Chapter 7

The sub-seafloor replacement origin of the Cambro-Ordovician Highway-Reward massive sulfide deposit, Mount Windsor Subprovince

7.1 Introduction

The literature on volcanic-hosted massive sulfide (VHMS) deposits emphasises formation on the seafloor by accumulation of sulfides precipitated from exhaling hydrothermal fluids (e.g. Large, 1992; Lydon, 1988a,b). Support for a seafloor exhalative origin initially came during studies of pristine ancient examples from uplifted and eroded subaqueous volcanic successions (Solomon, 1976; Franklin et al., 1981). The discovery of sulfide chimney mound deposits on the modern seafloor gave credence to the hydrothermal exhalative model for the genesis of VHMS deposits, but raised questions as to the viability of mineral precipitation by exhalation at the seawater-substrate interface. Sulfide accumulation from buoyant hydrothermal plumes above black smokers is a highly inefficient process. It has been estimated that more than 99% of the metal carried by hydrothermal fluids is dispersed in the water column by the plume and incorporated into distal sediments (Rona, 1984). Studies of the structure of modern sulfide chimneys and mounds (e.g. Goldfarb et al., 1983; Koski et al., 1984), and the texture and metal zonation in ancient deposits (e.g. Large, 1977), have highlighted the importance of sulfide accumulation by open space filling and replacement within the sulfide mound. There is increasing evidence to suggest that these processes may extend into the sub-seafloor environment and that some VHMS deposits form by replacement of the host volcanic and sedimentary rocks.

There are few detailed descriptions of sub-seafloor replacement deposits in modern and ancient volcanic successions. Young sub-seafloor deposits have been mapped at Middle Valley; a sediment-covered ridge located along the Juan de Fuca spreading centre (Goodfellow and Blaise, 1988; Goodfellow and Franklin, 1993). The deposit comprises a small sulfide mound that passes down into a discordant pipe-like body of massive sulfide, which extends more than 93 m into the underlying siltstone. The best studied examples of sub-seafloor replacement style VHMS deposits are confined to ancient volcanic successions. These include deposits hosted by silicic to intermediate sequences (Allen, 1988, 1992; Khin Zaw and Large, 1992; Doyle and McPhie, 1994; Bodon and Valenta, 1995; Galley et al., 1995; Allen et al., 1996b) and mafic volcanic successions (Zierenberg et al., 1988). The paucity of examples is probably a reflection of the difficulty of recognising these deposits, rather than their abundance.
This chapter focuses on the problems associated with distinguishing between exhalative and sub-seafloor replacement style VHMS deposits, with the aims of clarifying the terminology, constraining the diagnostic/critical evidence for sub-seafloor replacement, and assessing the role of host lithofacies in determining the character of the resulting deposit. On the basis of published descriptions of sub-seafloor replacement style VHMS deposits and a detailed study of the Highway-Reward deposit, speculative models for the interaction between hydrothermal fluids and host lithofacies in the sub-seafloor environment are presented.

7.2 Terminology

The term "volcanic-hosted massive sulfide deposit" is used for syn-genetic accumulations of massive sulfide which are hosted by submarine volcanic successions (e.g. Solomon, 1976; Franklin et al., 1981; Lydon, 1988a; Large, 1992). Most deposits comprise a stratiform and sometimes strata-bound sulfide zone overlying a discordant massive sulfide and/or stringer zone. Others (e.g. Mount Morgan, Mount Lyell, Highway-Reward) are dominated by massive sulfide pipes or stringer and disseminated styles of mineralisation.

In the context of massive sulfide deposits, the term "exhalation" has been used to indicate fluid emanations into the hydrosphere from the lithosphere (Franklin et al., 1981). Most primary textures in mound-style deposits are indicative of sulfide replacement and sulfide infilling of pore space, rather than precipitation from exhaling hydrothermal fluids at the seawater-sediment interface. Growth of sulfide chimneys and the mound is largely attributed to the deposition of anhydrite and barite on the outer surfaces of the mound, with sulfates being continually replaced by sulfides during mound growth (Lydon, 1988b). For this reason, the term "exhalative ore" is avoided here in favour of the term "seafloor massive sulfide deposit". The position of the seafloor is variable throughout the life of the hydrothermal system due to mound growth, sedimentation, volcanism (strata building) and/or oxidation of sulfides and erosion (strata destruction). The term "seafloor massive sulfide accumulation" is used for the process of sulfide deposition at successive seafloor positions without significant contributions of volcanic detritus or sediment. "Seafloor massive sulfide deposit" is used for the products of this style of hydrothermal activity.

Replacement is defined as a "change in composition of a mineral or mineral aggregate, presumably accomplished by diffusion of new material in and old material out, without breakdown of the solid state" (Bates and Jackson, 1987). In the context of VHMS deposits, sub-seafloor replacement refers to the syn-genetic formation of sulfide minerals by replacement and infiltration of pre-existing volcanic or sedimentary deposits. No
restriction of depth beneath the seafloor is placed on the term. The term does not refer specifically to the process of zone refining (Large et al., 1989) within the developing deposit, although this is probably important during sub-seafloor replacement. Neither does the term incorporate mineralisation which is vein-hosted or not syn-genetic.

Separate lenses or segments of a single deposit can form by different processes and both seafloor massive sulfide accumulation and sub-seafloor replacement may be involved in constructing an orebody (e.g. Vivallo, 1985; Zierenberg et al., 1988; Galley et al., 1993; Humphris et al., 1995). Clearly there is a spectrum from wholly sub-seafloor replacement type deposits to seafloor massive sulfide deposits.

7.3 The role of sub-seafloor replacement vs. seafloor accumulation

Studies of ancient VHMS deposits suggest that there are interdependent criteria for evaluating the role of sub-seafloor replacement during syn-genetic sulfide (or other minerals) deposition: (1) presence of precursor particles or relic coherent facies within the massive sulfide; (2) facies characteristics indicating that mineralisation post-dates deposition of the host; (3) identification of syn-depositional replacement fronts; (4) discordance with the enclosing host lithofacies; and (5) the presence of hanging wall alteration zones with footwall affinities. In most cases, more than a one criterion is required to demonstrate a seafloor or sub-seafloor origin for the mineralisation.

1. The presence of precursor particles or coherent facies

Volcanic and sedimentary particles can sometimes be preserved within the massive sulfide mineralisation. The particles may be partially or completely replaced by sulfide minerals, or are altered and contain disseminated sulfides (e.g. Bodon and Valenta, 1995; Galley et al., 1995). Fragment types, shape, composition and texture help constrain the particle forming mechanism and, when combined with the lithofacies character (bedforms, geometry, internal organisation), can be used to establish the character (porosity, permeability) of the precursor lithofacies and mechanisms of sulfide accumulation in the sub-seafloor environment. Considered alone, precursor particles are consistent with either sub-seafloor replacement or synchronous sedimentation and sulfide precipitation.

In some VHMS deposits, the matrix of autoclastic breccia is replaced by sulfides (e.g. Galley et al., 1995), or the massive sulfide contains segments or patches of strongly altered, mineralised coherent igneous rock (e.g. Highway-Reward). Parts of the massive sulfide mineralisation contained within relic coherent facies or autoclastic breccia can only have formed by replacement and infiltration. Where emplacement as a lava or intrusion cannot be proven, it remains possible that the igneous component was resedimented onto
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seafloor massive sulfide or sourced from subsurface environment and transported with the hydrothermal fluid (e.g. Humphris et al., 1995).

2. Evidence for rapid emplacement of the host facies
This criterion involves a genetic interpretation of the host, with particular attention to transport and depositional mechanisms and the nature and position of contacts between the host rock and mineralisation. Massive sulfide mineralisation which is hosted by rapidly or mass-flow emplaced units can only have formed by replacement and impregnation (Allen, 1994; Allen et al., 1996b). Most often the host will be a lava or intrusion and associated autoclastic breccia (e.g. Zierenberg et al., 1988), or syn-eruptive pumiceous mass-flow deposit (e.g. Allen, 1994; Khin Zaw and Large, 1992). Parts of some sub-seafloor replacement style massive sulfide deposits are hosted by thinly bedded volcano-sedimentary units rather than a single thick depositional unit (e.g. Bodon and Valenta, 1995; Galley et al., 1995). In these, the possibility remains that sedimentation was synchronous with hydrothermal activity and that precipitation of sulfides occurred at, above, and below the seafloor over the life of the hydrothermal system.

