister and Crawford (1981), and Roedder (1981; 1984), that is, that fluid inclusions displayed:

- 1) No evidence of necking or leaking.
- 2) Dissociation from obvious secondary fluid inclusion trails.
- 3) An isolated occurrence.

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4) The presence of a semifaceted tabular shape or a crystal negative shape. In this study inclusions, termed "primary", displayed all of the above characteristics. In total four fluid inclusion types were identified.

### Type I

Type I were primary fluid inclusions, with dimensions which ranged from 8 to 12 microns and 3 to 5 microns. These inclusions were tabular in shape (see Figure 7.1a) and, at room temperature contained small percentages of vapour (liquid: vapour  $\leq 1\%$ ). Evidence of CO<sub>2</sub> within the gas phase of the fluid inclusions was evident, as a dark vapour bubble.

### Туре П

Type II fluid inclusions were predominant in the barite samples examined and were secondary in nature. They ranged in size from 8 to 10 microns and 3 to 6 microns, with an observed liquid:vapour ratio of 2% to 4% (Figure 7.1b).

### Туре Ш

Secondary fluid inclusions which commonly formed wide trails of inclusions which were less than 3 microns in size.

### Type IV

Secondary fluid inclusions with large ( $\geq 20$  microns in size), irregular, often angular shapes. They are commonly CO<sub>2</sub> rich inclusions and have large liquid:vapour ratios ( $\geq 8\%$ ).

Microthermometric data was not collected from Type III and Type IV secondary inclusions as they clearly represent entrapment of some later fluid. The origin of Type II inclusions was unclear, as these inclusions displayed many features of primary inclusions. As a result, a number of Type 2 secondary inclusions were also examined. The results of the study are shown in Table 7.1.



| Γ  | Туре | Tm   | Th           | Tclath | Wt. % Na | Tmclath NaCl | d.c. temp |
|----|------|------|--------------|--------|----------|--------------|-----------|
| Γ  |      |      |              |        |          |              |           |
| l  | 1    | -1.4 | 222.8        |        | 2.4      |              |           |
|    | 1    | -1.9 | 245.6        |        | 3.2      |              |           |
| L  | 1    | -1.4 | 240.6        |        | 2.4      |              |           |
| ł. | 1    | -1.6 | 242.1        |        | 2.7      |              |           |
|    | 1    | -0.9 | 138.2 - ikd? |        | 1.6      |              |           |
| L  | 1    | -1.3 | 198.0        |        | 2.2      |              |           |
| L  | 1    | -3.2 | 214.8        |        | 5.2      |              |           |
| l  | 1    | -0.9 | 184.9        |        | 1.6      |              |           |
|    | 1    | -1.8 | 186.7        |        | 2.8      |              |           |
| ŀ  | 1    | -2.3 | 242.3        |        | 3.9      |              |           |
| I  | 1    | -6.3 | n.d          |        | 9.5      |              |           |
|    | 1    | -0.6 | n.d.         |        | 1.0      |              |           |
| ł  | 1    | -1.5 | 136 - lkd?   |        | 2.6      |              |           |
| I  | 1    | -2.3 | 238.7        |        | 3.9      |              |           |
| I  | 1    | -2.1 | 235.1        |        | 3.5      |              |           |
| 1  | 1    | -1.6 | 238.1        |        | 2.7      |              |           |
|    |      |      |              |        |          |              |           |
|    | 2    | -0.1 | d.c          |        | n.d.     |              | 165.7     |
| Ì  | 2    | -0.3 | d.c          |        | n.d.     |              | 148.6     |
| 1  | 2    | -0.2 | n.d.         |        | n.d.     |              |           |
|    | 2    | -0.3 | 116.2        |        | n.d      |              |           |
|    | 2    | 0.1  | 120.5        |        | 0.0      |              |           |
| ł  | 2    | n.d. | 124.9        |        | n.d.     |              |           |
|    | 2    | 0.3  | 155.3        |        | 0.0      |              |           |
|    | 2    | -0.5 | 145.9        |        | 0.0      |              |           |
|    | 2    | -0.4 | 163.7        |        | 0.7      |              |           |
|    | 2    | -0.1 | 123.5        |        | 0.0      |              |           |
|    | 2    | n.d. | d.c          | 0.9    | n.d.     | 14.7         | 188.9     |
|    | 2    | n.d. | 163.5        | 2.4    | n.d.     | 12.8         |           |
|    | 2    | n.d. | 119.3        | 0.7    | n.d.     | 14.9         |           |
|    |      |      |              |        |          |              |           |

\* n.d. = not determined
\*\*d.c temp = decrepitation temperature

\*\*\*lkd? = leaked

 Table 7.1:
 Fluid inclusion results

### 7.3.3 Final Melt Temperatures (Tm)

The temperatures of final melt (Tm) for Type I inclusions ranged from -0.6 to -6.3 °C with a mean of value of -2°C. The temperature range and the mean correspond to 1.0 to 9.5 and 3.2 weight % NaCl equivalent (Figure 7.2).

T<sub>m</sub> for Type II fluid inclusions range from -0.5 to +0.1 °C (mean of -0.25°C) with a corresponding salinity value of 0 weight % NaCl equivalent (Figure 7.3). Three inclusions contained clathrates with a final melt Tmclath temperature range of +0.7 to +2.4°C. Tmclath values correspond to salinities of 12.8 and 14.9 weight % NaCl equivalent respectively (Figure 7.4). In the fluid inclusions with clathrates, only the temperatures of clathrate dissociation (Tmclath) were recorded as the Tm temperatures were obscured by the clathrate.

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Figure 7.3: Type II Inclusions - wt. % NaCl Distribution







Tmclath wt. % NaCl equivalent

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### 7.3.5 Homogenisation Temperatures (Th)

Temperature of homogenisation of the vapour phase for Type I inclusions ranged between 184.9 to 245.6°C, with a mode at 230 to 250°C (Figure 7.5). For Type I inclusions, two homogenisation temperatures fall below the main distribution having a Th of 136.0°C and 138.2°C. These two inclusions are assumed to have leaked during the heating process.

Type II inclusions have a significantly lower range of homogenisation temperatures and range from 120.5 to 163.7°C (mean of 135.7°C; see Figure 7.6). They frequently decrepitated by fracturing or leaking: temperatures of decrepitation ranged between 148.6 and 188.9 °C. Homogenisation temperatures of Type II inclusions were often not reproducible, and a change in the liquid:vapour ratio of up to 3% would suggest stretching of these fluid inclusions during the heating process.

### 7.4 Discussion

The interpretation of the data obtained from barite of the Hellyer baritic cap depends critically on two assumptions; that inclusions are indeed primary and that no later modification in the form of stretching and/or leaking has occurred. The former assumption has been addressed previously, however, the later is problematical, and the suitability of barite for fluid inclusion studies remains controversial. Ulrich and Bodnar (1988) and Pisutha-Arnond and Ohmoto (1983) have addressed problems associated with the examination of fluid inclusions in barite. The authors concluded that inclusions in soft cleavable minerals, such as barite, are susceptible to non systematic stretching or leakage, requiring only small internal pressures to initiate mass decrepitation. The authors also vindicate that a wide range of homogenisation temperatures do not necessarily indicate inclusions have stretched or leaked. Thus microthermometry of fluid inclusions in barite must be approached cautiously; accompanied by systematic procedures and detailed documentation. The application of such procedures for this study, resulted in firm identification of primary and secondary inclusions.

It can be suggested that the composition of the fluid phase for Type II inclusions is either that of meteroic water or that of a fluid containing dissolved constituents in the fluid phase. With respect to the latter, the presence of NaHCO<sub>3</sub> and Na<sub>2</sub>CO<sub>3</sub> as dissolved constituents in the fluid phase may cause temperatures of final melt temperatures to be close to those which could be obtained for meteroic waters (Borisenko, 1977). Since the presence of meteroic water in a submarine seawater environment at the time of the barite formation is unlikely, the compositions of Type II inclusions remain unknown, and the presence of dissolved constituents in the fluid phase is concluded.

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Figure 7.5: Type I Inclusions - Th Distribution





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The presence of low salinity and temperature fluid inclusions in barite has previously been observed at Mt. Charter by Rand (1988). The author recognised a bimodal distribution of fluid types, the first with salinities of 0 wt. % NaCl equivalent (corresponding to Type II fluid inclusions) and the second with 2.6 wt. % NaCl equivalent (corresponding to Type I). Rand (1988) concluded that the former type of fluid inclusions were primary in nature and, either represented a fluid distinct from seawater or that of a fluid modified after entrapment. In view of these issues, the Type II fluid inclusions which show; low temperatures of formation, decrepitation, observed changes in liquid volume ratios and non reproducible results, do not represent true fluids of formation

Type I inclusions formed from fluids with an average temperature of between 230 to  $250^{\circ}$ C and salinity of 2 wt. % NaCl equivalent. Variations in salinity and temperature for Type I inclusions may result from variations in fluid compositions in space and time. The systematics of these compositional variations were not investigated. With respect to depth and pressure, conditions under which the Hellyer deposit formed are not known accurately (Gemmell, 1989), and as a result, observed homogenisation temperatures have not been corrected for pressure. Consequently  $T_h$  values represent minimum temperatures of formation.

### 7.5 Conclusion

In conclusion, data obtained from primary fluid inclusions is consistent with previous work of Rand (1988). The temperature and salinity values obtained from barite at the Hellyer deposit are comparable to the temperatures and salinities of formation for barite horizons associated with other VHMS deposits (Large, 1977; Eldridge et al., 1983; Solomon et al., 1988) and a minimum temperature of formation of 230 to 250°C for the barite cap is suggested.

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# Chapter Eight Formation of the Baritic and Siliceous Caps : Conclusions

### 8.1 Kuroko Model

The formation the Hellyer deposit has been likened to that of the Kuroko deposits, Japan (McArthur, 1989; 1990). The following summary of the formation of the Kuroko deposits is derived from Eldridge et al. (1983), Ohmoto et al (1983), Kalogeropoulos and Scott (1983) and Kusakabe and Chiba (1983).

Eldridge et al. (1983) proposed a model of precipitating ore minerals on or above the sea floor from plumes of hydrothermal ore minerals. The author proposed that the observed stratification of the Kuroko deposits was the result of the superposition of ore minerals. Textural studies by Eldridge et al. (1983) suggested sulphides, sulphate and quartz to have formed in open ocean water, which were recrystallised during insulation in the middle and lower parts of the ore accumulation (Figure 8.1).

Kalogeropoulos and Scott (1983) proposed two stages of tetsusekiei formation (Figure 8.2): Stage I formation, corresponding to an intensifying hydrothermal system, where tetsusekiei formation is distal to the locus of hydrothermal activity, and Stage II formation during the waning of hydrothermal activity. Ohmoto et al. (1983) however, proposed a slightly different model. The authors postulated that if a major localised heat source was a necessary part of the genesis of the Kuroko deposits, then the type of deposit which formed was dependent on their thermal history of the hydrothermal systems and the distance from a heat source (Figure 8.3). Formation of the tetsusekiei could therefore have occurred either early or late, or both early and late in the thermal history of the hydrothermal system.

Kusakabe and Chiba (1983) report sulphates to have precipitated from the mixing of cold seawater with upwelling hydrothermal fluids. Eldridge et al. (1983) proposed that an orebody becomes mature when the pyrite ore (massive and siliceous) begins forming. The orebody, which has acquired all of its features, continues to grow in size thereafter (refer Figure 8.1). As a result the barite horizons of the Kuroko deposits, which result from late stage hydrothermal fluids, develop with the mound (Eldridge et al., 1983).

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Figure 8.1: Diagrams showing the steps in the development of an ideal orebody presented in the Kuroko model of formation. 1 = tetsusekiei or chert-hematite layer, 2 = barite ore; 3 = massive black ore (sphalerite + pyrite + galena + barite) where the fine dotted line separates the overlying fine-grained ore from the coarser grained ore below; 4 = massive semiblack ore (sphalerite + pyrite + chalcopyrite); 5 = massive yellow ore (chalcopyrite + pyrite); 6 = massive pyrite ore (pyrite + quartz); 7 = siliceous black ore (sphalerite + pyrite + galena + quartz); 8 = siliceous yellow ore (chalcopyrite + pyrite + chalcopyrite); 9 = siliceous pyrite ore (pyrite + quartz); 10 = transported, fragmental massive ore (mostly black); 11 = late-stage sulfide veins which can be either black or yellow ore. In this sequence the fragmental massive ore is mostly black ore which, by its movement, is effectively removed from further alterations by the hydrothermal fluids (from Eldridge et al., 1983).

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Figure 8.2: Stages of development of tetsusekiei with fluctuations in the thermal and fluid flow regime of the hydrothermal system. Sections (left) are schematic. Plans (right) are actual distributions of tetsusekiei and ore at Fukazawa, Japan. During stage III (not shown) tetsusekiei was modified by high-temperature fluids and assumed its final form (from Kalogeropoulos and Scott, 1983).



Figure 8.3: A model relating the distribution of ore types to the thermal history and to the relative distance from heat source (a and b). Y = yellow ore; C = composite ore; B = black ore; H = hematite ore; A = anhydrite ore. The central part of fluid discharge (i.e. ore zone  $\equiv$  sericite-chlorite alteration zone) in (b) and (c) is typically ~1.5 x ~3 km in area (~1.5km in the direction perpendicular to the heat source and ~3km parallel to the heat source) and is likely to have been the marginal zone of a resurgent caldera (after Ohmoto and Takahashi, 1983 in Ohmotot et al., 1983).

### 8.2 Recent Hydrothermal Activity

The presence of actively venting hydrothermal solutions to the sea floor provides additional evidence of the processes associated with active sulphide deposition. Mineral zoning in hydrothermal chimneys is controlled by the precipitation and replacement of minerals, which occur in response to changes in temperature and composition of the hydrothermal fluid (Woodruff and Shanks, 1985). Induced changes include the degree of seawater interaction, activity of sulphur species, oxygen fugacity and pH (Fouquet et al., 1990). Zoning within chimneys reflect the growth history of the chimney (Woodruff and Shanks, 1985). Chimney growth, in association with mound growth, is illustrated in Figure 8.4.

Examination of modern hydrothermal chimneys reveal fluids which contain significant quantities of amorphous silica, pyrite and barite (Speiss et al., 1980; Haymon, 1983; Fouquet et al, 1990). Black and white smokers are classified according to particulates which are suspended in venting solutions. High temperature black smoker vents are characterised by vigorous deposition of predominantly sulphide mineral phases (Haymon, 1983). Studies on the East Pacific Rise, 21°N, show black smokers to be associated with minor anhydrite, barite and silica (Janecky and Seyfried, 1984). By comparison, white smokers are generally of lower temperatures and composed predominantly of anhydrite, pyrite, barite and amorphous silica (Haymon, 1983).

Lydon (1988) showed that as a sulphide mound matured, its permeability decreased. In such regions, the author suggests that high temperature replacement within the mound is accompanied by low temperature, diffuse fluid flow, resulting in white smoker chimneys. In many modern hydrothermal systems, the deposition of barite and silica is interpreted to be contemporaneous or late stage where the site of precipitation is controlled by seawater mixing (Fouquet et al, 1991; Herzig et al. 1988; Alt et al., 1988).

### 8.3 The Deposition of the Barite Cap

Due to the low solubility of barite, barite precipitation occurs on mixing of barium enriched hydrothermal fluids with oxidised ambient seawater (Blount, 1977; Ohmoto et al., 1983). Shanks and Seyfried (1987) observed barite to be associated with regions of slow discharge of fluids into the mound on the seafloor. The authors suggest that a low flux rate of venting fluids allows diffuse mixing with seawater and consequently the deposition of barite. Shimazaki and Horikoshi (1990) concurringly conclude that the crystallisation of minerals from the cooling of upwelling solutions occurs rapidly, but depends critically on the rate of

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Figure 8.4: Schematic representation of the growth of a modern mound-chimney sulphide deposit, based on the descriptions by Hekinian and Foquet, 1985; Goldfarb et al., 1983; Jonasson et al. 1986 (from Lydon 1988).

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**Figure 8.5**: Illustration of the effects of conductive cooling, mixing only, and conductive cooling and mixing of fluids saturated with respect to quartz (from Herzig et al. 1988).

the out flow. Fouquet et al. (1981), in studies within the Lau back-arc basin, found barite to be both concentrated on the outer portions of the chimneys and the youngest veins of the stockwork. Actively venting chimneys of the East Pacific Rise (11° and 13° N), show continuous dissolution of sulphides and sulphates to occur on the inner walls of active structures (Bluth and Ohmoto, 1988). In non-active chimneys of the Franklin Seamount, Woodlark Basin, fluid conduits were lined with barite crystals (Binns et al., in prep). Barite precipitation can therefore be associated with periods of low flux or discharge, such as during the incipient growth stages, intermittent periods of non-active sulphide deposition, or the waning of the hydrothermal system (Ohmoto et al., 1983).

