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Broken Hill lead-zinc-silver deposit

by R Morland[1] and A E Webster[2]

INTRODUCTION

The deposit is at lat 31°58′S, long 141°28′E in NSW, on the Broken Hill (SH 54–15) 1:250 000 scale and the Broken Hill (7134) 1:100 000 scale map sheets. It is one of the richest accumulations of lead, zinc and silver in the world. Mining by the Broken Hill Proprietary Company Limited began in 1883 and continues today in the Southern Operations of Pasminco Mining - Broken Hill.

This paper documents results of significant research work and mine exploration that has taken place at both the North Mine and Southern Operations since the description by Mackenzie and Davies (1990).

RESOURCES AND PRODUCTION

The Broken Hill deposit originally consisted of about 185 Mt of mineable ore (R Morland, unpublished data, 1995), associated with an additional 100 Mt of mineralisation exceeding 3% combined lead and zinc (Haydon and McConachy, 1987). Besides lead and zinc approximately 28.7 Mkg silver and 23 t gold have also been produced as byproducts of base metal mining since mining commenced.

Pasminco Mining - Broken Hill was formed in 1988 by the merger of the North (North Broken Hill Limited) and the Zinc and NBHC Mine operations (ZC Mines Pty Limited). The North Mine produced an estimated 34 Mt of ore typically 14% lead, 230 g/t silver and 11.5% zinc to a depth of 1.7 km prior to its closure in 1993 (R Morland, unpublished data, 1993), mainly from the underground operation but with 0.7 Mt from Number 1 open cut. Between 1991 and 1993, a total of 80 000 t of Zinc lode ore grading 5.5% lead, 100 g/t silver and 9.5% zinc were mined at the North Mine from a Measured and Indicated Resource of 175 000 t (A Aitchison, unpublished data, 1993). Between 1911 and 1995, ZC Mines produced 89.6 Mt of ore (R Morland, unpublished data, 1995). Some remnant mining and mine rehabilitation work continues at the South Mine central leases currently held by the Poseidon Ltd subsidiary Minerals Mining and Metallurgy Limited (MMM), but ore is no longer treated on site. MMM and their predecessors produced 51.9 Mt of ore to the end of 1990 (R Morland, unpublished data, 1995).

In 1996, 2.5 Mt of ore was produced from the Pasminco underground operation at grades of 5.5% lead, 54 g/t silver and 7.7% zinc (Pasminco Limited, 1996).

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After 113 years of mining the Broken Hill orebodies still rank as one of the largest lead-zinc deposits in Australia, with a Proved plus Probable Reserve of 28.0 Mt of ore containing 5.9% lead, 55 g/t silver and 8.5% zinc (Pasminco Mining, 1996).

DEPOSIT GEOLOGY

The Broken Hill deposit lies within the Broken Hill Group of the Palaeoproterozoic Willyama Supergroup (Willis *et al*, 1983; Stevens *et al*, 1983) and consists of nine separate but closely related orebodies that are stacked within a single stratigraphic package in the Hores Gneiss of the Broken Hill Group. They are known from mine base to top as 3 lens (3L), 2 lens (2L), 1 lens lower (1LL), 1 lens upper (1LU), A lode lower (ALL), A lode upper (ALU), Southern A lode (SAL), Southern 1 lens (S1L) and B lode (BL). A tenth body of disseminated stratabound mineralisation, C lode (CL), lies above BL and has recently been well enough defined to be mined.

THE MINE SEQUENCE

The deposit lies within a distinctive stratigraphic package known as the mine sequence This has been shown to be remarkably consistent having been traced for 25 km along strike and to a depth of 2 km (Carruthers and Pratten, 1961; Carruthers, 1965; Johnson and Klingner, 1975). The stratigraphic setting of the deposit has also been described in detail by Haydon and McConachy (1987) and by Wright, Haydon and McConachy (1987, 1993).

The orebodies lie within a unit of the mine sequence known as the lode horizon (Johnson and Klingner, 1975) which is subdivided into four units in the mine area, named from lowermost to uppermost, the clastic and calc-silicate horizon (CCH), the garnet quartzite horizon (GQH), the C lode horizon (CLH) and the 4.5 mineralisation (4.5H) by A E Webster (unpublished data, 1995). Orebodies rich in calcite, fluorite, lead and rhodonite (2L, 1LL, 1LU and to a lesser extent 3L) are located within the CCH, a unit dominated by clastic psammopelitic to pelitic rocks with some well developed calc-silicate layers, weak amphibolite and Potosi gneiss. The orebodies that are rich in primary quartz (ALL, ALU, S1L, SAL, BL) lie within the GQH.