The rate of sediment accumulation will determine the relative importance of seafloor and sub-seafloor processes in massive sulfide accumulation. If sedimentation surpasses sulfide precipitation at the seafloor, then sub-seafloor replacement will become important. Growth rates for sulfide mounds are poorly constrained. Chimneys on the mound can grow 8 to 30 cm per day (Goldfarb et al., 1983; Hekinian et al., 1983). Although a single typical black smoker chimney produces around 250 tonnes of sulfide per annum, much of this is dispersed by currents and incorporated into distal sediments (Scott, 1992). Sulfide precipitation at seafloor chimney mounds may be intermittent and separated by long periods dominated by ambient sedimentation (e.g. Rona et al., 1993). Regional sedimentation rates for oceanic spreading centres are generally low (e.g. 1.8 cm/kyr, TAG, Scott et al., 1978), whereas in back arc basin settings sedimentation can be rapid (e.g. Taylor et al., 1991). In the Sumisu Rift of the Izu-Bonin island arc, sediments accumulated at between 90 mm/kyr and 6 m/kyr from 0.1 to 1 Ma (Taylor et al., 1991). The basin fill includes hemipelagic sediment and voluminous volcaniclastic turbidites sourced from arc volcanoes (Nishimura and Murakami, 1988). Volcanism, especially explosive volcanism, has the potential to release large volumes volcaniclastic detritus into submarine settings (e.g. Cas and Wright, 1991; McPhie and Allen, 1992). Burial of chimney mound deposits by volcaniclastic mass flows or lavas can occur during the life of the hydrothermal system, interrupting or terminating seafloor sulfide deposition (e.g. Haymon et al., 1993). As the hydrothermal system attempts to re-establish a seafloor position, sub-seafloor replacement of the intervening lithofacies by sulfide minerals may become important (e.g. Haymon et al., 1993; Humphris et al., 1995).
3. Identification of syn-depositional replacement fronts
Bodon and Valenta (1995) documented primary and tectonic features in the Currawong Zn-Cu-Pb VHMS deposit, Benambra. At the margins of one massive sulfide lens there are replacement fronts passing from the various ores into sandstone beds. Intercalated siltstone laminae are not replaced. A thin quartz-sericite alteration halo extends out from the margins of the sulfide lenses into relic sandstone beds and provides critical evidence for replacement of a pre-existing lithology. Galley et al. (1995) identified similar replacement fronts in the Ansil VHMS deposit, Canada. Alteration intensity increases towards contacts between the massive sulfide lens and tuffaceous host rocks, and beds can be traced into the massive sulfide. Within the ore zone, bases of sandstone beds are mineralised and finer grained tops are silicified. Thin veins cut across silicified tops of beds and link the sphalerite-rich mineralisation. At South Hercules, massive sphalerite mineralisation often passes out through a zone of altered host rock with “spotty” sphalerite ore, into the enclosing pumiceous units (Khin Zaw and Large, 1992). Khin Zaw and Large (1992) interpreted the zonation to record the lateral and vertical migration of hydrothermal fluids within the pre-existing host lithofacies. The “spotty” ore records the nucleation of sulfides within the pumiceous host (Khin Zaw and Large, 1992) and can be considered one type of replacement front. Partially replaced beds and/or clasts are good evidence that bedforms in sulfide can be the product of selective replacement and that these parts of a deposit formed by sub-seafloor replacement of permeable sedimentary horizons.

4. Discordance within the enclosing lithofacies
Discordance within the enclosing volcano-sedimentary package can provide evidence for replacement of a precursor lithofacies (e.g. Khin Zaw and Large, 1992; Galley et al., 1993). However, progressive burial of the older parts of a growing mound/lens by sedimentation or volcanism concurrent with massive sulfide deposition might generate sharp discordant contacts. Accordingly, the criterion cannot be used alone and requires consideration of the transport and depositional mechanisms of the host lithofacies, and the recognition of the seafloor position(s) at the time of mineralisation.

5. Hanging wall alteration zones with footwall affinities
In seafloor VHMS deposits, the upward termination of intense hydrothermal alteration at the position of stratiform sulfides indicates that the ore-forming hydrothermal activity occurred after emplacement of the footwall rocks and before deposition of the hanging wall rocks. Zones of subtle hanging wall alteration have been reported above mineralised intersections in a number of Australian VHMS deposits (e.g. Mount Chalmers, Large and Both, 1980; Hellyer, Jack, 1989). These are interpreted to record weak hydrothermal activity during deposition of the hanging wall volcano-sedimentary package. In contrast, zones of intense hanging wall alteration suggest that ore-forming hydrothermal activity
was continuing during deposition of the hanging wall lithologies or that massive sulfide deposition was entirely sub-seafloor. Given that many volcanic facies are rapidly emplaced, strong hanging wall alteration is entirely plausible even for seafloor exhalative deposits. Burial of seafloor massive sulfide by lavas (e.g. Haymon et al., 1993) or volcaniclastic units can only be discounted by considering the lithofacies character of the host. Intense hanging wall alteration may be mineralogically similar to alteration in the footwall and can contain significant pipe- or vein-style mineralisation (e.g. Highway-Reward, Doyle, 1995; Scuddles, Ashley et al., 1988) and separate massive sulfide lenses/mounds/chimneys at successive seafloor positions (e.g. Haymon et al., 1993).

An assessment of other textures and structures in VHMS deposits

Chimneys and chimney fragments provide strong evidence for sulfide accumulation at the seafloor (Lydon, 1988b) and have been recognised in ancient deposits (e.g. Oudin and Constantinou, 1984). Fossil tube worms and bivalves in chemolithotrophic communities which colonise modern seafloor sulfide mounds can sometimes be preserved by sulfide minerals and are characteristic of seafloor deposits (Haymon et al., 1984; Oudin and Constantinou, 1984). Few other textures or structures in VHMS deposits have genetic significance in distinguishing seafloor deposits from sub-seafloor deposits. Many massive sulfide textures form through open space filling (e.g. colloform banding, network textures). However, this can include intramound porosity, primary lithological porosity, and/or space formed by fluid-rock-mineral interaction (e.g. dissolution of anhydrite). A critical line of evidence in support of a seafloor origin for VHMS deposits has been the recognition of sedimentary structures within some massive sulfide lenses. Graded bedding, cross bedding, and intercalations of laminated and fragmental ore have been identified in the Kuroko deposits (e.g. Ohmoto and Skinner, 1983) and Australian deposits (e.g. Mount Chalmers, Large and Both, 1980). The recognition of similar structures in sub-seafloor replacement style deposits suggests that selective replacement of clasts in pre-existing lithofacies can form similar structures (e.g. Bodon and Valenta, 1995; Galley et al., 1995). Apparent interbedding of sulfide and sediment can result if more permeable laminae are selectively replaced and fine-grained (impermeable) laminae remain unaffected (Bodon and Valenta, 1995). Breccia ore facies can also form in situ within sulfide mounds by dissolution of anhydrite in the matrix to sulfide patches (e.g. TAG, Humphris et al., 1995). Banded sulfides are a common feature of VHMS deposits. In most cases, it is difficult to determine whether the banding is primary or due to later deformation (e.g. Large et al., 1988).

Iron oxide-silica units ("ironstones", Chapter 6) that form the ore equivalent horizon to VHMS deposits can provide evidence for a seafloor position which includes the ore
horizon. However, very similar iron-oxide silica units can from by sub-seafloor replacements of pre-existing strata (Chapter 6). Microaerophilic chemolithotrophic organisms can colonise sub-seafloor sediments (Chapter 6) so are not characteristic of a seafloor position. In some cases, the favourable horizon is not represented by a chemical sediment but sulfide-clast bearing mass-flow deposits (e.g Hercules, Allen and Hunns, 1990; Hellyer, Waters and Wallace, 1992). Mass flows can erode several metres down into the substrate and successive mass flows up to 10’s of metres. Sulfide clasts indicate only that massive sulfide accumulation occurred at or near the seafloor.

7.4 Highway-Reward massive sulfide deposit

The Highway Member (Trooper Creek Formation) at Highway-Reward hosts two spatially associated copper-gold-rich massive sulfide orebodies: Highway and Reward (Fig. 1.1). After Thalanga, the Highway-Reward deposit is the largest known VHMS deposit in the Mount Windsor Subprovince. The Highway orebody is located approximately 200 m NNW of the Reward orebody beneath the abandoned Highway open pit (Fig. 7.1). The massive sulfide deposit consist of sub-vertical pipe-like bodies of massive pyrite-chalcopyrite that are associated with minor marginal discordant and strata-bound zones of pyrite-sphalerite±galena±barite mineralisation. Supergene and oxide ores overlie the primary ores at both Highway and Reward. Most of the oxide resource at Highway was mined from the Highway open cut by North Queensland Resources in the period 1986 to 1988. A significant primary resource remains at Highway and the Reward orebody is presently undeveloped (Table 7.1).

Table 7.1 Grade and tonnage data for the primary, oxide and supergene ore zones at Highway-Reward. The Highway oxide resource is a pre-mining resource estimate. Data from Beams and Dronseika (1995).

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<th>Highway</th>
<th>Reward</th>
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<tr>
<td>Primary</td>
<td>1.2 m.t. @ 5.5% Cu, 6.5 g/t Ag, 1.2 g/t Au</td>
<td>0.2 m.t. @ 3.5 Cu, 13 g/t Ag, 1 g/t Au</td>
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<tr>
<td>Supergene</td>
<td>0.07 m.t. @ 6.04 g/t Au</td>
<td>0.1 m.t. @ 33 g/t Ag, 6.49 g/t Au</td>
</tr>
<tr>
<td>Oxide</td>
<td>0.3 m.t. @ 11.6% Cu, 21 g/t Ag, 1.8 g/t Au</td>
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Previous investigations have briefly addressed various aspects of the Highway-Reward deposit: geophysics and discovery (Kay, 1982; Beams et al., 1989, 1993; Beams et al., 1990; Beams and Dronseika, 1995), geology of the mineralisation and host rocks (Kay, 1987; Berry et al., 1992; McPhie and Large, 1992; Large, 1992; Doyle, 1994), sulfur and lead isotope geochemistry of the massive sulfide (Huston, 1992; Dean and Carr, 1992), deformation style and strain partitioning around the orebodies (Laing, 1988; Berry, 1989); and exploration geochemistry (Beams and Jenkins, 1995). The interpretations presented here are based on detailed diamond drill core logging (61 holes), 1:250 scale mapping of the Highway open pit and the few available surface outcrops, and detailed petrography of the host lithofacies.

