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# SYN-DEPOSITIONAL FAULT CONTROLS ON THE HELLYER VOLCANIC-HOSTED MASSIVE SULPHIDE DEPOSIT

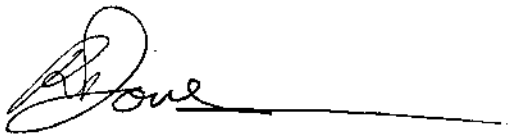
Richard C. Downs B.AppSc.

A thesis submitted in partial fulfilment  
of the requirements for the degree of  
Master of Economic Geology

Geology Department  
University of Tasmania

March 1993

This thesis contains no material which has been accepted for the award of any other higher degree or graduate diploma in any tertiary institution and, to the best of my knowledge and belief, the thesis contains no material previously published or written by another person, except when due reference is made in the text of the thesis.

A handwritten signature in dark ink, appearing to read 'R. C. Downs', followed by a long horizontal line extending to the right.

**Richard C. Downs**

# Abstract

Hellyer is a late-Middle Cambrian volcanic-hosted massive sulphide deposit, situated within the Mount Read Volcanics of western Tasmania.

The effects of post-depositional folding and wrench faulting have been removed from the deposit to produce an interpreted Cambrian seafloor topographic contour map. This map reveals that the massive sulphide orebody formed within a north-south striking, fault controlled basin. Intersections of active, syn-depositional faults appear to have channelled hydrothermal fluids, and hence, controlled the location of massive sulphide formation.

The most intense hydrothermal fluid flux was focussed on the intersection of three major structural elements:-

- i) north-south striking basin bounding faults,
- ii) a northeast striking fault, and
- iii) a northwest striking ridge.

Metal-rich stringer veins within the footwall indicate that the orebody formed during the period of time when northeast striking faults were actively dilating due to northwest directed extension.

During the waning stages of the hydrothermal system, basaltic magma rose up through a similar set of fissures and erupted onto the seafloor, burying and preserving the deposit.

# Acknowledgements

I would like to thank Aberfoyle Limited for the generous support given to me during the two years of this Masters degree. Particular thanks go to Gary McArthur (Chief Geologist, Hellyer) for his encouragement, intellectual stimulation and critical evaluation of this thesis and to Neil Ryan for his skilful and patient drafting.

Many of the ideas presented in this thesis developed from discussions with the following geologists: Gary McArthur, Chris Drown, Steve Richardson, Henry Kurth, Graham Howard, Bruce Gemmell, Ron Berry, John Waters, Mike Etheridge and Jacqui Windh.

Finally, special thanks go to my wife, Samantha, for her love, patience and encouragement during the preparation of this thesis.

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# Chapter One

## Introduction

The Hellyer volcanic-hosted massive sulphide (VHMS) deposit is situated approximately 90 km south of Burnie in western Tasmania (figure 1). The deposit lies within the late-Middle Cambrian Mount Read Volcanics. Its pre-mining ore resource was 16.5 million tonnes averaging 13.9% Zn, 7.2% Pb, 168g/t Ag, 2.5g/t Au and 0.39% Cu (McArthur et al., 1992).

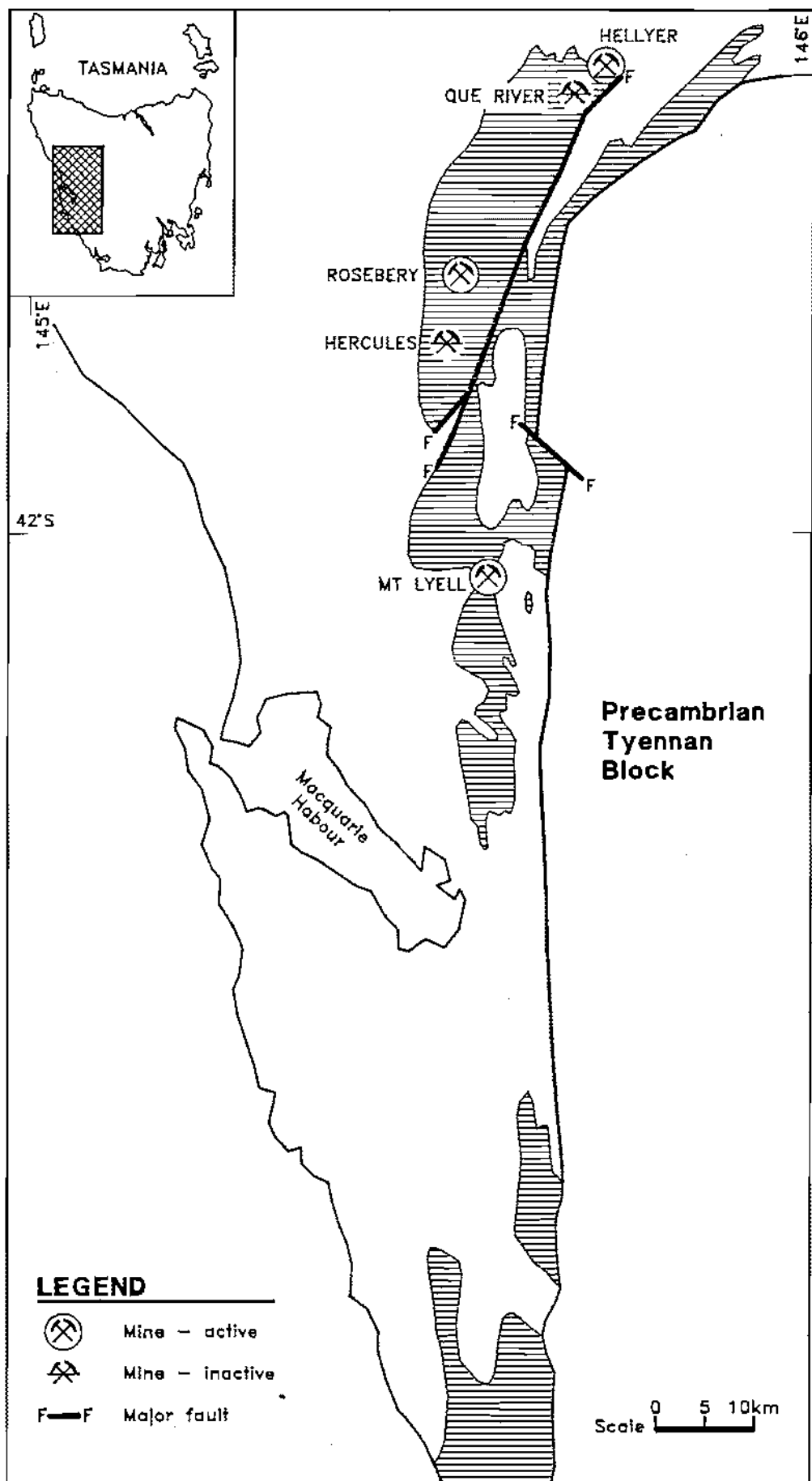
Hellyer was discovered by Aberfoyle Limited in August 1983 when diamond drill hole HL3 (which was targetted at coincident *UTEM* and Pb soil geochemical anomalies in an area of intense fuchsite alteration and barite veining) intersected 24m of massive sulphide at a vertical depth of 120m (Eadie and Silic, 1984; Eadie, Silic and Jack 1985).

Since the discovery of Hellyer over 20,000m of underground development and 100,000m of diamond drilling have been completed. This has provided excellent exposure of the deposit and its host rocks.

### 1.1 Outline Of Thesis

The important role of faulting in the formation of modern-day seafloor massive sulphide deposits has long been recognised (Rona, 1988; Embley et al., 1988). Modern-day deposits are studied by means of submersibles, conductivity-temperature-depth





**Figure 1:** Location of the Hellyer deposit within the Mount Read Volcanics (stripes) of Tasmania. From Gemmell and Large (1992).

probes, video imagery and sidescan sonar techniques (Rona and Clague, 1989). Typically, detailed mapping of the seafloor reveals numerous escarpments, ridges and valleys which are interpreted to reflect the local fault pattern. The massive sulphides are usually located on top of, or alongside, active faults in localised basins within broader topographic highs, such as seamounts or spreading ridges. Intersections of two or more faults are important sites of hydrothermal fluid discharge (Rona and Clague, 1989). Often there is associated active volcanism localised on similar structures, this magmatic activity probably reflects the underlying "heat-engine" driving the hydrothermal system (Embley et al., 1988).

The Hellyer deposit was preserved almost intact and, with an absence of intense deformation and low metamorphic grade, it provides an excellent opportunity to compare the environment of formation of a Cambrian massive sulphide occurrence with modern analogues.

The aims of this study are to:-

- i) re-construct the Cambrian seafloor topography, and
- ii) outline the likely locations and orientations of syn-depositional structures (ie. faults active during the formation of the orebody) and specifically to identify those structures which provided the primary channelways of the massive sulphide forming hydrothermal solutions.

Small to medium scale Cambrian features, in the form of base metal and barite feeder veins and planar basalt dykes, are recorded during routine mapping and diamond drill core logging. In order to delineate larger scale Cambrian structures the effects of post-depositional deformation have been removed from the present deposit geometry to produce an interpreted Cambrian seafloor topographic contour map. (Post-depositional deformation includes Devonian-age folding and more recent brittle wrench faulting.) This map was then used in a fashion analogous to modern seafloor surveys in order to identify likely syn-depositional structures.

## Chapter Two Geology

### 2.1 Regional Geology

The Hellyer deposit lies within the late-Middle Cambrian Mount Read Volcanics in a suite of basic to intermediate, calc-alkaline, submarine volcanics known as the Que-Hellyer Volcanics (Komyshan, 1986).

The Que-Hellyer Volcanics (QHV) lie toward the northernmost exposure of the Mount Read Volcanics on the Tasmanian west coast (figure 1). Less than 1km north<sup>1</sup> of Hellyer the Cambrian volcanics are unconformably overlain by up to 300m of Tertiary basalt.

The eastern and southwestern margins of the QHV are controlled by the Henty-Mt.Cripps Fault and the Mt.Charter Fault respectively (figure 2). This has led some workers to suggest that the QHV formed within a fault controlled submarine basin (Corbett and Komyshan, 1989).

The QHV were deformed during the Middle-Devonian producing upright, open folds about north-south and east-west trending axes (Corbett and Komyshan, 1989). A later, brittle deformation event followed during the Mesozoic (Berry, 1989). This event formed

---

<sup>1</sup>All orientations quoted in this report are based on Aberfoyle's Hellyer-Que River mine grid unless otherwise specified. The mine grid north is 22.1° east of AMG north and was 10° east of magnetic north during 1992.

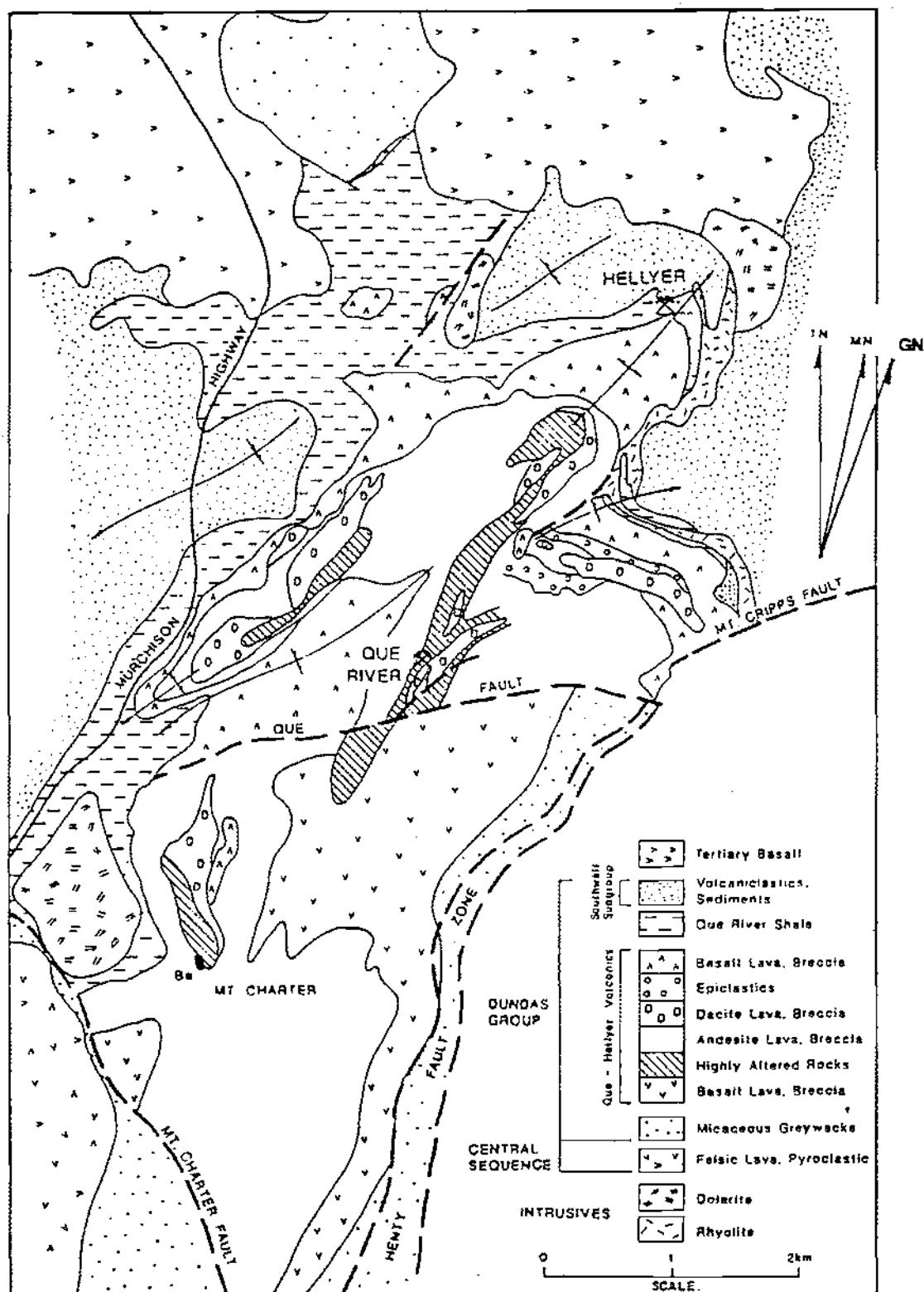


Figure 2: Que-Hellyer Volcanics, regional geology map.  
From Richardson and Drown (1990).

wrench faults in association with sinistral movement along the Henty Fault.

The smaller Que River VHMS deposit lies approximately 3km to the south of Hellyer. A broad zone of hydrothermally altered rocks lies between the two deposits.

Regional metamorphic grade is prehnite-pumpellyite facies (Whitford, et al., unpubl. data, 1982).

## **2.2 Tectonic Models for the Formation of the Mount Read Volcanics**

Several models have been proposed for the tectonic setting of the formation of the Mount Read Volcanics (MRV). While the models differ in detail they generally place the MRV within a locally extensional setting adjacent to a convergent plate boundary.

A summary of recent tectonic models is given in Crawford et al. (1992). They include:-

- i) an intracontinental rift adjacent to an extensional plate boundary,
- ii) an Andean-type arc setting, located over an east-dipping subduction zone, erupted on to the Precambrian Tyennan continental basement,

iii) a convergent plate boundary over a west-dipping subduction zone,

iv) an extensional setting within an active continental margin with associated strike-slip faulting.