The  $\delta^{34}$ S values of barite from the Hellyer caps vary between 26 per mil to 52 per mil, whilst coeval pyrites show a wide  $\delta^{34}$ S ratio variation between 6 per mil to 26 per mil. The source of sulphur for barite precipitation is suggested to be a hydrothermal fluid which contained a significant proportion of partially reduced seawater sulphur and rock sulphur. The precipitation of barite from a partially reduced fluid is suggested by Solomon et al. (1988) to be the result of a lack of reductants in the system. As hydrothermal fluids encroaching the sea floor have precipitated most of their sulphides, Solomon et al. (1988) suggests that the reductants have been previously spent. Barite precipitation under oxidising conditions during periods of low solution flux, would cause an increase in the water to rock ratio, due to the open framework and high porosity in the upper regions of the mound. As a result Green et al. (1981) suggested conditions at the Rosebery deposit favoured the reduction of sea water sulphate to H<sub>2</sub>S. Variations in both coeval barite and pyrite isotopic ratios may therefore correspond to variation in concentration of reduced sulphate in the solutions precipitating barite. Such variation may relate to fluctuations between the proportions of seawater sulphate and magmatic sulphur in the hydrothermal solutions. A varying contribution of sulphur from at least two sources may be integrated with other factors such as modulating fluid, temperature changes, and seawater supply to understand the controls on barite deposition.

The deposition of barite is estimated to occur between temperatures of 230°C and 250°C in other massive sulphide deposits(Green et al. 1981; Fouqet et al., 1991). Fluid inclusion studies of barite from the Hellyer barite cap are not corrected for pressure effects and yield an average of 185°C, with a mode between 230 to 250°C.

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### 8.4 The Deposition of GSP

Edmond et al. (1979) suggested that iron-quartz rocks forming in massive sulphide environments, are contemporaneous or late stage low temperature products of hydrothermal fluids. The formation of most quartz associated with hydrothermal activity, is the result of reheating and recrystallisation of opal rich material, although some quartz may precipitate directly from the hydrothermal solution (Herzig, 1988). Kinetic effects are important in controlling the formation SiO<sub>2</sub> precipitates (Hannington and Scott, 1988). Rimstidt and Barnes (1979) explain the predominance of amorphous silica to be the result of the nucleation kinetics of quartz. Alt et al. (1987) and Alt (1988) demonstrated that amorphous silica can be reprecipitated at low temperature (15°C to 100°C) from solutions which are evolved from relatively high temperature (175°C to 350°C) hydrothermal fluids saturated with respect to quartz and seawater. At the East Pacific Rise, 21°N, high temperature solutions (greater than 300°C) do not precipitate silica, due to the low solubility of silica associated with decreasing temperatures (Rimstidt and Barnes, 1988). The formation of amorphous silica is best achieved by mixing the hydrothermal solution with seawater and conductively cooling the mixed seawater because the cooling of solutions by seawater mixing alone will not reach amorphous silica saturation (Herzig et al., 1988). Janecky and Seyfried (1984) therefore invoke additional conductive cooling, to cause the precipitation of silica at temperatures between 15°C to 100°C (Figure 8.5). While conductive cooling may cause silica precipitation, the necessity of a seawater sulphate source requires that mixing also occur to precipitate barite (Hannington and Scott, 1988).

Hydrothermal cherts often contain of Fe oxides (for example tetsusekiei as described by Kalogeropoulous and Scott, 1983 and ironstones at Thalanga described by Duhig, 1991). The oxidation of Fe<sup>2+</sup> species to Fe<sup>3+</sup>, required to form hematite, is unlikely in venting hydrothermal fluids due to their low residence time on mixing with seawater (Kester, 1975; Stumm and Morgan, 1981). Duhig (1991) concluded that the presence of iron oxidising bacteria were significant in the formation of Fe oxides at Thalanga. SEM investigations showed no evidence at Hellyer to suggest the presence of baterial filaments and as a result, pyrite is the main Fe repository.

Arsenopyrite is formed in equilibrium with silica in the GSP. Arsenopyrite deposition cannot occur in equilibrium with barite precipitation (Huston et al., 1991), as exemplified by thermodynamic modelling of the Rosebery deposit by Green et al. (1981). The model (Figure 8.6) shows that in order to precipitate arsenopyrite, a change in the total  $SO_4/H_2S$ 

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**Figure 8.6**: Thermodynamic modelling by Green et al. (1981). Log  $\Sigma SO_4/\Sigma H_2 S$  versus T diagram displaying the possible fields of formation of the massive sulfide and barite orebodies at Rosebery, Western Tasmania. Key: dotted line =  $\delta^{34}S_{112S}$  values assuming  $\delta^{34}S_{\Sigma S} = 30$  %o; dashed line = mole percent FeS in sphalerite. Solution contitions:  $M_{\Sigma S} = 0.002$ ; pH = 1 unit acid; mCl<sup>-</sup> = 1.0; mNa<sup>+</sup> = 0.9; mK<sup>+</sup> = 0.1; mCa<sup>+2</sup> = mMg<sup>+2</sup> = mBa<sup>+2</sup> = 0.001. Data from Helgeson (1969) and Ripley and Ohmotot (1977) and Table 9, using a program based on Ripley and Ohmoto (1980). Mole percent FeS contours from Craig and Scott (1974) and Czamanske (1974) and arsenopyrite field from Kretschmar and Scott (1976).



Figure 8.7: (a) Density temperature relationships of hot NaCl solutions mixed with seawater at 10°C (after Sato, 1972) illustrating the definition of Sato's (1972) three types of hydrothermal solutions. (b) Schematic representation of the buoyancy behaviour of and sulphide precipitation from Sato's (1972) three types of hydrothermal solutions.

ratio is required. Arsenopyrite therefore deposits at a lower oxygen fugacity to that of barite, but similar temperature.

Formation of the GSP must therefore have occurred at lower oxygen fugacities than barite, due to fluctuations in the proportions of  $H_2S$  and  $SO_4$  in the hydrothermal fluid. Eldridge et al. (1983) proposes that hematite formation in the tetsusekiei horizons was caused by the fluctuations in the amount of reduced sulphur in the hydrothermal fluid discharge. The authors concluded that the amount of reduced sulphur discharge was not sufficient to dominate the local environment, and consequently oxygen in the seawater forced hematite formation after the exhaustion of hydrothermal  $H_2S$ . An increased expulsion from venting solutions would therefore cause a localised dominance of  $H_2S$ , which reduces the  $SO_4/H_2S$ ratio and initiates pyrite and arsenopyrite formation.

### 8.5 Controls on Depositional Sites

Sato (1972) postulated that the discharge of fluids behaves according to the temperature, density and degree of mixing with seawater (Figure 8.7). The type of solutions characterise the morphology of the deposit. Type I solutions, a highly saline solution with a density greater than seawater, give rise to a tabular sheet like morphology (Lydon, 1988). Type II solutions, which although are less than seawater at some stage in the mixing pass through a maximum greater than seawater, give rise to a mound-type morphology. Type III solutions, less dense than seawater, remain buoyant and give rise to extensive fall out (Lydon, 1988).

The cap zones at Hellyer, localised within the margins of the massive sulphides, form a semi-continuous irregular layer, which closely follows the trend of the underlying stringer system. The barite cap, which is more extensive than the GSP, shows a close spatial affinity to the central feeder. Zones of bedded barite at the peripheries of the sulphide mound form narrow lenticular layers (for example HL417 on Section 10630 N), with sharp contacts to underlying massive sulphides. Based on the observations of Sato (1972), barite may have formed by particulates settling out of the expulsed hydrothermal fluids. Such a model would account for the observed bedding in some of periphery barite, as well as sharp contacts with the massive sulphides, which indicates they were not directly sourced. Alternatively, deposition of such barite may have been the result of satellite hydrothermal vents. The proximity of the GSP to the main feeder, indicates that proximal depositional mechanisms were involved. The observed salinity of hot solutions venting from black and white smokers

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is very close to that of seawater; that is, the density of the solutions making the chimney structure is lower than coeval seawater (Lydon 1988; Shimazaki and Horikoshi, 1990).

### 8.6 A Model of Formation

A spatial and genetic association is observed between the barite cap, GSP and massive sulphides at Hellyer. The diverse textural characteristics of minerals, reflect different environments of deposition which precludes formation in the same place at the same time. They may however, form in different places at the same time. Three stages to the model of formation of the cap zones (Figure 8.8) have been proposed; primary deposition, main sulphide deposition and waning.

### 8.6.1 Stage 1 : Primary Deposition

Primary depositional events included the precipitation of barite followed thereafter by GSP. Pyrite pseudomorphs may represent the existence of a substrate prior to barite deposition. Barite and pyrite could therefore have precipitated at or above the sea floor in areas of low flux, from hydrothermal solutions containing incompletely reduced seawater sulphur.

The GSP deposited after precipitation of the barite from solutions where  $H_2S$  locally dominated the expulsion of fluid. Arsenopyrite, pyrite, sphalerite and galena precipitated coevally with the GSP. Microcrystalline quartz of the GSP was deposited as amorphous silica via a process of seawater mixing and conductive cooling. Amorphous silica was reverted to microcrystalline quartz however, no evidence was found to suggest this event was coeval. Textures indicate the framework during Stage 1 to be highly porous.

### 8.6.2 Stage 2 : Main Sulphide Deposition

Continued hydrothermal activity, associated with increasing temperature and sulphide deposition, caused a decrease in the porosity of the precipitates of Stage 1. Spent hydrothermal fluids bathing Stage 1 precipitates, deposited Stage 1 minerals at the new mound-seafloor interface.

Resultantly in the lower regions of Stage 1, the continued deposition of late sulphide and sulphate minerals decreased the porosity and the former Stage 1 precipitates became encompassed by the sulphide mound. Dissolution of Stage 1 minerals may have occurred with the increased temperature.

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FIGORE 8.8: Model of formation of the baritic & siliceous caps

Barite GSP

### 8.6.3 Stage 3 : Waning

The cooling of the system, due to waning, resulted in the sealing of hydrothermal conduits where barite was the predominant precipitate. The sealing of hydrothermal passages formed barite veinlets and crustiform veins within the massive sulphide. The extrusion overlying lavas during waning, resulted in the formation of a hangingwall barium alteration zone.

### 8.7 Discussion

The model proposed for the formation of the cap zones at Hellyer, is consistent with that model set forward by Eldridge et al (1983). Textural similarities exist between cap zones of the Hoydal deposit (Norwegian Caledonies), Kuroko deposits of Japan, as well recent actively forming sulphide deposits of seamounts of the Eastern Pacific (Hekinian and Fouquet, 1985).

Ohmoto et al. (1983) suggested that the amounts and proportions of minerals in the Kuroko ores depend on the oxygen content of cold water, rates of reactions among various oxidised and reduced aqueous species, rates of chemical reactions, rates of fluid mixing as well as the concentration of reduced sulphur, oxidised sulphur and metals in the ore forming fluids. Stage 1 and Stage 2 of the cap precipitation may therefore occur at any time during mound growth. These two stages most likely represent fluctuations caused by the growth of the mound. For example the conditions of formation required to precipitate the GSP might occur simultaneously to those required to precipitate barite, at different vent sites. Sealing of chimneys is often observed in modern hydrothermal fields, where vents become choked. The choking of fluid flux, may cause precipitation of barite on the outer margins of chimneys and the precipitation of GSP in the inner parts. The observed interdigitating relationship between the barite and the GSP could therefore be explained by the fluctuation between the Stage 1 and Stage 2 systems proposed, which is controlled by the local environment, which is in turn controlled by the underlying feeder system.

The above model proposes that barite and silica precipitation were an integral part of the ore forming processes, and furthermore, that they were present during active sulphide precipitation. The conceptual model of mound growth as proposed by Eldridge et al. (1983) incorporates a zone refining process, which is applicable to the Hellyer deposit including the baritic and siliceous caps. Lower portions of the caps become increasingly insulated from oxygenated seawater and consequently, as evidenced from zonal studies, experienced increased deposition of sulphide phases (Stage 2) replacing or exsolving barite and GSP. In

such cases many of the sulphide phases which originated from early open space precipitation were overgrown and preserved in the  $H_2S$  dominated environment.

### 8.8 Summary and Conclusions

The deposition of the Hellyer baritic and siliceous caps were contemporaneous with ore formation and growth of the sulphide mound. The caps precipitated from spent upwelling hydrothermal solutions due to mixing with coeval seawater. The preferential deposition of the barite or silica regime is thought to be a combination of the chemical conditions which prevailed local to the site of deposition and the physical conditions at the site of deposition. Barite and GSP precipitation occurred from hydrothermal fluids which contained significant proportions of incompletely reduced sulphur. Fluctuating or pulsating conditions of formation are indicated in the immediate ore forming environment. The sites of cap deposition was controlled by the underlying centres of hydrothermal activity.

## REFERENCES

Adachi, M., Yamamoto, K. and Sugisaki, R., 1986. Hydrothermal chert and associated siliceous rocks from the northern Pacific: Their geological significance as indication of ocean ridge activity. *Sed. Geol.*, 47: 125-148.

A.G.I Glossary, 1957. Glossary of geological and related sciences, Washington, p. 102.

- Alt, J.C., 1988. The chemistry and sulfur isotope composition of massive sulphide and associated deposits on Green Seamount, eastern Pacific. *Econ. Geol.*, 83: 1026-1033.
- Alt, J.C., Lonsdale, P., Haymon, R. and Muehlenbachs, K., 1987. Hydrothermal sulphide and oxide deposits on seamounts near 21°N, East Pacific Rise. Geological Soc. Amer., 98:157-168
- Barnes, H.L., 1979. Solubilities of ore minerals, In: Barnes H.L., (Ed.) Geochemistry of hydrothermal ore deposits, 2nd Edition, Wiley, New York, p. 404-460.
  - Binns, R.A., Scott, S.D., Bogdanov, Y.A., Lisitsin, A.P., Gordeev, V.V., Gurvich, E.G., Finlayson, E.J., Boyd, T., Dotter, L.E., Wheller, G.E. and Muravyev, K.G., in prep. Hydrothermal oxide and gold-rich sulphate deposits of Franklin Seamount, western Woodlark Basin, Papua New Guinea.
  - Blount, C.W., 1974. Synthesis of barite, celestite, anglesite, witherite and strontianite in aqueous solutions. *Amer. Min.*, 59:1209-1212.
  - Blount, C.W., 1977. Barite solubilities and thermodynamic quantities up to 300°C and 1400 bars. Amer. Miner., 62:942-957.
  - Bluth, G.J. and Ohmoto, H., 1988. Sulphide-sulphate chimneys on the East Pacific Rise, 11<sup>0</sup> and 13<sup>0</sup> N latitudes. Part II:sulphur isotopes: *Can. Mineral.*, v. 26, 505-515.
  - Borisenko, A.S., 1977. Study of the salt compositions of solutions of gas-liquid inclusions in minerals by the cryometric method. *Soviet Geol.and Geophys.*, 18(8):11-17.
  - Burke, W.H., Denison, R.E., Hetherington, E.A., Koepnick, R.B., Nelson, H.F. and Otto, J.B., 1982. Variation of seawater <sup>87</sup>Sr/<sup>86</sup>Sr throughout Phanerozoic time. Geology, 10: 516-519.

K

- Claypool, G.E., Holser, W.T., Kaplan, I.R., Sakai, H. and Zak, I., 1980. The age curves of sulphur and oxygen isotopes in marine sulfate and their mutual interpretation: *Chem. Geology*, 28: 199-260.
- Corbett, K.C., 1989. Stratigraphy, Palaeogeography and Geochemistry of the Mt Read Volcanics. In Burrett, C.F. and Martin, E.L. (Eds) Geology and mineral resources of Tasmania. Spec. Pub. Geol. Soc. Aus., 15, p. 86-106.
- Corbett, K.C. and Solomon, M., 1989. Cambrian Mt. Read Volcanic and associated mineral deposits. In Burrett, C.F. and Martin, E.L. (Eds) Geology and mineral resources of Tasmania. Spec. Pub. Geol. Soc. Aus., 15, p. 84-181.
  - Craig, J.R. and Vaughan, D.J., 1990. Compositional and textural variations of the major iron base metal sulphide minerals. In Gray, P.M.J., Bowyer, G.J., Castle, J.F., Vaughn, D.J. and Warner, N.A., (Eds)., Sulphide deposits - Their origin and processing. AusIMM., Parkville, Victoria, p.1-16.
  - Deer, W.A., Howie, R.A. and Zussman, J., 1962. Rock forming minerals. Vol. 5 Non Silicates. Longman, p. 186-225.
- Drown, C.G. and Downs, R.C., 1990. Deformational style and strain partitioning at the Hellyer volcanogenic massive sulphide deposit. Geol. Soc. Australia, Spec. Pub. No. 25, p. 176-177.
  - **Duhig, N.C.**, 1991. The geology of East Waddy's Mill and the geochemical and textural aspects of ironstones near Thalanga, north Queensland. *Unpub. Honours thesis, University of Tasmania*, p. 1-96.
  - Eadie, E.T., Silic, J. and Jack, D.J., 1985. The application of geophysics to the discovery of the Hellyer ore deposit, Tasmania. *Expl. Geophys.*, 16:207-209.
  - Edmond, J.M., Measures, C., Mangum, B., Grant, B., Sclater, F.R., Collier, R. and Hudson, A., 1979. On the formation of metal rich deposits at ridge crests. *Earth Planet. Sci. Lett.*, 46:19-30.
- Eldridge, C.S., Barton, P.B. and Ohmoto, H., 1983. Mineral textures and their bearing on formation of the Kuroko orebodies. In Ohmoto, H. and Skinner, B.J. (Eds.), The Kuroko and Related Volcanogenic Massive Sulphide Deposits. Econ. Geol. Monograph 5, p. 241-281.
  - Fernandez-Diaz, L., Putnis, A. and Cumerbatch, T.J., 1990. Barite nucleation kinetics and the effects of additives. *Eur. J. Mineral.*, 2: 495-501.