Figure 7.1. Surface projection of the Highway and Reward orebodies from approximately 175 m RL (150 m below surface). Stippling highlights the distribution of Cu-rich massive sulfide. Modified from Aberfoyle Resources Limited.
7.4.1 Local geology

The lithofacies associations which host the Highway-Reward deposit are addressed in Chapter 5 and briefly reviewed here. The massive sulfide deposit is hosted by a silicic intrusive and volcanic succession intercalated with sedimentary facies that indicate a submarine, below-storm-wave-base environment of deposition (cf. Beams et al., 1989; Berry et al., 1992; McPhie and Large, 1992; Beams et al., 1993). Contact relationships and phenocryst mineralogy, size and percentages indicate the presence of more than thirteen distinct porphyritic units in a volume of 1 x 1 x 0.5 km. The peperitic upper margins to many porphyritic units demonstrate their intrusion into wet unconsolidated sediment (e.g. Allen, 1992; McPhie et al., 1993). Syn-sedimentary sills, cryptodomes, partly extrusive cryptodomes and associated in situ and resedimented autoclastic deposits have been recognised. These are the principal facies in the environment of mineralisation and represent a proximal facies association from intrabasinal, non-explosive, syn-sedimentary intrusion-dominated magmatism.

Porphyritic units are intercalated with a volcaniclastic and sedimentary facies association comprising suspension-settled siltstone, sandstone turbidites and thick, non-welded pumice- and crystal-rich sandstone and breccia units. Pumiceous and crystal-rich deposits record episodes of explosive silicic volcanism in a shallow marine, basin margin or extrabasinal environment, and were emplaced by cold, water-supported, high-concentration sediment gravity currents. Unaltered andesite dykes cut across the massive sulfide and altered host rocks.

Volcanic host rocks in the Highway-Reward area are weathered to depths in excess of 100 m. The weathered and oxidised zone is more extensive at Reward and extends upward to surface from near the top of the massive sulfide orebody on most sections. Prior to development the Highway orebody was marked by a gossan at surface. The Reward orebody occurs under 100 m combined thickness of Tertiary fluvialite sediments (Campaspe Formation) and weathered gossanous volcanics (e.g. Beams et al., 1989). Bedding measured in drill core suggests a shallow dip of around 10° south east in the subsurface volcanics (cf. Laing, 1988). Flow banding in rhyolite from the Highway open pit has steeper dips (18-55°), but may be at a high angle to bedding.

7.4.2 The massive sulfide orebodies

The mineralisation can be divided into five principal types on the basis of mineralogy, textures and the relationships to the host rocks (cf. Beams et al., 1989; McPhie and Large, 1992; Beams and Dronseika, 1995). These are: (1) pyrite-chalcopyrite pipes; (2)
pyrite-sphalerite±galena±barite; (3) footwall stringer; (4) hanging wall stringer; and (5) gossanous breccia.

*Pyrite-chalcopyrite pipes*

The Highway and Reward pyrite-chalcopyrite pipes are discordant to bedding, but parallel to S4, and have a plunge sub-parallel to a sub-vertical mineral lineation (cf. Berry et al., 1992). The Highway pipe is a NE trending, chalcopyrite-rich massive pyrite body that is approximately 175 m long. To the south, the pipe is less than 20 m wide and 200 m thick (section 10050N; Figs. 7.2, 7.3). On central and northern sections the deposit comprises two or three pipes spaced less than 3 to 10 m apart (section 10100N; Fig. 7.4) or a single "dome" or "tooth-shaped" massive sulfide body. Reward consists of one main and several smaller subvertical, NNE trending, massive pyrite pipes (Fig. 7.4). The largest pipe is saddle-shaped in plan, with a bulbous top in cross-section (Fig. 7.4). The pipe is 100 m x 150 m in plan and up to 250 m thick. It contains around 5 million tonnes of massive pyrite (Beams et al., 1989), which includes a small chalcopyrite-rich zone.

*Mineralogy, textures, and contact relationships*

The massive pyrite-chalcopyrite pipes have a relatively simple mineralogy of pyrite and chalcopyrite, with minor tennantite, sphalerite, quartz and sericite (Fig. 7.5A). Trace minerals include chlorite, aikinite, galena, barite, hematite, rutile and a carbonate (Huston, 1992). Pyrite is typically subhedral to euhedral and fine to medium grained (20-500 μm). Patches of coarse-grained (2-5 mm) pyrite are often associated with shear zones. Rarely pyrite has a lath-like habit (e.g. REM 150, 159.3 m) and may be replacing an earlier mineral such as hematite, barite, or anhydrite (cf. Large, 1992). Pyrite can also be spongy, shreddy, frambooidal, or exhibit snowflake texture (Huston, 1992). Chalcopyrite flecks, veinlets (< 1 mm wide) and patches cut across massive pyrite. Chalcopyrite fills the interstices between pyrite crystals. Barite, quartz-carbonate and anhydrite veins cut across the pyrite-chalcopyrite mineralisation. In some samples, barite occurs as tabular laths interstitial to pyrite and is replaced by quartz (e.g. REM 147, 140 m).

Matrix gangue is generally absent, other than along the margins of the massive sulfide pipes where quartz or sericite±quartz±pyrite-altered volcanic rock is abundant. The exception is a small segment of the Highway pipe (e.g. REM 551, 228-285), where interstitial sericite (now clay) comprises around 10% of the pipe. In most other holes, semi-massive and massive pyrite with 30-60% relic patches and segments of altered coherent rhyolite to dacite and peperite occur within a 1 to 10 m wide zone at the margins and tops of the pipes (Fig. 7.5B). Relic quartz phenocrysts are rarely preserved within the sulfide, but quartz and/or feldspar are common in altered volcanic intervals. The rhyolitic or dacitic component of the peperite is often more pyritic than siltstone in the matrix or
Figure 7.2. Simplified geological cross-section of the Highway-Reward deposit at 10025N. The positions of the main rhyolite units (R1, R3-6) are also shown.
Figure 7.3. Simplified geological cross-section of the Highway-Reward deposit at 10050N. RL = relative position above sea level. The locations of dacite D1, rhyodacite RD2 and the main rhyolite units (R3-7) are also shown.
Figure 7.4. Simplified geological cross-section of the Highway-Reward deposit at 10100N. RL = relative position above sea level. Dacite D1, rhyodacite RD2 and rhyolites R2-4 and R6 occur on this section.
filling fractures in the breccias (e.g. REM 142, 170-177 m). Interstitial anhedral quartz constitutes up to 20 to 30% of the pipe along some of the contacts. Quartz is intergrown with pyrite, forms patches up to 2 cm across, or occurs in bands of pyrite-quartz±barite (Fig. 7.5A-2). Contacts vary from sharp to finely bulbous and many are sheared. A halo of disseminated and patchy pyrite extends cut into the surrounding altered rhyolite and dacite or peperite.

**Sphalerite-galena mineralisation**

The pyrite-chalcopyrite pipes are surrounded by a halo of Pb-Zn-Ba-rich mineralisation up to 500 m wide in an east-west direction and around 225 m long from north to south. Within this halo there are four styles of Zn±Pb±Ba mineralisation. They are: (1) veins and veinlets of sphalerite±galena-barite within altered volcanic rocks along the margins and tops of the pyrite pipes (Fig. 7.2); (2) disseminated, patchy and spotty sphalerite within sericite-quartz-chlorite-altered rocks at the tops of the pipes (Fig. 7.5C-1); (3) lenses of strata-bound massive pyrite-sphalerite-chalcopyrite-barite closely associated with volcaniclastic mass-flow units in the hanging wall to the Reward pipe (Fig. 7.2; 7.5C-2); (4) massive to semi-massive pyrite-sphalerite-chalcopyrite±barite at the margins of the pyrite pipes (Fig. 7.5C-3).

(1) The first style consists of low grade Pb-Zn and can be found throughout the host succession above and adjacent to the walls of the pipes. However, the strongest vein development occurs along the margins of the Reward pipe (Fig. 7.2). (2) Disseminated and patchy sphalerite and galena form a halo above the Highway pipe and extend around 5 m into the peperitic base of the hanging wall rhyolite (e.g. REM 155, 195-200 m). Above Reward, supergene clay, sphalerite, bornite and covellite occur as disseminations and patches in near surface, partially oxidised samples. (3) The halo of Pb-Zn mineralisation extends up to 20 m into the hanging wall, 80 m laterally and includes a small strata-bound pyrite-sphalerite-chalcopyrite-barite lens around 60 m in length. The massive sulfide lens is spatially associated with, but physically separated from, the main Reward pipe (Figs. 7.2-7.4). Drilling to date suggests that southern part of the lens comprises massive and finely banded sphalerite-rich massive sulfide (Fig. 7.2). Banded sulfide textures are common towards the base of the interval, and comprise thin sulfide bands and siltstone bands which are deformed by small F4? folds. The northern part of the lens has a progressively thickening pyrite-rich base and grades into a discordant massive pyrite pod (Fig. 7.3, 7.6). The pod occurs around 20 m above the southern margin of the Reward pipe (Fig. 7.4). Sphalerite-barite-rich massive sulfide intersected at a similar stratigraphic position in drill holes further to the east is interpreted as continuation of the pyrite pod. (4) The fourth style of massive sulfide occurs within a thin (<1 m) zone at the margins of the pyrite-chalcopyrite pipes (e.g. REM 150, 224-228 m).
Figure 7.5

(A) 1. Massive pyrite-chalcopyrite mineralisation from the Highway pipe. REM 142, 194.4 m. 2. Banded pyrite-chalcopyrite-quartz mineralisation from the margin of the main Reward pipe. Chalcopyrite is aligned in the foliation (bar). REM 560 205.4 m.