Berry and Crawford (1988) and Crawford and Berry (1991) have proposed a model of formation within a post-collisional environment, in which east-directed subduction resulted in a Middle Cambrian arc-continent collision. During this collision fore-arc crust was thrust over the passive margin leading edge. "Downwarping of the foreland associated with ophiolite emplacement formed the Dundas Trough. Extension, possibly related to relaxation rifting of the newly thickened crust, led to rebounding and exhumation of the underthrust, thinned Precambrian crust, forming the Tyennan region. In this model, Mount Read Volcanics magmatism was post-collisional in origin and localised to grabens along the eastern side of the Dundas trough" (Crawford et al., 1992).

#### **2.2.1 Geochemical Classification of the Mount Read Volcanics**

Crawford et al. (1992) have divided the MRV into three calc-alkaline suites (I to III) and two tholeiitic suites (IV and V):-

i) Suite I andesites, rhyolites and dacites are characterised by "medium to high K calc-alkaline rocks.....and are the least light REE-enriched calc-alkaline lavas in the Mount Read Volcanics" (Crawford et al., 1992).

ii) Suite II andesites and dacites are more  $P_2O_5$  and light REE- enriched than Suite I.

iii) Suite III basalts and andesites have a broad compositional range including  $P_2O_5$  and REE-enriched shoshonites which in modern terrains indicate post-collisional volcanism.

iv) Suite IV are high  $TiO_2$  tholeiitic basalts.

v) Suite V are low Ti, light REE-depleted tholeiitic basalts.

Suites I and III occur within the QHV. Suite I andesites underlie Hellyer and Suite III basalts form the hangingwall to the deposit. The geochemical signatures of the QHV indicate that Hellyer formed within a locally extensional setting in a post-collisional tectonic environment.

## **2.3 Deposit Geology**

A comprehensive description of the geology of the Hellyer deposit is given in McArthur (1986) and McArthur and Dronseika (1990). The essential features of the geology are shown in figure 3.

**2.3.1** Underlying the deposit is a 170m (minimum) thick sequence of andesite lavas, autobreccias, hyaloclastites and some reworked epiclastic units (Waters, 1990). This sequence, locally termed the feldspar phyric sequence (FPS), falls into Crawford et al.



(1992) Suite I geochemical classification of the Mount Read Volcanics.

**2.3.2** Immediately below the massive sulphide the footwall is cut by a well developed alteration pipe (McArthur, 1986 and Gemmell and Large, 1992). This pipe is concentrically zoned and comprises:-

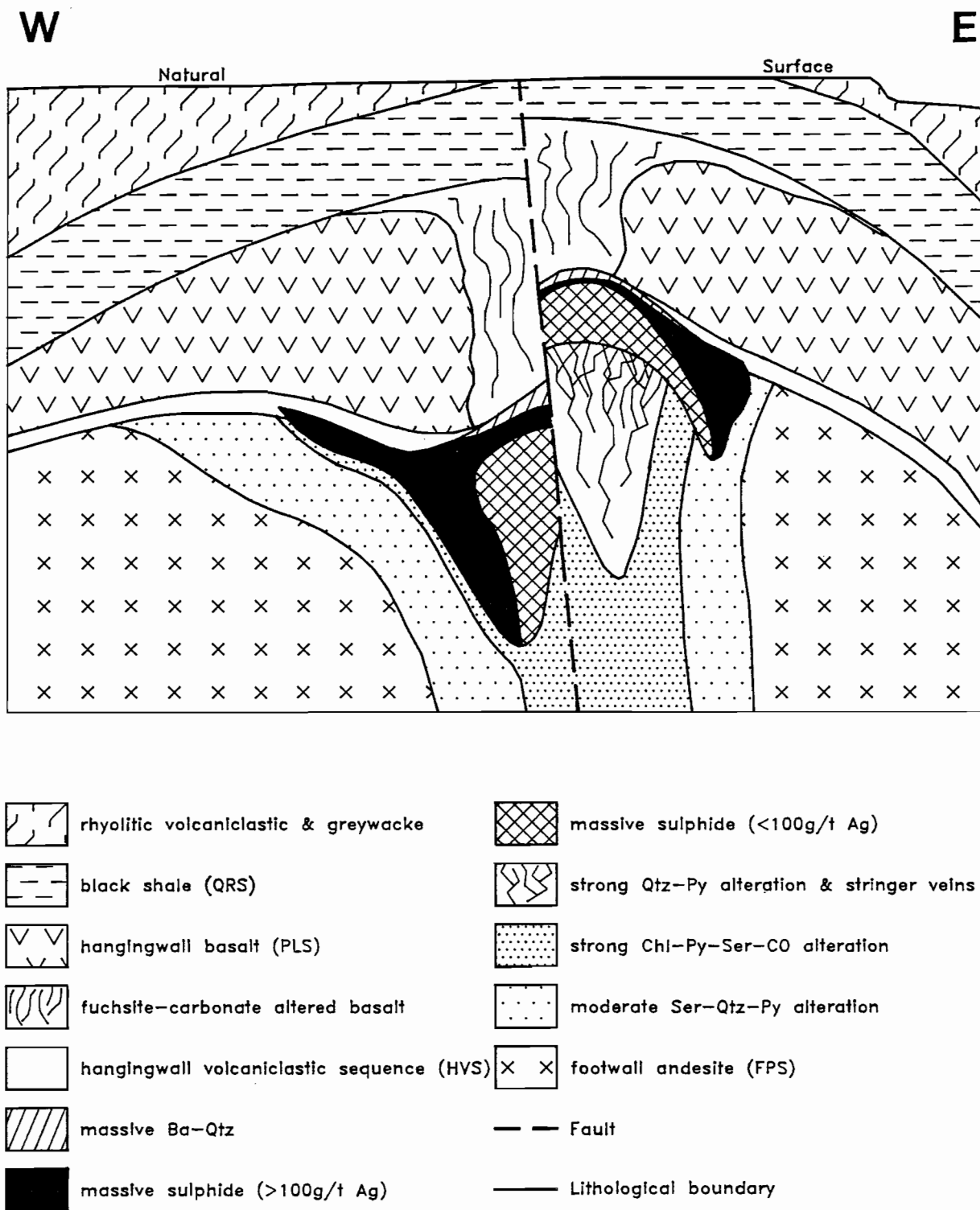
- i) an inner zone of silica-pyrite alteration (the siliceous core) with numerous, well preserved base metal stringer veins (plate 1). The siliceous core is overlain by Fe-Cu rich massive sulphides and is interpreted by McArthur (1986) and Gemmell and Large (1992) to have been the main centre of hydrothermal activity,

- ii) a second shell of massive chlorite-sericite-carbonate-pyrite alteration with a strongly developed north-south striking cleavage. These two inner shells together comprise the stringer zone (STZ),

- iii) an outer shell of sericite-silica-pyrite alteration known as the stringer envelope zone (SEZ).

The intense hydrothermal alteration of the STZ has over-printed the primary lithological textures with a set of alteration textures. However, rocks of the SEZ are less strongly altered and, in places, resemble polymict volcanoclastic breccias.

**2.3.3** The massive sulphide is located in the hinge zone of an upright, open anticline which plunges at 20° to the north. The



**Figure 3:** Schematic cross-section (looking north) through the Hellyer orebody and host rocks.

deposit "is unusually sulphide rich, averaging 54% pyrite, 20% sphalerite, 8% galena,.....and 1% chalcopyrite with minor tetrahedrite" (McArthur and Dronseika, 1990). The deposit is separated into eastern and western lenses by the Jack Fault, a north-south striking sinistral wrench fault. The massive sulphide extends for over 800m in a north-south direction, 200m east-west and averages 43m vertical thickness (McArthur and Dronseika, 1990). The lack of interbedded pelagic sediment or volcanoclastics suggest that the orebody formed quite rapidly (Waters and Wallace, 1992).

The "mound-like" orebody displays metal and textural zonation typical of VHMS deposits (McArthur, 1986 and Large, 1992). The central part of the mound is relatively pyrite-chalcopyrite rich and tends to be medium to coarse grained and texturally massive. The outer, or "hangingwall enriched", zone is defined by a sharp increase in Ag grade to above 100g/t. This zone is characterised by sphalerite-pyrite-galena banding which is usually parallel to cleavage. A cap of barite-quartz-pyrite overlies the central portion of the massive sulphide (Sharpe, 1991).

**2.3.4** The hangingwall volcanoclastic sequence (HVS) is laterally equivalent to and on-laps the massive sulphide orebody. The HVS consists of a series of mass-flow deposited polymict breccias to ash-sized epiclastics and mudstones (Waters, 1990). Clast lithologies within the HVS are highly varied and include andesite, dacite, hydrothermally altered volcanics, massive sulphide, barite and basalt. The HVS is up to 15m thick off the flanks of the massive sulphide but lenses out over the centre of the mound.

**2.3.5** The pillow lava sequence (PLS) basalts overlies the HVS and the orebody. This sequence consists of pillow lavas, massive lavas, hyaloclastites, peperites, autobreccias and interbedded sediments (Waters, 1990). The PLS is up to 250m thick over the orebody. The PLS falls into the Suite III category of Crawford et al. (1992).

The PLS probably formed very soon after the HVS. Several underground exposures show that the upper, mud-rich horizons of the HVS were unconsolidated during the deposition of the PLS. In addition, the hangingwall fuchsite alteration plume indicates that some form of hydrothermal activity continued after the deposition of the PLS. (Jack, 1989)

Several dyke-like bodies of basaltic composition (with Suite III geochemical characteristics) intrude the FPS, STZ, SEZ and the orebody. These dykes are interpreted to be feeders to the PLS based on their geochemistry and observed relationship to the facies within the PLS.

**2.3.5** The PLS is overlain by black shales and siltstones of the Que River Shale (QRS), which are in turn overlain by rhyolitic volcaniclastics of the Southwell Subgroup locally referred to as the upper rhyolitic sequence (URS).

## **2.4 Previous Studies**

Previous studies of the Cambrian structural history of the Hellyer deposit have identified the presence of north-south



**Plate 1:** Cambrian sphalerite-galena-chalcopyrite-pyrite-barite stringer veins cutting quartz-chlorite-pyrite altered footwall. 415 level, 83-82 west cross-cut. (Note hammer for scale.)

striking normal faults forming full or half-grabens which host the mineralisation (Downs, 1990; Drown, 1990; Etheridge and Windh, 1992).

Drown (1990) proposed a two-stage model in the structural evolution of the orebody. In this model a north-south striking graben with east striking transfer faults formed in response to east-west extension. The graben was partially filled with epiclastic deposits. With a  $45^{\circ}$  clockwise rotation of the extensional direction to the northwest, an  $045^{\circ}$  striking extensional structure formed. In this model Hellyer is located at the point where this  $045^{\circ}$  trending structure intersected the pre-existing north-south striking graben.

Etheridge and Windh (1992) considered that rotation of the extensional direction occurred as a distinct "stress-pulse" which caused a pre-existing, linked fault network to dilate, allowing voluminous hydrothermal fluid flow.

## Chapter Three

### Post-Cambrian Deformation

The Hellyer deposit has been subjected to at least three deformation events since its formation; Middle Devonian folding, brittle-ductile shearing, and later wrench faulting. All of these events have modified the original geometry of the orebody.

#### 3.1 Brittle Faults

Sinistral movement on the Jack Fault occurred after the Devonian folding and was probably associated with the Mesozoic wrench movement on the Henty-Mount Cripps Fault (Berry, 1989). The lack of ductile structures and the dominance of fault breccias and cataclasite fault gouge indicate that the faulting occurred at less than 5km depth (McClay, 1987). The offset along the Jack Fault was determined by matching the displaced ore contacts and HVS either side of the fault. This showed that north of 10740N (Hellyer-Que River mine grid) the east block moved 130m north and 30m up (ie. McArthur and Dronseika, 1990) however, south of 10740N the offset reduces to 110m and 10m respectively.

A set of east-southeast striking dextral faults developed with the Jack Fault. Movement along these faults is usually less than 5m.

#### 3.2 Devonian Deformation

The major folding event was caused by east-west compression related to the Tabberabberan Orogeny (Komyshan, 1986) which produced the dominant northerly striking cleavage within the

Mount Read Volcanics. At Hellyer this deformation produced upright, open folds, plunging  $20^{\circ}$  north with steeply east dipping axial planar cleavage and reverse faults and shear zones (figures 4a and 4b). Reverse faults and shear zones with east-block up offset are common but generally show displacements of less than 5m. These structures are particularly well developed on the massive sulphide-stringer zone contact where there is a high competency contrast between the lithologies (plate 2).

### **3.2.1 Strain During the Devonian Deformation.**

The deformational style and interpreted strain partitioning at Hellyer are described in Drown and Downs (1990). The Devonian deformation was dominated by folding and reverse shearing with top-block west vergence.

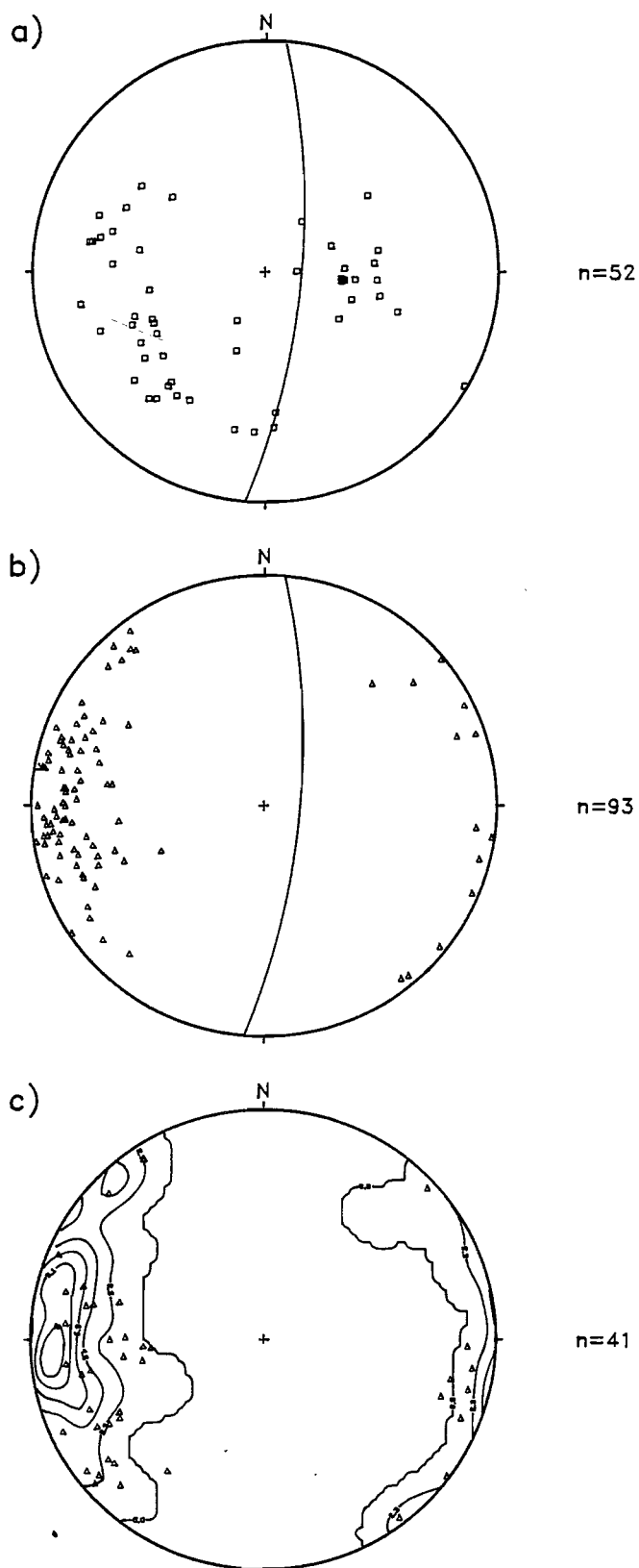
The nature of strain indicators are highly dependent upon host rock type:-

