AGSO Journal of Australian Geology & Geophysics, 17(4), 229–237

Broken Hill-type deposits

S.G. Walters

BHP Discovery, 40 McDougall St, Milton, Queensland, 4064, Australia.

EXPLORATION MODEL

Examples

Broken Hill Main Lode (New South Wales), Cannington (Queensland), Zinkgruvan (Sweden), Aggeneys-Gamsberg (South Africa), possibly Sullivan (Canada)

Target

- Too few economic examples to develop a robust average; examples used range from 30 to >250 Mt.
- Large single deposits dominating a district are the norm.
- Economic grades in order of 10–20% Pb+Zn.
- Strong Pb–Zn zonation trends a feature.
- High Pb:Zn and very high Ag credits (>100ppm) characteristic.
- High Cd, Sb, Mn and Fe, with localised elevated As, Cu, W, Bi and Au.

Mining and treatment

- Complex, variable and highly deformed nature of mineralisation can make cost-efficient mining difficult.
- However, often include zones of extremely high-grade, structurally remobilised mineralisation.
- Coarse grain size enhances recovery and reduces milling costs.
- High Fe and Mn in sphalerite is a problem.
- High F in fluorite, fluorapatite and silicates.

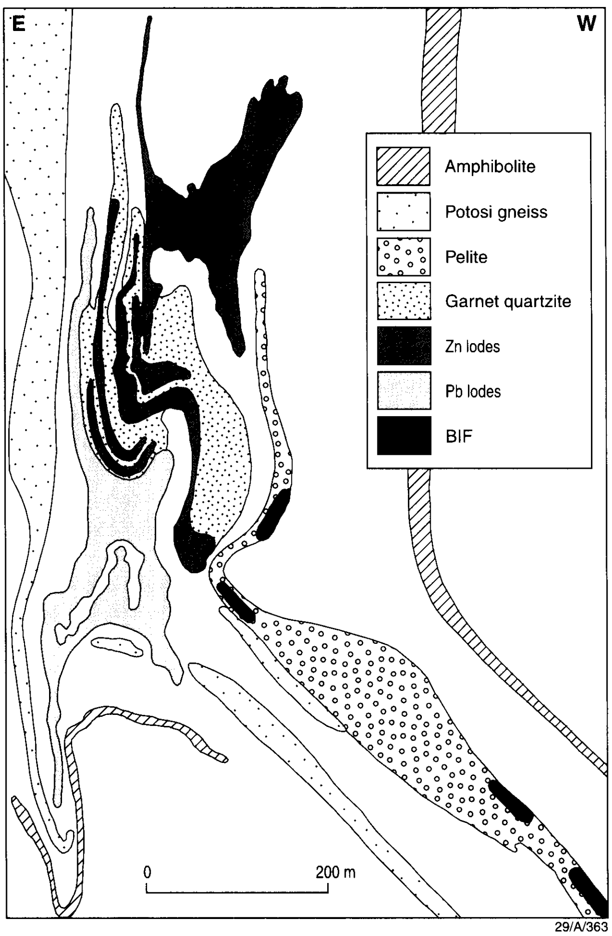

Figure 1. Simplified cross-section of the Broken Hill Main Lode, looking south, in the region of the Zinc Corp main shaft (after Haydon & McConachy 1987).

- Low pyrite can be a smelting advantage.

Regional geological criteria

- Restricted age range in lower-mid Proterozoic mobile belts with a long thermal history.
- Hosted in amphibolite–granulite facies metamorphic terranes.
- Rift-related tectonic setting, with transition from quartzo-feldspathic-dominant lower stratigraphy to psammopelitic and pelitic sequences in upper stratigraphy.
- BHT mineralisation concentrated at transition from lower to upper sequences.
- Oxidised clastic metasediments most probable host lithology, although metamorphism is a complicating factor in interpretation of protoliths.

Local geological criteria

- Thin exhalite units (e.g. quartz-gahnites) define lateral markers and prospective packages.
- Multiple 'exhalite' horizons common.
- Graphite and pyrite not common in near-ore environments.
- Other styles of mineralisation occur in BHT districts, in particular ironstone-associated Cu–Au in lower stratigraphy.
- Concentration of amphibolites and possible acid volcanics in near-ore and footwall sequences.

Mineralisation features

- Mineralisation hosted by diverse range of skarn-like Ca–Mn–Fe–P–F rich assemblages.
- Galena–sphalerite dominant with subordinate pyrrhotite and minor pyrite; variable magnetite.

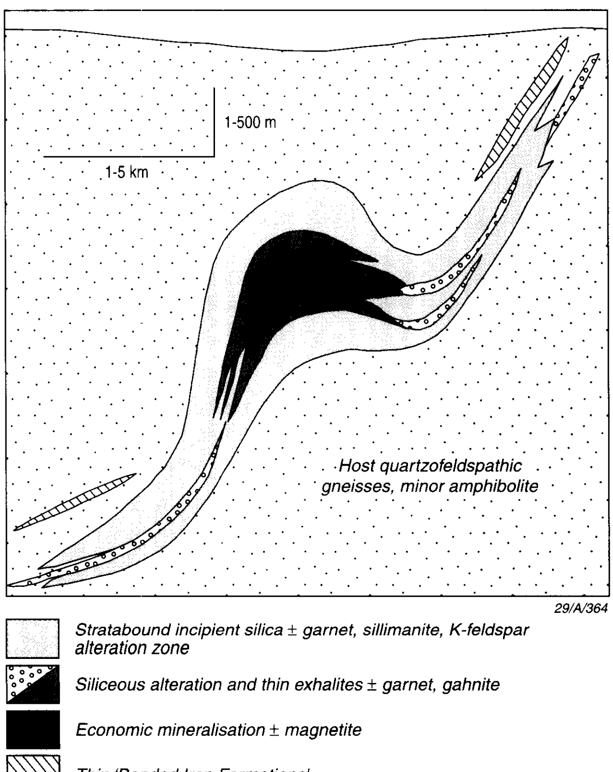

Figure 2. Schematic BHT ore environment.

- Coarse-grained recrystallised and annealed textures, with complex ductile breccias.
- Stacking of low-aspect ore lenses common.
- Strong Pb–Zn zonation, rapid internal variation.
- High Mn–Ca–Fe expressed as garnets, pyroxenes and pyroxenoids, e.g. bustamite, pyroxmangite, rhodonite and spessartine.
- Structural upgrading and complex retrograde metasomatism characteristic features.