The 3L orebody, which is also rich in primary quartz, has some garnet quartzite independent of the GQH but lies within the CCH. The CLH and elements of the 4.5H and CCH persist beyond the main deposit area and are represented on a district scale. There appears to be a link between the style of mineralisation and the host rock type.

Significant mineralisation occurs in several horizons outside the main orebodies, especially in unit 4.5 H, which contains widespread zinc mineralisation, including the Potosi orebody (Larsen, 1994; Morland and Leevers, this publication).

GEOMETRY OF THE MINERALISATION

The 2L and 3L orebodies are the largest and second largest in the field respectively and are stratigraphically continuous for a strike length of 8 km. They have produced most of the ore at Broken Hill. The ALL orebody is the next most extensive mineralised position in the field, persisting for 5 km, though structural and/or stratigraphic discontinuities are present. The orebodies strike NE and are arranged in an en echelon manner which is most pronounced at the southern end of the field where the greatest number of lenses occur. 3L and 2L are structurally terminated at the northern end of the deposit by the Globe–Vauxhall Shear Zone. Their continuations NE of the shear, known as the 2K zone, have been located but their size and extent are unknown.

All Broken Hill ore lenses and associated mineralisation are strongly linear, approximately parallel in strike and lenticular in cross section. The extreme stratigraphic linearity and great strike length of 2L, 3L, ALL and CL-style mineralisation and the 4.5 mineralisation produce a series of 'ribbons' of mineralisation within the Pasminco mining leases. The 2L and 3L orebodies describe a boomerang-shaped arch in longitudinal projection (Fig 1). This arch plunges to the north at around 40°, steepening to 70° at the northern end of the field and is southerly plunging at approximately 20° in the Southern Operations. The arch culmination occurs in the middle of the field where erosion has removed about 60 Mt of ore. The plunge variations of 2L and 3L also affect all other ore lenses and the 4.5 mineralisation.

Although there are numerous local discordances each orebody shows a consistent, conformable relationship with the surrounding strata and occurs in a characteristic stratigraphic position within the mine sequence. Orebodies and associated lode rocks form strongly linear positions within otherwise essentially tabular stratigraphic units.

OREBODY TYPES

Traditionally the Broken Hill orebodies have been divided into two categories; the zinc lodes and the lead lodes, based on the single criterion of lead to zinc ratio (Gustafson, 1939; King and O'Driscoll, 1953). However a closer examination of all of the geological features of the ore lenses show that this definition is too simplistic. The Broken Hill orebodies are still classifiable into two main types (Webster, 1996b), but based on a much greater number of their features. They are described below.

Calcitic orebodies

The calcitic orebodies (2L, 1LL, 1LU) contain calcite, rhodonite-bustamite, apatite, garnet and/or fluorite, abundant lead and are largely hosted by clastic metasediment within the CCH. Calcitic orebodies also contain a suite of unusual gangue minerals, including knebelite [(Fe, Mn)$_2$SiO$_4$], wollastonite, hedenbergite and ilvaite [Ca Fe_2^{2+} Fe^{3+} (SiO_4)$_2$ OH]. These more unusual minerals tend to occur in zones at the contacts of calcitic and rhodonitic mineralisation.

Primary quartz orebodies

The second and most common type is the primary quartz orebodies (ALL, ALU, SAL, S1L, BL, 3L) which are rich in primary quartz and garnet. They also contain gahnite and cummingtonite, have little or no calcite or calc-silicate minerals, relatively low lead, and lie in characteristic stratigraphic positions within the GQH. The 3L orebody has no physical association with the GQH but develops garnet quartzite layers along its margins in the north, central and southern parts of its length.

The primary quartz orebodies mostly lie in the upper part of the southwestern end of the deposit, and the calcitic orebodies lie in the lower part of the sequence. Garnet quartzite is the dominant host of ALL and the orebodies lying above, and 1LL and 1LU merge with the GQH in the southern part of their strike length. The 2L orebody is not associated with garnet quartzite, except at the extreme south end of the deposit where its upper contact meets the footwall of the GQH.

The 3L orebody lies at the base of the deposit and differs from other primary quartz orebodies by its size, great strike length, clastic metasedimentary host, weakly developed garnet quartzite association, abundant fluorite and high lead grade at the northern end. The 3L and ALL bodies are the only primary quartz orebodies to contain significant rhodonite-bustamite mineralisation.