- i) within the Zn-Pb-Ag rich portions of the orebody, a strong banding has developed parallel to S1 (figure 4c). This banding comprises alternating layers of sphalerite-galena-pyrite. Pyrite layers are often boudinaged or fractured perpendicular to the sulphide banding. These fractures are filled with galena, chalcopyrite, tetrahedrite, quartz, chlorite, carbonate or barite (plate 3). Cross-cutting, pre-Devonian veins of pyrite, quartz or barite are strongly folded about the sulphide banding,

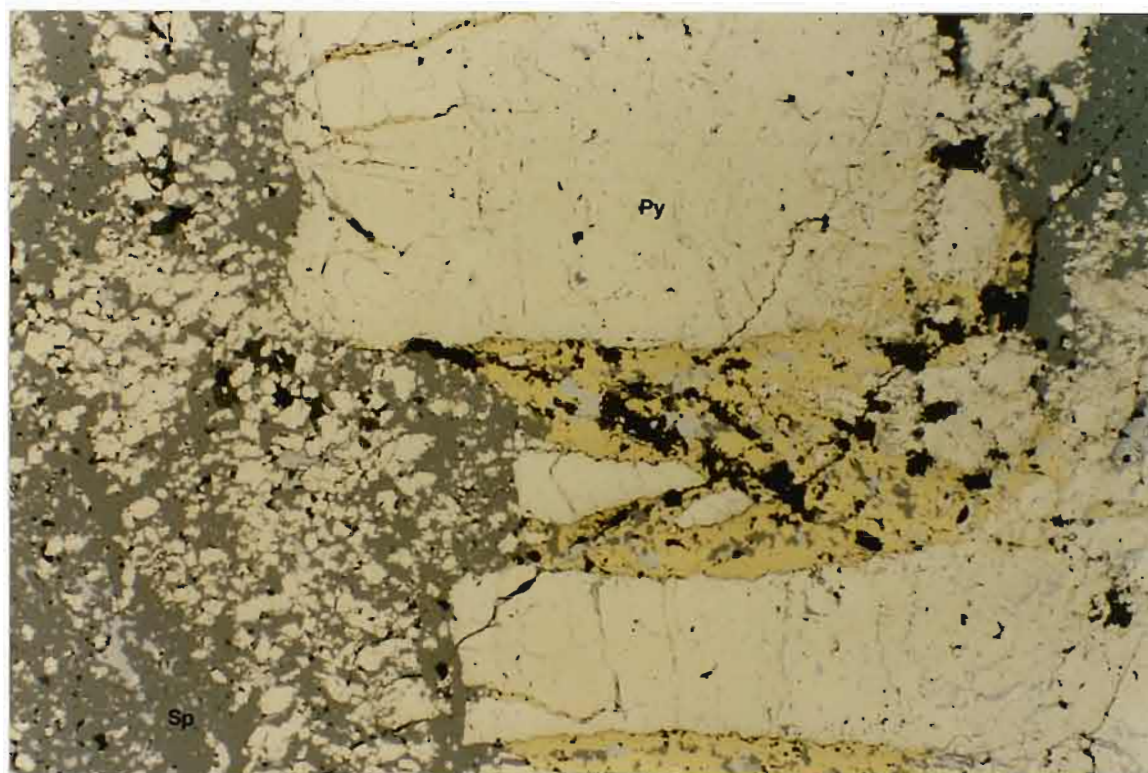




**Plate 2:** Devonian reverse fault and shearing above orebody hangingwall. HVS (upper right) has been thrust over sheared PLS (lower left). 300 level, 99-90 east cross-cut. (Note hammer for scale.)



**Figure 4:** a) Poles to bedding. Average cleavage shown as great circle.  
 b) Poles to cleavage. Average cleavage dips at  $78^\circ$  toward  $094^\circ$ .  
 c) Poles to sulphide banding in massive sulphide, overlain on contours of cleavage poles.



Py - Pyrite

Sp - Sphalerite

**Plate 3:** Cleavage parallel banding in sphalerite-galena rich massive sulphide. Pyrite-rich layers have been pulled apart perpendicular to the banding during the Devonian deformation. The fractures are infilled with chalcopyrite, galena and quartz. (Field of view approx. 3.6mm.)

ii) the Fe-Cu rich core of the orebody displays brittle structures due to its relatively lower proportion of ductile sulphide species,

iii) in the unaltered host rocks and the siliceous core of the stringer zone strain is expressed as brittle-ductile reverse shear zones, often with well developed sigmoidal vein sets (plate 4). These sigmoidal veins contain fibrous crystals of quartz, calcite and chlorite, with minor epidote, tremolite and sulphides,

iv) the phyllosilicate-rich rocks of the footwall and hangingwall alteration zones have a well developed axial planar cleavage. Pressure shadow overgrowths of quartz or sericite on pyrite crystals indicate minor east-block up shearing (plate 5).

### **3.2.2 Brittle-Ductile Shear Zones.**

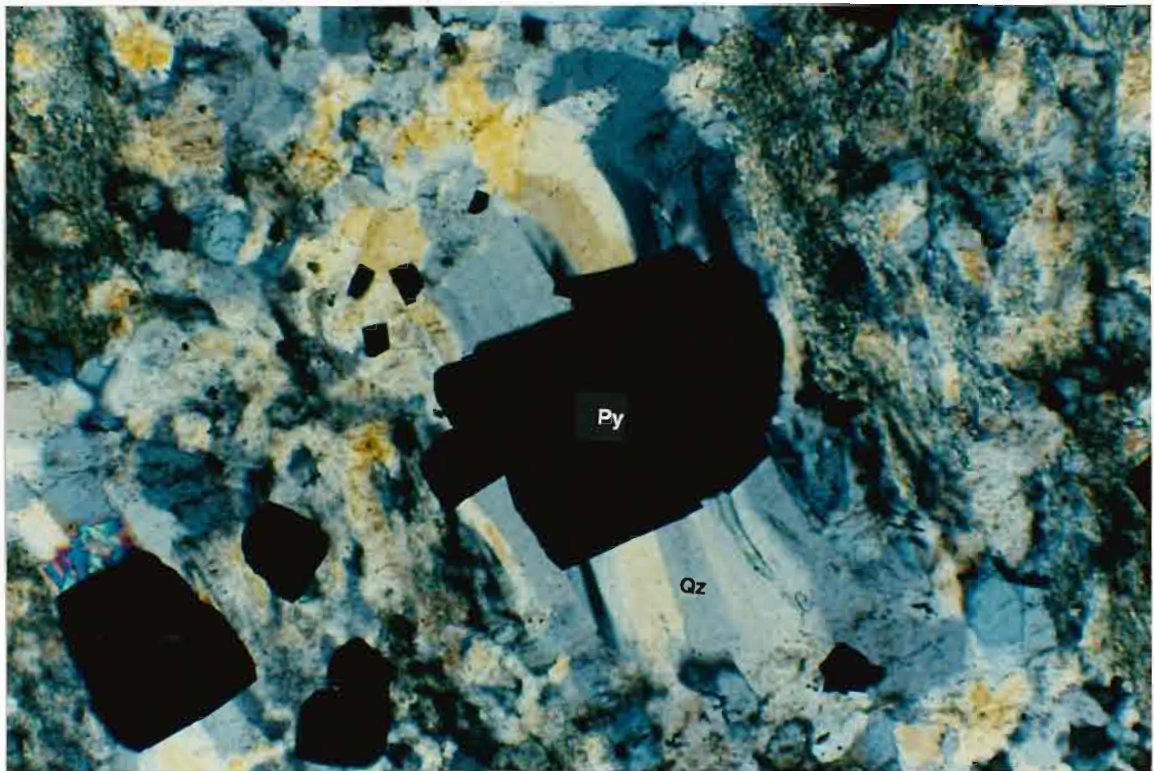
Sigmoidal veins associated with brittle-ductile shears are common within and around the orebody. The veins are filled with mineral components derived from the host rock immediately adjacent to the vein wall. Plate 6 shows an example from the footwall stringer zone in which the mineralogy of a single vein varies from quartz-calcite dominant to recrystallised chalcopyrite-sphalerite dominant, where it crosses a pre-existing base-metal rich stringer vein.

The orientations of the compressive stress axes have been determined from the semi-brittle shear vein arrays (McClay, 1987,



**Plate 4:** Sigmoidal quartz-calcite filled veining in association with Devonian-age brittle-ductile shear zones in siliceous footwall rock. 260 level, 88-86 north drive. (Note hammer for scale.)





Py - Pyrite

Qz - Quartz

**Plate 5:** Pressure shadow overgrowths of quartz on pyrite crystals. The view is oriented perpendicular to cleavage. (Field of view approx. 0.9mm.)



SpCp - Cambrian Vein

**Plate 6:** Devonian shear veins cross-cutting Cambrian sphalerite-rich 2B vein. Note that the mineralogy of the Devonian sigmoidal vein changes from quartz-carbonate dominant to sphalerite-chalcopyrite dominant as it crosses the 2B vein. 260 level 88-86 north drive. (Note pencil for scale.)

appendix B).

The principal stress directions were:-

Maximum compressive stress  $20^{\circ}$  toward  $280^{\circ}$

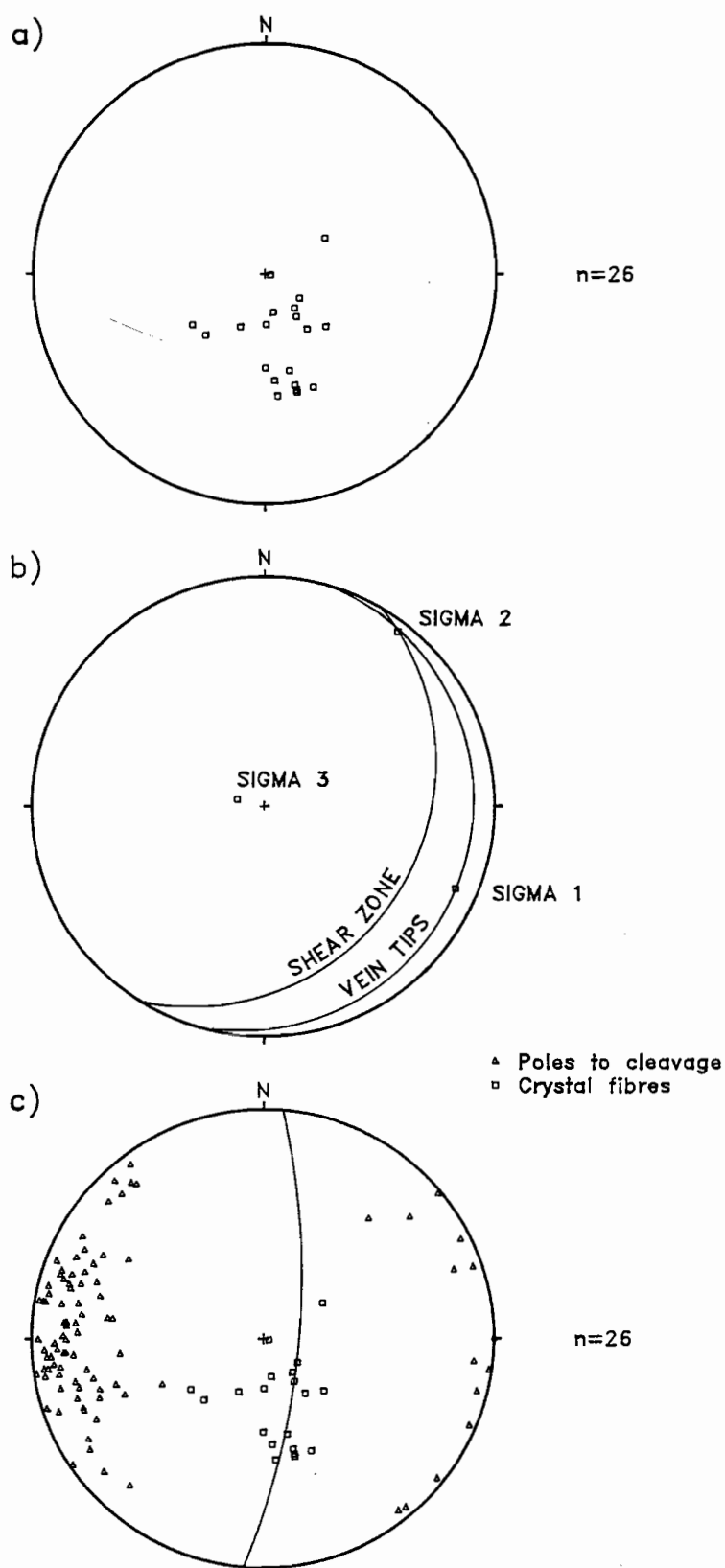
Intermediate stress  $16^{\circ}$  toward  $014^{\circ}$

Minimum stress  $68^{\circ}$  toward  $154^{\circ}$

The minimum stress direction agrees well with the orientation of crystal fibres within the sigmoidal veins (figure 5), the maximum compressive stress axis is approximately normal to the axial planar cleavage S1, ie. parallel to the shortening direction.

The coincidence of maximum compressive stress, as indicated by the brittle-ductile structures, and the maximum shortening direction (poles to cleavage) indicates that the deformation history was predominantly non-rotational (ie. pure shear).





**Figure 5:** a) Orientation of crystal fibres in Devonian sigmoidal veins. The fibres grow in the sigma-3 orientation.  
 b) An example of calculation of sigma-1, 2 & 3 using brittle ductile shear zones.  
 c) Stereonet shows crystal fibres cluster around average cleavage great circle.