Alteration

- No obvious focussed footwall feeder zones with intense alteration.
- More abundant sillimanite and disseminated garnet form large-scale stratabound alteration envelopes in host quartzo-feldspathic sequences.
- High levels of K-feldspar in alteration halos are associated with 'lode pegmatite' sweats, often with pale-green Pb-bearing microcline.
- Fe–Mn garnet 'quartzites' and 'sandstones' form immediate envelope to ore system.

Deposit geochemical criteria

- High levels of Mn–Ca–Fe–P–F in gangue, high As, Bi, Sb and Ag in minor sulphide phases.
- Extreme zonation between siliceous Zn-rich and more Mn–Ca–Fe 'calc-silicate' Pb–Ag-rich end-members.
- High F and Cl associated with fluorite, apatite and amphiboles.
- Widespread Pb–Zn–Mn anomalism in thin regional marker horizons.
- Elevated base metals in non-sulphide phases, e.g. gahnite, feldspar, magnetite.
- High Ag:Pb ratios with argentiferous galena and freibergite the most common primary Ag-bearing phases.
- Strong fractionation of REE, in particular Eu.

Surficial geochemical criteria

- Of the main examples listed, all except Cannington were discovered on the basis of historical prospecting of prominent outcrops.
- Ca–Fe–Mn-rich zones can give rise to spectacular gossans with Pb-rich Mn oxides.
- Large routine soil and stream sediment anomalism associated with outcropping examples.
- Thin lateral markers easily overlooked in widely spaced surveys.
- The Zn-spinel, gahnite, is a characteristic mineral in regional markers, but a resistant phase not easily digested in routine analysis.

Geophysical criteria

- Magnetite a variable association of economic mineralisation, with only minor magnetite in the Broken Hill Main Lode. However, magnetite is an important component at Cannington and in the Aggeneys group of deposits, producing a direct magnetic target.
- Pyrrhotite the dominant Fe sulphide, but tends to occur in discrete zones, which gives rise to variable EM responses.
- Graphite not a common association with ore.
- Abundant garnet and Fe-rich pyroxenes, pyroxenoids and amphiboles together with galena-rich mineralisation give strong gravity contrasts.

Fluid chemistry and source

- Due to metamorphosed nature of BHT deposits, it is difficult to define fluid chemistry.
- Low levels of Cu suggest temperatures below 250°C.
- Lack of Mg-rich alteration assemblages.
- Nature of host sequences and general lack of pyrite indicate probable oxidised ore fluid.
- Most BHT deposits characterised by extensive retrograde metasomatism, which may involve externally derived fluid overprints. The economic role of this metasomatism and the nature of the fluids involved are currently under debate.

Comments on genesis

- Most authors have considered Broken Hill to be exhalative, based on the form, chemistry and regional relationships of the mineralisation.
- However, there is little in the way of unequivocal relict textures or key pre-metamorphic relationships which can be used to demonstrate this 'beyond reasonable doubt'.
- Haydon & McConachy (1987) proposed a modified 'inhalative' or sandstone-replacement model based on detailed studies at Broken Hill.
- Textures dominated by coarse-grained, equigranular and annealed skarn-like assemblages, with indications of several generations of metasomatism—these are not pristine deposits!
- Restriction to mobile belt type settings indicates a relationship between rifting, metamorphism and mineralisation which is not fully understood at this stage.

Is there a BHT classification?

- Most previous classification systems have not generally recognised a discrete or robust 'Broken Hill Type' category.
- Most authors still consider Broken Hill to be a metamorphosed variant of the Sedex family, despite a range of critical differences regarding chemistry and setting.
- Any model which emphasises the recognition of inferred pre-metamorphic relationships in amphibolite–granulite terranes is unrealistic.
- Exploration strategies are different for Sedex versus BHT deposits. On a pragmatic level they need to be differentiated accordingly.
- The recent discovery of the Cannington deposit, offers the chance to refine the classification using a new world-class example.

Introduction

Broken Hill-type (BHT) deposits represent an important but not widely appreciated category of stratiform base-metal mineralisation, which includes the world-famous Broken Hill Main Lode, New South Wales. Characteristic features include a fundamental association with lower-middle Proterozoic mobile belt terranes, and a direct relationship with a variety of unusual lithologies often referred to as 'exhalites'. While this can include classic thin banded iron formations (an association which is often emphasised, e.g. Stanton 1976), these are a minor part of a much more diverse suite of Fe–Si–Mn–Ca-rich host lithologies, with coarse-grained skarn-like textures and mineralogy.

As a consequence of the mobile belt settings, all BHT terranes have undergone a prolonged history of complex deformation, metamorphism and metasomatism, which makes the study and interpretation of BHT deposits and districts difficult and often controversial. This is reflected in the general absence of a distinct Broken Hill-type category in the majority of well-established classification schemes for stratiform base-metal deposits (e.g. Gustafson & Williams 1981). Most authors have generally regarded the Broken Hill Main Lode as a metamorphosed example of 'Sedex' mineralisation, such as the Mount Isa or McArthur River Pb–Zn–Ag deposits (e.g. Sangster 1990, Goodfellow et al. 1993). However, Beeson (1990), Parr & Plimer (1993) and Walters (1996) have proposed and defined a separate Broken Hill-type classification.

The most important districts considered to be representative of the Broken Hill type (Table 1) include the Broken Hill Block, New South Wales (Stevens et al. 1988), Aggeneys-Gamsberg, South Africa (Joubert 1986, Rozendaal 1986), Bergslagen, Sweden (Parr & Plimer 1993) and the Soldiers Cap terrane of the Mount Isa Eastern Succession, including the recently discovered Cannington deposit (Blake 1987, Walters & Bailey 1996). Within Australia, other prospective BHT terranes, with as yet only sub-economic occurrences, include the Georgetown Inlier (e.g. Mount Misery; Stanton 1982) and parts of the Arunta Inlier (e.g. Jervois; Mackie 1984).

The Sullivan deposit (B.C., Canada) is generally regarded as an example of Sedex mineralisation (Goodfellow et al. 1993). However, its overall early rift-fill setting with an immature clastic host sequence; associations with intense alteration, including tourmalinite, garnet–muscovite and quartz–albite zones; and relationship to voluminous high-level basic intrusions (Hamilton et al. 1982), suggest some affinities with BHT deposits (Parr & Plimer 1993).

Despite the obvious difficulties of establishing genetic models for mineralisation which has undergone complex prograde and retrograde overprints, there are clear differences in exploration strategies between Sedex and BHT deposits, which provide pragmatic support for a separate and meaningful classification. Key aspects of a BHT exploration strategy involve the selection of specific styles of rift-related 'transition zone' lithostratigraphic sequences on a regional scale, and the recognition of a range of unusual rock-type associations as lateral markers and indicators towards prospective BHT systems on a deposit scale.