108

E.

- Fouquet, Y., Stackelberg, U.V., Charlou, J.L., Donval, J.P., Foucher, J.P., Erzinger, J., Herzig, P., Muhe, R., Wiedicke, M., Soakai, S. and Whitechurch, H., 1991. Hydrothermal activity in the Lau back-arc basin: Sulphides and water chemistry. *Geol.*, 19: 303-306.
- Franklin, J.M., Lydon, J.W. and Sangster, D.F., 1981. Volcanic-associated massive sulphide deposits. Econ. Geol., 75th Anniversary Vol., 485-627.
  - Gemmell, J.B., 1988. Hellyer stringer zone project: Progress report. No. 1: Unpub. company report for Aberfoyle Resources Ltd., p. 42.
  - Gemmell, J.B., 1989. Hellyer stringer zone project: Progress report. No. 2: Unpub. company report for Aberfoyle Resources Ltd., p. 55.
  - Gemmell, J.B., 1990. Hellyer gold study, preliminary results. Unpub. company report for Aberfoyle Resources Ltd., p. 14.
- Gemmell, J.B. and Large, R.R., in press. Stringer system and alteration zones underlying the Hellyer volcanogenic massive sulphide deposit, Tasmania, Australia.
- Gemmell, J.B., Large, R.R., McArthur, G.J., Drown, C.G. and Downs, R.C., 1990. Formation of the alteration pipe and stringer zone beneath the Hellyer massive sulphide depoşit, Tasmania. [abstr.]: Geol. Soc. Australia, Spec. Pub. No. 25, p.8-9.
  - Graham, U.M., Bluth, G.J. and Ohmoto, H., 1988. Sulphide-sulphate chimneys on the East Pacific Rise, 11°N and 13°N latitudes. Part I: mineralogy and paragenesis. *Can. Miner.*, 26: 487-504.
  - Green, G.R., Solomon, M. and Walshe, J.L., 1981. The formation of the volcanichosted massive sulphide deposit at Rosebery, Tasmania. *Econ. Geol.*, 76: 304-338.
  - Grenne, T. and Vokes, F.M., 1990. Sea-floor sulphides at the Høydal volcanogenic deposit, central Norwegian Caledonides. *Econ. Geol.*, 85: 344-359.
  - Hannington, M.D. and Scott, S.D., 1988. Mineralogy and geochemistry of a hydrothermal silica-sulphide-sulphate spire in the caldera of Axial Seamount, Juan de Fuca Ridge. *Canadian Miner*. 26:603-625.
  - Haymon, R.M., 1983. Hydrothermal deposition on the East Pacific Rise at 21°N. J. Geochem. Expl., 19:493-495.

Ł

Hekinian, R. and Fouquet, Y. 1985. Volcanism and metallogenesis of axial and offaxial structures on the East Pacific Rise near 13°N. *Econ. Geol.* 80:221-249.

- Herzig, P.M., Becker, K.P., Stoffers, P., Backer, H. and Blum, N., 1988. Hydrothermal silica chimney fields in the Galapagos spreading centre at 86°W. *Earth and Planet. Sci. Lett.*, 89: 261-272.
- Huston, D.L., Botrill, R.S., Creelman, R.A., Zaw, K., Ramsden, T.R., Rand, S.W., Gemmell, J.B., Jablonski, W., Sie, S. and Large, R.R., in press Geological and geochemical controls on the mineralogy and grain size of goldbearing phases, eastern Australian volcanic-hosted massive sulphide deposits.
- Huston, D.L., 1988. Aspects of the geology of massive sulphide deposits from the Balcooma district, northern Queensland and Rosebery, Tasmania: Implications for ore genesis. *PhD Thesis, University of Tasmania*, p. 182-320.
- Huston, D.L. and Large, R.R., 1989. A chemical model for the concentration of gold in volcanogenic massive sulphide deposits. *Ore Geol. Rev.*, 4:171-200.
- Huston, D.L. and Large, R.R., 1986. Distribution, mineralogy, and geochemistry of gold and silver in the north end orebody, Rosebery, Tasmania. *Econ. Geol.*, 83: 1181-1192.
- Huston, D.L. and Zaw, K., 1988. Controls on the fineness and grain size of electrum. In Controls on gold and silver grades in volcanogenic sulphide deposits (84/P210). AMIRA Final Report, p. 184.
- Sack, D.J., 1989. Hellyer host rock alteration. Unpub. Masters thesis, University of Tasmania, p. 1-181.
  - Jack, D.J., 1990. Geochemistry and alteration of the hangingwall basalts to the Hellyer volcanogenic massive sulphide deposit, Tasmania. [abstr.]: Geol. Soc. Australia, Gondwana; Terranes and resources, Tenth A.G.C., Hobart, Australia, Feb 1990, No. 25, p. 7.
  - Janecky, D.R. and Seyfried, W.E., Jr., 1984. Formation of massive sulphide deposits on oceanic ridge crests: Incremental reaction models for mixing between hydrothermal solutions and seawater. *Geochim. et Cosmochim. Acta*, 48:2723-2738.
  - Janecky, D.R. and Shanks, W.C., 1988. Computational modelling of chemical and sulphur isotopic reaction processes in seafloor hydrothermal systems: chimneys, massive sulphides and subadjacent alteration zones. *Can. Miner.*, 26: 859-869.

Į.

- Kalogeropoulos, S.I. and Scott, S.D., 1983. Mineralogy and geochemistry of tuffaceous exhalites (Tetsusekiei) of the Fukazawa Mine, Hokuroku district, Japan. In Ohmoto, H. and Skinner, B.J. (Eds.), The Kuroko and Related Volcanogenic Massive Sulphide Deposits. Econ. Geol. Monograph 5, p. 412-432.
- Kester, D.R., 1975. Dissolved gases other than CO<sub>2</sub>. In Riley, J.P. and Skirrow, G. (Eds) Chemical Oceanography: Academic Press, London, 498-556.
- Koski, R.A., Shanks, W.C., Bohrson, W.A. and Oscarson, R.L., 1988. The composition of massive sulphide deposits from the sediment-covered floor of Escanaba Trough, Gorda Ridge: implication for depositional processes. *Can. Miner.*, 26: 655-673.
- Kusakabe, M. and Chiba, H., 1983. Oxygen and sulphur isotope composition of barite and anhydrite from the Fukazawa deposit, Japan. In Ohmoto, H. and Skinner, B.J. (Eds.), The Kuroko and Related Volcanogenic Massive Sulphide Deposits. Econ. Geol. Monograph 5, p. 292-301.
- Large, R.R., 1977. Chemical evolution and zonation of massive sulphide deposits in volcanic terrains. *Econ. Geol.*, 72:549-572.
- Large, R.R., 1991. Importance of mineral zonation in understanding the chemistry and processes of ore formation. CODES Masters Econ. Geol. Short Course Manual, 12: 1-12.
- Leblanc, M. and Billaud, P., 1990. Zoned and recurrent deposition of Na-Mg-Fe-Si exhalites and Cu-Fe sulphides along synsedimentary faults (Bleida, Morocco). *Econ. Geol.*, 85: 1759-1769.
- Lydon, J.W., 1988. Volcanogenic massive sulphide deposits Part 1: a descriptive model. Geoscience Canada, 11:195-202.
- McArthur, G.J., 1986. The Hellyer massive sulphide deposit, In Large, R.R. (Ed.), The Mount Read Volcanics and associated ore deposits. *Geol. Soc. Aus., Tasmania Division*, p. 11-19.
- McArthur, G.J., 1989. Hellyer. In Burrett, C.F. and Martin, E.L. (Eds) Geology and mineral resources of Tasmania. Spec. Pub. Geol. Soc. Aus., 15, p. 144-148.
- McArthur, G.J., 1990. Metal and textural zonation in the Hellyer massive sulphide deposit. [abstr.]: Geol. Soc. Australia, Gondwana; Terranes and resources, Tenth A.G.C., Hobart, Australia, Feb 1990, No. 25, p. 108-109.

Ř

- McArthur, G.J. and Dronseika, E.V., 1990. Que River and Hellyer zinc-lead deposits. In Hughes, F.E. (Ed.), Geology of the mineral deposits of Australia and Papua New Guinea. Mono. 14, AusIMM, Parkville, Victoria, p.1229-1239.
  - McArthur, G.J. and Kuipers, A.J., 1990. Computer methods for mine geology at Hellyer. *Mine geologists conference, Mt. Isa*, 49-55 p.
  - McGoldrick, P., 1988. Sulphur isotope studies at Que River. Final Report to AMIRA, p. 47-52.
  - Ohmoto, H., 1986. Stable isotopes geochemistry of ore deposits: In Valley, J.W., Taylor, Jr., H.P., and O'Neil, J.R., (Eds.), Stable Isotopes in High Temperature Geological Processes. Min. Soc. America, Rev. in Mineralogy, 16: 491-560.
- \*Ohmoto, H., Mizukami, M., Drummond, S.E., Eldridge, C.S., Pisutha-Arnond, V. and Lenagh, T.C., 1983. Chemical processes of Kuroko formation. In Ohmoto, H. and Skinner, B.J., (Eds.), The Kuroko and Related Volcanogenic Massive Sulphide Deposits. Econ. Geol., Monograph 5, p. 570-604.
- Ohmoto, H. and Rye, R.O., 1979. Isotopes of sulphur and carbon: In Barnes, H.L., (Ed.), Geochemistry of hydrothermal ore deposits: New York, J. Wiley and Sons, p. 509-567.
- Phillips, W.R. and Griffen, D.T., 1981. Optical mineralogy: The non opaque (minerals. W.H. Freeman and Co., p. 86-94.
- Pisutha-Arnond, V. and Ohmoto, H., 1983. Thermal history, and chemical and isotopic conditions of the ore-forming fluids responsible for the Kuroko massive sulphide deposits in the Hokuroko District of Japan: In Ohmoto, H. and Skinner, B.J., (Eds)., The Kuroko and Related Volcanogenic Massive Sulphide Deposits, Econ. Geol., Monograph 5, p. 523-558.
  - Ramsden, A.R., Kinealy, K.M., Creelman, R.A. and French, D.H., 1990. Precious and base metal mineralogy of the Hellyer volcanogenic massive sulphide deposit, northwest Tasmania - A study by electron microprobe. In Gray, P.M.J., Bowyer, G.J., Castle, J.F., Vaughn, D.J. and Warner, N.A. (Eds.), Sulphide deposits - Their origin and processing. AusIMM., Parkville, Victoria, p. 49-71.
  - Rand, S.W., 1988. The geology and mineralisation of the Mt. Charter prospect. Unpub. Honours thesis, University of Tasmania, p. 1-96.
  - Ridler, R.H., and Shilts, W.W., 1974. Mineral potential of the Rankin Inlet. *Canadian Min. Jour.*, 95(7): 32-42.

112

ł

- Roedder, E., 1981. Origin of fluid inclusions and changes that occur after trapping In Hollister, L.S. and Crawford, M.L. (Eds), Short course in fluid inclusions: Applications to petrology. Min. Assoc. Canada, Calgary, 6:101-129.
- Sato, T., 1972. Behaviours of ore-forming solutions in seawater. Mining Geology, 22: 31-42.
  - Shanks, W.C. III and Seyfried, W.E. Jr., 1987. Stable isotope studies of vent fluids and chimney minerals, southern Juan de Fuca Ridge: sodium metasomatism and seawater sulphate reduction in Special section on the Southern Juan de Fuca Ridge: hydrothermal fluids, sulphides and geophysical studies. J. Geophys. Res., 92B(11):11387-11399.
  - Shimazaki, H. and Horikoshi, E., 1990. Black ore chimney from the Hanaoka Kuroko deposits, Japan. *Mining Geol.*, 40(5): 313-321.
  - Sise, J.R. and Jack, D.J., 1984. Exploration History of the Hellyer Deposit, In Baillie, P.W. and Collins, P.L. (Eds.), Mineral Exploration and Tectonic Processes in Tasmania. Geol. Soc. Aus. Tasmanian Divsion, p. 48-49.
  - Solomon, M., Eastoe, C.J., Walshe, J.L. and Green, G.R., 1988. Mineral deposits and sulphur isotope abundances in the Mount Read Volcanics between Que River and Mt. Darwin, Tasmania. *Econ. Geol.*, 83: 1307-1328.
  - Speiss, F.N., MacDonald, K.C., Atwater, T., Ballard, R., Carranza, A., Cordoba, D., Cox, C., DiazGarcia, V.M., Francheteau, J., Guerrero, J., Hawkins, J., Haymon, R., Hessler, R., Juteau, T., Kastner, M., Larson, R., Luyendyk, B., Macdougall, J.D., Miller, S., Normark, W., Orcutt, J. and Rangin, C., 1980. East Pacific Rise: Hot springs and geophysical experiments. Science, 207: 1421-1433.
  - Staff, Aberfoyle Resources Limited, 1990. Geology and discovery of the Que River and Hellyer polymetallic sulphide ores, Tasmania. In Glasson, K.R. and Rattigan, J.H., Geological aspects of the discovery of some important mineral deposits in Australia. AusIMM. Mono. 17, Parkville, Victoria, p. 187-196.
  - Stumm, W. and Morgan, J.J., 1981. Aquatic Chemistry, 2nd Edition, Wiley, New York, p. 780.
  - Ulrich, M.R. and Bodnar, R.J., 1988. Systematics of stretching of fluid inclusions II: Barite at 1 atm confining pressure. *Econ. Geol.*, 83: 1037-1046.

Whitford, D.J. and Craven, S.J., 1986. Strontium isotopic studies at Que River and Hellyer. In Large, R.R., The Mount Read Volcanics and associated ore deposits. Geol. Soc. Australia, Tas Div., p. 87-88.

1

ŕ

- Williams, L.A. and Crerar, D.A., 1985. Silica diagenesis, II. general mechanisms. J. sed. Pet., 55: 312-321.
- Williams, L.A., Parks, G.A. and Crerar, D.A., 1985. Silica diagenesis, I. solubility controls. J. Sed. Pet., 55: 301-311.
- Woodruff, L.G. and Shanks, W.C., 1985. Sulphur isotope study of chimney minerals and hydrothermal fluids from 21°N, East Pacific Rise: hydrothermal sulphur sources and disequilibrium sulphate reduction. *Jour. Geophys. Res.*, 93,: 4562-4572.
- Zierenberg, R.A. and Schiffman, P., 1990. Microbial control of silver mineralisation at a sea floor hydrothermal site on the northern Gorda Ridge. *Nature*, 348: 155-157.