## Chapter Four

### Cambrian Structures

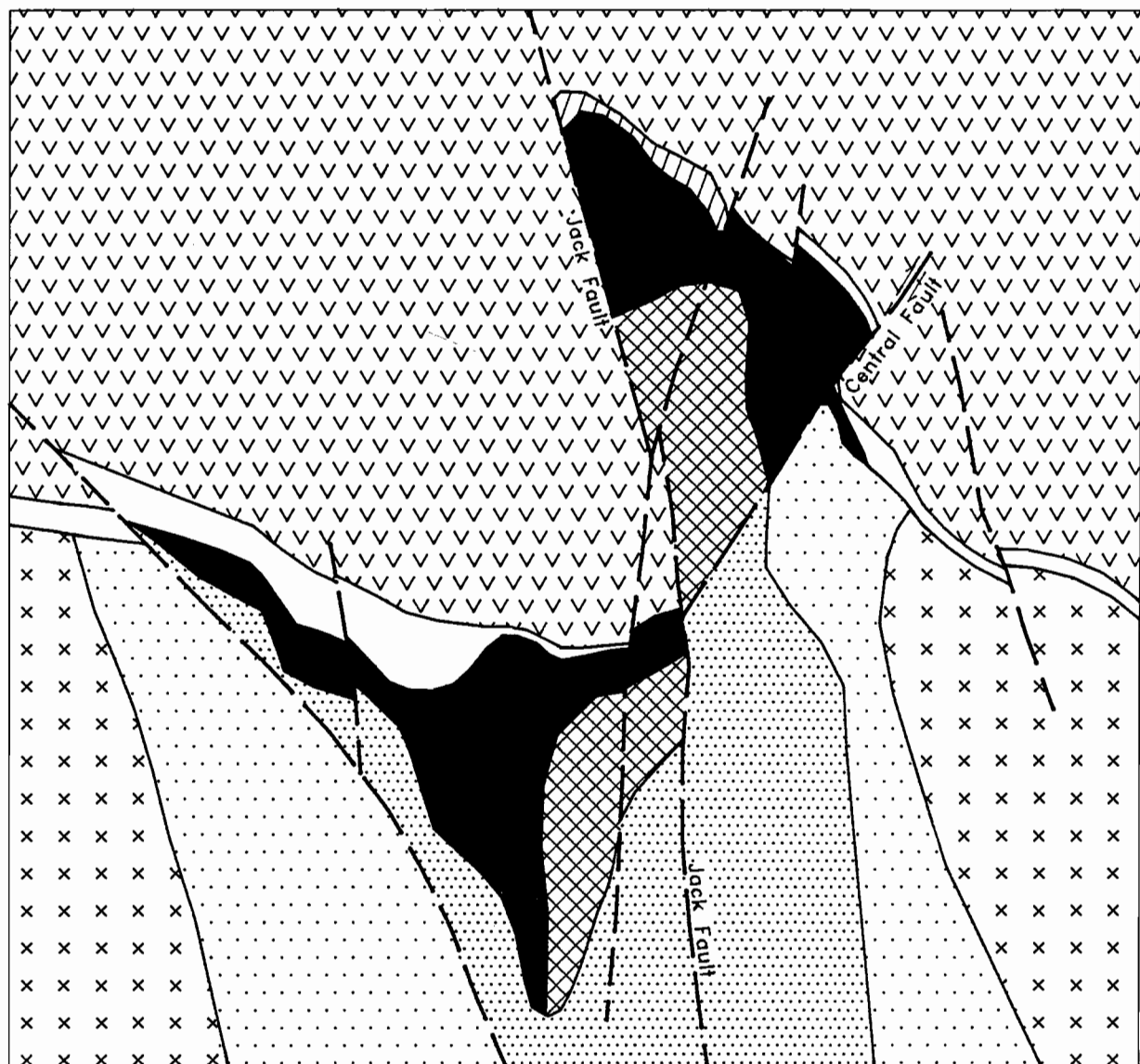
Cambrian structures are considered to be any planar features that were present prior to the Devonian folding event. In some cases they are quite obvious (ie. stringer veins or basalt dykes), in other cases (ie. Cambrian faults) they are more subtle.

Base metal rich stringer veins formed synchronously with (and basalt feeder dykes very soon after) the Hellyer massive sulphide. Ninety-four stringer veins and five basalt dykes have been recorded during routine mapping and core logging. These structures are important as their orientations indicate the likely principal extensional directions during the period of time which included the formation of the orebody. Active, dilatant structures offer the optimum pathways for expelling large volumes of metal-rich hydrothermal fluids and basaltic magma onto the seafloor.

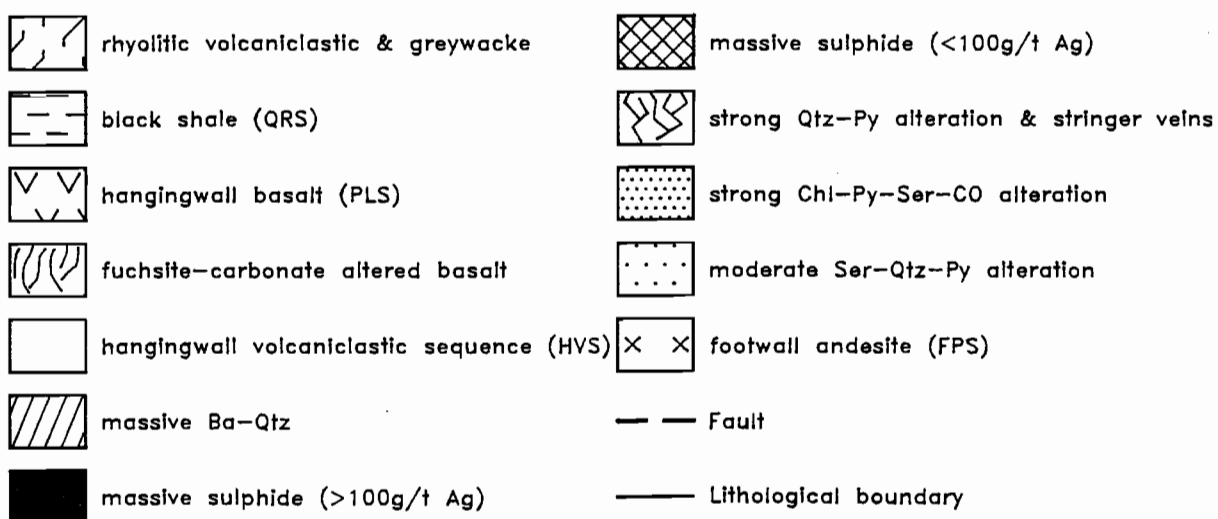
Cambrian age faults at Hellyer are more difficult to recognise as they have often been re-activated during successive deformations. Each re-activation has produced its own set of fault striations and fault gouge which obscure the original set. However, they have been interpreted to exist in areas where rapid changes in thickness of lithologic units occur across a fault (figure 6).

#### 4.1 Footwall Stringer Veins

Base metal and barite-rich stringer veins are well preserved in the siliceous core of the footwall stringer zone. The mineralogy



Scale 0 25 50m



**Figure 6:** 10750 N cross-section showing an interpreted Cambrian normal fault –the Central Fault– which shows Devonian reverse movement.

and paragenesis of the vein sets within the footwall alteration zone are described in Gemmell and Large (1992). They recognise eight stages of veining in the stringer zone (figure 7) with three syn-mineralisation stages:-

- i) Stage 2A. Pyrite, quartz, carbonate.
- ii) Stage 2B. Sphalerite, chalcopyrite, galena, pyrite.
- iii) Stage 2C. Barite, pyrite, quartz.

The stage 2A, 2B and 2C veins may be over 1m wide and are often quite planar (although they may anastomose over the small to medium scale (plate 1)). Individual 2B veins are known to extend over 30m in strike length and 50m down dip. Figure 8 shows that there is a strong northeasterly trend to the 2B and 2C veins with a subordinate east-west striking set.

The 2A, 2B and 2C veins post-date the siliceous alteration in the footwall stringer zone and they often have selvages of sericite-chlorite that overprint the siliceous alteration (Gemmell and Large, 1992).

#### **4.2 Basalt Dykes**

Basaltic dykes of similar geochemical composition to the overlying PLS intrude the footwall andesite, stringer zone and massive sulphide. The dykes range from a few centimetres to 2m thick and comprise grey/green, fine grained, aphyric massive lava with chilled margins. They are usually quite planar and can be traced for tens of metres of strike length. The dykes are either

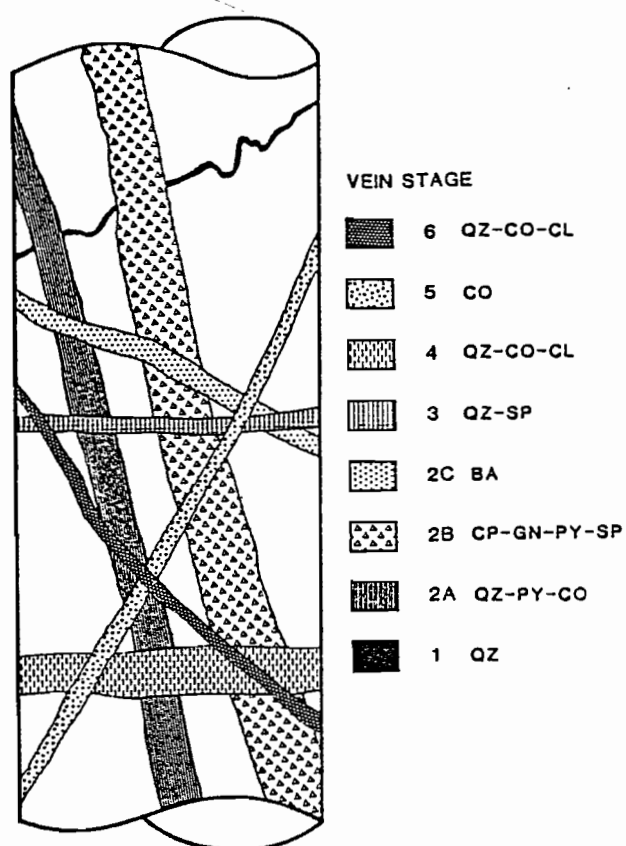


Figure 7: Vein paragenesis in the stringer zone. Stage 1 is pre-mineralisation, stages 2A, 2B and 2C are synmineralisation, and stages 3 to 6 are post-mineralisation.

BA - Barite, CL - Chlorite, CO - Carbonate, CP - Chalcopyrite, GN - Galena, PY - Pyrite, QZ - Quartz, SP - Sphalerite. From Gemmell and Large (1992).

weakly fuchsite altered or unaltered. Their relationship to the lava facies in the PLS indicates that they are related to its formation (figure 9), this places their emplacement at, or soon after, the deposition of the HVS.

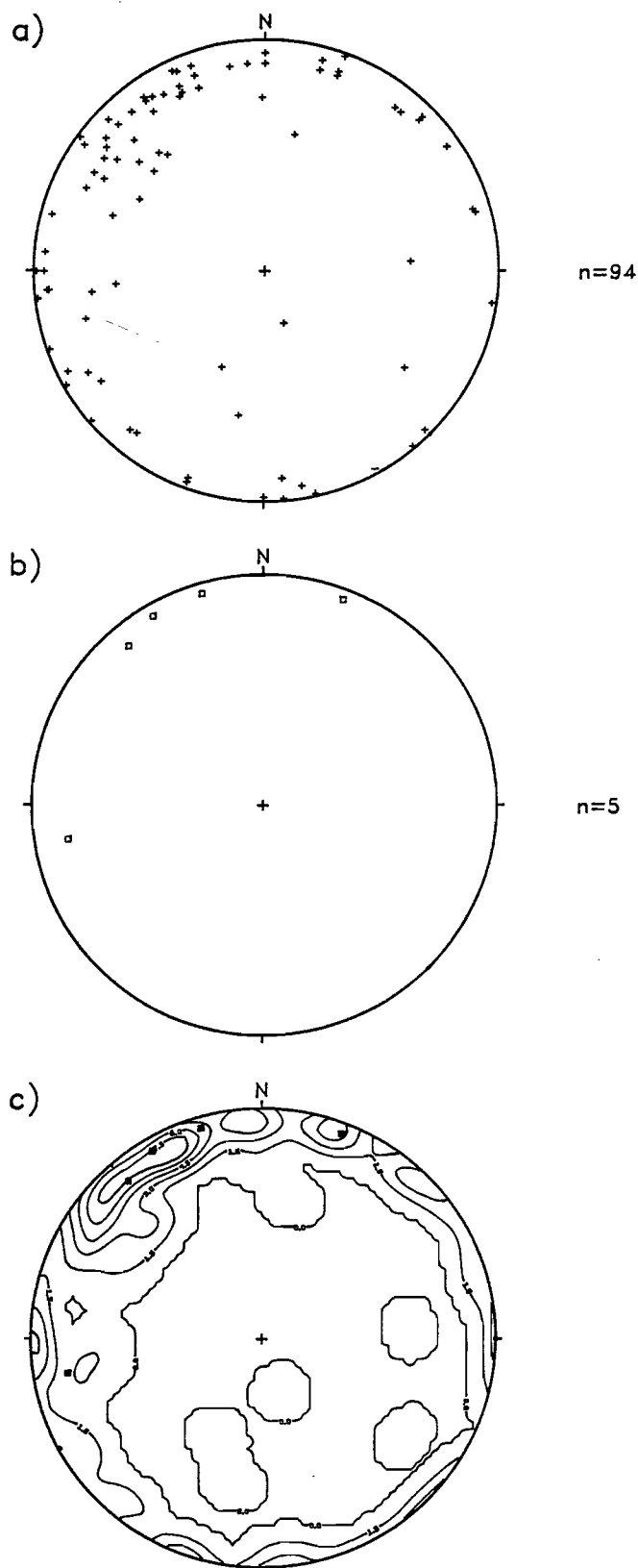
The basalt dykes have a similar orientation to the 2B and 2C stage stringer veins. They dominantly strike northeast and a subordinate set strike east-west (figure 8c). The implication is that the basaltic magma rose up through a similar set of fissures to the ore-forming fluids. That is, a set of extensive northeast striking fissures (and a lesser east-west set) were dilatant throughout the formation of the orebody until at least the early stages of formation of the PLS.

#### **4.3 Cambrian Age Faults**

Faults of probable Cambrian age have been recognised in areas of rapid change in thickness and facies of lithological units. The interpretation is that these faults had some topographic relief during the formation of the orebody and the associated volcanics and volcaniclastics.

An example of the above is shown in figure 6, 10750N cross-section, where the eastern lens of the massive sulphide orebody thins from 100m to less than 5m thick over the Central Fault. This rapid thickness change suggests the presence of a seafloor scarp at this position during the formation of the orebody. The Central Fault has been re-activated as a reverse fault with west-block up offset.

Re-activation of syn-depositional faults has been described at other massive sulphide deposits. At Buchans in Newfoundland, Thurlow and Swanson (1987) have recognised that many thrust faults propagated along early, high-angle normal faults which controlled the seafloor topography and were active at the time of deposition of the ore. They suggested that footwall hydrothermal alteration zones were weakened by early structural breaks and that they formed the locus for later fault movements. Thus, the empirical association of structural complexity and ore has an inferrable genetic link.