Regional lithostratigraphy of BHT districts

Broken Hill Block–Willyama Supergroup

The premier example of the Broken Hill-type is the Broken Hill Main Lode (New South Wales). Estimates of the pre-erosion and mining size are in the order of 300 Mt grading in excess of 15% Pb+Zn and 150 g/t Ag, including a resource of around 150 Mt in excess of 20% Pb+Zn (Haydon & McConachy 1987).

As a result of a long history of mining and research, and a number of regional mapping initiatives, the Broken Hill Block represents one of the most intensively studied and documented BHT districts. The vast amount of published literature on the Broken Hill Block reflects this status, with key papers including Stevens et al. (1988), Barnes (1988), Haydon & McConachy (1987), Stevens (1986), Willis et al. (1983), and Stevens (1980). The lithostratigraphic characteristics of the Willyama Supergroup in the Broken Hill Block, and relationships to mineralisation have been summarised in Stevens et al. (1988), Parr & Plimer (1993) and Walters (1994), and can be used as a comparative model for the setting of other major BHT districts and deposits.

The dominant lithostratigraphic trend in the Willyama Supergroup (Fig. 3), is from quartzo-feldspathic-rich sequences in the Thackaringa Group and lower formations into clearly metasediment-dominated sequences in the Sundown and Paragon Groups. The Broken Hill Group represents a transition between these end members, with mainly metasediments and subordinate quartzo-feldspathic and basic gneisses associated with the maximum development and diversity of BHT mineralisation and 'lode horizon' marker units such as quartz–gahnite lithologies (Fig. 3). This can be interpreted as a progression from early syn-rift clastics and volcanics to a thermal subsidence phase of more uniform clastic sedimentation above the Broken Hill Group, in an intracratonic setting (Parr & Plimer 1993). There is a distinct absence of significant regional carbonates or calc-silicates in this rift-fill sequence.

However, it should be noted that due to amphibolite–granulite facies metamorphism, all sequences are highly deformed and protolith interpretation, particularly regarding depositional environments, is a difficult and contentious process (e.g. Wright et al. 1993).

A characteristic feature of early rift-related lithostratigraphic sequences in the Thackaringa Group, Thorndale Gneiss and Redan Gneiss (Fig. 3), is a dominance of unusually sodic 'albitite' gneisses and migmatites, which can display banding textures with locally abundant magnetite–albite–quartz–hornblende (Stevens & Corbett 1993). These have been variably interpreted as arkosic sediments (Haydon & McConachy 1987) or sodic alteration of glassy volcanics in a sabkha or playa lake evaporitic setting (Stevens et al. 1988). Similar lithologies in the adjacent Olary Block associated with scapolite, tourmaline with isotopically light B, and possible pseudomorphs after anhydrite, are also interpreted as indicating evaporitic conditions in a continental rift (Cook & Ashley 1992).

The role of evaporites in providing high-salinity oxidised fluids related to hydrothermal activity in the overlying Broken Hill Group has been suggested by a number of authors (e.g. Plimer 1994). This may be linked to the intrusion of high-level granitic sills in the Thackaringa Group, such as the Alma Gneiss (Fig. 3), coeval with the Main Lode mineralisation (Plimer & Parr 1993).

The Broken Hill Group is marked by the widespread development of metasediments, interpreted to represent a sudden deepening of the rift and the onset of more significant hydrothermal activity (Plimer 1985). The Parnell Formation (Fig. 3) is characterised by dominant metasediments, with a distinctive spatial association of subordinate basic gneiss and garnetiferous quartzo-feldpathic 'Potosi' gneiss, with widespread minor lode-horizon-type lithologies and subeconomic BHT prospects. Stevens et al. (1988) interpreted this as an episode of bimodal volcanism of rhyodacitic–tholeiitic affinities, with associated base-metal and Mn–Fe–Si-enriched exhalative activity.

This association is also repeated in the stratigraphically higher Hores Gneiss, which hosts the Main Lode. U–Pb zircon dating of 'Potosi' gneiss lithologies from the Hores Gneiss in the northern part of the Block (Page & Laing 1992), gives an interpreted magmatic age of 1680–1690 Ma, which is widely quoted as the inferred age of mineralisation at Broken Hill. However, high-resolution age dating in complex BHT metamorphic terranes is a difficult and contentious process, and the 'mineralisation age' of all the BHT deposits listed in Table 1 remains open to interpretation.