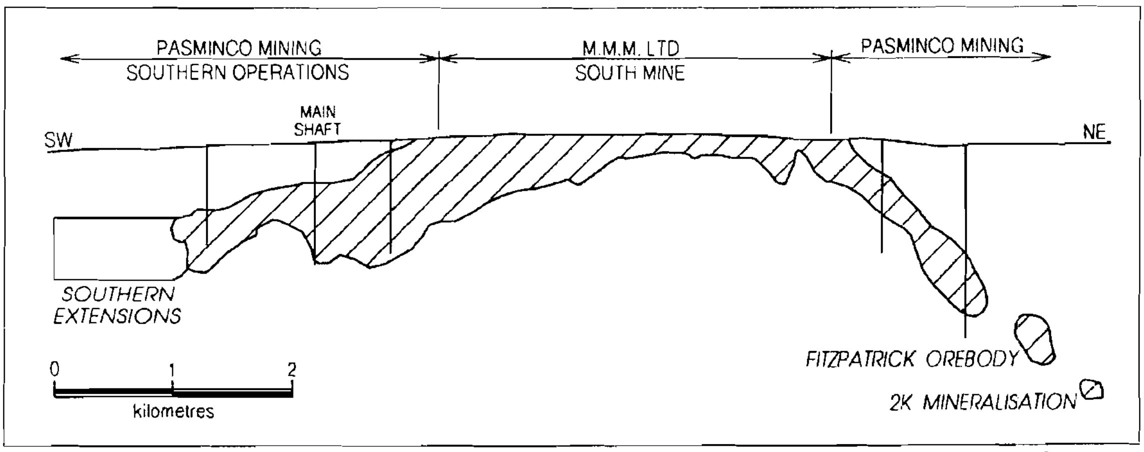

FIG 1 - Cross section, looking SW, showing the main elements of Western A Lode at Southern Operations (from M Hudson, unpublished data, 1994).

Calcitic and quartzitic styles of mineralisation are transitional, with the major changes taking place between 1LU and ALL. There is no transition between 3L and 2L though they do share some common characteristics which suggest a close relationship. Such features include rhodonite-bustamite units, fluorite gangue (restricted in distribution in 2L), calcitic gangue (minor zones with a 2L metal ratio develop in 3L) and greater lead than zinc (only in northern 3L).

THE NATURE OF MINERALISATION

The impression that the Broken Hill orebodies are all massive sulphides with little else has long been dispelled (Hodgson, 1968; Maiden, 1972; Webster, 1993, 1994a). Not only can different styles of mineralisation be identified but the information also gives valuable insights into the ways the deposit has responded to deformation and also to the predeformation characteristics of the deposit and therefore its genesis.

Massive sulphides form only a minor part of each orebody and are most common in deformed regions of the lenses. Sulphide-rich mineralisation is more often coarsely banded by variations in gangue mineral and sulphide abundance. Each orebody contains a high percentage of gangue minerals, including primary calcite, calcium or manganese pyroxenoids or pyroxenes, or quartz, that are distributed through the mineralisation as discrete bands, layers and stratigraphic horizons. Sphalerite (marmatite) is the dominant sulphide constituent of all ore lenses and the percentage of galena diminishes in each orebody from 3L to BL. The zinc grade is comparable for all orebodies but lead diminishes upwards from 3L to BL. Lead content also diminishes along strike from NE to SW in 3L even though the zinc grade remains relatively constant. Lead grade diminishes from base to top in the mine as calcite decreases as a gangue component. Important accessory sulphides include pyrrhotite, chalcopyrite and loellingite.

The orebodies have not been 'scrambled' by deformation but preserve most of their predeformational features, including internal layering and banding defined by sulphide and gangue mineral abundance, wall rock associations and their stratigraphic position within the lode horizon and mine sequence. All orebodies preserve structural fabrics in the form of fluid phase and mechanically mobilised sulphides, gangue mineral changes and zones of greatly coarsened gangue minerals with unusual calc-silicate assemblages. Characteristic structural fabrics and associated mineralogical changes were developed within the orebodies during each of the recognised structural events which affected the Willyama Supergroup in the mine area.