(B) Semi-massive pyrite-chalcopyrite (p) with relic patches and segments of strongly altered coherent dacite (d) and peperite. Core is 5 cm wide. HMO 62, 157-162 m; Reward.

(C) Sphalerite-galena mineralisation. 1. Spotty sphalerite (arrow) within sericite-quartz-chlorite-altered sandstone at the top of the Highway pipe. REM 152, 160.8 m; 2. Sample of banded pyrite-sphalerite-chalcopyrite-barite mineralisation from a strata-bound lens above the main Reward pipe. REM 122, 157.7 m. 3. Sphalerite-pyrite mineralisation from the margin of the Highway pipe. REM 150, 225.4 m.

(D) Banded pyrite-quartz-barite-sphalerite mineralisation replacing rhyolite peperite along the upper margin of the Reward pipe. The rhyolite (r) is strongly chloritised and pyritic, whereas the siltstone (s) is silicified. REM 116, 182-190 m; Reward.

(E) Photomicrograph of strata-bound pyrite-sphalerite±barite-rich mineralisation from the Reward orebody. Apparent grading in this quartz-sericite-altered unit is defined by euhedral pyrite (p). Plane polarised light. REM 122, 157 m.

(F) As for E, but in reflected light.

(G) Pyrite-quartz veins (v) in sericite-quartz-altered dacite below the Highway orebody. Fibre quartz forms a halo around the veins (1) or fills fractures within the pyrite mineralisation (2). REM 154, 314.4 m; REM 154, 257.5 m.

(H) In situ brecciated (tectonic) massive pyrite-chalcopyrite mineralisation from the Reward orebody. Core is 5 cm wide. HMO 60, 145-150 m; Reward orebody.
Figure 7.6. (A) Selected drill logs showing internal textural variations and contact relationships of sphalerite-rich mineralisation and volcanic facies to the south of the Reward pipe. Alteration facies as illustrated in 7.8. Alteration codes outlined in appendix C. (B) Plan projection of diamond drill holes in HA".
It consists of massive to finely banded pyrite-chalcopyrite-sphalerite-barite replacing peperite. The bands are 1-2 mm wide, strongly contorted, and mimic contacts between the massive sulfide and altered volcanic rock. (Fig. 7.5D; REM 116, 182-190 m).

Mineralogy and textures

This mineralisation style consists of varying proportions of pyrite, sphalerite, chalcopyrite and galena, with a gangue dominated by quartz, sericite and barite. Minor and trace minerals include tennantite, carbonate, chlorite, bismuth minerals, marcasite, hematite and electrum (Huston, 1992). Minerals in the supergene zone are clay, bornite and covellite. Pyrite is euhedral or exhibits snowflake, colloform, or spongy textures (Huston, 1992). Sphalerite occurs as anhedral intergrowths with pyrite and chalcopyrite, and often exhibits chalcopyrite disease. Barite laths are commonly pseudomorphed by quartz.

Fine laminated in the strata-bound pyrite-sphalerite-chalcopyrite-barite mineralisation closely resembles bedded sulfide sediments (cf. Huston, 1992). A limited microscopic study (REM 122, 157.7 m) suggests that laminae consist of 1-2 mm microcrystalline bands of anhedral quartz intergrown with pyrite, alternating with 1-20 mm bands of pyrite-sphalerite-chalcopyrite with interstitial coarser grained (0.05-0.2 mm) anhedral quartz and minor sericite. The grainsize of pyrite grains decreases from the base to the top of the thicker bands and resembles sedimentary grading (Fig. 7.5E-F). Pyrite is euhedral to subhedral and generally associated with sphalerite. Chalcopyrite occurs as anhedral grains and as chalcopyrite disease in sphalerite. Banding in the strata-bound interval is cross-cut, and partially replaced by, veins and veinlets of pyrite and quartz with diffuse boundaries. Similar veins dissect massive sphalerite mineralisation at the margins of the pyrite pipes.

Footwall and hanging wall stringer veins

Pyrite±quartz±sericite stringer veins occur below the Highway and Reward pipes and adjacent to the walls of the pipes (Fig. 7.5G). On some sections, stringer pyrite±covellite±chalcopyrite veins also occur in sericite-quartz-altered volcanic rocks above the pyrite pipes (e.g. REM 147, 101-116; Fig. 7.4). Small veins are dismembered in the cleavage and larger veins are fractured internally. Fibre quartz fills the fractures or forms a selvedge surrounding a pyrite±sericite±quartz core. A few veins comprise discontinuous, finely bulbous bands of quartz and pyrite. In general, disseminated fine to coarse-grained, euhedral to subhedral pyrite accounts for 10-20% of the wall rock beneath the pyrite pipes and veins vary from 0.5 to 15 cm across, but are mostly around 1 cm wide. Towards the centre of the stringer zone, vein spacing decreases from 0.5-1 m to 15-30 cm (e.g. REM 142, 275-290 m). In the hanging wall, stringer veins are thinner
Mineralisation

(0.1-1 cm wide) and spaced 30 to 40 cm apart (e.g. REM 560, 101-120; REM 147, 102-116 m). The wall rock typically contains only 6-10 % disseminated pyrite.

Gossanous breccia zones

Gossanous zones occur within volcaniclastic units and coherent rhyolite overlying the pyrite pipes and exposed in the base of the Highway pit (Fig. 7.3). They comprise heavily silicified and/or clay weathered volcanic rock with iron oxide-filled veinlets and cubic hollows after disseminated pyrite. Relic quartz phenocrysts are preserved in intervals of gossanous rhyolite. Some quartz-bearing zones contain siltstone seams and patches and may be altered peperite. Veins and patches of tabular barite crystals (1-2 mm long) are abundant in a few cores (e.g. REM 132, 58-69 m).

7.4.3 Effects of deformation and metamorphism on the massive sulfide orebodies

The host lithofacies, mineralisation and associated alteration have the same tectonic fabric, although the intensity of the fabric varies. The massive pyrite pipes have been fractured and dilated by the deformation and include local domains of cataclasite (e.g. HMO 60, 133-151 m; Fig. 7.5H). The alteration halo has sheared parallel to the subvertical S4 cleavage. Shearing has been focussed along the margins of the pyrite pipes and porphyries. Spotty and disseminated sphalerite have been drawn out into the cleavage and bands in strata-bound pyrite-sphalerite lens folded. Fibre quartz has grown in the pressure shadows of disseminated euhedral pyrite grains. Stringer veins have been dismembered in the cleavage, whereas gypsum veins are crenulated by S4 (e.g. REM 149, 169.8 m). Chalcopyrite was mobilised into the cleavage which cuts across primary quartz-pyrite banding at the margins of the pipes.

7.4.4 Alteration mineralogy and distribution

Detailed drill core logging of alteration and volcanic facies allow for investigation of the interplay between primary volcanic texture, the texture and mineralogy of each alteration stage, and mineralisation. Graphic lithological logs have been used to record the nature and positions of contacts, volcanic textures and facies, alteration mineralogy and mineralisation (Appendix C). Textural relationships between each alteration stage and the pre-alteration texture, mineral abundances and associations, and chronology have been recorded using a code system which is detailed in Appendix C.
The Highway and Reward orebodies occur within a well-developed discordant alteration envelope. The envelope extends from at least 150 m below the orebodies to over 60 m above the Highway pipe (Fig. 7.7). At Reward, intense weathering and oxidation obscure the hanging wall alteration on most sections (Fig. 7.8). Footwall alteration occurs along the entire length of the deposit in a 500 m by 250 m post-deformational elliptical shape. Small zones of footwall alteration also occur peripheral to the orebodies at Gateway (200-250 m west of Highway) and 200 m east of Reward.

Hydrothermal alteration at Highway-Reward is complex, reflecting primary heterogeneity modified by subsequent faulting. Broadly the alteration envelope has a mineralogical zoning which is defined by assemblages of sericite, chlorite-sericite, quartz-chlorite-sericite, chlorite±anhydrite, quartz-sericite±pyrite, albite±sericite-chlorite-quartz and hematite±chlorite-sericite-quartz. Disseminated pyrite is a common accessory in all but the latter two assemblages. Although the stringer veining and sulfide orebodies at Highway and Reward are spatially distinct, the alteration zones associated with each overlap, and some alteration zones partially envelop both orebodies. A quartz-sericite±pyrite zone is centred beneath the pyrite pipes and on some sections extends into the hanging wall succession (Figs. 7.7-7.8). Small domains of intense chlorite±anhydrite alteration occur within the footwall quartz-sericite±pyrite zone and along some margins of the pipes (Fig. 7.7). Quartz-sericite±pyrite alteration gives way laterally and vertically to domains of sericite-chlorite-quartz and chlorite-sericite alteration. Beyond the hydrothermal alteration halo, rocks of rhyolitic to dacitic composition contain various assemblages of feldspar (albite), calcite, sericite, chlorite, quartz and hematite±chlorite-sericite-quartz (Fig. 7.8). Contacts between the alteration zones are typically gradational. Less intense alteration, as indicated by variable preservation of feldspar phenocrysts and volcanic textures, occurs more commonly marginal to the orebodies and in the hanging wall. The most intense alteration occurs in the stringer zone beneath the pyrite pipes, and on some sections, in quartz-sericite-altered hanging wall rocks.