In the area of the Main Lode, the Hores Gneiss comprises

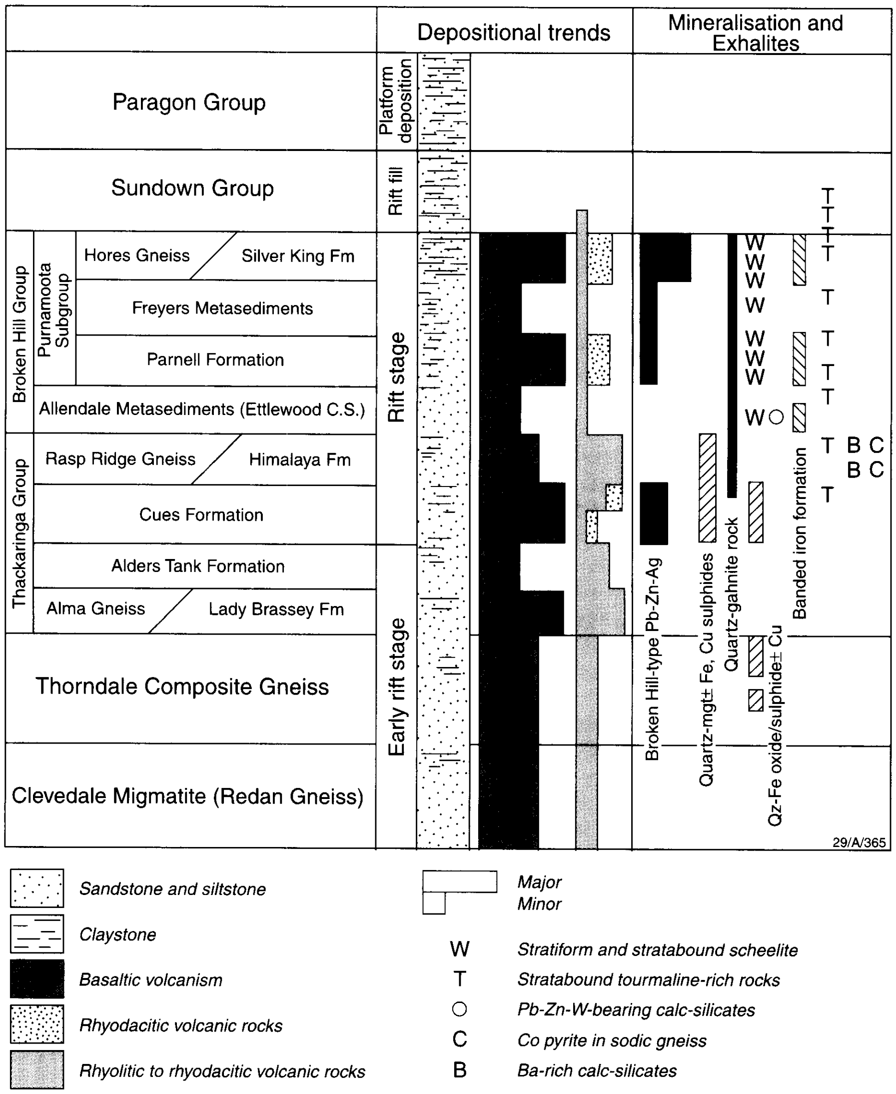

Figure 3. Lithostratigraphy of the Willyama Supergroup and distribution of main mineralisation styles (from Parr & Plimer 1993).

two main units of 'Potosi' gneiss, enclosing a sequence of pelitic and psammopelitic metasediments grading into blue quartz-rich cherts, garnet-spotted psammopelite and garnet-quartzites enclosing the Main Lode. Rapid variations in thickness of the 'Potosi' gneiss units and gradations into more siliceous lithologies are evident, with an inverse spatial relationship between the Main Lode and 'Potosi' gneiss thickness (Haydon & McConachy 1987; Wright et al. 1993).

Basic gneiss and garnetiferous quartzo-feldspathic 'Potosi' gneiss in the Parnell Formation and Hores Gneiss, tend to display a greater range of more unusual geochemical trends compared to similar lithologies in the Thackaringa Group. Basic gneiss in the Broken Hill Group is notably more Fe-rich, interpreted as an igneous differentiation trend (James et al. 1987) or a result of pre-metamorphic hydrothermal alteration (Phillips et al. 1985). 'Potosi' gneiss represents one of the most contentious and controversial lithologies in the Broken Hill Block. Its close association with numerous lode-horizon occurrences and, in particular, the Main Lode points to a significant genetic link or marker for stratiform mineralisation. Haydon & McConachy (1987) summarised the wide range of protolith interpretations proposed for Potosi gneiss over the past 100 years, which range from calcareous greywackes, rhyodacitic tuffs to arkosic sediment wedges. The unusual and variable geochemical trends and the close spatial association with, rather than actual hosting of, mineralisation suggest that the Potosi gneiss may have acted as semi-regional fluid channels for hydrothermal activity (Haydon & McConachy 1987).

The overlying Sundown Group (Fig. 3) is dominated by turbiditic muds and silts, with graphite-bearing pelitic schists and fine-grained psammites in the Paragon Group. There is a marked absence of bimodal volcanics or lode horizon above the Broken Hill Group, and the sequences represent late rift-fill and sag phase sedimentation.

Bergslagen district, Sweden

The progression from a quartzo-feldspathic dominant early rift fill with unusual sodic versus potassic enrichments to more sag phase clastic sedimentation, via a transition zone associated with maximum exhalative activity, is a common theme in other well-studied BHT districts. This is particularly evident for the Bergslagen district, Sweden (reviews in Parr & Plimer 1993, Walters 1994). However, there are significant differences in setting between the Broken Hill Block and the Bergslagen district, which emphasise the variations incorporated within the current BHT classification.

Supracrustal sequences in the Bergslagen province formed as juvenile crust during the early Proterozoic Svecofennian Orogeny, and occur as domains within extensive synorogenic granitoids (Oen 1987, Baker et al. 1988). These sequences give consistent radiometric dates in the range 1880–1900 Ma, representing a significantly older rift setting compared with

Table 1. BHT districts with size and grades for selected deposits (after Parr & Plimer 1993).

Location	*Age (Ma)*	*Deposit*	*Pb (%)*	*Zn (%)*	*Cu (%)*	*Ag (g/t)*	*Fe (%)*	*Size (Mt)*
Broken Hill Block, NSW	1.67–1.69	Broken Hill	10.0	8.5	0.14	148	~8	280
Bergslagen, Sweden	1.87–1.89	Zinkgruvan	5.5	10.0		100		40
Namaqua Belt, South Africa	~1.6	Gamsberg	0.55	7.1	0.02	6	~30	150
		Broken Hill	6.35	2.9	0.45	82	~35	38
		Black Mtn	2.67	0.59	0.75	30	~30	82
		Big Syncline	1.01	2.45	0.09	13	~35	101
Mount Isa Inlier, Qld	~1.68	Cannington	11.1	4.4	0.05	500	~15	45
Purcell Basin, Canada	1.4	Sullivan	6.1	5.9		68	28	155

the Willyama Supergroup.

There is a common lithostratigraphic progression in the supracrustal belts, comprising a thick (5–10 km) lower sequence of fine-grained quartzo-feldspathic gneisses or 'leptites', which are generally interpreted as felsic volcanics, ignimbrites and coarse pyroclastics deposited in shallow-water (Parr & Rickard 1987). These grade into a sequence of more bedded tuffaceous lithologies with fewer coarse pyroclastics and more abundant basic volcanics, with interbeds of clastic metasediments and carbonates. This is overlain in turn by a sequence of dominant metasediments, with greywackes, shales and mass flow deposits (Fig. 4).

Extreme Na:K variation is characteristic of the leptite sequences, with a general subdivision into lower sodic and upper potassic units. This is generally regarded as a regional hydrothermal alteration process, related to diagenesis and seawater interactions within the porous volcanic pile (Baker et al. 1988). Shallow water, evaporitic lithologies associated with the overlying tuffite-rich bedded sequences may also have been important in contributing saline groundwater during diagenesis, analogous to the mechanism noted earlier for the lower sequences of the Willyama Supergroup.

Three distinct styles of stratiform base-metal and Fe–Mn mineralisation styles occur in the Bergslagen district. Extensive but thin Mn–P–Ca-rich iron formations with elevated base metals (e.g. Langban—Bostrom et al. 1979) have historically been exploited for iron ore, and mainly occur in association with metasedimentary packages in the leptite-dominant lower sequences. The Falun type of Zn–Pb–Cu–Ag–(Au) deposit is hosted by altered metavolcanics with marble and metasediment interbeds, close to the transition zone with dominant clastic metasediments. Lensoid stratiform massive sulphide mineralisation in the Falun type is pyritic and associated with footwall stockwork zones and Mg-rich alteration zones, which are characterised by cordierite–anthophyllite–chlorite–dolomite assemblages, analogous with metamorphosed volcanic-hosted massive sulphide (VHMS) deposits.