Appendix 1

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### Aberfoyle Resources Limited HELLYER DIVISION DIAMOND DRILL LOG VALID CODES SHEET 1 OF 2 LITHOLOGY VOLCANICLASTIC MATRIX STRATIGRAPHY COLOUR Upper Rhyolitic Sequence Que River Shale Pillow Lava Sequence Hanging Wall Volcaniclastic Sequence Hellyer Mineralized Sequence Feldspar Phyric Andesite Sequence Lower Epiclastic Sequence URS QRS PLS HVS HMS FPS LES Composition D = Dark L = Light B = Bright PREFIX Cryetal Glasey Lithic Vitric X G Ľ Bar Gyr ke pd hw Black Black Brown Green Grey Orange Pink Polychro Purpie Red White Yellow or any standard mineralogy code Stringer Enveloper Zone Stringer Zone SEZ STZ LOWER CONTACT Gradation ROCK TYPE Sharp but not faulted SF Composition Prefix Faulted Gradational up to 1m 1—1Dm over 10m Composition Prefix Barite Basalt Basalt Basa Metal Sulphides Chert Peldspar Phyric Andesite Glassy silica – colloform pyrite ore Highly Altered (obliterating primary texturee) Massive Chalcopyrite Massive Pyrite Polymict Pumice "Quellite" Khyolite G1 G2 G3 Ba BMS Ch D FP VOLCANICLASTIC FRAGMENTS Composition Style Conformable Interfingering Irregular As per rock type composition prefix codee C F I GSP HA MCPy MPy Y Pu Q R Ss Sh Sorting Well sorted Moderately sorted Poorly sorted ₩ M P VESICLES Concentration Rhyolite Sandstone, Siltstone Shale Shape Trace Weak Angular Sub-angular Sub-rounded Rounded Arcuate Eutaxitlc Variable 2345 Moderate Strong Extreme A ARRAXVE Volcanic Texture Suffix Ash volcaniclastic (0-2mm) Ash volcaniclastic (2-4mm) fine (2-8mm) medium (8-32mm) coarse (32-64mm) Breccia volcaniclastic (>64mm) Lava 잡고 한 한 한 과 . 며 와 Shape Annular sub-vesicles Elongate Elongate AESV Elongate Spherical Variable Lava Pillow Lava Variolitic pillow lava Aberfoyle Resources Limited HELLYER DIVISION DIAMOND DRILL LOG VALID CODES SHEET 2 OF 2 ALTERATION FAULTS Mineralogy Texture Gouge Disseminated Interpillow Nodular Pervosive Pillow Margins Pseudomorphous As per mineralogy codee used for alteration and mineralisation, e.g. C0 51 C1 E9 Brecciated Cavernous Br Cv Pu Rh Si D P N P M N R F Puggy Rehealed Slickensided Rim Selected fragments MINERALISATION Carbonate Chlorite C0 C1 Texture Stockwork Structure controlled Veins Mylonite Quartz Rubble K S V My Si Ru Se Banded Brecciated Colloform Disseminated Euhedral Fragmental Framboidal \$\$\$CDULLE99226225095998 Sericite Intensity FOLIATION As per standard intensity coding 1 2 3 4 5 Туре Inter-pillow Joint Plane Coating Bedding Clast Alignment Massive Nodular Clast Algnment Cleavage Flow Banding Shearing Sulphide Banding Vesicle Alignment Pillow margin Recrystallised Reworked Mineralogy Carbonate Chlorite Epidote Feldspar Fuchsite Dlite K-Feldspar Pyrite Sericite Silica Sheared Shrinkage Shadows Veins Vein Selvedge Boxwork Veining Fragment Rim WEATHERING Type prefix, standard intensity coding suffix Mineralogy and Contents 0 Oxidiaed Hernatite Mineralogy prefix, percentage suffix (tr for trace), I for emphasis Tremolite Arsenopyrite Barite Chalcopyrite Galena Code in order of predominance, use brackets for trace content. VEINING Pyrite Sphalerite Intensity Gangue As per standard intensity coding 12345 ł

### Appendix 1.1: Logging Codes Employed at Hellyer

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# Appendix 2

|            |                 |        |           |        |          |         |      | Department        |
|------------|-----------------|--------|-----------|--------|----------|---------|------|-------------------|
| SAMPLE     | FROM            | TO     | Rock Type | BHID   | Northing | Easting | R.L. | Catalouge Numbers |
| DEcot      | <b>FF 7</b>     | 55.0   | P- OVC    | 11.000 | 40070    | 5070    |      |                   |
| R5001      | 55.7            | 00.04  | Ba/BMS    | HL386  | 10670    | 5679    | 441  |                   |
| R5002      | 99.1            | 99.24  | Ba        | HL365  | 10691    | 5762    | 488  |                   |
| RS005      | 90.3            | 90.4   | GSP       | HL363  | 10691    | 5/51    | 491  |                   |
| RECOR      | 139.42<br>ED 4E | 50.57  | Da        | HL322  | 10/10/   | 5778    | 528  |                   |
| H5006      | 52.45           | 52.57  | GSP/BA    | HL324  | 10/12    | 5745    | 447  |                   |
| H5007      | 49.1            | 49.2   | GSP/Ba    | HL324  | 10/12    | 5743    | 444  |                   |
| H2008      | 123.5           | 123.7  | Contact   | HL324  | 10/10    | 5783    | 507  |                   |
| 10         | 106.5           | 106.7  | BMS/Ba    | HL413  | 10633    | 5727    | 510  |                   |
| 11         | 115.5           | 115.6  | Ba vein   | HL413  | 10633    | 5728    | 519  |                   |
| 12         | 118.5           | 118.7  | Ba        | HL413  | 10633    | 5729    | 522  |                   |
| 13         | 130.1           | 130.2  | GSP       | HL413  | 10633    | 5731    | 533  |                   |
| 14         | 134.6           | 134.8  | Ba        | HL413  | 10634    | 5731    | 537  |                   |
| 15         | 72.5            | 72.65  | Contact   | HL417  | 10629    | 5686    | 472  |                   |
| 17         | 119             | 119.1  | GSP/BMS   | HL414  | 10632    | 5718    | 523  |                   |
| 18         | 127.1           | 127.3  | Ba        | HL414  | 10632    | 5719    | 531  |                   |
| 19         | 136.25          | 136.58 | Ba        | HL414  | 10632    | 5719    | 540  |                   |
| 20         | 134.7           | 134.83 | Contact   | HL414  | 10632    | 5719    | 539  |                   |
| 21         | 140.7           | 140.9  | Ba        | HL414  | 10632    | 5719    | 545  |                   |
| 22         | 148.8           | 149.5  | Ba        | HL414  | 10632    | 5720    | 553  |                   |
| 23         | 150.7           | 150.8  | B-pl      | HL414  | 10632    | 5720    | 555  |                   |
| 24         | 103.3           | 103.4  | BMS/Ba    | HL410  | 10649    | 5719    | 507  |                   |
| 25         | 105.1           | 105.3  | Ba        | HL410  | 10649    | 5719    | 509  |                   |
| 26         | 118.5           | 118.87 | Contact   | HL410  | 10649    | 5719    | 523  |                   |
| 27         | 115.9           | 116    | Ва        | HL410  | 10649    | 5719    | 520  |                   |
| 28         | 129.3           | 129.5  | Ва        | HL410  | 10649    | 5719    | 533  |                   |
| <b></b> 29 | 141.2           | 141.3  | Ba/BMS    | HL410  | 10648    | 5719    | 545  |                   |
|            |                 |        |           |        |          |         |      |                   |

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| SAMPLE | FROM   | то     | Rock Type | BHID  | Northing | Easting | R.L. | Department        |
|--------|--------|--------|-----------|-------|----------|---------|------|-------------------|
|        |        |        |           |       |          |         |      | Catalogue Numbers |
| 30     | 145.5  | 145.6  | Ba        | HL410 | 10648    | 5719    | 550  |                   |
| 31     | 84.6   | 84.7   | Ba vein   | HL452 | · 10612  | 5709    | 490  |                   |
| 32     | 91     | 91.3   | GSP       | HL452 | 10612    | 5709    | 496  |                   |
| 33     | 78     | 78.2   | GSP       | HL452 | 10612    | 5709    | 483  |                   |
| 34     | 99.7   | 99.8   | GSP       | HL452 | 10612    | 5710    | 504  |                   |
| 35     | 102.75 | 102.9  | Ba/BMS    | HL452 | 10612    | 5710    | 507  |                   |
| 36     | 110.05 | 110.1  | Ba        | HL452 | 10613    | 5710    | 515  |                   |
| 37     | 115.9  | 116    | B-pl      | HL452 | 10613    | 5710    | 520  |                   |
| 38     | 183.3  | 184.4  | Ba/BMS    | HL329 | 10803    | 5818    | 554  |                   |
| 39     | 187.5  | 189    | Contact   | HL329 | 10803    | 5820    | 557  |                   |
| 40     | 189.9  | 190.2  | Contact   | HL329 | 10803    | 5822    | 559  |                   |
| 41     | 190.6  | 190.7  | Ba        | HL329 | 10803    | 5823    | 559  |                   |
| 42     | 163    | 163.15 | GSP       | HL295 | 10814    | 5789    | 551  |                   |
| 43     | 165.3  | 165.4  | GSP       | HL295 | 10814    | 5790    | 553  |                   |
| 44     | 168.6  | 168.75 | GSP/BMS   | HL295 | 10814    | 5791    | 556  |                   |
| 45     | 117.15 | 117.2  | GSP       | HL346 | 10831    | 5797    | 503  |                   |
| 46     | 118.95 | 119.03 | B-pl      | HL346 | 10831    | 5798    | 504  |                   |
| 47     | 118.8  | 118.9  | Ba        | HL346 | 10831    | 5798    | 504  |                   |
| 48     | 139.5  | 139.6  | GSP       | HL364 | 10752    | 5759    | 536  |                   |
| 49     | 140.55 | 140.65 | Ba        | HL364 | 10752    | 5759    | 537  |                   |
| 50     | 140.95 | 141.05 | Contact   | HL364 | 10752    | 5759    | 538  |                   |
| 51     | 152.6  | 152.7  | X-tal     | HL364 | 10752    | 5763    | 549  |                   |
| 52     | 155.1  | 155.25 | BMS\GSP   | HL364 | 10752    | 5763    | 551  |                   |
| 53     | 158.3  | 158.4  | Contact   | HL364 | 10752    | 5764    | 554  |                   |
| 54     | 159.2  | 159.3  | Ba        | HL364 | 10752    | 5764    | 555  |                   |
| 55     | 168.75 | 168.85 | Contact   | HL364 | 10752    | 5767    | 564  |                   |
| 56     | 171.7  | 171.8  | Ba        | HL364 | 10752    | 5768    | 567  |                   |
| 57     | 180.35 | 180.45 | GSP       | HL364 | 10752    | 5770    | 575  |                   |
| 58     | 182.8  | 182.9  | Ba        | HL364 | 10752    | 5772    | 578  |                   |
| 63     | 174.95 | 175.1  | Contact   | HL315 | 10771    | 5810    | 560  |                   |

# Appendix 2.1: Sample locations and Geology Department Catalouge numbers.

| SAMPLE | FROM   | то     | Rock Type           | BHID  | Northing | Easting | R.L. | Department        |
|--------|--------|--------|---------------------|-------|----------|---------|------|-------------------|
|        |        |        |                     |       |          |         |      | Catalogue Numbers |
| 64     | 173.35 | 173.5  | GSP                 | HL315 | 10771    | 5811    | 562  |                   |
| 65     | 175.9  | 176    | GSP                 | HL315 | 10771    | 5811    | 562  |                   |
| 66     | 178.4  | 178.5  | B-pl Contact        | HL315 | 10771    | 5812    | 565  |                   |
| 67     | 247.5  | 247.6  | Ba Xial             | HL461 | 10434    | 5685    | 459  |                   |
| 68     | 75.97  | 76.17  | Ba Xtal             | HL625 | 10285    | 5667    | 613  |                   |
| 69     | 81.8   | 81.9   | BMS/GSP             | HL625 | 10285    | 5665    | 608  |                   |
| 70     | 85.5   | 85.7   | Ba vein             | HL625 | 10285    | 5664    | 604  |                   |
| 71     | 94.8   | 94.9   | GSP                 | HL625 | 10284    | 5662    | 595  |                   |
| 72     | 154.6  | 154.8  | GSP veins in Ba     | HL366 | 10747    | 5754    | 553  |                   |
| 73     | 160.5  | 160.6  | Banded Ba           | HL366 | 10746    | 5755    | 559  |                   |
| 74     | 162.1  | 162.3  | GSP in Ba           | HL366 | 10746    | 5756    | 560  |                   |
| 75     | 162.4  | 162.55 | Si/GSP in Ba        | HL366 | 10746    | 5756    | 561  |                   |
| 76     | 162.9  | 163    | GSP/ Ba             | HL366 | 10746    | 5756    | 561  |                   |
| 77     | 163.6  | 163.7  | BMS/Ba Contact      | HL366 | 10746    | 5756    | 562  |                   |
| 78     | 164    | 163.9  | GSP/BMS Contact     | HL366 | 10746    | 5756    | 562  |                   |
| 79     | 167.6  | 167.7  | Ba in BMS           | HL366 | 10746    | 5757    | 566  |                   |
| 80     | 168.4  | 168.5  | Zoned Sp with Ba    | HL366 | 10746    | 5757    | 566  |                   |
| 81     | 169    | 169.1  | HGO with Ba         | HL366 | 10746    | 5757    | 567  |                   |
| 82     | 176.05 | 176.15 | HGO                 | HL366 | 10746    | 5757    | 574  |                   |
| 83     | 177.8  | 177.95 | Ba fragment in BMS  | HL366 | 10746    | 5759    | 576  |                   |
| 84     | 185.4  | 185.5  | GSP                 | HL366 | 10746    | 5761    | 583  |                   |
| 85     | 188    | 188.1  | B-pl fragment in Ba | HL366 | 10746    | - 5762  | 585  |                   |
| 86     | 10.7   | 10.8   | GSP                 | HL349 | 10731    | 5763    | 445  |                   |
| 87     | 12.75  | 12.95  | GSP with carbonate  | HL349 | 10731    | 5764    | 444  |                   |
|        |        |        |                     |       |          |         |      |                   |
| 89     | 15.3   | 15.45  | Ba/GSP              | HL349 | 10731    | 5766    | 442  |                   |
| 90     | 106.85 | 106.93 | HVS Contact         | HL610 | 10316    | 5638    | 594  |                   |
| 91     | 106.7  | 106.8  | Si Vein             | HL610 | 10316    | 5638    | 593  |                   |
| 92     | 107.1  | 107.2  | HVS in Ba           | HL610 | 10316    | 5637    | 593  |                   |
| 93     | 109.49 | 109.5  | Bn Ba/BMS           | HL610 | 10316    | 5637    | 593  |                   |

| Sample  | FROM   | TO     | Rock Type          | BHID  | Northing | Easting | R.L. | Depatrment Catalogue numbers |
|---------|--------|--------|--------------------|-------|----------|---------|------|------------------------------|
| 94      | 110    | 110.95 | Contact Ba/BMS     | HL610 | 10316    | 5636    | 590  |                              |
| 95      | 105.25 | 105.5  | Massive Ba         | HL610 | 10316    | 5638    | 590  |                              |
| 100     | 127.05 | 127.25 | Ba Vn in BMS       | HL326 | 10804    | 5769    | 517  |                              |
| 101     | 132.75 | 132.83 | Ba in BMS          | HL326 | 10804    | 5772    | 522  |                              |
| 102     | 139.1  | 139.2  | Ba in LGO          | HL326 | 10804    | 5774    | 528  |                              |
| 103     | 148.9  | 149    | Si vein            | HL326 | 10804    | 5779    | 536  |                              |
| 104     | 149.4  | 149.5  | BMS/GSP            | HL326 | 10804    | 5780    | 537  |                              |
| 105     | 167.7  | 167.8  | Zoned Sp & Ba      | HL326 | 10804    | 5788    | 553  |                              |
| 106(i)  | 168.4  | 168.5  | BMS/GSP            | HL326 | 10804    | 5788    | 554  |                              |
| 106(ii) | 170.7  | 170.8  | Fr BMS/GSP         | HL326 | 10804    | 5790    | 556  |                              |
| 107     | 174.6  | 174.75 | Cherty Fr in BMS   | HL326 | 10804    | 5791    | 559  |                              |
| 108     | 177.65 | 177.75 | Ba with pyrite     | HL326 | 10804    | 5793    | 562  |                              |
| 109     | 181.85 | 181.95 | Contact Ba/GSP     | HL326 | 10803    | 5795    | 566  |                              |
| 110     | 183    | 183.1  | BMS/GSP(?)         | HL326 | 10803    | 5795    | 567  |                              |
| 111     | 187.4  | 187.5  | Banded Ba          | HL326 | 10803    | 5797    | 570  |                              |
| 112     | 190.4  | 190.6  | B-PI               | HL326 | 10803    | 5799    | 573  | •                            |
| 113     | 191.2  | 191.3  | Interpillow margin | HL326 | 10803    | 5799    | 574  |                              |
| 114     | 192.3  | 192.4  | Altered Basalt     | HL326 | 10803    | 5800    | 575  |                              |
| 115     | 195.7  | 195.8  | B-pl               | HL326 | 10803    | 5801    | 578  |                              |
| 116     | 197.8  | 198    | Fu/Se altered B-pl | HL326 | 10802    | 5802    | 580  |                              |
| 117     | 202.1  | 202.2  | Se/Fu altered B-pl | HL326 | 10802    | 5804    | 583  |                              |
| 118     | 202.9  | 203    | B-pi               | HL326 | 10802    | 5805    | 584  |                              |
| 120     | 125.6  | 125.7  | HVS                | HL381 | 10667    | 5762    | 523  |                              |
| 121     | 126.8  | 126.7  | Altered HVS        | HL381 | 10670    | 5762    | 524  |                              |
| 122     | 126.3  | 126.4  | Altered HVS        | HL381 | 10667    | 5762    | 524  |                              |
| 123     | 126.9  | 127    | Banded HVS         | HL381 | 10667    | 5762    | 525  |                              |