Quartz-sericite±pyrite zone

Within this zone, the relative proportions of quartz and sericite varies considerably, and either can be the dominant phase. Quartz-dominant alteration is more common beneath the pipes. The quartz-sericite±pyrite alteration is pervasive or patchy and obscures or destroys original volcanic textures creating apparent elastic textures (Fig. 7.9A). Relic quartz phenocrysts are locally recognisable along the margins of the zone, particularly in sericite apparent clasts enclosed by more intensely silicified wall rock. In some samples, disseminated pyrite preferentially replaced the sericitic component. The quartz-sericite±pyrite alteration encloses domains of intense pervasive quartz alteration which are associated with strong, quartz-pyrite stringer vein development (Fig. 7.8). In
Figure 7.7: Simplified geological cross section showing the distribution of volcanic facies, alteration and mineralisation at 10100N. RL = relative position above sea level.
Figure 7.8. Simplified geological cross section showing the distribution of volcanic facies, alteration and mineralisation at 10150N. RL = relative position above sea level.
the hanging wall, a discordant zone of strong quartz-sericite±pyrite alteration extends up to more than 60 m (10075N) above the Highway pipe into the overlying rhyolite and volcaniclastic deposits (Fig. 7.7). A similar, but poorly preserved zone occurs above the main Reward pipe. This style of alteration obscures primary textures, but only in the most silicified domains are the lithofacies unrecognisable.

**Chlorite±anhydrite zone**

Small zones of intense pervasive chlorite alteration are developed sporadically within the footwall quartz-sericite zone. In a few samples, chloritised wall rock contains lath- and ovoid-shaped quartz spots, 0.5-2 mm in diameter. The quartz may be pseudomorphing an earlier mineral such as barite or carbonate. At the margins of the Reward pipe, pods of very fine-grained (30-50 μm), weakly foliated chlorite contain abundant euhedral anhydrite crystals up to 1.5 cm (Fig. 7.9B). The foliation wraps around the anhydrite, which indicates a pre- or syn-kinematic timing for anhydrite crystallisation (Fig. 7.9C; cf. Huston, 1992). This observation contradicts the late-kinematic timing for anhydrite proposed by Beams et al. (1989, 1990). The chlorite-anhydrite alteration contains rare relic quartz-sericite patches.

**Sericite alteration**

This style of alteration is distributed throughout the alteration envelope, but is particularly common within shear zones at the margins of the Highway and Reward orebodies (Fig. 7.7). Sericitised wall rock also occurs as the gangue in semi-massive pyrite-chalcopyrite at the margins of the pyrite pipe. Subsequent tectonic foliation is strongly developed in the sericitic domains and has obscured or destroyed primary textures in the volcanic rock.

**Quartz-chlorite-sericite zone**

Outward from the quartz-sericite zone is a widespread quartz-chlorite-sericite zone. The zone comprises a complex alteration assemblage in which the dominant phase can be chlorite, sericite-quartz, or chlorite-sericite. Alteration within this zone is strongly controlled by primary volcanic textures, particularly fracture and matrix permeability. Pale to dark phyllosilicate-rich alteration is typically pervasive. Quartz-sericite±pyrite alteration is often strongly controlled by fractures and the matrix in autoclastic breccia, and has overprinted earlier phyllosilicate-rich alteration assemblages (Fig. 7.9D). Domains of chlorite-sericite and chlorite alteration are often preserved within more extensive quartz-sericite alteration supporting the paragenesis. However, chlorite stringer veins with diffuse margins sometimes cut across the quartz-sericite alteration, suggesting that there
Examples of typical alteration features at Highway-Reward.

(A) Quartz-sericite ± pyrite zone. Drill core showing quartz-sericite ± pyrite alteration in lithofacies from the footwall (1) and hanging wall (2) of the Reward and Highway orebodies.REW 807, 454.7 m; REM 137, 168.9 m.

(B) Chlorite±anhydrite zone. Intensely chlorite-altered volcanic rock containing abundant euhedral anhydrite crystals (a). Core is 5 cm wide. HMO 41, 283.6 m; Reward.

(C) Chlorite±anhydrite zone. The foliation (arrow) wraps around the anhydrite (a) suggesting a pre- or syn-kinematic timing for anhydrite. Plane polarised light. HMO 41, 283.6 m; Reward.

(D) Quartz-chlorite-sericite zone. This breccia is strictly monomictic, comprising blocky and cuneiform dacite clasts (c) that form jigsaw-fit aggregates. Brecciation was probably caused by quench fracturing of a formerly glassy cryptodome, producing in situ hyaloclastite. Quartz-sericite alteration (q) along and adjacent to the matrix overprints earlier, pervasive chlorite-sericite alteration. Core is 5 cm wide. REM 560, 305 m; Highway.

(E) These three drill core samples come from a pumiceous, subaqueous mass-flow deposit. Cores 1 and 2 contain nodular domains (n) of albite alteration, separated by sericite-chlorite-altered pumice clasts (arrow). Alignment of compacted pumice clasts defines a bedding-parallel compaction foliation (S1). In core 3, nodules merge and form patches within the pumice breccia. Core is 5 cm wide. REW 805 (277.9-278.4 m).

(F) Samples of pumice breccia are composed of variably compacted pumice clasts and are non-welded. Sericite-chlorite-altered pumice clasts (c) are compacted around the more competent albite-altered pumice clasts (p) and define a diagenetic compaction foliation. The albite-altered pumice clasts have uncompacted tube vesicles (bar). Plane polarised light. REW 578, 203.7 m.

(G) The formerly glassy groundmass of this rhyolite contains relic classical perlite fractures. The fractures are delineated by chlorite and sericite (c). The remainder of the glass has been replaced by albite (a) and quartz (q). Plane polarised light. REW 802, 183.1 m.

(H) These four samples are from a rhyolitic intrusion. In situ hyaloclastite (core 1) passes gradationally down into peperite comprising rhyolite clasts and a pumiceous matrix (core 2, 3). Clasts and the matrix in the breccia have been silicified, sericitised and hematite-altered (core 3). Pumice breccia away from the contact (core 4) is sericite-quartz-altered. Core is 5 cm wide. HMO 52, 146-160 m, Highway-Reward.
are several generations of chlorite alteration. The polyphase alteration has resulted in the widespread development of patchy, mottled, wispy and apparent clastic textures.

**Chlorite-sericite alteration**

Low intensity chlorite-sericite alteration with minor carbonate, characterises this alteration zone. The assemblage is largely restricted to domains within more widespread quartz-chlorite-sericite alteration and is common towards the northern end of the Highway orebody. Near the hanging wall contact of the Highway pipe, quartz-sericite-pyrite alteration passes gradationally out through a chlorite-sericite zone into weak pervasive chlorite alteration (e.g. REM 562, 100-197 m). Along the contacts, quartz-sericite alteration often occurs as a “wash” within the chlorite-sericite zone and overprints earlier chlorite and sericite alteration.

**Feldspar (albite & K-feldspar) ±carbonate-chlorite-sericite-quartz alteration**

Many formerly glassy rhyolitic to dacitic volcanic rocks in the Trooper Creek Formation have altered to various assemblages of feldspar, carbonate, chlorite, sericite and quartz. At Highway-Reward, these assemblages are restricted to hanging wall lithofacies greater than 200 m from the orebodies (Fig. 7.8). The alteration is regionally distributed but selectively replaces glassy parts of lavas and intrusions, pumiceous units and crystal-vitric breccia and sandstone beds. This style of alteration is very heterogeneous, forming pale feldspar±quartz-rich domains and green chlorite-sericite-rich areas. In pumiceous and shard-rich deposits, secondary feldspar or carbonate nucleated around feldspar phenocrysts and moved out as nodular zones (Fig. 7.9E), infilling vesicles and replacing formerly glassy vesicle walls (Fig. 7.9F). The feldspar alteration was incomplete, leaving weakly altered domains which were subsequently altered to more phyllosilicate-rich compositions. The phyllosilicate-altered domains are often strongly elongate and define a bedding-parallel diagenetic compaction (or early tectonic) foliation (cf. Allen and Cas, 1990; Chapter 2). In the glassy parts of lavas and intrusions, early feldspar-carbonate-chlorite alteration was typically pervasive or fracture controlled. More advanced phyllosilicate-dominated alteration generally spread outward from fractures or the matrix, overprinting earlier feldspar alteration (Fig. 7.9G).

**Hematite±quartz-sericite-chlorite**

A second common alteration style in the Trooper Creek Formation, as represented in lithofacies 50-200 m from the Highway-Reward deposit, is widespread hematite±quartz-sericite-chlorite alteration. Occasionally, small zones of hematite-rich alteration are preserved along the margins of the orebodies (e.g. REM 122, 125-136 m). The alteration
is pervasive or domains of hematite, chlorite-sericite and chlorite-carbonate alteration, generate patchy, mottled or pseudoclastic textures. Formerly glassy, porous and permeable facies (e.g. pumice breccia and sandstone, fractured glassy lava) are particularly susceptible to hematite-quartz-sericite-chlorite alteration (Fig. 7.9H). In other cases, hematite overprints lamination and bedding within siltstone. The alteration is generally restricted to a single depositional unit or only a few beds.

Alteration paragenesis

The regional distribution of the feldspar-carbonate-chlorite-sericite-quartz alteration assemblage is consistent with an early diagenetic or regional metamorphic origin. The albitic alteration protected some pumice clasts from diagenetic compaction, suggesting alteration occurred prior to or during diagenesis. The diagenetic compaction foliation is crenulated by the regional cleavage indicating that the alteration was complete prior to regional deformation. The domainal feldspar-carbonate-chlorite-sericite-quartz alteration is similar to that documented by Allen and Cas (1990) in pumiceous breccia units at Rosebery and Hercules, in western Tasmania. Allen and Cas (1990) suggest that two phase albite-K-feldspar and chlorite alteration occurred prior to tectonic deformation during the onset of diagenetic compaction. Elements such as Na, K, Al and Si necessary to form the widespread albite-K-feldspar alteration were probably derived by dissolution of glassy pyroclasts and/or hydrothermal leaching of glass deeper in the volcanic pile. In the Trooper Creek Formation, the widespread development of a bedding parallel stylolitic dissolution foliation in the pumice breccia beds is good evidence for dissolution of glass in the volcanic pile (cf. Allen and Cas, 1990). It is uncertain whether albite and K-feldspar were the first alteration minerals formed or if they replaced earlier minerals such as zeolite.