The Ammeberg type of Zn–Pb–Ag deposit (Sundblad 1994) is more comparable with a BHT occurrence and includes the economically significant Zinkgruvan deposit (Hedstrom et al. 1989). Mineralisation is hosted by marbles, calc-silicates, tuffites and migmatitic metasediments (Fig. 4), close to the transition into the upper metasediment-dominant package, and occurs as a tabular lens 5–25 m thick and over 5 km strike length. Sphalerite and galena are the dominant sulphides, hosted in siliceous metatuffite with minor garnet, tremolite, diopside and calcite. Garnet-quartzite and calc silicate/carbonate interbeds occur in the ore zone, which is overlain by lensoid units of garnet-quartzite, marble and calc-silicate bedded metatuffite with fine-scale interlayered quartz, metatuffite and diopside–calcite–garnet rock with minor base-metal sulphides. The transition zone from metatuffite to biotite-rich sillimanite bearing metasedimentary gneisses is marked by concordant zones of disseminated pyrrhotite with anomalous Zn–Pb (Hedstrom et al. 1989). While large irregular zones of intense K-rich microcline–quartz alteration occur, focussed Mg-rich alteration is not a feature at Zinkgruvan compared to the Falun type.

The Bergslagen district differs from the Broken Hill Block (and other BHT districts such as Aggeneys-Gamsberg and the Soldiers Cap terrane) in the close spatial occurrence of two distinct BHT and VHMS style variants, an older Palaeoproterozoic age, and a greater dominance of marbles and calc-silicates in the rift-fill sequence. Within Australia comparable features occur within the Arunta Inlier, with a division into Mg-rich Oonagalabi-style and more BHT Jervois-style mineralisation (Mackie 1984, Stewart et al. 1984, Warren & Shaw 1985).

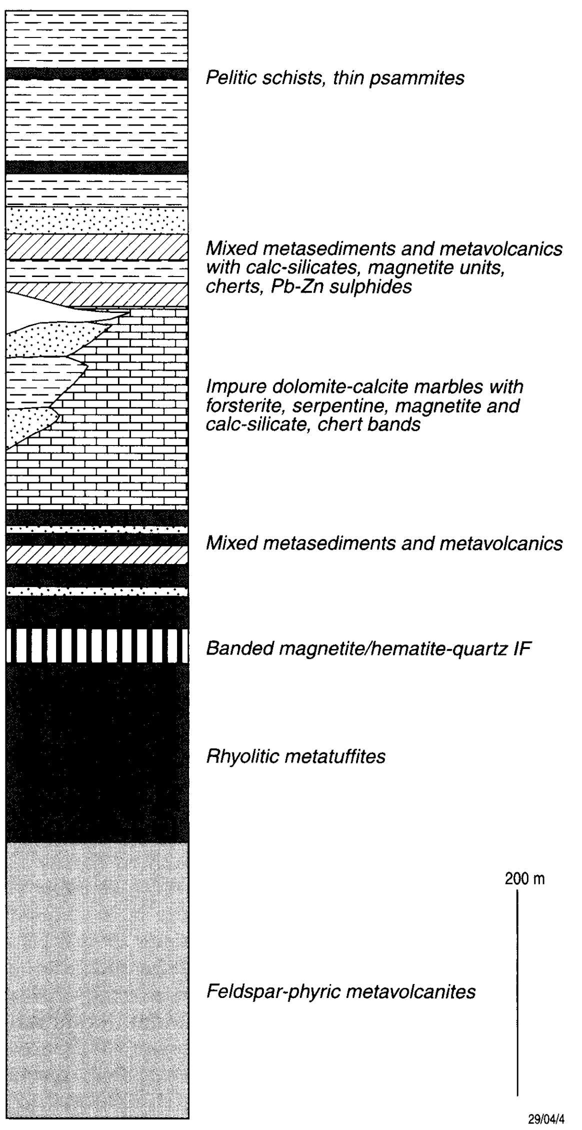

Figure 4. Schematic lithostratigraphy of the Bergslagen district, Sweden, showing distribution of main mineralisation types.

Table 2. Mineralogy of principal 'exhalite' types in BHT districts (after Plimer 1986).

Type	*Dominant phases*	*Minor phases*
Siliceous	Quartz (commonly blue)	Spessartine, gahnite, sulphides, magnetite, muscovite
Manganiferous	Spessartine–almandine, quartz, rhodonite, bustamite, pyroxmangite	Apatite, gahnite, scheelite, sulphides, arsenopyrite, biotite, sillimanite, magnetite, piedmontite
Ferruginous		
• Sulphide	Pyrite, pyrrhotite, quartz	Muscovite, Ca–Fe pyroxene, fayalite, rhodonite
• Carbonate	Fe–Ca–Mn carbonates	Sulphides, grossular–spessartine, epidote
• Silicate	Grunerite, Ca–Fe pyroxene, quartz	Magnetite, fayalite, almandine–spessartine, sulphides,
• Oxide	Quartz, magnetite	Sulphides, fayalite, grunerite, spessartine–almandine
Zincian	Gahnite, quartz	Sphalerite, Pb orthoclase, spessartine–almandine, galena, sillimanite, apatite, tourmaline, muscovite
Ba-rich	Barite or celsian, hyalophane	Sulphides, quartz, sillimanite, biotite, muscovite
Calcareous	Grossular, diopside, wollastonite, plagioclase, calcite, idocrase, quartz	Tremolite–actinolite, fluorite, graphite, scheelite, sphalerite, epidote, clinozoisite, sulphides, gahnite
Boron-rich	Quartz, tourmaline	Feldspars, spessartine–almandine, biotite, muscovite, graphite, sillimanite, apatite, sulphides, magnetite

Unusual rock-type associations related to BHT mineralisation

BHT deposits are characterised by an association with a great diversity of unusual rock types, which contrast markedly with their enclosing host sequences. In most instances there are no obvious igneous or sedimentary protoliths. Plimer (1986) recognised seven principal geochemical associations, based on dominant mineralogy (Table 2).

These associations can be regarded as a diverse suite of Si–Fe–Mn–Ca-dominant meta-exhalites and alteration-related lithologies. Recognition and interpretation of these unusual lithologies is one of the key routine aspects of BHT exploration. This is complicated by a highly diverse range of skarn-like mineralogy and rapid variation, particularly near major BHT centres.