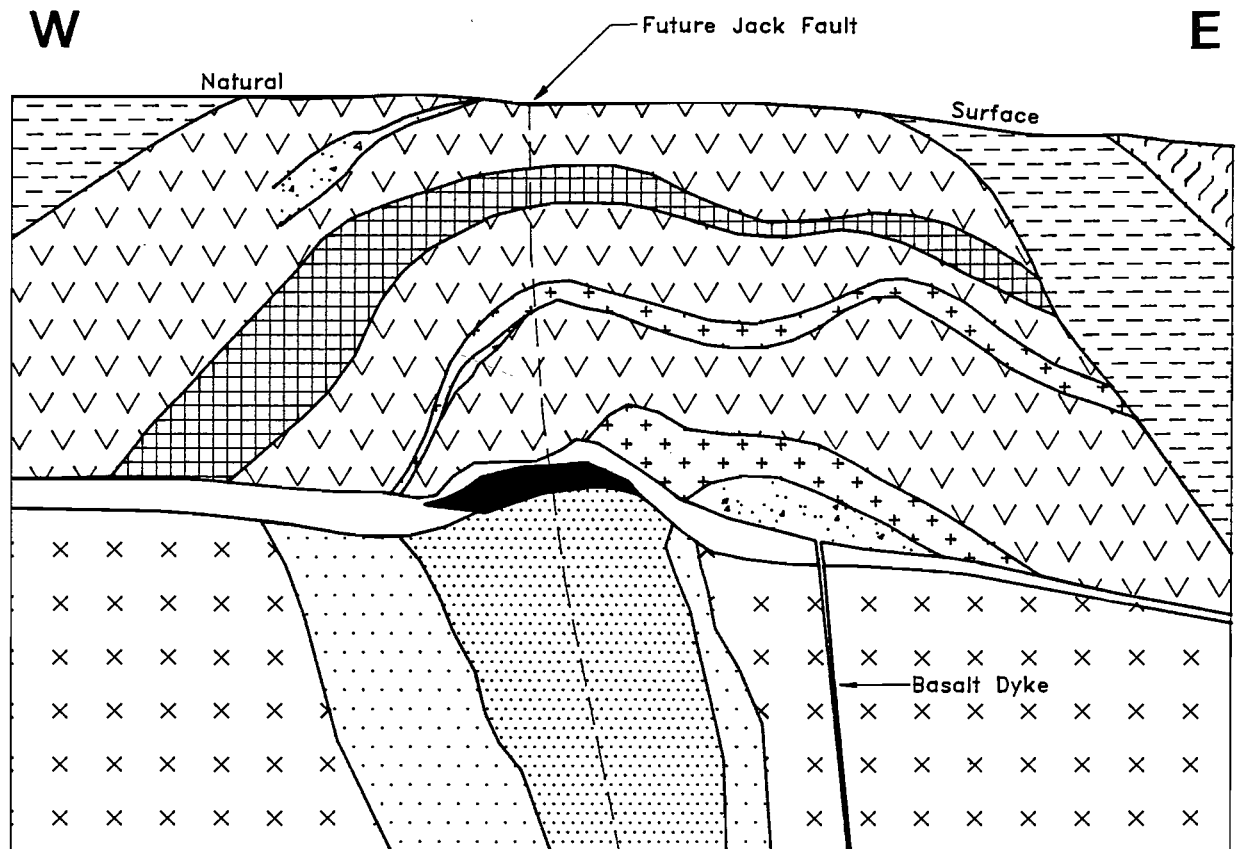


**Figure 8:** a) Poles to 2B and 2C stringer veins.

b) Poles to basalt feeder dykes.





c) Poles to basalt dykes overlain on contours of stringer vein poles. Note that the NE strike is dominant in both sets.





#### Pillow Lava Sequence Stratigraphy

Scale 0 50 100m

-  hyaloclastite, autobreccias
-  massive lava
-  variolitic pillow lava
-  pillow lava

**Figure 9:** Composite 10570 N/10700 N cross-section (Jack Fault offset removed) showing the relationship of basalt dyke to pillow lava sequence stratigraphy. Refer to Figure 3 for major stratigraphic legend.

## Chapter Five

# Removal of Post-Depositional Deformation

In order to outline the Cambrian seafloor topography the effects of later folding and faulting were removed from the deposit. This led to the construction of an interpreted Cambrian seafloor contour map.

### 5.1 Assumptions

The restoration of the deposit to its pre-deformation geometry is based on the following assumptions:-

5.1.1 That the Hellyer massive sulphide formed as an exhalative body resting entirely on top of the Cambrian seafloor at the time of its formation. That is, no part of the massive sulphide formed by replacing existing rock.

There is good evidence that the massive sulphide formed a mound on the seafloor, principally the presence of massive sulphide "rip-up" clasts within the overlying HVS and the on-lapping nature of the HVS contact with the massive sulphide.

5.1.2 That the footwall contact of the massive sulphide is a chronostratigraphic marker horizon which represents the seafloor at the time at which the orebody formed and that this horizon can be extrapolated away from the edges of the orebody using the base of the HVS as the equivalent horizon.

5.1.3 That the top surface of the HVS was originally horizontal. This assumption has the greatest impact on the final shape of the

unfolded geology. In using this graphical technique it was necessary to have one initially horizontal surface to use as a reference plane. The upper surface of the HVS provides the closest approximation to an horizontal layer, however, given the nature of mass-flow deposits it is likely that some irregularities existed in the upper surface, post-deposition.

**5.1.4** That the footwall stringer zone formed as a vertical, pipe-like body, cutting up through the footwall prior to post-depositional deformation.

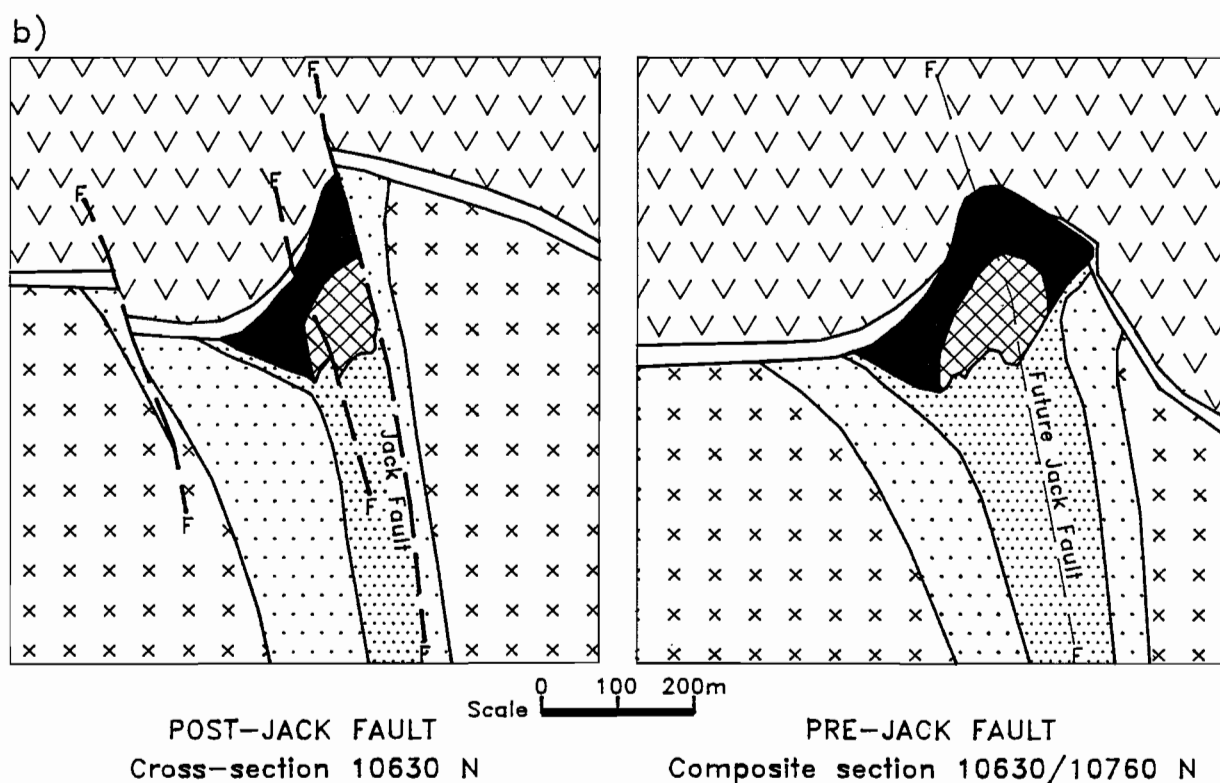
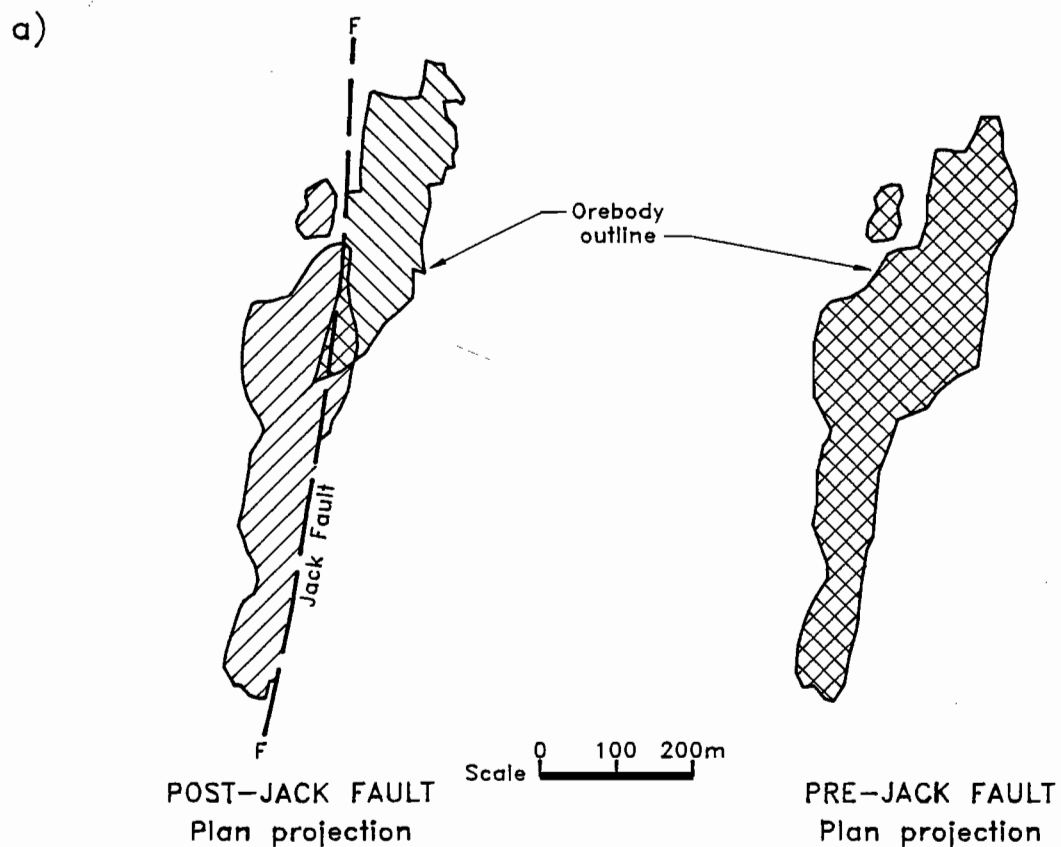
**5.1.5** That the deformation which produced the folding was plane strain in the plane of the sections and that there was no movement of rock in or out of the cross-section during the folding event.

**5.1.6** That strain was homogenous throughout the section. Typically, the amount of shortening was in the order of 33%.

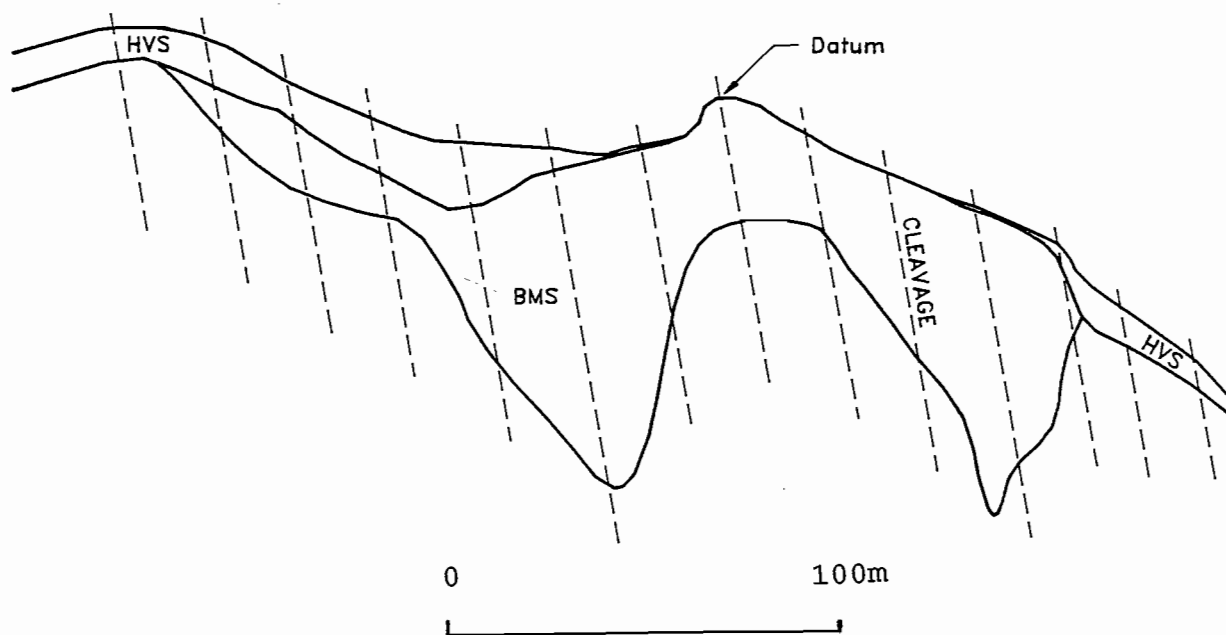
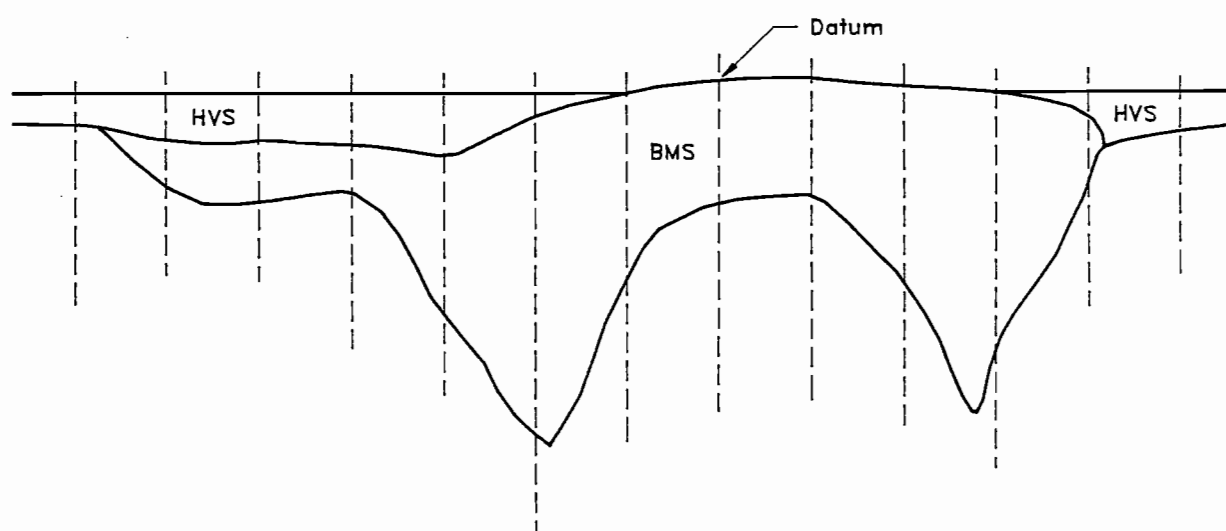
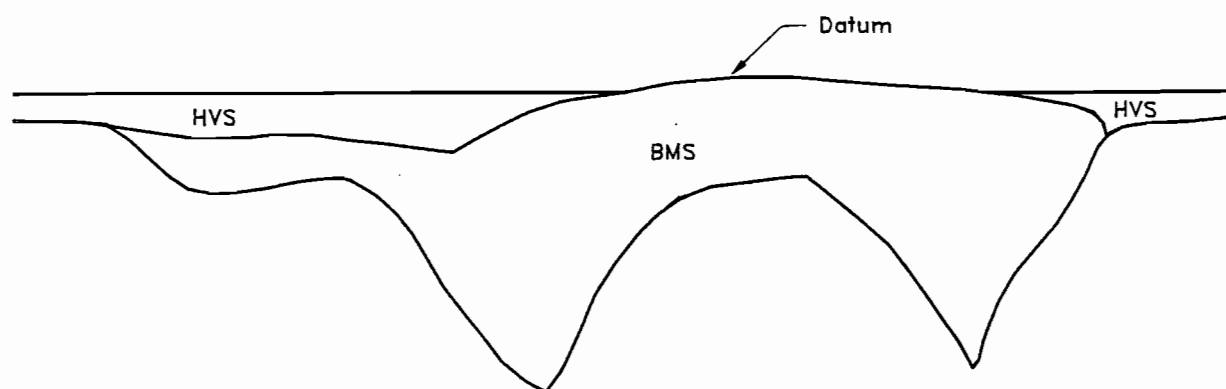
## **5.2 Technique**