HL381

10667

5762

525

124

127.9

128

GSP/HVS Contact

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| SAMPLE | FROM   | то    | Rock Type           | BHID   | Northing | Easting | R.L. | Department        |
|--------|--------|-------|---------------------|--------|----------|---------|------|-------------------|
|        |        |       |                     |        |          |         |      | Catalogue Numbers |
| 125    | 128    | 128.1 | GSP/HVS Contact     | HL381  | 10667    | 5762    | 525  |                   |
| 126    | 128.2  | 128.3 | Banded HVS          | HL381  | 10667    | 5762    | 525  |                   |
| 127    | 129.35 | 129.4 | HVS with GSP        | HL381  | 10667    | 5763    | 527  |                   |
| 128    | 55.9   | 60.1  | Ba/GSP with BMS     | HL385  | 10670    | 5693    | 453  | -                 |
| 129    | 60,5   | 60.65 | Ba fragments in HVS | HL385  | 10670    | 5691    | 457  | -                 |
| RS200  | 164.9  | 165.1 |                     | HL.678 | 10202    | 5587    | 514  |                   |
| RS201  | 181.5  | 181.6 |                     | HL.678 | 10202    | 5591    | 498  |                   |
| RS202  | 181.6  | 181.7 |                     | HL678  | 10202    | 5591    | 498  |                   |
| RS203  | 182.9  | 183.1 |                     | HL678  | 10202    | 5591    | 497  |                   |
| RS204  | 184.1  | 184.3 |                     | HL678  | 10202    | 5592    | 495  |                   |
| RS205  | 184.5  | 184.7 |                     | HL678  | 10202    | 5592    | 495  |                   |
| RS210  | 14.2   | 14.35 | GSP                 | HL349  | 10731    | 5765    | 443  |                   |
| RS211  | 49.9   | 51.5  |                     | HL324  | 10712    | 5744    | 445  |                   |
| RS212  | 47.9   | 48    | -                   | HL386  | 10770    | 5684    | 435  |                   |
| RS213  | 53     | 53.25 |                     | HL386  | 10770    | 5681    | 439  |                   |
| RS219  | 66.4   | 66.5  |                     | HL649  | 10489    | 5699    | 533  |                   |
| RS220  | 67.9   | 68    |                     | HL.649 | 10490    | 5697    | 534  |                   |
| RS221  | 68.6   | 68.7  |                     | HL649  | 10490    | 5697    | 534  |                   |
| RS222  | 103.1  | 103.2 |                     | HL522  | 10352    | 5690    | 614  |                   |
| RS223  | 103.5  | 103.6 |                     | HL522  | 10352    | 5690    | 614  |                   |
| RS224  | 109.7  | 109.8 |                     | HL522  | 10352    | 5686    | 609  |                   |
| RS225  | 63.3   | 63.4  |                     | HL597  | 10529    | 5708    | 506  |                   |
| RS226  | 174.3  | 174.4 |                     | HL530  | 10375    | 5684    | 571  |                   |
| RS227  | 176.4  | 176.5 |                     | HL530  | 10375    | 5682    | 570  |                   |
| RS228  | 49.6   | 49.7  |                     | HL240  | 10909    | 5823    | 437  |                   |
| RS229  | 85.3   | 85.4  |                     | HL594  | 10251    | 5647    | 617  |                   |
| BS230  | 88.1   | 88.2  |                     | HL594  | 10250    | 5645    | 615  |                   |

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| Sample         | Easting | Northing  | Description       | RL. |
|----------------|---------|-----------|-------------------|-----|
| TICENI         |         |           |                   |     |
| TICSVI         |         |           | Ba crystal        | 405 |
| 73-75SD450A    | 5755    | 10730     | Si vein/ Ba       | 450 |
| 73-75SD450B    | 5755    | 10730     | GSP replacement   | 450 |
| 73-75SD450C    | 5755    | 10730     | GSP               | 450 |
| 73-75SD450D    | 5755    | 10730     | GSP               | 450 |
| 73-75SD450E    | 5755    | 10730     | GSP/Ba Contact    | 450 |
| 73-75SD450F    | 5755    | 10730     | Crystals in Ma Ba | 450 |
| 73-75SD450G    | 5755    | 10730     |                   | 450 |
| 73-75SD450H    | 5755    | 10730     |                   | 450 |
| 73-75SD450I    | 5755    | 10730     |                   | 450 |
| 73-75SD450J    | 5755    | 10730     |                   | 450 |
| 73-75SD450K    | 5755    | 10730     |                   | 450 |
| 63S405(i)      | 5745    | 10620/640 | Ba veining in BMS | 405 |
| 63S405(ii)     | 5745    | 10620/640 | Ba veining in BMS | 405 |
| 78-80WXC.1     |         |           | Ba nodule in LGO  | 495 |
| 78-80WXC.2     |         |           | Ba/LGO Contact    | 495 |
|                |         |           |                   |     |
| 59-73ND450(1)  | 5732    | 10607     | Frag Py, Ba Bn    | 450 |
| 59-73ND450(2)  | 5732    | 10607     | Ba Bn             | 450 |
| 59-72ND450(3)  | 5724    | 10595     | Ba xtal STZ       | 450 |
| 73-77SD495(1)  | 5772    | 10709     | Bn BMS            | 495 |
| 73-77SD495(2)  | 5770    | 10714     | Ba                | 495 |
| 73-77SD495(3)  | 5775    | 10715     | Ba Vn             | 495 |
| 73-77SD495(4)  | 5770    | 10721     | Ba Vn             | 495 |
| 74-82WXC525(1) |         |           | Ba                | 525 |
|                |         |           |                   |     |

Appendix 2.2a: Coordinates used in the construction of the plan projection of the Hellyer barite cap. The Eastings are derived largely from existing mine Sections.

| Northing       | Relation to Jack Fault | Min Easting | Max Easting |
|----------------|------------------------|-------------|-------------|
| 11030          | East                   | 5870        | 5877        |
| 10930          | East                   | 5867        | 5892        |
| 10910          | East                   | 5806        | 5866        |
| 10890          | East                   | 5824        | 5835        |
| 10890          | East                   | 5838        | 5869        |
| 10870          | East                   | 5791        | 5837        |
| 10870          | East                   | 5848        | 5863        |
| 10850          | East                   | 5766        | 5789        |
| 10850          | East                   | 5810        | 5864        |
| 10830          | East                   | 5780        | 5784        |
| <i>-</i> 10830 | East                   | 5789        | 5856        |
| 10810          | East                   | 5803        | 5820        |
| 10810          | East                   | 5834        | 5854        |
| 10790          | East                   | 5780        | 5830        |
| 10790          | West                   | 5727        | 5736        |
| 10770          | East                   | 5753        | 5780        |
| 10770          | East                   | 5753        | 5816        |
| 10770          | East                   | 5759        | 5812        |
| 10770          | East                   | 5836        | 5851        |
| 10770          | West                   | 5760        | 5770        |
| 10750          | East                   | 5743        | 5770        |
| 10750          | East                   | 5780        | 5805        |
| 10730          | East                   | 5771        | 5804        |
| 10710          | West                   | 5722        | 5777        |
| 10710          | East                   | 5747        | 5793        |
| 10710          | East                   | 5737        | 5798        |
| 10690          | East                   | 5746        | 7755        |
| 10690          | West                   | 5677        | 5700        |
| 10690          | West                   | 5752        | 5769        |
| 10670          | West                   | 5670        | 5708        |
| 10670          | West                   | 5725        | <u> </u>    |
| 10650          | West                   | 5642        | 5702        |
| 10650          | West                   | 5714        | 5751        |
| 10630          | West                   | 5679        | 5703        |
| 10630          | West                   | 5713        | 5737        |
| 10630          | West                   | 5748        | 5750        |
| 10610          | West                   | 5686        | 5730        |
| 10590          | West                   | 5688        | 5725        |
| 10570          | West                   | 5701        | 5723        |
| 10570          | West                   | 5670        | 5692        |
| 10570          | West                   | 5638        | 5640        |
| 10550          | West                   | 5674        | 5720        |
| 10530          | West                   | 5655        | 5700        |
| 10510          | West                   | 5651        | 5706        |
| 10490          | West                   | 5711        | 5650        |
| 10470          | West                   | 5680        | 5634        |
| 10450          | West                   | 5690        | 5640        |
| 10430          | West                   | 5696        | 5680        |
| 10410          | West                   | ?           | ?           |
| 10350          | East                   | 5697        | 5680        |
| 10350          | West                   | 5690        | 5623        |
| 10330          | West                   | 5665        | 5635        |
| 10285          | West                   | 5664        | 5630        |
|                |                        |             |             |

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Appendix 2.2b: Coordinates used in the construction of the plan projection of the Hellyer siliceous cap. The Eastings are derived largely from existing mine Sections

| Northing | Relation to Jack Fault | Min Easting | Max Easting |
|----------|------------------------|-------------|-------------|
| 10870    | East                   | 5803        | 5814        |
| 10850    | East                   | 5766        | 5787        |
| 10830    | East                   | 5794        | 5814        |
| 10810    | East                   | 5772        | 5828        |
| 10790    | East                   | 5794        | . 5830      |
| 10790    | West                   | 5726        | 5732        |
| 10770    | East                   | 5753        | 5807        |
| 10770    | East                   | 5775        | 5826        |
| 10770    | East                   | 5835        | 5851        |
| 10770    | West                   | 5768        | 5774        |
| 10750    | West                   | 5651        | 5691        |
| 10750    | West                   | 5709        | 5716        |
| 10750    | West                   | 5722        | 5732        |
| 10750    | East                   | 5753        | 5787        |
| 10730    | West                   | 5660        | 5680        |
| 10730    | West                   | 5733        | 5778        |
| 10730    | East                   | 5778        | 5808        |
| 10710    | West                   | 5741        | 5777        |
| 10690    | West                   | 5643        | 5654        |
| 10690    | West                   | . 5742      | 5758        |
| 10670    | West                   | 5727        | 5745        |
| 10670    | East                   | 5745        | 5770        |
| 10630    | West                   | 5697        | 5703        |
| 10630    | West                   | 5713        | 5723        |
| 10610    | West                   | 5675        | 5690        |
| 10590    | West                   | 5688        | 5694        |
| 10590    | West                   | 5700        | 5721        |
| 10530    | West                   | 5685        | 5702        |
| 10370    | West                   | 5688        | 5643        |
| 10350    | West                   | 5697        | 5675        |
| 10330    | East                   | 5695        | 5675        |
| 10330    | West                   | 5685        | 5665        |
| 10310    | West                   | 5670        | 5656        |

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# Appendix 3

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### Appendix 3.1: Whole Rock XRF Results

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| Sample      | SiO2  | TiO2   | A1203 | Fe2O3 | MnO  | MgO  | CaO   | Na2O  | K2O  | P2O5 | LOI   | Total  |
|-------------|-------|--------|-------|-------|------|------|-------|-------|------|------|-------|--------|
| <b>RS18</b> | 9.51  | 0.32   | 1.32  | 0.96  | tr   | tr   | 0.64  | <0.10 | 0.21 | <.1  | 1.11  | 100.25 |
| RS20        | 82.2  | < 0.05 | 0.95  | 5.23  | 0.08 | 0.84 | 2.56  | 0.35  | 0.57 | 0.15 | 4.55  | 100.46 |
| RS64        | 22.65 | <0.05  | 1.25  | 31.77 | 0.04 | 0.39 | 0.2   | 0.24  | 0.47 | 0.15 | 15.19 | 96.76  |
| R \$95      | 7.42  | 0.33   | 2.99  | 5.57  | 0.09 | 0.41 | 5.33  | <0.10 | 0.94 | 0.25 | 3.94  | 98.69  |
| RS112       | 39.14 | 0.44   | 14.34 | 6.34  | 0.14 | 2.58 | 17.86 | <0.10 | 3.4  | 0.18 | 15.42 | 99.84  |
| RS117       | 34.55 | 0.62   | 19.47 | 1.37  | 0.21 | 0.98 | 18.57 | 0.14  | 5.81 | 0.23 | 15.71 | 97.66  |
| RS118       | 45.87 | 0.36   | 10.46 | 16.25 | 0.11 | 1.13 | 10.9  | 0.11  | 2.9  | 0.18 | 11.13 | 99.48  |
| RS228       | 3.87  | 0.39   | 2.6   | 1.12  | 0.04 | 0.56 | 0.36  | <0.10 | 0.84 | 0.28 | 1.31  | 101.1  |
| RS128       | 45.45 | 0.4    | 13.21 | 7.4   | 0.08 | 1.07 | 6.33  | 0.18  | 4.31 | 0.16 | 7.72  | 98.81  |
| RS230       | 23.41 | 0.17   | 8.88  | 6.06  | 0.27 | 1.12 | 25.9  | <0.10 | 2.72 | 0.1  | 18.02 | 99.24  |

| Sample      | Nb (ppm) | Zr (ppm) | Y (ppm) | Sr (ppm) | Rb (ppm) | La (ppm) | Ce (ppm) | Nd (ppm) | Zn (ppm) | Cu (ppm) | Ni (ppm) | Cr (ppm) | V (ppm) | Ba (ppm) | Sc (ppm) | As (ppm) | Pb (ppm) |
|-------------|----------|----------|---------|----------|----------|----------|----------|----------|----------|----------|----------|----------|---------|----------|----------|----------|----------|
| <b>RS18</b> | bd       | bd       | bd      | 6820     | bd       | NA       | NA       | NA       | 10800    | tr       | NA       | NA       | NA      | 493300   | NA       | 39.6     | 5200     |
| <b>RS20</b> | <1       | <3       | <3      | 48       | 3        | NA       | NA       | NA       | 26000    | 501      | 20.7     | 4        | 9.5     | 3879     | 8.4      | 22000    | 2910.5   |
| RS64        | bđ       | bd       | bd      | <4       | bd       | NA       | NA       | NA       | 121008   | 2600     | bd       | 18.7     | 21.6    | 436      | 13.2     | 48.7     | 123000   |
| RS95        | bd       | bd       | bd      | 4850     | bd       | NA       | NA       | NA       | 10300    | tr       | NA       | NA       | NA      | 407700   | NA       | NA       | 4900     |
| RS112       | 4        | 63       | 14      | 236      | 90       | 32.2     | 55.4     | 24       | 67.4     | 84.8     | 219.2    | 854.8    | 297.5   | 2608     | 53.1     | 69.5     | 12.5     |
| RS117       | 7        | 94       | 19      | 160      | 151      | 60.8     | 120.7    | 46       | 21       | 103.8    | 167.5    | 1414.7   | 378.4   | 2919     | 75.4     | 5.6      | 4.7      |
| RS118       | 2        | 47       | 12      | 117      | 74       | 19.7     | 38.4     | 15.4     | 81.4     | 98.1     | 204.6    | 671.8    | 193.3   | 1524     | 36.9     | 76.5     | 47.9     |
| RS228       | bd       | bd       | bd      | 10570    | bd       | NA       | NA       | NA       | 1500     | tr       | NA       | NA       | NA      | 519800   | NA       | 20.8     | 1500     |
| RS128       | 5        | 109      | 11      | 594      | 136      | 36       | 117      | 34       | 3900     | 718.8    | 31.7     | 79.8     | 107     | 117800   | 21.3     | 396.9    | 7923.7   |
| RS230       | 2        | 74       | 16      | 1814     | 102      | 41       | 73       | 29       | 228.5    | 26.9     | 8.4      | 18.7     | 60      | 123800   | 13       | 122.4    | 84       |

\*NA = not analysed

.