Thin, laterally extensive, siliceous units with variable minor gahnite, apatite, sulphides and garnet are the most common lateral markers in BHT districts rather than any direct BIF-type association. Envelopes of Mn–Fe-rich 'garnet quartzites' and silicification are characteristic of increasing proximity to more significant BHT centres. Diverse Ca–Fe–Mn-rich assemblages, comprising pyroxenoids, hedenbergitic pyroxenes, grunerite amphibole, fluorite, spessartine garnet, fayalitic olivine and carbonates, are a distinctive association of highly prospective proximal BHT systems. Retrograde metasomatism is also common and involves phases such as pyrosmalite, ilvaite, chlorites and garnet.

Strong zonation is a characteristic feature of large BHT systems, with more Zn-dominant mineralisation associated with siliceous zones, and Pb–Ag-dominant mineralisation with Ca–Fe–Mn-rich mineralogy. This is particularly evident for the Broken Hill Main Lode with a series of stacked Pb- and Zn-dominant ore lenses (Johnson & Klinger 1975). Extreme Pb–Zn–Ag zonation and stacking also occur in the recently discovered Cannington deposit (Walters & Bailey 1996; Table 3).

Large scale stratabound but unfocussed alteration zones are associated with many BHT deposits, but are generally difficult to recognise, owing to metamorphic overprints. Alteration is characterised by garnet spotting and a greater abundance of sillimanite–K feldspar in the host quartzo-feldspathic sequences (Wright et al. 1993), and the recognition of these relationships can represent useful regional exploration tools.

Geochemical exploration techniques

Geochemical anomalism is widespread in individual lode-horizon-type marker units or alteration zones, and routine geochemical techniques are a useful first-pass tool. However, primary geochemical anomalism is often confined to thin (<2 m) units in a distal setting and represents a restricted target. A number of phases, such as gahnite or Mn-garnets, can be useful resistate indicators in regional exploration. Whole-rock REE systematics also show distinctive variations related to proximal and distal settings, in particular, involving positive versus negative Eu anomalies and, to a lesser extent, Ce fractionation (Lottermoser 1989, Parr 1992).

A range of other geochemical criteria has been used or proposed as exploration techniques, which includes Na/K ratios on a regional scale (e.g. Beeson 1990); geochemistry and B isotope systematics of tourmaline (Slack et al. 1984, 1989); Mn content of garnets (Stanton 1976); and Pb isotope systematics (Gulson et al. 1985). Radiometrics can be used to detect the more intense potassic alteration zones associated with some BHT deposits (e.g. Zinkgruvan).

Geophysical exploration techniques

One of the key exploration tools within BHT terranes in recent years has been the use of high-quality regional aeromagnetics. Given the complex nature of deformation and the difficulties of mapping and correlation in poorly exposed areas, regional magnetics can provide the essential overview of lithostratigraphic and structural trends (e.g. Whiting 1986). Prospective transition-zone sequences between metasediment-dominant and felsic-dominant packages often have a distinctive magnetic signature, characterised by extensive linear responses largely due to magnetic amphibolites in an otherwise subdued metasediment response.

Economic BHT deposits are characterised by high base metal to sulphur ratios, with Pb–Zn in a variety of non-sulphide phases. Pyrrhotite is the dominant Fe sulphide and occurs in restricted zones, which can limit the application of EM techniques as a direct targeting tool in many districts. However, some exceptions occur; in particular, the Aggeneys-Gamsberg deposits are associated with more abundant pyrrhotite–pyrite and locally significant graphite (Rozendaal 1986, Ryan et al. 1986).

The magnetic response of economic mineralisation is also a highly variable feature. While the Broken Hill Main Lode and Zinkgruvan are essentially non-magnetic, Aggeneys-Gamsberg and Cannington show strong direct magnetite associations, which

Table 3. Mineralogy and typical grades of mineralisation types, Cannington deposit.

	Pb %	*Zn* %	*Ag* *ppm*	*Sb* *ppm*	*Fe* %	*Mn* %	*As* *ppm*	*Cu* *ppm*	*F* %	*P* *ppm*	*Au* *ppm*
Nithsdale											
A. Galena, fluorite, hedebergite, pyroxmangite, magnetite											
M. Sphalerite, pyrrhotite, Mn fayalite, pyrosmalite, ilvaite, quartz, hornblende, talc, chlorite	11.0	1.8	720	630	19.1	1.6	490	5005	4.40	1000	0.51
T. Arsenopyrite, chalcopyrite, friebergite											
Cuckadoo											
A. Quartz, sphalerite											
M. Arsenopyrite, loellingite, chalcopyrite, pyrite, galena, chlorite, garnet, carbonates	0.8	5.4	35	44	4.9	0.1	1700	860	0.1	510	0.18
T. Gahnite, epidote, apatite, ilvaite, feldspar											
Colwell											
A. Sphalerite, hedenbergite, magnetite, pyrrhotite, fluorite											
M. Galena, Mn fayalite, pyrosmalite, ilvaite, hornblende, arsenopyrite, loellingite, pyrite, quartz	0.2	5.5	24	28	14.9	0.4	1780	1260	0.6	1000	0.23
Glenholme											
A. Sphalerite, galena, quartz, carbonates	11.8	8.0	367	456	4.2	0.2	135	390	0.2	2300	0.08
M. Apatite, chlorite, montmorillonite, fluorite, talc	14.8	9.0	570	745	3.3	0.2	123	320	0.3	2600	0.07*
T. Friebergite, pyrargyrite											
Burnham											
A. Galena, fluorite, hedenbergite, pyroxmangite, magnetite											
M. Sphalerite, Mn fayalite, pyrosmalite, ilvaite, quartz, hornblende, talc, chlorite	15.4	2.5	760	540	22.1	12.2	610	520	4.9	790	0.08
T. Arsenopyrite, pyrrhotite, chalcopyrite, friebergite											
Broadlands											
A. Galena, hedenbergite, pyroxmangite, garnet, quartz											
M. Sphalerite, pyrosmalite, ilvaite, quartz, hornblende, talc, chlorite, fluorite	2.7	0.5	82	110	7.1	0.9	150	120	0.4	2150	0.02

* Glenholme Breccia Lode within Brolga Fault Zone.

in the case of the non-outcropping Cannington deposit provided the key discovery technique (Skrzeczynski 1993).

Genetic models and speculation

Current genetic models for BHT deposits are heavily biased towards concepts developed at Broken Hill, and generally involve a syngenetic or, in more recent times, a modified 'inhalative' model with mineralisation controlled by primary porosity in clastic wedges (Haydon & McConachy 1987). However, as a result of granulite-facies metamorphism, current paragenetic and textural relationships within the Main Lode ore lenses cannot be used to unequivocally resolve either of these models. The more regional field relationships of 'lode horizon' in the Broken Hill Block, established by decades of mapping and research (e.g. Stevens et al. 1988), are critical in providing support for a stratiform/stratabound model.