The graphical technique used to un-deform the massive sulphide involved the following steps:-

**5.2.1** A set of 1:500 scale north-looking cross-sections (ie. perpendicular to the axial planar cleavage) at 10m northing intervals was produced which covered the orebody from 10250N to 11000N. Complex faulting beyond 11000N made reconstruction of the geology difficult. This, unfortunately, leaves the northern



**Figure 10:** Shows the first stage in removing post-depositional deformation from the deposit. The wrench faulting associated with the Jack Fault was removed producing 69 cross-sections showing the deposit as it would have appeared following Devonian folding.

a) Cross-section area  $9,280\text{m}^2$ b) Cross-section area  $10,800\text{m}^2$ c) Cross-section area  $9,290\text{m}^2$ 

**Figure 11:** Cross-section 10740 N/10870 N showing the main stages in unfolding the deposit.

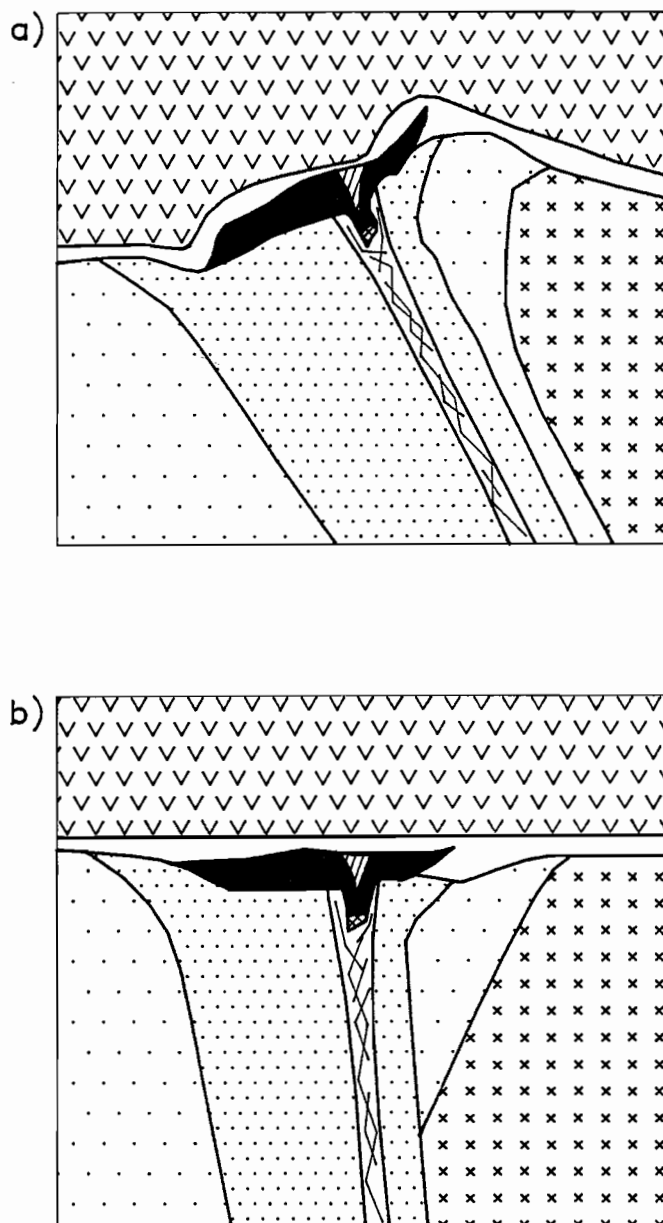
termination of the orebody open. A total of 82 sections were drawn.

**5.2.2** Brittle stage faulting associated with the Mesozoic deformation was removed. This primarily involved removing the sinistral displacement of the Jack Fault and the 5-10m displacements of associated dextral faults (figure 10). A total of 69 sections (at 10m spacing) showing the massive sulphide and its host rocks in their post-folding geometry were produced.

**5.2.3** Lines parallel to cleavage were drawn at 25m intervals from a datum along the top surface of the HVS (figure 11a). The cleavage direction is sub-parallel to the boundaries of the footwall stringer zone which was assumed to have cut vertically up through the footwall andesite. Thus, the set of cleavage parallel reference lines would have been vertical prior to folding. These reference lines were drawn through the massive sulphide footwall and the distance to the footwall position was measured along each line.

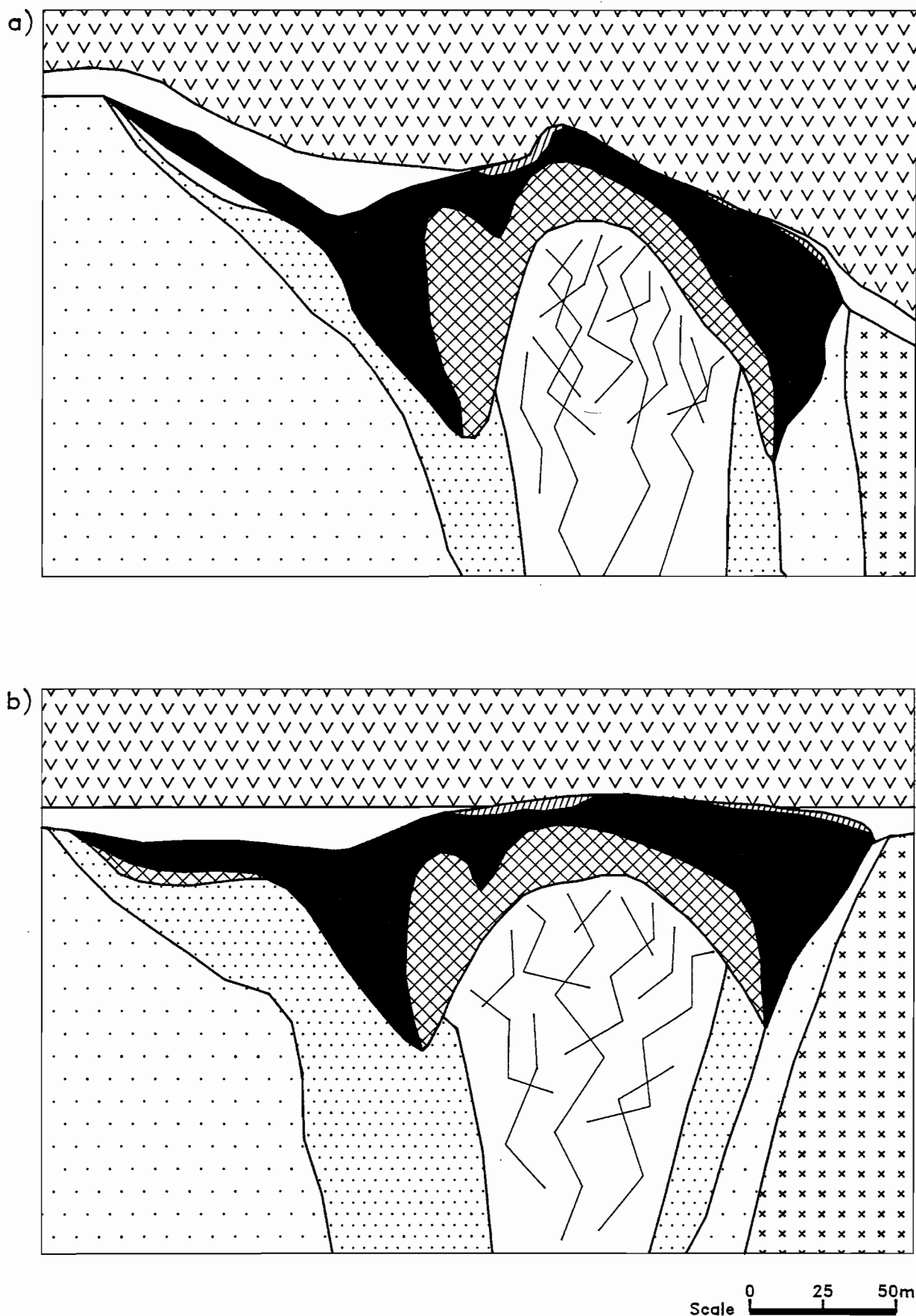
**5.2.4** Shortening perpendicular to cleavage was removed. The top surface of the HVS was drawn as an horizontal surface and vertical reference lines were drawn at 25m intervals from a datum point. The lower surface of the massive sulphide and HVS were then plotted on these new sections by transferring the measurements from step 5.2.3. onto the vertical reference lines (figure 11b).

**5.2.5** Extension parallel to cleavage was removed to return the



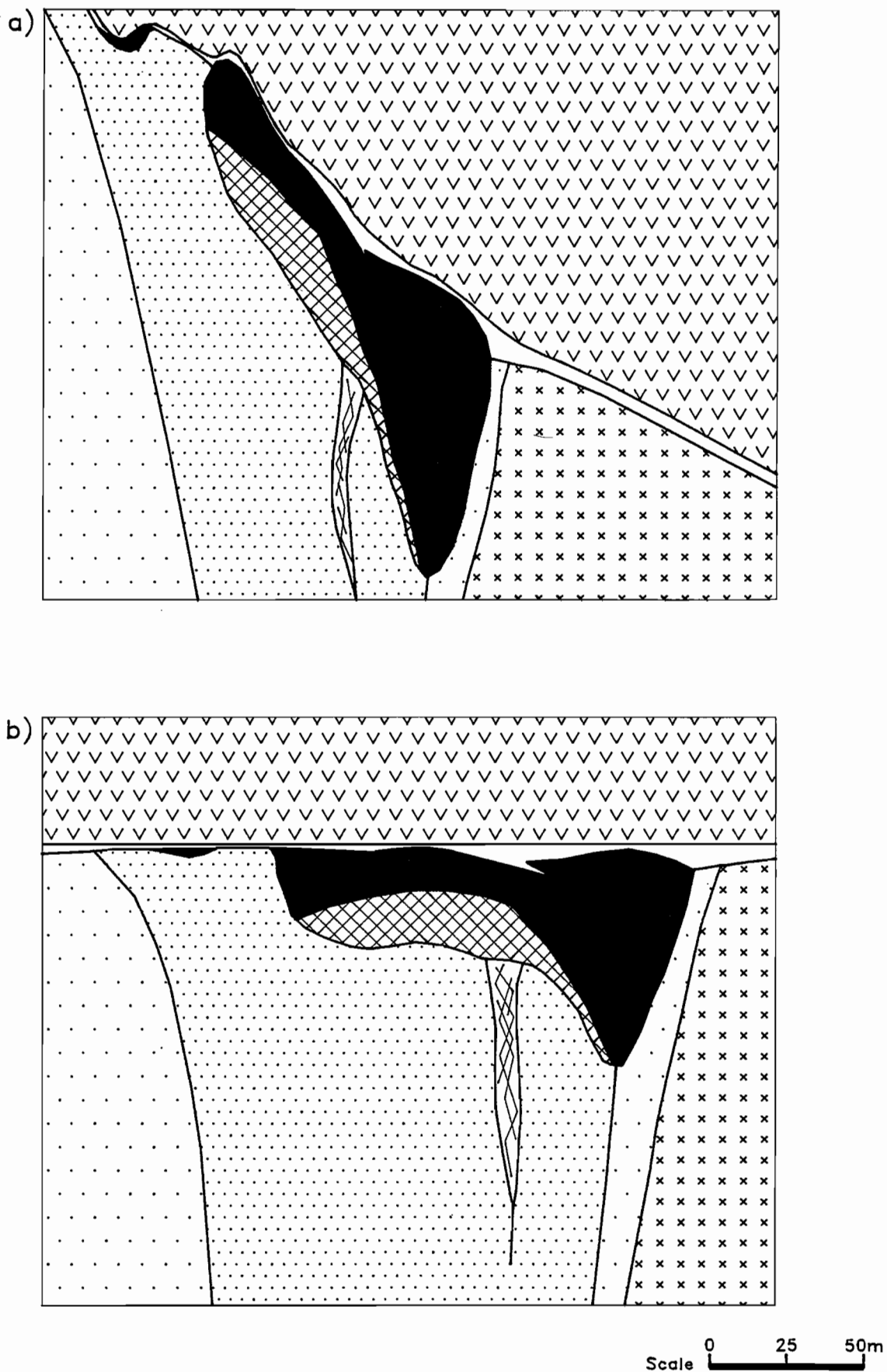
Scale 0 25 50m

**Figure 12:** 10520 N/10640 N cross-section prior to unfolding a), and after unfolding b). Refer to Figure 3 for stratigraphic legend.



**Figure 13:** 10740 N/10870 N cross-section prior to unfolding a), and after unfolding b). Refer to Figure 3 for stratigraphic legend.





**Figure 14:** 10840 N/10970 N cross-section prior to unfolding a), and after unfolding b). Refer to Figure 3 for stratigraphic legend.

deposit to its present area, producing 69 unfolded, areally balanced cross-sections (figure 11c). Figures 12, 13 and 14 show examples of cross-sections before and after the effects of folding have been removed.

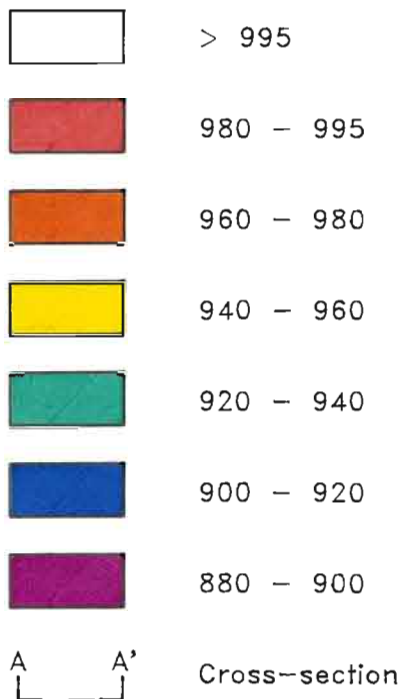
**5.2.6** Structure contours of the seafloor surface were hand-drawn from the 1:500 scale unfolded sections<sup>2</sup>. These contours were then digitised using DATAMINE software (figures 15 and 20). This package was then used to generate a three-dimensional wireframe model of the Cambrian seafloor which could be sliced to produce cross-sections in any desired orientation (figure 17).