°`>-

\*\*tr = trace

\*\*\*bd = below detection

### Appendix 3.2: Microprobe Barite Analysis

| Location                             | Sr (%)       | Ba (%) | S (%)         | O (%)   | Total         |
|--------------------------------------|--------------|--------|---------------|---------|---------------|
| RS32                                 |              |        |               |         |               |
| Small repl. Ba point 1               | b.d.         | 59.77  | 13.81         | 28.05   | 101.66        |
| Small repl. Ba point 2               | 0.50         | 58.57  | 1 <b>3.69</b> | 27.88   | 100.76        |
| Ring 1 Grain Traverse                | 0.07         | 67 (1  | 12.00         | . 27.01 | 100 20        |
| Length Point 1                       | 0.97         | 50.31  | 13.80         | 27.91   | 100.50        |
|                                      | 0.02         | 54.70  | 13.34         | 26.92   | 05 87         |
|                                      | 1 18         | 57 52  | 13.98         | 28.21   | 100 91        |
|                                      | 1.16         | 58.27  | 13.67         | 27.83   | 100.84        |
| 6                                    | 0.89         | 58.17  | 13.71         | 27.82   | 100.59        |
| Length Point 7                       | 0.86         | 58.04  | 13.47         | 27.46   | 99.82         |
| Luigu I onit ?                       |              |        |               |         |               |
| Ring 1 Grain Traverse                |              |        |               |         |               |
| Vertical Point 1                     | 0.82         | 58.56  | 13.35         | 27.33   | 100.06        |
| " " Point 2                          | 0.87         | 58.30  | 13.58         | 27.65   | 100.39        |
| <ul> <li>Point 3</li> </ul>          | 0.63         | 57.31  | 13.80         | 27.86   | 99.60         |
| " " Point 4                          | b.d.         | 58.71  | 13.83         | 27.95   | 100.50        |
| Ring 2 Barite Grain Traverse         | 0.14         | 50.50  | 12.00         | 20 15   | 101 70        |
| Point 1                              | 0.14         | 59.32  | 13.89         | 28.15   | 00.54         |
| Point 2                              | 0.a.<br>0.77 | 57 37  | 13.70         | 27.71   | 08 50         |
| Point 5                              | 0.17         | 59.28  | 13.43         | 27 44   | 100 30        |
| Ping 3 Sireal Bal                    | b.15         | 59.20  | 13.72         | 27.87   | 100.50        |
| Ring 3 Si repl. Ba 2                 | b.d.         | 58.87  | 13.72         | 27.83   | 100.07        |
| Ring 4 Pelict Ba crystal 1           | b.d.         | 59.55  | 13 29         | 27.26   | 100.10        |
| Ring 4 Relict Ba crystal 1           | b.d.         | 56.05  | 13.29         | 27 30   | 96.63         |
| Ring 4 Relict Da crystal 2           | b.d.         | 59.05  | 13.57         | 27 59   | 100.26        |
| Ring 5 Ba 2                          | 0.58         | 58.37  | 13.40         | 27.34   | 99.69         |
| Ring 6 Ba vein traverse              | 0.20         | 50.57  | 101.10        | 2.12    | ,,,,,,        |
| Width Point 1                        | b.d.         | 59.02  | 13.39         | 27.40   | 99.81         |
| " " Point 2                          | b.d.         | 58.61  | 13.12         | 26.88   | 98.61         |
| " " Point 3                          | b.d.         | 58.76  | 13.22         | 27.05   | 99.02         |
| " " Point 4                          | 0.15         | 59.41  | 13.92         | 28.15   | 101.64        |
| Vert Point 1                         | b.d.         | 59.52  | 13.67         | 27.80   | 101.00        |
| " " Point 2                          | b.d.         | 57.09  | 12.82         | 26.40   | 96.31         |
| " " Point 3                          | b.d.         | 59.31  | 13.48         | 27.49   | 100.28        |
| Ring 7 Barite Point 1                | b.d.         | 59.51  | 13.35         | 27.33   | 100.19        |
| Ring 7 Barite Point 2                | b.d.         | 58.95  | 13.62         | 27.66   | 100.23        |
| Ring 7 Barite Point 3                | 0.14         | 58.99  | 13.47         | 27.47   | 100.07        |
| RS18                                 |              |        |               |         |               |
| Large Barite Grain Length Traverse   |              |        |               |         |               |
| Point 1                              | 1.52         | 56.96  | 13.70         | 27.79   | <b>99.9</b> 6 |
| Point 2                              | 1.45         | 57.08  | 13.88         | 28.06   | 100.46        |
| Point 3                              | 0.33         | 59.42  | 13.82         | 28.02   | 101.59        |
| Point 4                              | 1.20         | 56.84  | 13.61         | 27.65   | 99.30         |
| Point 5                              | 1.15         | 57.53  | 13.79         | 27.93   | 100.41        |
| Point 6                              | 0.49         | 58.62  | 13.69         | 27.80   | 100.61        |
| Point 7                              | 1.10         | 57.52  | 13.77         | 27.87   | 100.25        |
| Point 8                              | 1.66         | 56.47  | 13.84         | 27.97   | 99.95         |
| Point 9                              | 1.94         | 56.39  | 13.85         | 28.04   | 100.23        |
| RS 57                                |              | 60.00  | 10.00         | 24.44   | 08 22         |
| Ring I Ba repl. by carb Point I      | D.d.         | 58.96  | 12.82         | 26.44   | 98.22         |
| Ring I Ba Repl. by Carb Point 2      | 0.44         | 58.34  | 12.89         | 26.50   | 98.17         |
| Ring I small ba                      | 0.00         | 51.12  | 12/1          | 20.24   | 91.33         |
| RS03<br>Bing 4 Lanas Balamin Baint 1 | 0.66         | 58 63  | 12 50         | 26.18   | 08.05         |
| Ring 4 - Large Da grain Foint 1      | 1.41         | 57.02  | 12.39         | 26.18   | 98.05         |
| " " Point 3                          | 1.41         | 57 30  | 12.00         | 26.53   | 07.00         |
| Ring S Large Lath Point 1            | 0.48         | 59.01  | 12.90         | 26.62   | 99.02         |
| Ring 5 Large Lath Point 2            | 1.63         | 56.98  | 12.98         | 26.70   | 98.28         |
| King 5 Dargo Dali 1 olik 2           | 1.05         | 20.70  |               | 20.70   | 20.20         |
| RS70                                 |              |        |               |         |               |
| Ring 1 P1 - Mid of acicular ba grain | 1.16         | 58.07  | 12.99         | 26.83   | 99.04         |
| ' Point 2                            | 1.35         | 57.06  | 12.95         | 26.71   | 98.06         |
| Point 3                              | 0.60         | 58.20  | 12.95         | 26.77   | 98.51         |
| Point 4 Rim                          | 0.25         | 53.60  | 13.93         | 29.02   | 96.80         |
| R2-3 random point                    | 1.49         | 56.87  | 12.92         | 26.64   | 97.92         |
| -                                    |              |        |               |         |               |
| RS70-R1 length traverse 1            | 0.51         | 54.28  | 12.70         | 26.58   | 94.07         |
|                                      | 0.82         | 56.25  | 11.94         | 25.33   | 94.34         |
| " "3                                 | 1.02         | 56.28  | 12.79         | 26.77   | 96.86         |

### Appendix 3.2: Microprobe Barite Analysis(cont.)

| Location                                   | Sr (%)       | Ba (%)         | S (%) | O(%)  | Total         |
|--|--------------|----------------|-------|-------|---------------|
| <b>*</b> *4                                | 1.48         | 56.80          | 12.11 | 25.88 | 96.27         |
| " "5                                       | 1.15         | 56.23          | 12.04 | 25.66 | 95.08         |
| " "6                                       | 1.10         | 56.18          | 12.51 | 26.66 | 96.45         |
| • •7                                       | 1.01         | 56.18          | 12.45 | 26.33 | 95.97         |
| " "8                                       | 0.91         | 56.65          | 12.40 | 26.18 | <b>96.</b> 14 |
| " "9                                       | 0.62         | 56.61          | 12.00 | 25.84 | 95.07         |
| <b>"</b> "10                               | 0. <b>69</b> | 56.93          | 12.28 | 26.00 | 95.90         |
| R 2-3 Point 1 lower section                | 0.25         | 58.91          | 12.93 | 26.70 | 98.79         |
| Point 2                                    | 0.33         | 58.81          | 12.68 | 26.34 | 98.17         |
| " "Point 3                                 | 0.30         | 58.36          | 12.90 | 26.62 | 98.19         |
| " Point 4                                  | 0.31         | 58.25          | 13.00 | 26.71 | 98.26         |
| " Point 5                                  | 0.33         | 58.69          | 12.82 | 26.53 | 98.30         |
| Point 6                                    | 0.75         | 50 56          | 12.94 | 20.07 | 98.02         |
| PS70                                       | 0.50         | 10-10          | 12.33 | 20.77 | 96.02         |
| K370                                       | 0.20         | 50 76          | 13 55 | 27 63 | 101.24        |
| Section 2 Long Ba Print 1                  | 0.29         | 57 55          | 13.55 | 27.05 | 00 52         |
| " " Point 2                                | 0.71         | 58 68          | 13.90 | 28 14 | 101 43        |
| " " Point 3                                | 0.87         | 58 37          | 13.05 | 28.17 | 101.45        |
| " " Point 4                                | 0.73         | 58.16          | 13.90 | 28.06 | 100.84        |
| " " Point 5                                | 0.99         | 58 11          | 13.83 | 20.00 | 100.04        |
| " " Point 6                                | 0.81         | 57.95          | 13.95 | 28.13 | 100.83        |
| " " Point 7                                | 0.69         | 57.80          | 13.47 | 27.36 | 99.31         |
| " " Point 8                                | 0.69         | 57.50          | 13.66 | 27.61 | 99.45         |
| " " Point 9                                | 0.78         | 57.47          | 13.49 | 27.40 | 99.15         |
| " " Point 10                               | 1.75         | 57.00          | 13.96 | 28.23 | 100.95        |
| " " Point 11-edge                          | 0.46         | 58.93          | 13.70 | 27.80 | 100.88        |
| Section 3 Long Ba Point 1                  | 1.24         | 57.62          | 13.88 | 28.07 | 100.80        |
| " " Point 2                                | 1.38         | 56.28          | 13.62 | 27.52 | 98.80         |
| " " Point 3                                | 1.58         | 57.46          | 14.11 | 28.42 | 101.57        |
| " " Point 4                                | 1.55         | 57.92          | 13.80 | 28.01 | 101.29        |
| " Point 5                                  | 1.65         | 57.41          | 13.82 | 28.02 | 100.89        |
| " " Point 6                                | 1.03         | 57.84          | 13.84 | 27.98 | 100.69        |
| " " Point 7                                | 0.94         | 57.49          | 13.49 | 27.39 | 99.30         |
| " Point 8                                  | 0.92         | 58.38          | 13.83 | 28.01 | 101.14        |
| " Point 9                                  | 0.99         | 58.27          | 13.72 | 27.86 | 100.84        |
| " " Point 10                               | 0.85         | 57.81          | 13.53 | 27.49 | 99.69         |
| " Point 11                                 | 1.38         | 56.12          | 13.65 | 27.56 | 98.70         |
| R-4 Length Traverse isolated Ba grain 1    | 0.12         | 59.79          | 13.60 | 27.70 | 101.21        |
| " Point 2                                  | 0.07         | 59.16          | 13.87 | 28.01 | 101.10        |
| " Point 3                                  | 0.10         | 58.63          | 13.54 | 27.47 | <b>99.7</b> 4 |
| " Point 4                                  | 0.27         | 59.14          | 13.85 | 28.00 | 101.26        |
| " Point 5                                  | 0.18         | 58.96          | 13.96 | 28.16 | 101.26        |
| " Point 6                                  | 0.33         | 58.94          | 13.77 | 27.89 | 100.93        |
| " Point 7                                  | 0.41         | 58.65          | 13.64 | 27.65 | 100.35        |
| " Point 8                                  | 0.21         | 59.62          | 13.71 | 27.85 | 101.40        |
| R-4 Width Traverse Isolated Ba grain 1     | b.d.         | 59.87          | 13.59 | 27.69 | 101.15        |
| Point 2                                    | 0.45         | 57.52          | 13.47 | 27.31 | 98.75         |
| Point 3                                    | 0.25         | 59.17          | 13.62 | 27.71 | 100.75        |
| R-5 Ba proximal to Rx pyrite rim - Point 1 | 0.20         | 58.71          | 12.53 | 26.08 | 97.52         |
| R-5 Ba Kx proximal to pyrite rim - Point   | 0.26         | 58.75          | 13.62 | 27.60 | 100.23        |
| R-1 Length traverse along 2mm Ba lath 1    | 0.83         | 58.59          | 13.79 | 27.95 | 101.15        |
| Point 2                                    | 0.92         | 58.60          | 13.86 | 28.08 | 101.46        |
| roint 3                                    | 1.28         | 57.70          | 13.87 | 28.06 | 100.98        |
|  | 1.22         | 21.81<br>50 AF | 13.00 | 21.19 | 100.53        |
|  | 1.02         | 36.03          | 12.00 | 28.33 | 101.50        |
| " " Point o                                | 1.01         | JO.99          | 13.99 | 28.21 | 100.80        |
| " " Doint ?                                | 115          | 57 50          | 12.0/ | 21.14 | 100.27        |
| " " Doint O                                | 1.15         | 57 /2          | 13.37 | 21    | 77.80         |
| " " Doint 10                               | 1.09         | 51.45<br>56 AF | 12.00 | 21.82 | 100.62        |
| Fount IV                                   | 1.40         | 20.40          | 13.81 | 21.84 | 79.37         |
| Detection Limit                            | 0.10         | 0.03           |       |       |               |

**Detection** Limit

0.10

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\*b.d. = below detection

### Appendix 3.3: Microprobe Carbonate Analysis

|                            | Mg       | Ca                | Mn           | Fe   | Sr   | Ba   | С     | 0     | Total  |
|----------------------------|----------|-------------------|--------------|------|------|------|-------|-------|--------|
| RS32                       | -        |                   |              |      |      |      |       |       |        |
| RS32 Ring 6-Carb 1         | 0.16     | 35.88             | 2.01         | 0.55 | 0.00 | 0.05 | 11.40 | 45.55 | 97.93  |
| RS32 Ring 6- Carb 2        | b.d.     | 36.74             | 1.69         | 0.19 | 0.01 | b.d. | 11.44 | 45.71 | 98.20  |
| RS32 Ring 2 - Carb 1       | 0.20     | 35.64             | 1.76         | 0.62 | 0.00 | 0.07 | 11.31 | 45.20 | 97.23  |
| RS32 Ring 2 - Carb 2       | 0.35     | 35.32             | 1.90         | 0.87 | 0.00 | 0.08 | 11.58 | 45.73 | 98.42  |
| RS63                       |          |                   |              |      |      |      |       |       |        |
| Ring 1- edge of ba repl.   | 0.27     | 37.14             | 0.61         | 0.08 | 0.36 | b.d. | 11.47 | 45.82 | 95.76  |
| Ring 5 - co in ba grain    | 0.28     | 36.36             | 0.48         | 0.20 | 0.57 | 0.04 | 11.27 | 45.02 | 94.23  |
| RS57                       |          |                   |              |      |      |      |       |       |        |
| Ring 1 in centre of carb   | 0.05     | 38.21             | 1.07         | 0.95 | 6.d. | 0.08 | 11.93 | 47.67 | 100.00 |
| Ring 3 in GSP Si impurity  | 0.18     | 39.35             | 1.61         | 1.63 | 0.54 | 0.05 | 12.66 | 50.58 | 106.59 |
|                            |          |                   | -            |      |      |      |       |       |        |
| Aberfoyle Resources Limite | d Microp | robe Carbon       | ate analyses | 5    |      |      | ,     |       |        |
| 1                          | 0.06     | 40.48             | 0.75         | 0.72 | b.d. | b.d. | 11.28 | 46.67 | 100.00 |
| 2                          | 0.03     | 36.87             | 2.83         | 0.73 | 0.23 | b.d. | 11.87 | 47.42 | 100.00 |
| 3                          | 0.18     | 37.97             | 0.85         | 0.92 | 0.40 | b.d. | 11.95 | 47.70 | 100.00 |
| 4                          | 0.04     | 40.62             | 0.24         | 0.12 | 0.12 | b.d. | 11.60 | 47.27 | 100.00 |
| 5                          | 0.03     | 40.00             | 0.24         | 0.13 | 0.08 | b.d. | 11.84 | 47.66 | 100.00 |
| 6                          | 0.08     | 39.49             | 0.51         | 0.84 | 0.06 | b.d. | 11.68 | 47.34 | 100.00 |
| 7                          | b.d.     | 40.57             | 0.35         | 0.07 | 0.08 | b.d. | 11.62 | 47.30 | 100.00 |
| 8                          | 0.11     | 38.89             | 0.42         | 0.94 | 0.08 | b.d. | 11.88 | 47.66 | 100.00 |
| 9                          | 0.17     | 37.52             | 2.45         | 0.58 | b.d. | b.d. | 11.82 | 47.45 | 100.00 |
| 10                         | 0.10     | 39.02             | 1.17         | 1.05 | b.d. | b.d. | 11.57 | 47.09 | 100.00 |
| 11                         | 0.15     | 38.78             | 0.41         | 0.39 | 0.32 | b.d. | 12.02 | 47.89 | 100.00 |
| 12                         | 0.24     | 39.19             | 0.35         | 0.41 | 0.06 | b.d. | 11.93 | 47.81 | 100.00 |
| 13                         | 0.31     | 39.58             | 0.10         | 0.46 | b.d. | b.d. | 11.84 | 47.70 | 100.00 |
| 14                         | 0.23     | 39.6 <del>9</del> | 0.14         | 0.53 | 0.10 | b.d. | 11.76 | 47.55 | 100.00 |
| 15                         | 0.11     | 38.83             | 0.23         | 0.40 | b.d. | b.d. | 12.18 | 48.21 | 100.00 |
| 16                         | 0.15     | 38.85             | 0.35         | 0.41 | 0.05 | b.d. | 12.11 | 48.09 | 100.00 |
| 17                         | 0.22     | 38.93             | 0.37         | 0.53 | 0.12 | b.d. | 11.97 | 47.86 | 100.00 |
| 18                         | 0.05     | 39.61             | 0.34         | 0.30 | 0.09 | b.d. | 11.89 | 47.72 | 100.00 |
| 19                         | 0.07     | 39.79             | 0.94         | 0.22 | 0.12 | b.d. | 11.62 | 47.24 | 100.00 |
| 20                         | 0.16     | 40.26             | 0.53         | 0.50 | 0.54 | b.d. | 11.31 | 46.70 | 100.00 |
| Average                    | 0.14     | 38.56             | 0.09         | 0.55 | 0.15 | b.d. | 11.33 | 45.57 |        |
|                            |          |                   |              | 0.04 |      |      |       |       |        |
| Detection limit            | 0.02     |                   | 0.04         | 0.04 | 0.04 | 0.04 |       |       |        |