Hematite-rich alteration and quartz-hematite veins are also regionally distributed and not preferentially associated with mineralisation. The hematite alteration is interpreted to have deposited from low temperature fluids circulating around lavas and intrusions and within the proximal facies association of shallow marine volcanoes (Chapter 6; cf. Einsele et al., 1980; Einsele, 1986; Boulter, 1993a). The convecting pore water leached Fe, Si, and other elements from the glassy volcanic rocks and reprecipitated the iron and silica by conductive cooling and mixing with seawater in the enclosing volcanic package (Chapter 6; cf. Sigurdsson, 1977). The same hydrothermal systems were probably important in contributing elements for regional diagenetic feldspar alteration.

The alteration paragenesis related to mineralisation appears complex and is beyond the scope of the present study. However, some preliminary comments can be made. From drill core, it appears that hydrothermal alteration associated with massive sulfide
deposition started with assemblages of sericite and chlorite which were subsequently overprinted by quartz-sericite alteration. Chlorite veinlets which cut across the quartz-sericite zone are probably late. The chlorite-anhydrite alteration is probably also late as these zones contains relic patches of earlier quartz-sericite alteration and anhydrite veins cut across the massive pyrite-chalcopyrite pipes and other alteration assemblages.

7.4.5 Interrelationships between lithofacies, mineralisation and alteration

The geometry and distribution of the Highway and Reward orebodies were strongly influenced by the position of cryptodomes in the host succession (Figs. 7.2-7.4; 7.8). The Highway pipe is bound by four porphyries: dacite 1 (western margin), rhyodacite 2 (footwall), and rhyolites 3 and 4 (hanging wall) (Figs. 7.3, 7.4). Rhyodacite 2 hosts most of the pyrite-chalcopyrite pipe and the associated stringer mineralisation. The upper contact of the pipe has partially replaced the peperitic lower margin of a rhyolitic partly extrusive cryptodome (rhyolite 4). The massive sulfide and peperite show no indications of mixing. Weak disseminated and semi-massive pyrite-sphalerite-barite mineralisation has replaced the sedimentary and rhyolitic components of the peperite. Intense quartz-sericite alteration and associated disseminated and stringer pyrite mineralisation extend for at least 60 m into the cryptodome. The Highway oxide resource occurs within this alteration zone, along the top of rhyolite 3 (cryptodome) and below an onlapping margin of rhyolite 4 (Fig. 7.3). The southern extent of the Highway pipe is limited by a substantial thickening of rhyolite 4, and termination of rhyodacite 2. Both rhyodacite 2 and significant pyrite-chalcopyrite mineralisation are absent north of 10200N.

The main Reward pyrite-chalcopyrite pipe straddles the boundary between two cryptodomes; rhyodacite 2 (western margin) and rhyolite 2 (eastern margin; Fig. 7.8). An underlying syn-sedimentary sill (rhyodacite 1) occurs below both rhyodacite 2 and rhyolite 2 implying that the cryptodomes are not in faulted contact. Stringer veins extend beneath the pyrite pipe into rhyodacite 2, the top of which is partially replaced by massive pyrite-chalcopyrite. As at Highway, rhyolite 4 forms the hanging wall to the main Reward pipe. On many sections the upper margin of the pipe corresponds to the extrusive top of rhyolite 4 (Fig. 7.4). Several smaller pyrite bodies cut across the overlying volcaniclastic units and intrusions (rhyolites 5-6; Figs. 7.3, 7.4). The southern extension of one small pyrite pipe comprises strata-bound sphalerite-pyrite-barite. The strata-bound mineralisation overlies resedimented hyaloclastite of rhyolite 4 and a distinctive syn-sedimentary sill (rhyolite 5) (Fig. 7.2). As at Highway, the northern extent of the Reward pyrite pipe is marked by the boundary between rhyodacite 2 and a northerly thickening cryptodome (rhyolite 9) (Fig. 7.2). The southern limit of the Reward pipe is poorly
constrained. Stringer vein-style mineralisation extends for at least 90 m north and 150 m south of the Highway and Reward pyrite pipes.

7.4.6 Evidence for a syn-volcanic origin

Laing (1988) and Beams et al. (1989, 1990) proposed two episodes of ore deposition at Highway-Reward: a Cambro-Ordovician event which deposited syn-genetic sphalerite-rich mineralisation, and a Siluro-Devonian syn-deformational episode which produced discordant pyrite-chalcopyrite pipes. Their interpretation of the pyrite-chalcopyrite pipes as syn-deformational was based on: (1) discordance with the host succession; (2) elongation of the pipes and associated stringer veins parallel to the S4 cleavage; and (3) the inferred late-kinematic timing for anhydrite. The textural and structural evidence presented by Laing (1988) and Beams et al. (1989, 1990) is inconclusive and not diagnostic of a syn-kinematic origin for the pyrite pipes. Rather, the available evidence suggests that the pyrite-chalcopyrite pipes and strata-bound lenses formed together and are syn-genetic (cf. Large, 1992; McPhie and Large, 1992; Huston, 1992).

Discordance with the host succession does not rule out a syn-genetic origin for the pyrite pipes. Large parts of many ancient and currently forming VHMS deposits display cross-cutting relationships with the host succession (e.g. Bodon and Valenta, 1995; Galley et al., 1995; Humphris et al., 1995). At Highway-Reward, the gradation from Cu-rich massive pyrite mineralisation into marginal sphalerite-rich mineralisation is consistent with a single mineralising event and is similar to the mineralogical zonation seen in many VHMS deposits (e.g. Lydon, 1988a; Large, 1992).

Rare patches of sulfide that crosscut cleavage occur in parts of the Highway-Reward deposit. However, almost all of the mineralisation and alteration have the same tectonic fabric as their host rocks. S4 cleavage and faults are the most prominent structures suggesting most of the ore predated the Siluro-Devonian deformation. Studies of comparable volcanic successions suggest that superimposed structures are often localised within mineralised zones due to the relative incompetence of the altered host rock and some mineralisation types (e.g. Large, 1992). The intensity of the cleavage at the margins of the pyrite pipes, relative to the massive sulfide, reflects the different responses to deformation by the incompetent phyllosilicate-rich alteration zone and competent massive sulfide. It is possible that the pyrite-chalcopyrite pipes and stringer zones were rotated into the D4 structures during deformation (cf. Huston, 1992). Alternatively, the D4 faults reactivated pre-existing structures that controlled the initial deposition of the pyrite pipes (Berry et al., 1992; Huston, 1992) and acted as conduits for rising magma.
The late-kinematic timing of anhydrite proposed by Beams et al. (1989) is not consistent with relationships between the cleavage and the crystals documented in present study. Rather, textures observed within both the pyrite-chalcopyrite pipes and marginal sphalerite-rich mineralisation provide strong evidence for a syn-genetic origin (cf. Huston, 1992). Pyrite with colloform, framboidal, spongy, and snowflake textures is common within VHMS deposits (e.g. Large, 1992). In particular, colloform pyrite is characteristic of open space filling (e.g. Guilbert and Park, 1986), which is inconsistent with a syn-deformational model for mineralisation. Chalcopyrite disease in sphalerite is characteristic, but not diagnostic, of syn-genetic VHMS deposits (Huston, 1992).

The zonation of hydrothermal alteration associated with the massive sulfide bodies is similar to that associated with other Australian VHMS deposits characterised by well developed alteration pipes (e.g. Large, 1992). The distribution of alteration minerals and textures is closely related to inferred initial patterns of permeability and compositional contrasts in the volcanic succession. Alteration associated with syn-deformational mineralisation is more likely to be controlled by fracture and fault patterns than by original volcanic textures (e.g. Oliver, 1996).

Further evidence consistent with a syn-genetic origin for the Highway and Reward orebodies is their occurrence in a regionally altered submarine volcanic succession hosting other VHMS deposits (e.g. Liotontown, Berry et al., 1992; Miller, 1996) and the strong stratigraphic control on mineralisation. The regional stratigraphy, depositional setting, sulfide mineralogy and alteration style are also similar to successions that contain relatively undeformed VHMS deposits. Sulfur isotope values for VHMS deposits in the Seventy Mile Range Group overlap with those of Permo-Carboniferous Mt Leyshon gold deposit, but are distinct from Devonian vein-hosted mineralisation (Huston, 1992).