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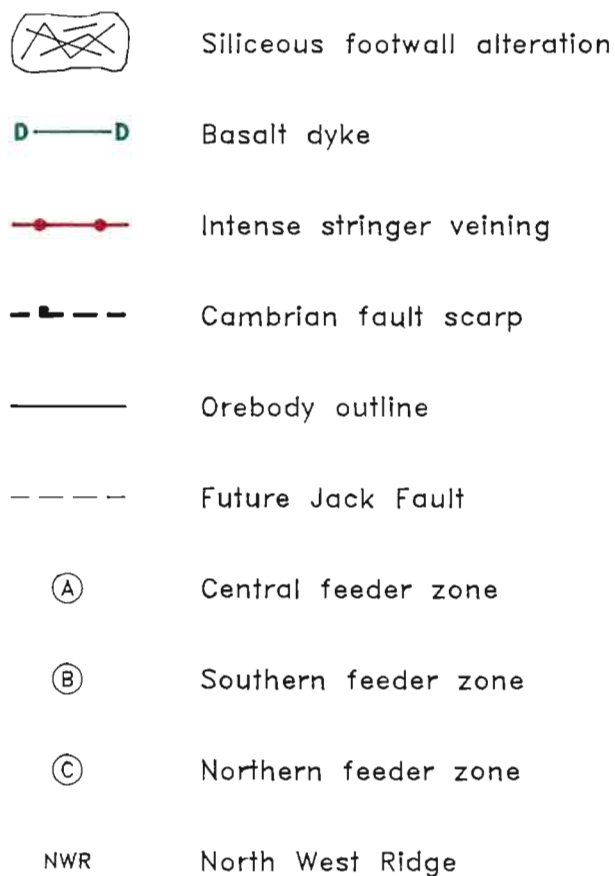
<sup>2</sup>All sections were restored to their eastern fault block northing coordinate. Therefore the composite 10670N/10800N section was plotted as 10800N. The datum point of 5.2.4 was assigned an arbitrary easting value of 300. The top of the HVS was assigned an arbitrary 1000m reduced level, so the structure contours effectively represent isopachs of the massive sulphide and the HVS (ie. a seafloor R.L. of 950m indicates that the massive sulphide + HVS is 50m thick).

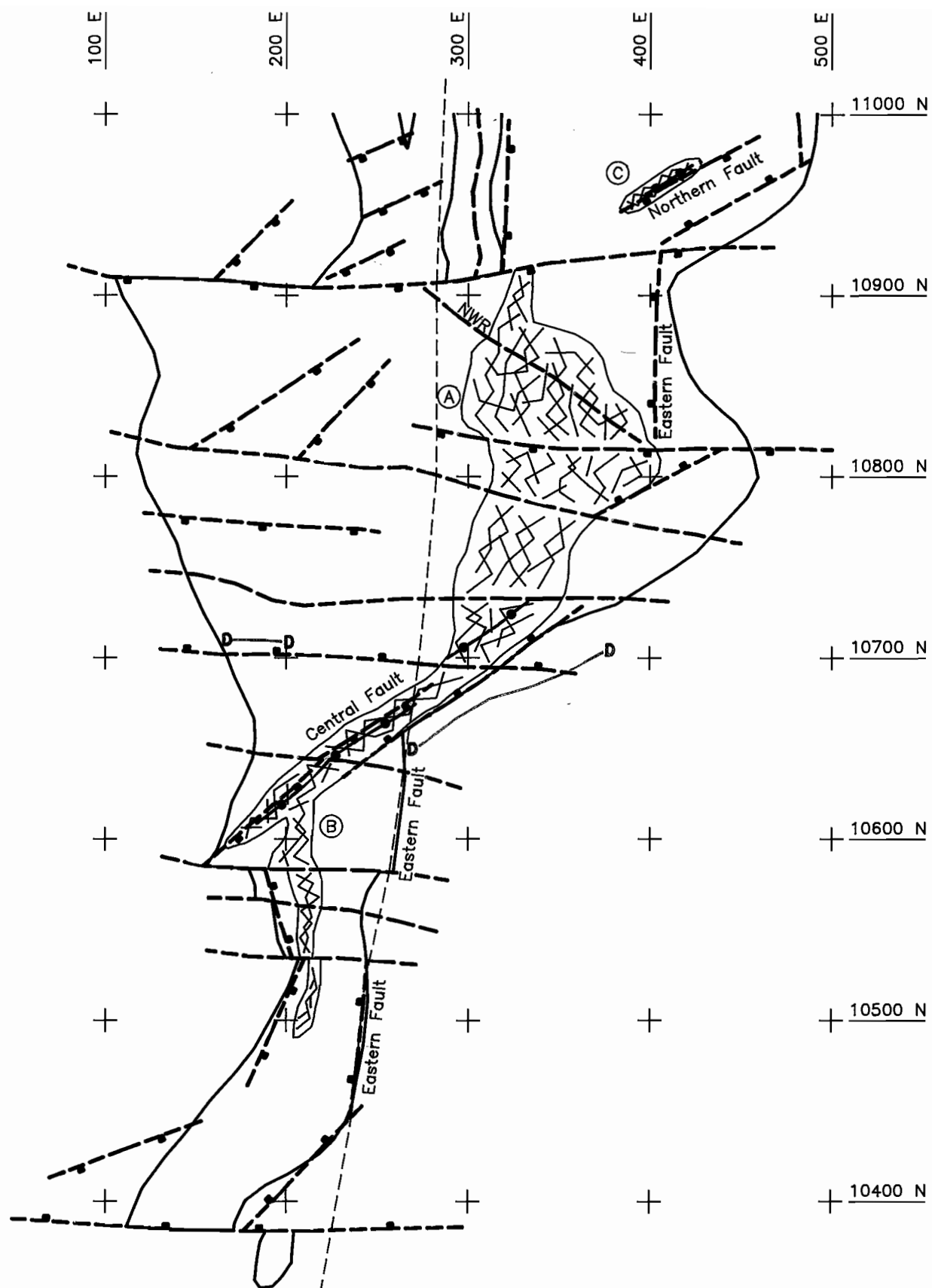
## LEGEND - Figure 15

(Height in metres above arbitrary level.)

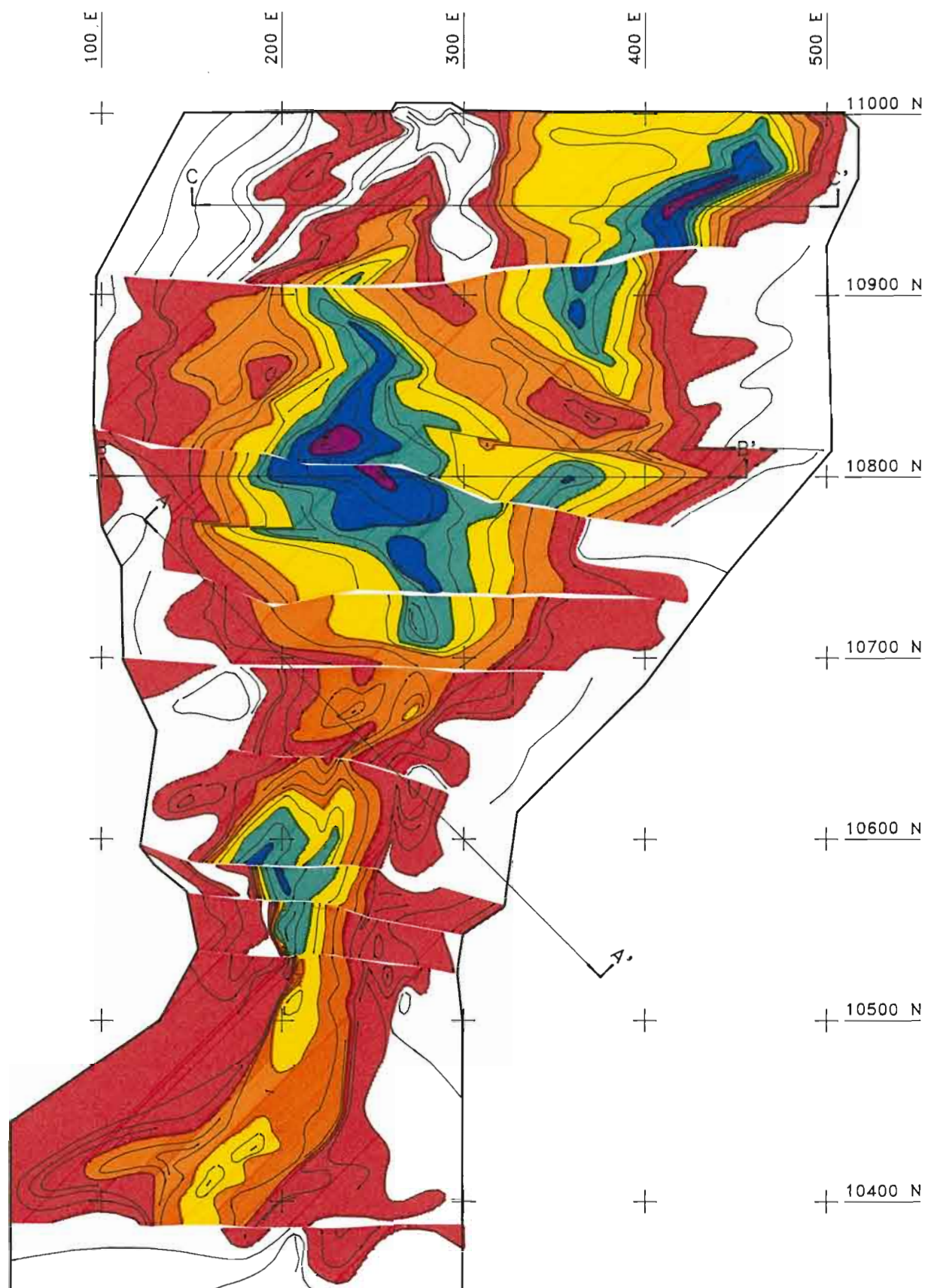


## LEGEND - Figure 16

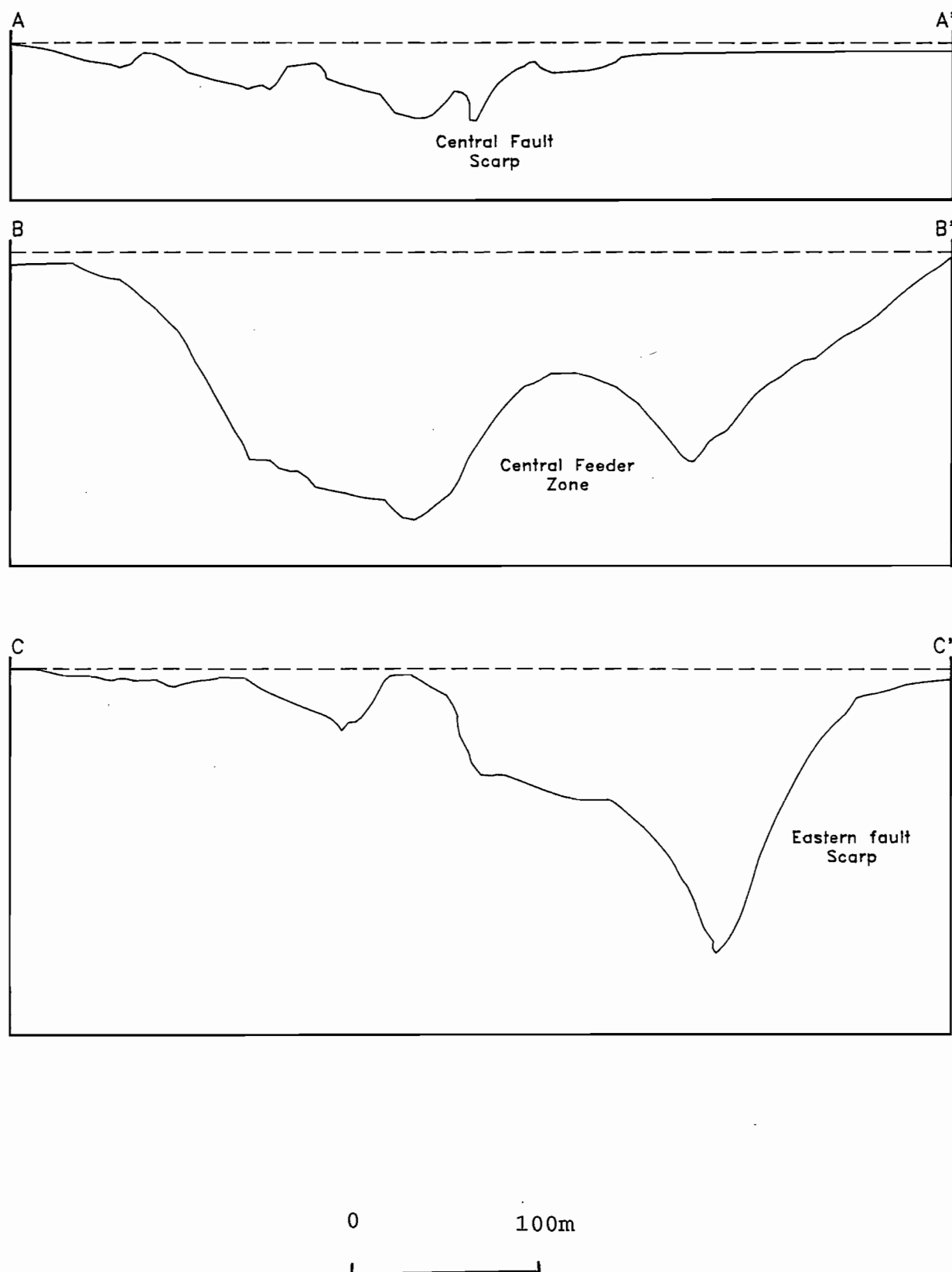




**Figure 16:** Structural elements of the unfolded footwall.



**Figure 15:** Structure contours of unfolded footwall.



**Figure 17:** Cross-sections through unfolded Cambrian seafloor. The dashed line Represents the top of the HVS. Refer to Figure 15 for location of sections.

## Chapter Six

# Cambrian Seafloor Architecture

### 6.1 The Cambrian Seafloor

The structure contours of the unfolded Cambrian seafloor show that the massive sulphide orebody formed within an area of considerable topographic relief (figure 15). The orebody is located within an elongate, north-south striking, fault controlled basin. **Linear** zones of steep topography (ie. escarpments) are interpreted to be pre- or syn-depositional faults, irregular steep topography may be related to constructional volcanic features, ie. lava domes. These faults, and other Cambrian age features are shown on figure 16. The faults lie in the following orientations:-

i) North striking scarps which form the eastern boundary to the basin south of 10670N and north of 10810N. These structures (the **Eastern Fault**) dip steeply to the west and have up to 100m of west-block down displacement. Less extensive north striking faults lie within the basin, some of these dip toward the east. North of 10900N the basin separates into two troughs separated by a ridge of highly altered footwall rock.

ii) A well developed northeast striking structure, the **Central Fault**, cuts through the central part of the basin. To the northwest of this structure the massive sulphide and footwall alteration zone broaden from about 50m to 150m in width and the basin deepens to over 100m.

At 10690N the Central Fault intersects the Eastern Fault, at this point the Central Fault becomes the eastern boundary structure up to 10810N.

A second northeast trending fault, the *Northern Fault*, is located north of 10930N.

Between 10600N and 10690N the Central Fault forms a narrow (15 to 20m wide), steep-sided trough (10 to 15m deep), filled with massive sulphide and underlain by numerous, thick 2B and 2C stringer veins (figure 12). The massive sulphide overlying the trough is cut by equally numerous 2C stage barite-silica veins.

iii) East-southeast striking scarps cross the elongate basin. These structures have between 5 and 30m vertical offset but they are generally less continuous than the other fault sets.

iv) Northwest striking ridges are especially well developed north of 10800N and they cut across the entire basin.