# Appendix 3.4: Microprobe Sphalerite Analysis $f_{c} \leq$

|                         |         |          | ¥ 6.                | د.            |          |          |          |          |       |
|-------------------------|---------|----------|---------------------|---------------|----------|----------|----------|----------|-------|
| Sample I.D.             | S (wt%) | Mn (wt%) | Fe (wt%)            | Cu (wt%)      | Zn (wt%) | Ag (wt%) | Hg (wt%) | Se (wt%) | Total |
| GSP                     |         |          |                     |               |          |          |          |          |       |
| RS42:R4-Sp1             | 32.87   | b.d.     | 1.80 <sup>7</sup>   | b.d.          | 65.11    | b.d.     | b.d.     | b.d.     | 99.87 |
| RS42:R4-Sp2-edge        | 33.00   | b.d.     | 1.80 <sub>2</sub> ( | 0.12          | 64.76    | b.d.     | b.d.     | b.d.     | 99.68 |
| RS42:R2-sp incl. in asp | 32.50   | b.d.     | 3.60 🔬              | o.13          | 61.24    | b.d.     | b.d.     | b.d.     | 97.49 |
| RS42:R6 sph in chert 1  | 32.48   | b.d.     | 1.83 🤋              | <b>ባ 0.21</b> | 61.65    | b.d.     | b.d.     | b.d.     | 96.26 |
| RS42:R6sph in chert 2   | 33.03   | b.d.     | 1.86                | 0.99          | 60.79    | b.d.     | b.d.     | b.d.     | 96.73 |
| RS42:R7 sph 1           | 32.76   | b.d.     | 2.32                | c b.d.        | 62.55    | b.d.     | b.d.     | b.d.     | 97.71 |
| RS106:R1 sph in aspy    | 32.93   | b.d.     | 2.81                | 1.37          | 60.41    | b.d.     | b.d.     | b.d.     | 97.68 |
| RS106:R3 Sph acic text  | 33.13   | b.d.     | 2.59                | ∖ b.d.        | 62.31    | b.d.     | b.d.     | b.d.     | 98.09 |
| Barite Cap              |         |          |                     |               |          |          |          |          |       |
| RS83- Ring 1 Sph1       | 32.93   | 0.04     | 3.77                | 0.37          | 61.41    | b.d.     | b.d.     | b.d.     | 98.51 |
| RS83-Ring 1 sph2        | 32.81   | b.d.     | 3.59                | b.d.          | 62.20    | b.d.     | b.d.     | b.d.     | 98.64 |
| RS83-R3sph              | 33.12   | b.d.     | 2.64                | 0.47          | 62.10    | 0.24     | 0.46     | b.d.     | 99.04 |
| RS83 R3 sph2            | 32.48   | b.d.     | 1.24                | 0.30          | 62.66    | 0.20     | b.d.     | b.d.     | 97.00 |
| RS83 R5 Sphalerite      | 32.91   | b.d.     | 1.26                | b.d.          | 64.73    | 0.09     | b.d.     | b.d.     | 99.20 |
| RS75 R1 sph             | 32.70   | b.d.     | 3.22                | 3.00          | 58.64    | 0.19     | b.d.     | b.d.     | 97.77 |
| RS75 R3 sph             | 33.09   | b.d.     | 0.57                | <b>b.d.</b>   | 63.42    | b.d.     | b.d.     | 0.04     | 97.13 |
| Detection Limit         |         | 0.04     | 0.06                | 0.10          |          | 0.05     | 0.21     | 0.04     |       |

\*\*b.d. = below detection limit

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## Appendix 3.5: Microprobe Pyrite Analysis

|                                  | Au (%) | As (%) | Ag (%) | S (%) | Fe (%) | Сц (%) | Se (%) | Total  |
|----------------------------------|--------|--------|--------|-------|--------|--------|--------|--------|
| GSP-RS57                         |        |        |        |       |        |        |        |        |
| Ring 3 - Py fm core              | N.A.   | 0.51   | 0.11   | 51.47 | 45.02  | b.d.   | 0.07   | 98.60  |
| Ring 3 - Py fm rim               | N.A.   | 0.22   | b.d.   | 52.17 | 45.40  | b.d.   | 0.07   | 98.96  |
| Ring 3 - Py euhed. point         | N.A.   | 1.34   | b.d.   | 52.64 | 45.44  | b.d.   | 0.09   | 99.64  |
| Ring 5 Zoned Py Point 1          | N.A.   | 1.43   | b.d.   | 52.67 | 45.75  | b.d.   | b.d.   | 100.11 |
| Point 2                          | N.A.   | 1.33   | b.d.   | 52.13 | 45.98  | b.d.   | 0.17   | 99.64  |
| " " Point 3                      | N.A.   | 1.53   | b.d.   | 51.79 | 45.46  | b.d.   | 0.04   | 99.03  |
| " " Point 4                      | N.A.   | 0.83   | b.d.   | 50.44 | 45.72  | b.d.   | b.d.   | 99.20  |
| " " Point 5                      | N.A.   | 1.24   | b.d.   | 52.72 | 45.41  | b.d.   | b.d.   | 99.51  |
| Point 6                          | N.A.   | 0.97   | b.d.   | 52.56 | 46.41  | b.d.   | b.d.   | 100.28 |
| RS42:R4-Py1                      | N.A.   | b.d.   | . 0.07 | 53.05 | 46.67  | b.d.   | b.d.   | 100.00 |
| RS42:R4-Py2                      | N.A.   | b.d.   | b.d.   | 53.47 | 46.77  | b.d.   | b.d.   | 100.46 |
| RS42:R4-Py-small grain           | N.A.   | b.d.   | b.d.   | 52.81 | 46.23  | b.d.   | 0.07   | 99.45  |
| RS42:R1-Py framboid              | N.A.   | 1.90   | 0.16   | 49.89 | 43.38  | b.d.   | b.d.   | 96.77  |
| RS42:R5-pyrite 1                 | N.A.   | 0.06   | b.d.   | 52.02 | 45.39  | b.d.   | b.d.   | 97.87  |
| RS42:R5-pyrite 2                 | N.A.   | 0.42   | 0.14   | 52.18 | 45.55  | b.d.   | b.d.   | 98.52  |
| RS42:R5-pyrite overgrowth on Ga  | N.A.   | 2.39   | b.d.   | 50.13 | 43.47  | 0.19   | 0.02   | 96.41  |
| RS42:R5-pyrite fmb-rim           | b.d.   | 1.00   | b.d.   | 50.61 | 43.34  | 0.35   | b.d.   | 95.32  |
| RS42:R5-pyrite fmb-core          | 0.06   | 0.68   | 0.10   | 51.93 | 43.67  | 0.62   | b.d.   | 97.06  |
| RS42:R5-pyrite fmb rim2          | b.d.   | 0.74   | 0.17   | 51.75 | 43.03  | 1.30   | 0.64   | 97.08  |
| RS42:R5-py overgrowth rim1       | b.d.   | 1.49   | b.d.   | 50.75 | 44.13  | 0.42   | b.d.   | 96.86  |
| RS42:R5-py overgrowth rim2       | b.d.   | 1.10   | b.d.   | 50.61 | 43.39  | 0.40   | b.d.   | 95.50  |
| RS42: Pyrite euhedra in chert    | b.d.   | 0.12   | b.d.   | 52.49 | 45.42  | 0.28   | 0.03   | 98.34  |
| RS106:R1-Euhedral pyrite         | b.d.   | b.d.   | 0.07   | 52.84 | 46.17  | 0.05   | 0.02   | 99.18  |
| RS106:R1-Colloform pyrite        | b.d.   | 2.39   | b.d.   | 51.52 | 44.24  | 0.73   | b.d.   | 98.90  |
| RS106:R1-Pyrite framboid         | 0.09   | 0.41   | b.d.   | 53.08 | 45.60  | 0.12   | b.d.   | 99.37  |
| RS106:R3-Euhedral Pyrite         | b.d.   | b.d.   | 0.06   | 53.88 | 46.83  | b.d.   | b.d.   | 100.80 |
| RS106:R3 PY acic text core 1     | 0.17   | b.d.   | 0.16   | 52.97 | 45.85  | 0.06   | b.d.   | 99.60  |
| RS106:R3 py acic text -edge1     | b.d.   | 0.14   | b.d.   | 52.82 | 46.67  | 0.05   | b.d.   | 99.74  |
| RS106:R3 py acic text - edge2    | 0.10   | 1.81   | 0.25   | 51.22 | 44.59  | 0.36   | b.d.   | 98.34  |
| RS106:R3 Euhedral pyrite         | b.d.   | b.d.   | 0.08   | 53.10 | 46.12  | b.d.   | 0.02   | 99.32  |
| RS106:R3 py acic text centre     | 0.06   | b.d.   | b.d.   | 52.92 | 46.62  | b.d.   | 0.02   | 99.66  |
| RS106:R3 Fmb pyrite rim          | 0.45   | 1.34   | b.d.   | 51.76 | 43.81  | 0.24   | 0.05   | 97.66  |
| RS106:R4pyrite overgrowth        | b.d.   | 2.87   | 0.10   | 50.81 | 45.26  | 0.08   | b.d.   | 99.13  |
| RS106:R4-pyrite euhedra core     | b.d.   | b.d.   | b.d.   | 53.07 | 46.57  | b.d.   | 0.04   | 99.69  |
| RS106:R4-py fmb in chert         | b.d.   | 1.26   | b.d.   | 48.09 | 40.08  | 0.10   | b.d.   | 89.53  |
| RS106:R4-pyrite euhedra in chert | b.d.   | b.d.   | 0.06   | 52.50 | 45.75  | b.d.   | 0.09   | 98.41  |
| RS106:R5-pyrite acicular texture | b.d.   | 0.25   | b.d.   | 52.77 | 46.33  | 0.05   | b.d.   | 99.41  |
| RS106:R5-acicular pyrite         | b.d.   | 0.08   | b.d.   | 52.95 | 46.32  | 0.04   | b.d.   | 99.39  |
| barite Cap                       |        |        |        |       |        |        |        |        |
| RS83 R2-small py euhedra         | b.d.   | 0.51   | 0.08   | 46.20 | 40.40  | 0.08   | 0.02   | 87.29  |
| RS83-R3 fluffy py                | b.d.   | 4.96   | 0.05   | 48.59 | 43.81  | 0.10   | 0.04   | 97.55  |
| RS83-R3 pyrite fluffy 2          | b.d.   | 2.69   | 0.08   | 51.27 | 44.34  | 0.08   | b.d.   | 98.48  |
| RS83 R3 Py frambiod              | 0.06   | 1.39   | 0.07   | 51.80 | 44.84  | 0.10   | 0.04   | 98.28  |
| RS83 R5 Small pyrite euhedra     | b.d.   | 2.14   | b.d.   | 51.85 | 44.25  | 0.22   | 0.02   | 98.55  |
| RS83 R5 Small pyrite framboid    | 0.08   | 1.53   | b.d.   | 52.24 | 45.14  | b.d.   | b.d.   | 99.03  |
| RS83 R6 small py framboid        | b.d.   | 0.07   | b.d.   | 52.88 | 45.39  | b.d.   | b.d.   | 98.36  |
| RS75 R1 py cuhedra               | b.d.   | 0.15   | b.d.   | 52.52 | 44.98  | b.d.   | 0.02   | 97.70  |
| RS75 R3 py cuhedra               | b.d.   | 1.40   | b.d.   | 52.11 | 46.08  | b.d.   | b.d.   | 99.60  |
| RS83 R6 py 2                     | b.d.   | 0.07   | b.d.   | 53.11 | 45.98  | b.d.   | b.d.   | 99.18  |
| Detection Limit                  | 0.06   | 0.06   | 0.05   |       |        | 0.04   | 0.02   |        |
| *N.A. Not Analysed               |        |        |        |       |        |        | -      |        |

\*\*b.d. below detection

## Appendix 3.6: Microprobe Arsenopyrite Analysis

| Sample I.D.                              | S (wt%) | Fe (wt%) | As (wt%) | Se (wt%) | Ag (wt%) | Au (w1%) | Total  |
|--|---------|----------|----------|----------|----------|----------|--------|
| GSP Asenopyrite Analyses                 |         |          | • •      |          |          |          | 1044   |
| RS42:R3-Euhedral Asp - Rim               | 21.50   | 34.97    | 43.80    | 0.07     | b.d.     | b.d.     | 100.34 |
| RS42:R3-" " -Core                        | 21.89   | 35.47    | 43.18    | b.d.     | 0.13     | 0.10     | 100.79 |
| RS42:R3-" -Rim                           | 21.59   | 35.00    | 44.29    | b.d.     | b.d.     | 0.13     | 101.02 |
| RS42:R2-Euhedral Asp - Rim point 1       | 22.08   | 35.48    | 41.98    | 0.11     | b.d.     | b.d.     | 99.65  |
| RS42:R2-Euhedral Asp - point 2           | 21.74   | 35.57    | 44.22    | b.d.     | 0.17     | b.d.     | 101.78 |
| RS42:R2-Euhedral Asp - point 3           | 21.84   | 35.74    | 43.79    | b.d.     | b.d.     | b.d.     | 101.38 |
| RS42:R2-Euhedral Asp - Rim point 4       | 21.58   | 35.42    | 44.60    | b.d.     | b.d.     | b.d.     | 101.93 |
| RS106:R1 Asp euhedra-rim 1               | 22.46   | 35.50    | 42.52    | 0.27     | 0.12     | b.d.     | 100.88 |
| RS106:R1 Asp euhedra-core 2              | 22.53   | 35.19    | 41.97    | b.d.     | b.d.     | b.d.     | 99.80  |
| RS106:R1 Asp euhedra-rim 3               | 22.50   | 35.16    | 42.00    | b.d.     | b.d.     | 0.11     | 99.83  |
| RS106:R3 Asp euhedra in acicular texture | 22.08   | 34.94    | 43.66    | b.d.     | 0.13     | b.d.     | 100.84 |
| RS106:R4-aps in gal overgrowths          | 22.21   | 34.42    | 43.09    | b.d.     | b.d.     | b.d.     | 99.85  |
| Detection Limits                         |         | 0.05     | 0.05     | 0.03     | 0.05     | 0.06     |        |

# Appendix 3.7: Microprobe Galena Analysis

| Sample I D                                  | S (wt%) | Pb (wt%) | Total          |
|---|---------|----------|----------------|
| GSP data                                    | - (,    |          |                |
|   | 12.86   | 86.40    | 99.27          |
|   | 13 59   | 90.12    | 103.77         |
| RS42:R4-Oaz                                 | 15.50   | 83.80    | . 99.31        |
| RS42:RS-Oa pseudomorph point 1              | 17.55   | 76.67    | 04.25          |
| K542:K5-Ga pseudomorph point 2(very spongy) | 17.55   | 70.07    | 74.22          |
| RS42:R5 Galena core of framboid py          | 13.37   | 87.73    | 101.14         |
| RS42:R5 Galena intergrowth with pyrite      | 13.45   | 84.44    | 97.89          |
| RS42:R7 Galena infillings                   | 13.41   | 88.77    | 102.23         |
| RS 106:R3 acicular textures                 | 13.52   | 86.96    | 100.54         |
| RS 106:R3-acicular textures                 | 13.58   | 86.71    | 100.34         |
| RS106:R4-matrix galena                      | 13.49   | 87.92    | 101.42         |
| RS 106:R4-core of pyrite framboid           | 13.78   | 84.54    | 98.38          |
| Barite Cap                                  |         |          |                |
| RS83 R2 galena                              | 13.45   | 84.83    | 98.28          |
| RS 83 Galena                                | 13.40   | 85.32    | 98.73          |
| RS83 R6 galena                              | 13.50   | 85.98    | 99 <i>-</i> 53 |
| RS83 R5 galena                              | 13.62   | 85.31    | 99.00          |
| RS75 galena R1                              | 13.70   | 86.00    | 99.71          |
| RS75 R3 galena                              | 13.27   | 86.20    | 99.57          |
| RS75 R2 galena                              | 13.59   | 86.00    | 99.65          |