However, many of the mineralogical and textural associations in BHT deposits are also comparable with distal Zn skarns, with no direct intrusive associations (Meinhart 1992). Ongoing debate regarding the application of a descriptive skarn terminology versus skarn genetic models to BHT deposits is largely the result of current research in the Eastern Succession of the Mount Isa Inlier (e.g. Williams & Heinmann 1993, Williams & Blake 1994, Bodon 1996, Walters & Bailey 1996).

As in all highly deformed and metamorphosed mineralised environments, the origin and paragenesis of the economic sulphides are contentious issues, with textural relationships largely reflecting the last significant overprint. On a mining scale, it is evident that the economics of BHT deposits largely reflect metamorphic, structural and metasomatic controls. This may be a function of ductile and fluid remobilisation of a pre-existing syngenetic Ag–Pb–Zn deposit or reflect externally derived syn and post peak-metamorphic mineralisation events, involving metasomatism of a reactive Mn–Ca–Fe-rich precursor.

Notwithstanding this debate, empirical exploration models can be developed, based on observational lithostratigraphic associations and the recognition of unusual direct ore-hosting lithologies. The recent discovery of Cannington as a prime example of a world-class BHT deposit indicates the exploration potential of this approach (Skrzeczynski 1993).

References

Baker, J.H., Hellingwerf, R.H. & Oen, I.S., 1988. Structure, stratigraphy and ore-forming processes. In: Bergslagen : Implications for the development of the Svecofennian of the Baltic Shield. Geologie en Mijnbouw, 67, 121–138.

Barnes, R.G., 1988. Metallogenic studies of the Broken Hill and Euriowie Blocks, New South Wales. Geological Survey of New South Wales, Bulletin 32, 250 pp.

Beeson, R., 1990. Broken Hill type lead-zinc deposits -an overview of their occurrence and geological setting. Institution of Mining and Metallurgy, Transactions, Section B99, 163–175.

Blake, D.H., 1987. Geology of the Mount Isa Inlier and environs, Queensland and Northern Territory. Bureau of Mineral Resources, Australia, Bulletin 225, 83 pp.

Bodon, S.B., 1996. Paragenetic relationships at the Cannington Ag–Pb–Zn deposit, Mount Isa Inlier, NW Queensland. In: MIC '96: The McArthur, Cloncurry minerals province; new developments in metallogenic research. Extended Conference Abstracts; James Cook University, Economic Geology Research Unit Contribution 55, 15–19.

Bostrom, K., Rydell, H. & Joensuu, 0., 1979. Langban—An exhalative sedimentary deposit? Economic Geology, 74, 1002–1011.

Cook, N.D.J. & Ashley, P.M., 1992. Meta-evaporite sequences and associated rocks in the Proterozoic Willyama Supergroup, South Australia: implications for metallogenesis. Precambrian Research, 56, 211–226.

Goodfellow, W.D., Lydon, J.W. & Turner, R.J.W., 1993. Geology and genesis of stratiform sediment-hosted (SEDEX) zinc-lead-silver sulphide deposits. In: Kirkham, R.V., Sinclair, W.D., Thorpe, R.I. & Duke, J.M. (editors), Mineral deposit modeling. Geological Association of Canada, Special Paper 40, 253–288.

Gulson, B.L., Porritt, P.M., Mizon, K.J., & Barnes, R.G., 1985. Lead isotope signature of stratiform and stratabound mineralisation in the Broken Hill Block, New South Wales, Australia. Economic Geology, 80, 488–496.

Gustafson, L.B., & Williams, N., 1981. Sediment-hosted stratiform deposits of copper, lead and zinc. Economic Geology, 75th Anniversary Volume, 139–178.

Hamilton, J.M., Bishop, D.T., Morris, H.C. & Owens, O.E., 1982. Geology of the Sullivan orebody, Kimberley, B.C., Canada. In: Hutchinson, R.W., Spence, C.D. & Franklin, J.M. (editors), Precambrian sulphide deposits (H.S. Robinson Memorial Volume): Geological Association of Canada, Special Paper 25, 597–665.

Haydon, R.C. & McConachy, G.W., 1987. The stratigraphic setting of Pb-Zn-Ag mineralisation at Broken Hill. Economic Geology, 84, 1235–1261.

Hedström, P., Simeonov, P. & Malström, L., 1989. The Zinkgruvan ore deposit, south-central Sweden : a Proterozoic proximal Zn-Pb-Ag deposit in distal volcanic facies. Economic Geology, 84, 1235–1261.

James, S.O., Pearce, J.A. & Oliver, R.A., 1987. The geochemistry of the Lower Proterozoic Willyama Complex volcanics, Broken Hill Block, New South Wales, In: Pharaoh, T.C., Beckinsale, R.D. & Rickard, D. (editors.), Geochemistry and mineralogy of Proterozoic volcanic suites. Geological Society of London, Special Publication 33, 395–408.

Johnson, I.R. & Klinger, G. D., 1975. Broken Hill ore deposit and its environment. Australasian Institute of Mining and Metallurgy, Monograph 5, 476–491.

Joubert, P., 1986. The Namaqualand Metamorphic Complex—a summary. In: Anhaeusser, C.R. & Maske, S. (editors), Mineral deposits of Southern Africa. Geological Society of South Africa, 1395–1420.

Lottermoser, B.G., 1989. Rare earth element study of exhalites within the Willyama Supergroup, Broken Hill Block, Australia. Mineralium Deposita, 24, 92–99.

Mackie, A.M., 1984. Geology of the Green Parrot and Reward silver-lead deposits—Jervois Range, Northern Territory. Proceedings, Darwin Conference, 1984. Australasian Institute of Mining and Metallurgy Transactions, 323–328.

Meinhart, L.D., 1992 Skarns and skarn deposits. Geoscience Canada, 119, 145–161.

Oen, I.S., 1987. Rift related igneous activity and metallogenesis in SW Bergslagen, Sweden. Precambrian Research, 35, 367–382.

Page, R.W. & Laing, W.P., 1992. Felsic metavolcanic rocks related to the Broken Hill Pb-Zn-Ag orebody, Australia: geology, depositional age, and timing of high-grade metamorphism. Economic Geology, 87, 2138-2168.

Parr, J.M., 1992. Rare earth element distribution in exhalites associated with Broken Hill Type mineralisation at the Pinnacles deposit, NSW, Australia. Chemical Geology, 100, 73-91.

Parr, J.M. & Plimer, I.R., 1993. Models for Broken Hill Type lead-zinc-silver deposits. In: Kirkham, R.V., Sinclair, W.D., Thorpe, R.I. & Duke, J.M. (editors), Mineral deposit modeling. Geological Association of Canada, Special Paper 40, 253-288.