The overall shape of the basin is suggestive of a half-graben with west-block down movement along the Eastern Fault. In plan view the hydrothermally altered footwall volcanics closely follow the north-south striking faults, and alteration is largely restricted to the basin.



## 6.2 The Jack Fault

Earlier workers (McArthur, 1986) have suggested that the Jack Fault was a Cambrian fault which provided a channelway for hydrothermal fluid and formed a basin to trap the exhaled massive sulphide. Figure 16 shows that the Jack Fault follows the Eastern Fault south of 10670N, but that north of the Eastern-Central Fault intersection it appears to have formed a new fracture plane unrelated to any pre-existing Cambrian structure. This suggests that the Jack Fault is a relatively recent structure which has re-activated pre-existing faults where they lie in a favourable orientation.

## 6.3 Hydrothermal Feeder Zones

Gemmell and Large (1992) identified three distinct feeder zones within the footwall stringer zone. These feeders are outlined by high concentrations of pyrite (>37% by weight) and base metals. Gemmell and Large (1992) suggested that the three feeders were aligned on a north-northeast striking structure at an acute angle to the Jack Fault and that the central feeder was located at the intersection of these two structures. However, this study shows that the Jack Fault was not a significant Cambrian structure and that the positions of the feeders were controlled by intersections of a different set of structures.

The siliceous core of the stringer zone has a complex shape and in plan view (figure 16) it appears to follow several north-south faults and the Central Fault. North of 10730N the siliceous core

broadens from 10m to 40-50m wide. This broad zone of siliceous alteration (location A, figure 16) hosts the central feeder of Gemmell and Large (1992). The southern feeder (location B, figure 16) is seen as the southerly extension of the central feeder, albeit offset across the Central Fault. The less extensive northern feeder (location C, figure 16) is located adjacent to the Northern Fault.

The central feeder is located in an area where several Cambrian structures intersect. It is situated on a northwest striking ridge (the *Northwest Ridge, NWR*) close to its intersection with the Central and Eastern faults. The southern feeder is situated at the intersection of the Central Fault and a north-south striking normal fault, the northern feeder is located adjacent to the intersection of the Northern and Eastern faults. The position of these three feeder zones highlights the importance of fault intersections in the formation of Hellyer. The significance of these fault intersections is that they form sites of high permeability and thus, have focussed hydrothermal fluid flow. Thus, the important role of fault intersections in controlling present-day seafloor hydrothermal systems, as described by Rona et al. (1990), is reflected in the Cambrian-age Hellyer deposit.

Etheridge and Windh (1992) noted that, in order to produce a massive sulphide deposit the size of Hellyer within a time span of a few thousand years metal-rich hydrothermal fluids would need to be discharged at a high rate. A mass-balance calculation based on the zinc metal content of the Hellyer orebody, shows that

approximately  $10^{10}$  to  $10^{11}\text{m}^3$  of hydrothermal fluid was required to form the orebody (assuming 10ppm Zn in the fluid). Thus, to form the orebody within a relatively brief period of say 10,000 years would require an average flow rate of 500 to 1000 litres/second of hydrothermal fluid. This high flow rate requires open, actively dilating structures to provide the "plumbing system". Etheridge and Windh (1992) concluded that in order to "maintain high permeability in the face of rapid precipitation from the mineralising fluid" active deformation must continue on the fault controlling the feeder zone.

#### **6.4 East-West Faults**

East-west striking escarpments cut across the basin and have some associated sub-parallel stringer veins and basaltic dykes. These veins and dykes are much less extensive and numerous than their northeast striking relatives suggesting that these structures were less favourably oriented with respect to the principal extension direction and that fluid flow was more spasmodic through these structures.

Vertical offsets along these faults may be due to oblique-slip movement rather than extensional, normal faulting.

#### **6.5 Basalt Dykes**

Basalt feeder dykes are also focussed on the Central Fault and are generally parallel to it. As mentioned in 4.2 it is likely that the basalt magma was erupted through the same set of fractures and fissures as the ore-forming fluids. It is possible that as the dilating faults penetrated deeper into the crust they

eventually tapped into up-rising basaltic magma. At this time the main centre of hydrothermal activity may have migrated to a new site on the same structure away from the basaltic volcanism.

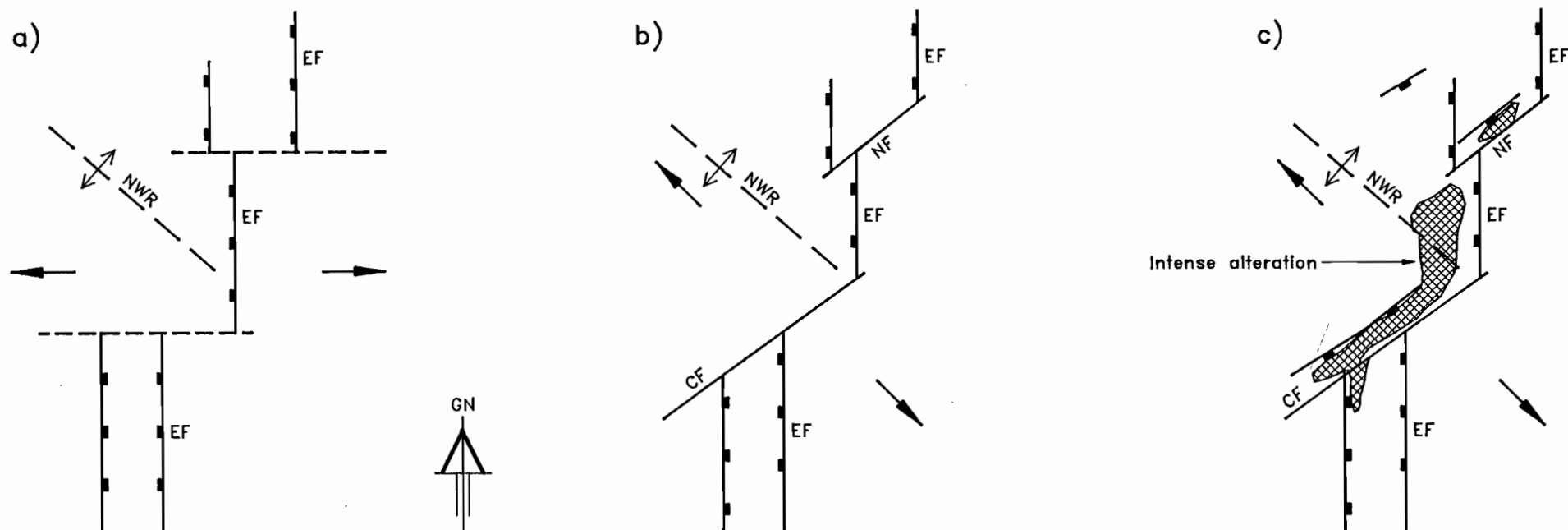
## Chapter Seven

### Interpretation of Syn-Depositional Fault Pattern

The geometry of the seafloor basin indicates that early extension was east-west, with normal offset on the Eastern Fault, and east-west striking transfer faults (figure 18a). A shift in the local extension direction to a NW-SE orientation caused the formation of the Central and Northern faults at an oblique angle to the earlier Eastern Fault (figure 18b).

The alignment of 2A, 2B and 2C stringer veins with the Central Fault and their oblique trend with the north-south basin and the hydrothermally altered footwall rocks suggest that the hydrothermal alteration and the veins formed during dilation of the Central and Northern faults (figure 18c). The outline of siliceous alteration shown in figure 16 suggests that the dominant hydrothermal activity prior to, and during, ore deposition was centred on the intersection of several structures. In particular, the central feeder localised on the intersection of the Eastern Fault, Central Fault and the Northwest Ridge.

The 2B and 2C veins have  $\delta^{34}\text{S}$  values equivalent to the massive sulphide. Stage 2A pyrite veins in the stringer envelope zone appear to be related to the early stages in the development of the stringer system, they have isotopically heavier sulphur than the massive sulphide and the 2B, 2C veins. Gemmell and Large (1992) explain the variations in sulphur isotope composition in terms of a model "where the hydrothermal fluid initially consists of totally to partially reduced seawater sulphate that evolves



**Figure 18:** Schematic plan view showing probable evolution of the syn-depositional fault pattern. CF – Central Fault, EF – Eastern Fault, NF – Northern Fault, NWR – North West Ridge.

- East-west extension forms north striking normal faults with east-west transfers. NWR forms due to re-activation of a NW striking basement-scale structure.
- Rotation of extension direction to NW-SE. CF and NF form.
- NW-SE extension causes dilation of CF and NF. Metal-rich hydrothermal fluids exhaled onto seafloor, followed by basalt magma.

into a fluid dominated by igneous sulphur (ore-forming fluid) as the convection system intensified and penetrated deeper into the footwall." Extensional opening of the Central Fault, appears to have coincided with the intensification of the convection system which accompanied the introduction of the ore-forming fluids.

Although the main alteration and ore-forming hydrothermal activity was associated with the extensional opening of the Central and Northern faults, it is unlikely that these faults had sufficient depth extent to control a large-scale hydrothermal convection cell which probably penetrated to several kilometres depth.

Stolz and Large (1992) calculated that  $70\text{km}^3$  of rocks would have to be leached to provide the metals contained in the Hellyer deposit. A  $70\text{km}^3$  leaching cone below Hellyer could penetrate over 4km into the crust (figure 19). Depths of this order most likely exceed the thickness of Cambrian volcanics and enter the Precambrian basement rocks. In order to channel fluids from these depths deep-seated (ie. basement-scale) structures are required.

### **7.1 The Northwest Ridge**

The Northwest Ridge (NWR) does not fit neatly into the two extensional regimes described above. Its significance should not be underestimated as:-

- i) it is one of three structures upon which the central hydrothermal feeder localised.

ii) there are some (admittedly not many) stringer veins lying in this orientation, and

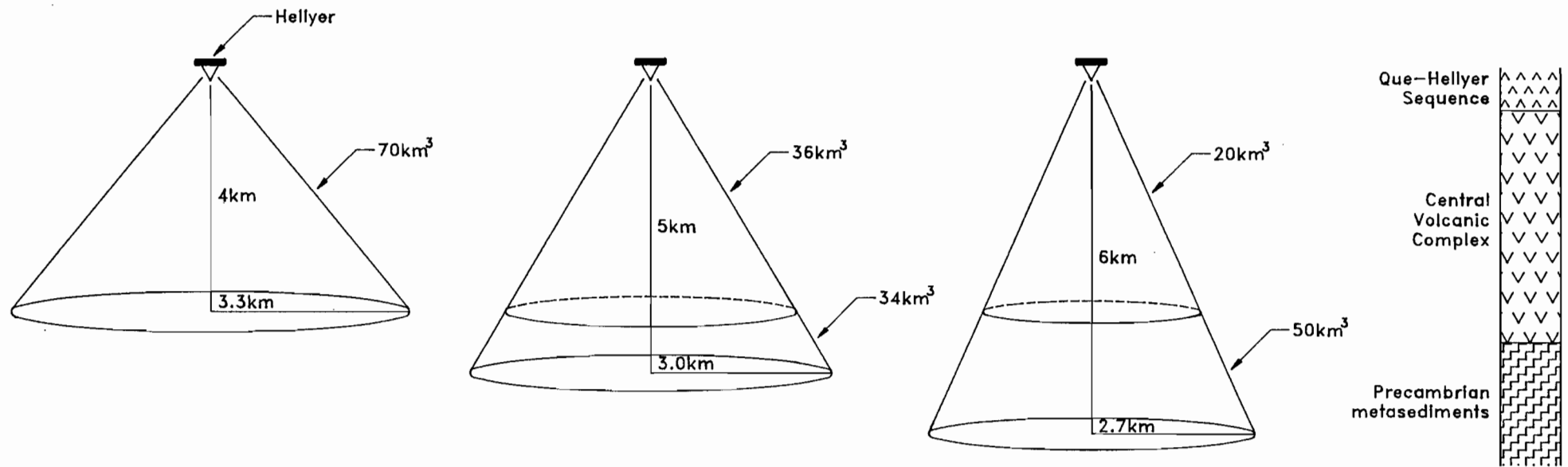
iii) it is sub-parallel to some regionally important faults. For example, the Mount Charter Fault, which appears to have controlled the southwestern margin of the Que-Hellyer Volcanics basin, has a grid NW stike. Thus, by analogy, the NWR may be a re-activated deep-seated structure, penetrating to the base of the QHV.

The interpetation presented here is that the NWR and the Eastern Fault represent basement-scale structures which were active during the mineralising event. The zone of intersection of the two structures may have been highly dilated and provided the depth of penetration required to tap into a deep, large-scale hydrothermal convection cell. The Central and Northern Faults probably provided the near-surface focus for the hydrothermal fluids.

This interpretation is supported somewhat by studies of some of the other major Tasmanian VHMS deposits. Berry et al.(1993) have demonstrated the importance of large-scale transfer faults on the location of Rosebery, Mt.Lyell and Que River. By analogy with these deposits, the NWR could represent an old transfer fault, albeit with a more northwesterly strike than those faults identified by Berry et al.(1993).

Thus, it is inferred that northwest and north-south striking faults at the Hellyer deposit represent basement-scale structures

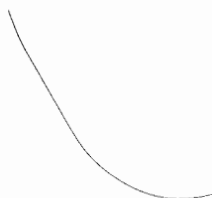




**Figure 19:** Possible dimensions of  $70\text{km}^3$  cones of leachable rock below the Hellyer deposit. From Stolz & Large (1992).

whose intersection has been the dominant control on hydrothermal fluid flow.

In summary, the early history of the Hellyer system saw the formation of a north-south striking fault-controlled basin possibly with some hydrothermal alteration of the footwall. With a clockwise rotation of the extensional direction, the Central and Northern faults formed. Hydrothermal fluids were channelled from about 4km depth by the intersection of the NWR and Eastern Fault. The dilating Central and Northern faults provided the near-surface focus for the discharging hydrothermal fluids.



## Chapter Eight Conclusion

Removal of the effects of post-depositional folding and faulting have led to the construction of a three-dimensional model of the Cambrian seafloor at the time of formation of the Hellyer massive sulphide. This model shows that the Hellyer deposit formed within an elongate, north-south striking, fault controlled basin. Those sites most important in terms of hydrothermal fluid flow, and hence massive sulphide deposition, were the intersections of important structural trends. The important role of intersecting structures in the formation of modern-day massive sulphides is thus reflected in Hellyer, a Cambrian-age example of this deposit style.

Early in the evolution of the hydrothermal system, east-west extension formed a north striking half-graben with east-west striking transfer faults. With the rotation of the extension direction toward the northwest, the Central and Northern faults formed. Hydrothermal fluid flow, with accompanying siliceous alteration of the andesite footwall, was focussed on the intersection of the Northwest Ridge with the Eastern and Central faults. The Northwest Ridge and Eastern Fault probably represent active basement-scale structures which provided the primary channelways of the massive sulphide forming hydrothermal solutions.

Following the formation of the siliceous core metal-rich hydrothermal fluids were exhaled onto the seafloor through fissures parallel to the Central and Northern faults. During the

waning stages of the hydrothermal system, following the formation of the orebody, basaltic magma rose up through a similar set of fractures and erupted onto the seafloor, burying and preserving the deposit.