7.4.7 Evidence for sub-seafloor replacement

With the exception of the strata-bound Pb-Zn ores, mineralisation and associated alteration at Highway-Reward are discordant to local bedding, and enclosed by intrusions and volcaniclastic deposits. Relics of coherent rhyolite, dacite and peperite are often preserved within the mineralisation. There is no evidence of mixing with sulfides at the margins of the intrusions and the evidence suggests that the massive pyrite pipes are syn-genetic. The massive sulfides must therefore be interpreted to postdate their host rock and have formed by syn-genetic sub-seafloor replacement and/or infiltration (cf. Large, 1992).
There are two possible interpretations for the strata-bound sphalerite-pyrite-barite mineralisation. Either the lens formed by sub-seafloor replacement of volcaniclastic deposits overlying rhyolite 4, or sedimentation was synchronous with hydrothermal activity and precipitation of sulfides occurred at, above, and below the seafloor during mineralisation. The former is more consistent with the available evidence and the criteria (1-5) for evaluating the role of sub-seafloor replacement in massive sulfide deposition. (1)

The mineralisation contains siltstone laminae and significant interstitial sericite and quartz that is presumably altered volcanic (glassy?) detritus. (2) The underlying and overlying lithic-crystal-pumice beds (1-7 m thick) display bedforms which suggest they were rapidly emplaced as sediment gravity flows. In some drill holes (e.g. REM 122, HMO 89 m), a peperitic syn-sedimentary sills (rhyolite 5) intruded siltstone and sandstone beds directly (0-30 cm) beneath the massive sulfide. The peperite and massive sulfide are not mixed suggesting that emplacement of the sill occurred after deposition of the overlying siltstone and sandstone beds, but prior to deposition of the sphalerite-rich mineralisation. The hanging wall rhyolite intrusion (rhyolite 6) is partially replaced by the massive sulfide lens and displays no evidence of mixing with massive sulfide mineralisation. It was also emplaced prior to the cessation of hydrothermal activity. Apparent graded bedding within some parts of the lens may result from replacement of primary grading in the volcanic precursor. The grading (normal) is defined by pyrite and unlikely to reflect reworking of sulfides on the seafloor because: (a) the pyrite is euhedral and displays no textural evidence of reworking; (b) spongy pyrite overgrows interstitial sericite, indicating that mineralising fluids passed through the sediments after they were deposited (cf. Huston, 1992); and (c) other sulfide minerals within the sample display no grain size trends.

(3-4) The strata-bound lens is zoned and grades from sphalerite-rich massive sulfide northward into progressively more pyrite-rich massive sulfide. The northern part of the lens is a discordant pyrite pod which partially replaces rhyolite 5 and the overlying syn-sedimentary intrusion (rhyolite 6). The pod clearly formed by replacement of the enclosing lithofacies. The gradation into progressively more sphalerite-rich mineralisation probably records a replacement front within the siltstone and sandstone beds which host the lens. Relic siltstone laminae within the sphalerite-rich part of the lens are also preserved within the pyrite-rich massive sulfide.

(5) Intense hanging wall quartz-sericite±pyrite alteration occurs above the pyrite pod and, although less intense, is also well developed above the strata-bound lens. At the southern end of the lens, domains of chlorite-sericite, feldspar-carbonate-chlorite-sericite-quartz and hematite-quartz-sericite-chlorite alteration are more abundant in the hanging wall intrusion (rhyolite 6). The alteration suggests that the ore-forming hydrothermal activity occurred after emplacement of the hanging wall syn-sedimentary intrusion. The zonation in alteration mineralogy is similar to that observed passing out from the margins of the
pyrite pipes into the host lithofacies. Quartz-sericite alteration is more intense above the pipes as these were probably zones of more focussed fluid flow.

The distance below the seafloor at which replacement occurred is difficult to interpret. At Highway, strong quartz-sericite alteration and pyrite veining extends more than 60 m into the hanging wall without any abrupt break in intensity. Consequently, the palaeoseafloor position at the time of mineralisation is not preserved. Prior to mining, barite-rich volcanic rocks were exposed at the surface (Kay, 1987). In VHMS systems, barite typically forms at the interface between ascending hydrothermal solutions and cold seawater and/or seawater saturated strata (e.g. Large, 1992). This suggests that the barite-rich mineralisation marks a near seafloor position.

At Reward, intense weathering and oxidation have obscured alteration and lithofacies above the main pipe hampering interpretation. On some sections, the top of the main pyrite-chalcopyrite pipe coincides with the extrusive top of rhyolite 4. It is possible that the top of the resedimented hyaloclastite units overlying rhyolite 4 was the seafloor at the time of ore formation, and replacement occurred right up to (and/or down from) the seafloor. Above the main pyrite pipe, small discordant pyrite pipes cut across the hanging wall volcaniclastic units and intrusions. Consequently, replacement and infiltration may have taken place beneath a series of seafloor positions as the host succession accumulated. Alternatively, all of the host rocks may have been deposited prior to significant hydrothermal activity, and replacement occurred at a number of stratigraphic positions below a seafloor position which is not preserved.

7.4.8 Fluid chemistry

Fluid inclusion studies did not form part of the present research and there is little suitable material available for this type of research. Studies of VHMS deposits suggest that zinc-rich zones deposit at temperatures of 225-300°C, whereas copper-rich mineralisation deposits from fluids in excess of 300°C (e.g. Large, 1992). At Highway-Reward, the copper-rich mineralogy of the pipes suggests that they deposited at >300°C. The sphalerite-rich mineralisation deposited at less than 300°C (cf. Huston, 1992). The gangue mineralogy and iron-rich composition of sphalerite in the pyrite pipes suggests that this mineralisation precipitated from reduced and acid fluids (Huston, 1992). Conversely, the strata-bound mineralisation deposited from oxidised and slightly more alkaline fluids which evolved from those which formed the pyrite-chalcopyrite mineralisation (Huston, 1992). The range of $\delta^{34}S$ values for the pyrite and sphalerite
mineralisation is consistent with a relatively low $\sum S0_4^{2-}/\sum H2S$ ratio, and suggests that redox reactions were not important during ore genesis (Huston, 1992).

7.4.9 A genetic model for the formation of the Highway-Reward deposit

The syn-genetic Highway-Reward deposit formed within a submarine, syn-sedimentary intrusion-dominated volcanic centre. Figure 7.10 is a schematic reconstruction showing successive stages in the evolution of the volcanic centre. At the onset of significant hydrothermal activity, the centre had the configuration shown in frame B or D. Intensification of the hydrothermal system followed the main phase of intrusion-dominated volcanism. The magmatism may have acted as a heat engine during seawater convection causing metals to be leached from the volcanic pile and/or contributed to the ore forming fluid. Initially, hydrothermal fluids may have ascended growth faults beneath the Highway and Reward positions (cf. Berry et al., 1992). Within a few hundreds of metres of the sea floor, hydrothermal fluid flow was possibly complicated by the intersection of faults and stratigraphic zones of lower permeability. Hydrothermal fluids were focussed within, but close to, the steep margins of cryptodomes that intruded the host volcano-sedimentary deposits while they were wet and poorly consolidated. Emplacement of the syn-sedimentary intrusions had transformed the sediments into relatively impermeable rocks compared to the fractured glassy margins of the cryptodomes. The indurated sediments may have prevented the development of broad convection cells and focussed ascending hydrothermal fluids into fractures within the host sequence and along the glassy margins of the cryptodomes. The porosity and permeability of the cryptodomes allowed infiltration of seawater which mixed with the high temperature (>300°C) hydrothermal fluid, promoting precipitation of pyrite-chalcopyrite in the developing pipes. Barite which is intergrown with the massive sulphide records the role of seawater in massive sulphide deposition (cf. Large, 1992). An advancing pyrite front gradually moved out through the host succession replacing rhyolite-dacite, volcaniclastic units and sediment. At Highway, a rhyolitic partly extrusive cryptodome (rhyolite 4) formed a barrier to ascending ore fluids and replacement occurred below and within it’s peperitic base. Although massive sulphide deposition was largely limited by the contact zone, fluid flow extended into the cryptodome, producing strong hanging wall quartz-sericite alteration enclosing pyritic stringer and disseminated styles of mineralisation. The outer alteration zones record the mixing of convecting seawater and ascending hydrothermal fluids along the margins of the pipes.

At Reward, it is possible that the hydrothermal system remained active during a small hiatus in volcanism, and that the pyrite pipes form a stacked system beneath two successive seafloor positions. If so, the extrusive top of rhyolite 4 was the seafloor
An advancing pyrite-chalcopyrite front progressively replaces earlier low-temperature (<300°C) sphalerite (Sp)- and barite (Ba)-rich mineralisation.

Figure 7.10. Schematic representation of successive stages in the genesis of the Highway and Reward orebodies.
position at the time the main pyrite pipe was forming, and replacement occurred up to near the seafloor (Fig. 7.10B–C). The Highway pipe may have formed beneath the same seafloor position, although it is not preserved above the orebody. Metals carried to the seafloor by the hydrothermal fluids were dispersed in the water column and incorporated into distal sediments. It remains possible that some strata-bound sphalerite-rich mineralisation deposited at this time. Volcaniclastic deposits and intrusions, which were emplaced above rhyolite 4 during renewed magmatism, were replaced by small discordant pyrite pipes below a new seafloor position (Fig. 7.10D). Alternatively, all of the mineralisation could have been emplaced within a single alteration pipe that extended through pre-existing volcanic units, beneath a palaeoseafloor position which is not preserved or is marked by pumiceous units at the top of the sequence (Fig. 7.10D). Poorly focussed fluid flow to the west and east of the Highway-Reward deposit produced zones of weak to moderate sericite-silica alteration.