Parr, J. & Rickard, D., 1987. Early Proterozoic subaerial volcanism and its relationship to Broken Hill-type mineralisation in central Sweden. In: Pharaoh, T.C., Beckinsale, R.D. & Rickard, D. (editors), Geochemistry and mineralogy of Proterozoic volcanic suites. Geological Society of London, Special Publication 33, 81–94.

Phillips, G.N., Archibald, N.L. & Wall, V.J., 1985. Metamorphosed high-Fe tholeiites: their alteration and relationship to sulphide mineralisation, Broken Hill, Australia. Bulletin of Mineralogy, 104, 801–810.

Plimer, I.R., 1979. Sulphide rock zonation and hydrothermal alteration at Broken Hill. Institution of Mining and Metallurgy, Transactions, Section B88, 161–176.

Plimer, I.R., 1985. Broken Hill Pb-Zn-Ag deposit—a product of mantle metasomatism. Mineralium Deposita, 20, 147–153.

Plimer, I.R., 1986. Sediment-hosted exhalative Pb-Zn deposits—products of contrasting ensialic rifting. Transactions of the Geological Society of South Africa, 89, 57–73.

Plimer, I.R., 1988. Broken Hill, Australia and Bergslagen, Sweden —why God and Mammon bless the Antipodes! Geologie en Mijnbouw, 67, 265–278.

Plimer, I.R., 1994. Strata-bound scheelite in meta-evaporites, Broken Hill, Australia,. Economic Geology, 89, 423-437.

Rozendaal, A., 1986. The Gamsberg deposit, Namaqualand District. In: Anhausser, C.R. & Maske, S. (editors), Mineral deposits of Southern Africa. Geological Society of South Africa, 1477–1488.

Ryan, P.J., Lawrence, A.L., Lipson, R.D., Moore, J.M., Paterson, A., Stedman, D.P. & Van Zyl. D., 1986. The Aggeneys base metal sulphide deposits, Namaqualand district. In: Anhausser, C.R. & Maske, S. (editors.). Mineral deposits of Southern Africa. Geological Society of South Africa, 1447–1473.

Sangster, D.F., 1990. Mississippi Valley type and Sedex lead zinc deposits : a comparative examination. Institution of Mining and Metallurgy, Transactions, Section B99, 21–42.

Skrzeczynski, R. H., 1993. From concept to Cannington: a decade of exploration in the Eastern Succession, in Symposium on

Recent Advances in the Mount Isa Block. Australian Institute of Geoscientists, Bulletin 13, 35–38.

Slack, J.F., Herriman, N., Barnes, R.F. & Plimer I.R., 1984. Stratiform tourmalinites in metamorphic terranes and their geological significance. Geology, 12, 713–716.

Slack, J.F., Palmer, M.R. & Stevens, B.P.J., 1989. Boron isotope evidence for the involvement of non-marine evaporites in the origin of the Broken Hill ore deposits. Nature, 342, 913–916.

Stanton, R.L., 1976. Petrochemical studies of the ore environment at Broken Hill, New South Wales: 1—Constitution of the banded iron formations and their immediate associates. Institution of Mining and Metallurgy, Transactions, Section B85, 33–46.

Stanton, R.L., 1982. Metamorphism of a stratiform sulphide ore-body at Mt Misery, Queensland, Australia: 1—Observations ;2—Implications. Institution of Mining and Metallurgy, Transactions, Section B91, 47–80.

Stevens, B.P.J. (editor), 1980. A guide to the stratigraphy and mineralisation of the Broken Hill Block, New South Wales. Geological Survey of New South Wales, Records, 21, 442.

Stevens, B.P.J., 1986. Post-depositional history of the Willyama Supergroup in the Broken Hill Block, New South Wales. Australian Journal of Earth Sciences, 33, 73–98.

Stevens B.P.J. & Corbett, G.J., 1993. The Redan geophysical zone: part of the Willyama Supergroup? Broken Hill, Australia. Australian Journal of Earth Sciences, 40, 319–338.

Stevens, B.P.J., Barnes, R.G., Brown, R.E., Stroud, W.J. & Willis, I.L. 1988. The Willyama Supergroup in the Broken Hill and Eurowie Blocks, New South Wales., Precambrian Research, 40–41, 297–327.

Stewart, A.J., Shaw, R.D. & Blake, L.P., 1984. The Arunta Inlier: a complex ensialic mobile belt in central Australia. Part 1 - stratigraphy, correlations and origin. Australian Journal of Earth Sciences, 31, 445–455.

Sundblad, K., 1994. A genetic reinterpretation of the Falun and Ammeberg ore types, Bergslagen, Sweden. Mineralium Deposita, 29, 170–179.

Walters, S.G., 1996, Broken Hill Type Pb-Zn-Ag deposits, geological characteristics and exploration models. CODES Master of Economic Geology Course Manual 4, University of Tasmania.

Walters, S.G. & Bailey, A., 1996. Geology and mineralisation of the Cannington Ag-Pb-Zn deposit -an example of Broken Hill Type Mineralisation in the Eastern Succession of the Mount Isa Inlier, NW Queensland, Australia. In: MIC '96: The McArthur, Cloncurry minerals province; new developments in metallogenic research. Extended Conference Abstracts. James Cook University, Economic Geology Research Unit, Contribution 55, 137–138.

Warren, R.G. & Shaw, R.O., 1985. Volcanogenic Cu-Pb-Zn bodies in granulites of the central Arunta Block, central Australia. Journal of Metamorphic Geology, 3, 481–499.

Whiting, T.M., 1986. Aeromagnetics as an aid to geological mapping—a case history from the Arunta Inlier, Northern Territory, Australia. Australian Journal of Earth Sciences, 33, 271–286.

Williams, P.J. & Blake, K.L., 1994. Alteration in the Cloncurry district. James Cook University, Economic Geology Research Unit, Contribution 49.

Williams, P.J. & Heinmann , M., 1993. Marramungee: a Proterozoic Zn skarn in the Cloncurry district, Mount Isa Inlier, Queensland, Australia. Economic Geology, 88,1114–1134.

Willis, I.L., Brown, R.E., Stroud, W.J. & Stevens, B.P.J., 1983. The early Proterozoic Willyama Supergroup : stratigraphic subdivision and interpretation of high to low-grade metamorphic rocks in the Broken Hill Block, New South Wales. Journal of the Geological Society of Australia, 30, 195–224.

Wright, J.V., Haydon, R.C. & McConachy, G.W., 1993. Sedimentary analysis and implications for Pb-Zn mineralisation at Broken Hill, Australia. James Cook University, Economic Geology Research Unit, Contribution 48.

Received 1 February 1996; accepted 30 October 1996