### Appendix 3.8: Microprobe Tetrahedrite Analysis

| Sample I.D.                       | S (wt%) | Fe (wt%) | Cu (wt%) | Zn (wt%) | As (wt%) | Ag (wt%) | Sb (wt%) | Bi (wt%) | Total  |
|-----------------------------------|---------|----------|----------|----------|----------|----------|----------|----------|--------|
| GSP                               |         |          |          |          |          |          |          |          |        |
| RS 42:Ring 4-Tetrahedrite point 1 | 24.66   | 2.70     | 37.64    | 4.46     | 0.06     | 2.83     | 28.60    | 0.08     | 101.03 |
| RS 42:Ring 4-Tetrahedrite point 2 | 24.65   | 2.82     | 37.62    | 4.34     | 0.34     | 3.04     | 28.35    | 0.00     | 101.16 |
| RS42:R7 Tetra,                    | 28.96   | 2.62     | 16.40    | 5.47     | 0.74     | 1.73     | 11.38    | 0.00     | 97.29  |
| Barite                            |         |          |          |          |          |          |          |          |        |
| RS75 R1 tetra                     | 23.88   | 0.04     | 14.73    | 0.01     | 19.44    | 0.00     | 19.50    | 17.60    | 95.20  |
| Detection Limit                   |         | 0.06     | 0.12     | 0.08     | 0.04     | 0.10     |          | 0.23     |        |

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#### Appendix 3.9: Microprobe Electrum Analysis

| Description         | Size (µ) | Ag (wt%) | Au (wt%) | Hg (wt%) |
|---------------------|----------|----------|----------|----------|
| Grain 1 Barite-core | 12.5     | 45.42    | 47.22    | 7.35     |
| Grain 1 Barite-rim  | 12.5     | 42.77    | 47.4     | 9.84     |
| Grain 1 Barite-core | 12.5     | 34.04    | 60.19    | 5.76     |
| Grain 2             | 9.5      | 19.12    | 80.51    | 0.37     |
| Grain 3             | 5.5      | 20.23    | 78.99    | 0.78     |
| Grain 4             | 4.5      | 20.38    | 79.44    | 0.18     |
| Grain 5             | 4.5      | 9.84     | 89.85    | 0.31     |
| Grain 6             | 10.5     | 21.49    | 78.27    | 0.24     |
| Grain 8             | 3        | 9.84     | 90.17    | b.d.     |
| Grain 9             | 2        | 20.91    | 79       | b.d.     |
| Grain 10            | 6        | 21.55    | 78.45    | b.d.     |
| Grain 10            | 6        | 21.3     | 78.7     | b.d.     |
| Grain 11- rim       | 25       | 19.09    | 80.7     | 0.21     |
| Grain 11- core      | 25       | 19.24    | 80.39    | 0.37     |
| Grain 11- rim       | 25       | 19.04    | 80.82    | 0.13     |
| Grain 12            | 7        | 9.83     | 90.18    | b.d.     |
| Grain 13-rim        | 20       | 19.18    | 80.61    | 0.21     |
| Grain 13- core      | 20       | 18.86    | 81.01    | 0.13     |
| Grain 13- rim       | 20       | 19.27    | 80.5     | 0.23     |
| Grain 15 Barite     | 6.5      | 53.33    | 38.98    | 7.68     |
| Grain 16            | 5        | 21.08    | 77.77    | 1.15     |
| Grain 17            | 6        | 10.59    | 89.41    | b.d.     |
|                     |          |          |          |          |

\*b.d. below detection

# Appendix 4

|            |  |         |           |          |         | <u> </u> | and a state of the advector of the state of |            | %a)    |
|------------|--|---------|-----------|----------|---------|----------|---|------------|--------|
| Sample No. | Description                                  | BHID    | DEPTH     | NORTHING | EASTING |          |   |            |        |
|            |  |         |           |          |         | Barite   | Pyrite  | Sphalerite | Gaiena |
|            |  |         |           |          |         |          |   |            |        |
| RS001      | contact between barite and BMS               | HL386   | 55.8      | 10670    | 5679    | 42.4     | 9.9   |            |        |
| RS008      | fragmental barite with recrystallized        | HL.324  | 123.5     | 10710    | 5783    | 26.0     |   |            | 7.I    |
|            | galena between fragments                     |         |           |          |         |          |   |            |        |
| RS10       | small acicular barite needles                | HL413   | 106.5     | 10633    | 5727    | 43.7     |   |            |        |
| RS11       | fine grained banded barite                   | HL413   | 115.5     | 10633    | 5728    | 45.4     |   | 7.6        |        |
| RS12       | pyrite, barite vein in massive barite        | HL.413  | 118.5     | 10633    | 5729    | 40.7     | 10.3  |            |        |
| RS14       | fragmental barite laths in barite matrix     | HL413   | 134.6     | 10634    | 5731    | 40.8     |   |            |        |
| RS15       | fine grained massive barite close to HVS     | HL417   | 72.5      | 10629    | 5686    | 36.0     |   |            |        |
| RS17       | siliceous cutting massive barite             | HL414   | 119       | 10632    | 5718    | 37.6     | 11  |            |        |
| RS18B      | barite lath in fine grained barite matrix    | HL414   | 127.1     | 10632    | 5719    | 37.8     |   |            |        |
| RS18C      | fine grained barite matrix                   | HL414   | 127.1     | 10632    | 5719    | 36.6     |   |            |        |
| RS19       | massive fine grained barite with silica      | HL414   | 136.3     | 10632    | 5719    | 34.0     |   |            |        |
|            | cavity infillings                            | HL414   |           |          |         |          |   |            |        |
| RS20       | massive fine grained barite near GSP contact | HL414   | 134.7     | 10632    | 5719    | 39.5     |   |            |        |
| RS22       | small barite acicular needles in barite      | HL414   | 148.8     | 10632    | 5720    | 38.2     |   |            |        |
| RS25       | fragmental BMS with framboidal pyrite in     | HL410   | 105.1     | 10649    | 5719    | 37.9     | 8.1   |            |        |
|            | fine grained massive barile                  | HL410   |           |          |         | 5.15     | 0.1   |            |        |
| RS26       | barite laths in fine grained pyrite matrix   | FΠ 410  | 118 5     | 10649    | 5719    | AA '0    |   |            |        |
| RS27       | fine grained barite in BMS/Ba                | HI 410  | 115.9     | 10649    | 5719    | 46.0     | 65  |            |        |
| R\$29      | harite in carbonate/BMS (ragmental           | Н 410   | 141.2     | 10649    | 5710    | 22.5     | 0.0   |            |        |
| R\$35      | fine grained harite with coarse by and soh   | нц 452  | 102.8     | 10612    | 5710    | 12 1     | 0 1   | 7.0        |        |
| R\$55      | handed purite and harite                     | HI 364  | 168.8     | 10752    | 5767    | 43.4     | 0.1<br>7 0  | 7.9        |        |
| R\$70      | acicular barite near BMS/Ba contact          | FIL 625 | 85 5      | 10785    | 5664    | 20.9     | 7.9   |            |        |
| R\$73      | handed havite and culnhides                  | HL 366  | 160.5     | 10265    | 5755    | 39.0     | 9.9   |            |        |
| R576       | purite voin crosscutting massive barite      | LII 266 | 162.0     | 10746    | 5756    |          | 10.1  |            |        |
| 2580       | Ba/BMS fine orginal basis matrix with        | LII 244 | 162.9     | 10746    | 5750    | 20.4     | 10.7  |            |        |
| 1000       | monutallized galana and good enhaled         | LII 266 | 106.4     | 10746    | 5151    | 39.0     |   |            |        |
| D 5 9 1    | recrystanized gatena and zoned sphalente     | TIL 266 | 160       | 10746    | 69.69   |          |   |            |        |
| R301       | DAS with source solars and anhalasite        |         | 109       | 10746    | 5/5/    |          | 1.5   |            |        |
| R302       | Bivis with coarse galeria and sphalerite     | HL 300  | 1/0.1     | 10746    | 5/5/    |          |   | 8.2        | 0.8    |
| K383       | contact between line grained massive barite  | HL300   | 1//.8     | 10746    | 5759    | 42.4     |   | 7.6        | 6.4    |
| D SO2      | and coarse sphalerite/galena BIVIS           |         | 100 5     |          |         |          |   |            |        |
| R393       | The grained banded barite                    | HL610   | 109.5     | 10316    | 5637    | 35.3     | 6.6   |            |        |
| K394       | contact between massive Ba/BMS               | HL610   | 110       | 10316    | 5636    | 35.2     |   | 6.1        |        |
| RSIOI      | bartle veins (0.5mm) cutting BMS             | HL326   | 132.8     | 10804    | 5772    |          | 8.7   |            |        |
| RS200      | south end tragmental barite                  | HL678   | 164.9     | 10201    | 5587    | 41.8     |   |            |        |
| RS219      | barite grain rimmed by pyrite in massive     | HL649   | 66.4      | 10489    | 5699    | 38.2     |   |            |        |
| -          | fine grained barite                          |         |           |          |         |          |   |            |        |
| RS223      | barite vein cutting massive barite           | HL522   | 103.5     | 10352    | 5690    | 43.7     |   |            |        |
| RS225      | fine grained fragmental barite with GSP      | HL597   | 63.3      | 10529    | 5708    | 41.9     |   |            |        |
| RS450E     | pyrite vein in massive barite                | U/G*    | 495 Level | 10730    | 5755    |          | 14.6  |            |        |
| 7375SDA    | barite veining in BMS - centre of vein       | U/G*    | 495 Level | 10730    | 5755    | 44.0     |   |            |        |
| 7482WXC 65 | massive interlocking barite - no sulphides   | U/G*    | 495 Level |          |         | 37.6     |   |            |        |
| /37/SD5A   | barite vein in BMS -centre of vein           | U/G*    | 495 Level | 10715    | 5755    | 41.5     |   |            |        |
| 1377SD5B   | barite vein in BMS -outer part of vein       | U/G*    | 495 Level | 10715    | 5755    | 42.0     |   |            |        |
|            |  |         |           |          |         |          |   |            |        |
|            |  |         |           |          | Average | 39.6     | 9.7   | 7.5        | 0.8    |

# Appendix 4.1: Barite Cap - Sulphur isotope sample descripitions, sample locations and $\delta^{34}S$ values.

\*U/G = Underground Sample

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| Sample No. | Description                                 | BIIID                | Deptii    | NORTHING | EASTING          | 234S value (%) |        |            |        |
|------------|---|----------------------|-----------|----------|------------------|----------------|--------|------------|--------|
|            |   |                      |           |          |                  |                |        |            |        |
|            |   |                      |           |          |                  | Barite         | Pyrite | Sphalerite | Galena |
|            |   |                      |           |          |                  |                |        |            |        |
| RS006      | fine grained pyrite in siliceous chert      | IIL324               | 52.5      | 10712    | 5745             |                | 9      |            |        |
| RS007      | rounded pyrite grain (2cm) in GSP           | IIL324               | 49.1      | 10712    | 5743             |                | 8.7    |            |        |
| RS13       | barite crystals in a siliceous vein         | HL413                | 130.1     | 10633    | 5731             | 47.3           |        |            |        |
| RS21       | colloform pyrite with sphalerite in GSP     | IILA14               | 140.7     | 10632    | 5719             |                | 32.2   | 10.4       |        |
| RS32       | framboidal pyrite in GSP/Ba /               | IIL452               | 91.3      | 10612    | 5709             | 49.6           | 9.5    |            |        |
| RS42       | colloform pyrite nodule in GSP              | HL 295               | 163       | 10814    | 578 <del>9</del> |                | 36.9   |            |        |
| RS43       | large (2cm) rounded pyrite grain in GSP     | HL295                | 165.3     | 10814    | 5790             |                | 23     |            |        |
| RS44       | low iron sphalerite in siliceous matrix     | 1 <del>11_2</del> 95 | 168.6     | 10814    | 5791             |                |        | 8.3        |        |
| RS57       | barite veining in GSP & framboidal pyrite   | HL364                | 180.4     | 10752    | 5770             | 43.4           | 8.2    |            |        |
| RS63       | rounded barite and pyrite in GSP            | 11L315               | 174.9     | 10771    | 5810             | 46.4           | 9.6    |            |        |
| RS64       | pyrite grain in GSP                         | HL315                | 173.4     | 10771    | 5811             |                | 9.7    |            |        |
| RS65       | fine grained pyrite in GSP                  | HL315                | 175.9     | 10771    | 5811             |                | 8.2    |            |        |
| RS67       | acicular needles of barite in milky chert   | III.461              | 247.5     | 10434    | 5685             | 45.0           | 7.8    |            |        |
| RS69       | large zoned sphalerite in GSP (Fe rich)     | IIL625               | 81.8      | 10285    | 5665             | ×              |        | 6          |        |
| RS69       | large zoned sphalerite in GSP (Fe poor)     | HIL625               | 81.8      | 10285    | 5665             |                |        | 6.1        |        |
| RS84       | low irom sphalerite in silica (pyrite poor) | HL366                | 185.4     | 10746    | 5761             |                |        | 7.5        |        |
| RS87       | pyrite in GSP                               | HL349                | 17.8      | 10731    | 5764             |                | 11.8   |            |        |
| RS89       | siliceous fragment in pyritic BMS           | HL349                | 15.3      | 10731    | 5766             |                | 12.3   |            |        |
| RS103      | framboidal pyrite at edge of siliceous vcin | HL326                | 148.9     | 10804    | 5779             |                | 11.1   |            |        |
| RS104      | GSP with high pyrite content                | HL326                | 149.4     | 10804    | 5780             |                | 11.1   |            | 5.5    |
| RS105      | centre of pyrite grain in GSP               | HL326                | 167.7     | 10804    | 5780             |                | 7.5    |            |        |
| RS106(i)   | framboidal pyrite in GSP                    | HL326                | 168.4     | 10804    | 5788             |                | 12.3   |            |        |
| RS106(ii)  | framboidal pyrite aggregate in GSP          | HL326                | 170.7     | 10804    | 5790             |                | 14.5   |            |        |
| RS202      | south end fragmental GSP/Ba                 | 11L678               | 181.6     | 10202    | 5591             | 42.8           |        |            |        |
| RS224      | barite grain in GSP                         | HL.522               | 109.7     | 10352    | 5686             | 40.8           |        |            |        |
| RS450F     | contact Ba/GSP with siliceous pyritic vein  | U/G*                 | 450 Level | 10730    | 5755             | 39.5           | 16.9   |            |        |
| 73774      | intergrowths of Ba & milky chert            | U/G*                 | 450 Level | 10715    | 5775             | 38.2           |        |            |        |
|            |   |                      |           |          |                  |                |        |            |        |
|            | <u>·</u>                                    |                      |           |          | Average          | 43.7           | 14.5   | 7.7        | 5.5    |

Appendix 4.2: Siliceous Cap - Sulphur isotope sample descripitions, sample locations and  $\delta^{34}$ S values.

\*U/G= Underground Sample

~ indicates no Au assay

Appendix 4.3: Hangingwall Volcaniclastic Sequence - Sulphur isotope sample descriptions, sample locations and  $\delta^{34}$ S values.

| Sample No. | Description                             |         | DEPTH     | NORTHING | EASTING | ∂34S value (‰) |        |            |        |
|------------|---|---------|-----------|----------|---------|----------------|--------|------------|--------|
|            |   | BHID    |           |          |         |                |        |            |        |
|            |   |         |           |          |         | Barite         | Pyrite | Sphalerite | Galena |
|            |   |         |           |          |         |                |        |            |        |
| RS68A      | barite fragment in HVS                  | IIL.625 | 76        | 10285    | 5667    | 40.64          |        |            |        |
| RS68B      | large barite crystals forming in IIVS   | IIL.625 | 76        | 10285    | 5667    | 41.784         |        |            |        |
| RS92       | fragmental barite in HVS                | HL610   | 107.1     | 10316    | 5637    | 40.675         |        |            |        |
| RS229      | barite grain close to HVS/Ba contact    | HL.594  | 85.3      | 10251    | 5647    | 41.084         |        |            |        |
| RS230      | barite fragment in HVS                  | IIL.594 | 88.1      | 10250    | 5645    | 36.509         |        |            |        |
| HVS450     | barite lath in fragmental & pyritic HVS | U/G*    | 450 Level | 10730    | 5755    | 40.929         |        |            |        |
|            |   |         |           |          |         | 40.2           |        |            |        |

\*U/G = Underground Sample

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