Dispersed fluids which escaped from the margins of the pyrite pipes into the fractured and glassy host rock, mixed with seawater and deposited a broad halo of disseminated and patchy sphalerite-galena-barite mineralisation. Similar mineralisation may have deposited during initial phase of hydrothermal activity (cf. Large, 1992). A small strata-bound sphalerite-pyrite-barite-rich lens formed above the main pyrite pipe by lateral migration of low temperature (<300°C) hydrothermal fluids through permeable units (Fig. 7.10D). The northern extent of the lens became progressively more pyrite-rich, being deposited from higher temperature (>300°C) fluids. An advancing pyrite-chalcopyrite front gradually moved out through the sphalerite-barite-rich lens. The common development of chalcopyrite disease suggests that lead and zinc leached at the advancing copper front were reprecipitated within the volcanic precursor along a Pb-Zn-Ba front. Sphalerite-galena-barite veins and disseminations probably formed at the same time and continued to deposit in the waning stages of hydrothermal activity, as the fluids cooled from a peak of >300°C down to <300°C. Anhydrite was deposited in zones of intense chlorite alteration as hydrothermal fluids mixed with seawater along the margins of the pipes.

This model suggests that there were three principal controls on the location and formation of the Highway-Reward VHMS deposit: (1) a progressively evolving submarine intrusion- and lava-dominated volcanic centre. The high geothermal gradient associated with magmatism provided heat to drive the hydrothermal fluid flow, and the lavas and intrusions focussed hydrothermal fluids along the discrete mineralising pathways; (2) an impermeable barrier promoted sub-seafloor ponding of hydrothermal fluids and replacement; and (3) the hydrothermal system remained active during continued volcanism, dewatering of the sediment pile by sya-sedimentary intrusions, and sedimentation.
7.5 Discussion

7.5.1 The importance of lithofacies in sub-seafloor replacement

Sub-seafloor deposition of massive sulfides involves dissolution, replacement, infilling of pore space, and precipitation of minerals along fluid pathways. Consequently, the shapes, dimensions and distribution of hydrothermal circulation (and therefore the mineralisation) are closely related to the initial patterns of permeability and compositional contrasts in the volcanic host rock.

Many sub-seafloor replacement ores occur within rapidly emplaced units, particularly pumiceous facies (e.g. Khin Zaw and Large, 1992; Allen, 1994; Allen et al., 1996b). The originally highly porous, permeable, water saturated, and glassy nature of these deposits make them favourable host rocks for sub-seafloor replacement deposits. Ascending hydrothermal fluids will be poorly focussed and permeate through the substrate to produce widespread strata-bound alteration and lens- or sheet-style massive sulfide mineralisation (cf. Large, 1992). Sulfide replacement of this type probably commences at the interface between the ascending hydrothermal fluid and overlying cold, seawater-saturated strata (e.g. Khin Zaw and Large, 1992; Allen et al., 1996b).

Within less permeable, syn-sedimentary intrusion- and lava-dominated volcanic piles fluids are likely to by focussed along faults, local autoclastic breccia intervals, or within the fractured glassy margins of lavas and intrusions. Under these circumstances, well focussed fluid flow gives rise to lens- or pipe-shaped massive sulfide mineralisation and well developed, zoned alteration pipes (e.g. Large, 1992). Massive sulfide deposition probably commences beneath a relatively impermeable barrier (e.g. massive crystalline/devitrified lava) and grows downward by mixing with seawater convecting through the fractured, glassy, porous and permeable parts of lavas and shallow intrusions and volcanioclastic deposits. In the absence of a barrier, ascending hydrothermal fluids are more likely to reach the seafloor, and may well form a seafloor massive sulfide deposit.

The distance below the seafloor at which infiltration and replacement take place is rarely well constrained. In some cases, mass-flow deposits directly overlying the host rocks to sub-seafloor replacement deposit contain clasts of the massive sulfide (e.g. Hercules, Allen and Hunns, 1990), suggesting that replacement and infiltration probably occurred within a few metres of the seafloor. The upper few tens of metres in the volcanosedimentary pile are probably the favoured position for replacement, as sediments are wet, porous and poorly consolidated in this zone, and at greater depths become progressively more compacted (e.g. Einsele, 1986) and less amenable to replacement and infiltration by hydrothermal fluids. Ascending hydrothermal fluids will meet and mix with
cold seawater before reaching the seafloor, and can precipitate some of their metals subsurface.

7.5.2 Models for sub-seafloor replacement

In this section, the various circumstances under which sub-seafloor replacement and infiltration may develop and the character of the resulting mineralisation are considered. The scenarios depend on the sedimentation rate and whether or not the host succession is dominated by relatively poorly porous rocks (e.g. lavas and shallow intrusions) or by incompetent, very porous deposits (e.g. pumiceous units). Figure 7.11 summaries the main attributes of possible sub-seafloor replacement style deposits. It does not aim to present a comprehensive account of all possible scenarios for sub-seafloor replacement, but simply to highlight the spectrum of deposit styles which may form and their relationship to the enclosing strata.

7.5.3 Implications for mineral exploration

Pipes or plumes of strong hanging wall alteration are characteristic of sub-seafloor massive sulfide deposits, and can extend from tens to hundreds of metres into the hanging wall volcanic succession. At Highway-Reward, this style of alteration hosts significant disseminated and stringer vein-style mineralisation and several small massive sulfide lenses. Intense hydrothermal alteration and veining are more typical of footwall alteration and stringer zones beneath seafloor massive sulfide deposits. Hanging wall alteration with footwall affinities has major implications for mineral exploration. Exploration requires consideration of the possibility: (1) that massive sulfides occur beneath alteration and veining that would otherwise be regarded as the stringer zone to a seafloor deposit; (2) that massive sulfide lenses, pipes, veins and/or disseminations may form a stacked system; and (3) that the seafloor position at the time of hydrothermal activity may be located tens to hundreds of metres above the position of sub-seafloor mineralisation.

This analysis reveals that the seafloor hydrothermal systems responsible for the Highway-Reward massive sulfide mineralisation operated within a small non-explosive, syn-sedimentary intrusion-dominated volcanic centre. The Handcuff massive sulfide mineralisation is hosted by a similar but separate lava- and intrusion-dominated volcanic centre. The volcanic facies associations which characterise syn-sedimentary intrusion-dominated volcanic centres are as prospective as parts of the Trooper Creek Formation dominated by lavas, sediments and volcaniclastic deposits. The spatial and temporal relationship of the massive sulfide mineralisation with volcanic centres, suggests that the mineralising hydrothermal systems were intimately and possibly genetically related to the
Mineralisation

magmatism associated with emplacement of the volcanic centres. The magma may have acted as the heat engine driving convection and/or contributed to the hydrothermal fluid (cf. Large, 1992).

- Sub-seafloor replacement of rapidly emplaced mass-flow deposits(s)
- Host commonly syn-eruptive & pumiceous
  (e.g. Rosebery, Allen, 1994; South Hercules, Khin Zaw & Large, 1995; Liontown, Miller, 1996; Långdal & Långsete, Allen et al., 1997b)

- Sub-seafloor sulfide replacement front within rapidly emplaced units

- Synchronous sedimentation & sulfide precipitation both above & below the seafloor
  (e.g. Currawong, Boden & Valenta, 1995; Ansil, Galley et al., 1995)

- Sub-seafloor replacement of a single rapidly emplaced unit
  (e.g. Renström, Allen et al., 1997b)

- Synchronous sedimentation & massive sulfide deposition by replacement, infiltration & exhalation

- Seafloor massive sulfide

- Burial; replacement of volcaniclastic deposits during ongoing hydrothermal activity
  (e.g. Que River, Large et al., 1988)

Figure 7.11. Schematic representation of the various scenarios in which ascending hydrothermal fluids can interact with the enclosing seawater-saturated strata and deposit mineralisation by replacement and infiltration of pre-existing volcaniclastic or sedimentary deposits.
Mineralisation

7.37.

A. Ponding of hydrothermal fluids beneath a syn-sedimentary sill. Sub-seafloor replacement of the sill margin & host.

B. Ascending fluids form a stacked system.
   (e.g. Rosebery, Allen, 1994)

- Sub-seafloor replacement within a discordant alteration envelope
- Stacked massive sulfide pipes & stratiform lenses
   (e.g. Highway-Reward)

A. Seafloor massive sulfide mineralisation

B. Burial by lavas. Hanging wall alteration develops during continued hydrothermal activity. May form a stacked system.
   (e.g. Fukazawa, Seto et al., 1979)

A. Seafloor massive sulfide

B. Replacement of in situ & reseparated autoclastic breccia units

Figure 7.11 continued. Cartoon showing various circumstances under which sub-seafloor replacement mineralisation may deposit. In these examples the host successions also includes lavas and intrusions.
7.6 Summary

The Highway-Reward deposit is hosted in the proximal facies association of a submarine (below storm wave base) silicic, syn-sedimentary intrusion-dominated volcanic centre. The characteristic facies associations of these volcanoes can be used as vectors to locate prospective parts of the volcanic succession. Pyrite-chalcopyrite pipes are surrounded by a zone of pyrite-sphalerite-galena-barite mineralisation. The pyrite-chalcopyrite pipes and sphalerite-rich mineralisation formed at the same time and are syn-volcanic, sub-seafloor replacements of the host sediment, syn-volcanic intrusions, partly extrusive cryptodomes, and volcaniclastic units. Alteration associated with mineralisation is zonally arranged around the pipes so that alteration in the footwall and hanging wall is similar. Intense quartz-sericite alteration and pyrite veins extend more than 60 m above the Highway orebody. The location, distribution, form and shape of massive sulfide mineralisation and alteration are closely related to inferred initial patterns of permeability in the host rocks. Pipe-shaped massive sulfide deposits are likely to form in host successions dominated by relatively poorly porous facies (e.g. lava- and intrusion-dominated volcanic centres).
Chapter 8

Synthesis: a palaeogeographic reconstruction of the Mount Windsor Formation and Trooper Creek Formation during the Cambro-Ordovician