CLASSIFICATION OF MINERALISATION STYLES

The orebodies contain a diverse group of visually distinctive styles of mineralisation. Their textures, location, gangue mineralogy and relationship with other ore types suggest several possible origins. These features vary from those which preserve the early stratification to those which suggest formation in response to deformation and/or metamorphism. The information that such relationships between styles of mineralisation preserve can be used to determine the structural and metamorphic history of the mineralisation and lode rocks. Gangue mineral assemblages show the metamorphic grade at which these styles of mineralisation crystallised and their textures suggest the processes that formed them. By preserving such features the mineralisation can be regarded as another metamorphic rock. This information shows the orebody to be highly structured and stratified and allows a model for the structural evolution of the mineralisation to be constructed (Webster, 1994a. b, 1996b). Compilation of existing geological mapping information and remapping in key areas have resulted in the recognition of three major mineralisation styles (Webster, 1993, 1994a, b, 1996b).

Stratiform mineralisation

Stratiform mineralisation is a suite of predeformational styles that occurs within all orebodies. They predate deformation and metamorphism and comprise the bulk of all orebodies at Broken Hill. Stratiform styles of mineralisation are variably banded by relative abundances of sulphide and gangue minerals, chiefly calcite or quartz. Massive rhodonite mineralisation, the most widespread type, forms conformable marker horizons (with variable amounts of bustamite) within 2L, 3L and ALL, and distinct fluoritic horizons have been observed in 2L (south end) and 3L (north end) by A E Webster (unpublished data, 1995). Stratiform mineralisation remains conformable with the surrounding metasediment and demonstrates the primary features of the orebodies, preserving syndepositional layering, stratification, stratiform metal zoning and conformity with the surrounding strata, including lode rocks. The primary features are modified and overprinted by syndeformational textures. Such textures preserve evidence of all deformational events recognised in the Broken Hill district (Laing, Majoribanks and Rutland, 1978; Webster, 1993, 1994a, 1996b; A E Webster, unpublished data, 1995).

Stratiform mineralisation shows that base metal deposition was associated with calcium carbonate, quartz and iron. Lead was preferentially deposited with calcium and possibly with fluorite. Zinc was deposited with iron and quartz. The deposition of both calcium and lead diminished up sequence from 2L to ALL as the system evolved with an increase in the deposition of quartz relative to calcium. Zinc and iron deposition was largely constant throughout the deposition of all the orebodies. All lead-zinc-silver deposition was antipathetic to manganese deposition, consequently all primary manganiferous rocks are barren of mineralisation. As a result, all orebodies have similar zinc grades but are richer in lead and calcium in the calcitic orebodies (2L, 1LL, 1LU, 3L). Lead and calcium deposition diminished with the onset of the formation of garnet quartzite.

Mobilised mineralisation

Mobilised styles of mineralisation overprint the primary stratigraphic and textural features of the orebodies and most preserve prograde gangue mineral assemblages which show that the D_2 deformation (Table 1) took place at granulite grade while others are retrograde in character.

Mobilised sulphides are generally rich in recrystallised primary gangue components such as rhodonite and bustamite (3L, 2L, ALL), particularly in the North mine. Hedenbergite, wollastonite and knebelite are also commonly found within mobilised sulphides or calc-silicate mineralisation that is associated with them, mainly in the calcitic orebodies. The two-pyroxene mineralogy of most mobilised styles of mineralisation clearly shows that they formed at granulite

Table 1
The structural evolution of the Broken Hill deposit.

D_1 (Olarian Orogeny)	D_2 (Olarian Orogeny)	D_{3A} (Olarian)	D_{3B} (Olarian)	D_{4A} (Delamerian)	D_{4B} (Delamerian)
Pegmatite intrusion crosscuts lode horizon and at margins of psammitic units in the Northern Leases	Asymmetric, south plunging tight folding throughout the deposit with east dipping axial surfaces transects the orebodies at 20° to their original strike	Belt of attenuation and the British shear develop 250–300 m sinistral movement, west block up (reversed)	Quartz-sericite-biotite shear zones develop - early biotite-rich phase, later sericite-rich phase	Brittle fault systems develop throughout the deposit. Hydrothermal activity along faults produces laminated veins and carbonate alteration of rhodonite-bustamite near fault systems	Late-stage faulting with chloritic, brittle and puggy stage of movement on D_4 faults
Biotite-sillimanite foliation (S_1) parallel to bedding in pelitic and psammopelitic rocks adjacent to the orebodies	Western antiform, Eastern synform, WAL-WK synform, Hangingwall synform, BH synform	Attenuation of F_2 folded geometry of 2L, 3L, 1LL, 1LU (Belt of Attenuation). 250 m sinistral, west block up displacement of 3L and 2L in the Browne Shaft area (Thompson shear). GQH dissected by BL Dropper shear and related structures	Final stages of Dropper shear development	Formation of ABH Consols siderite-silver vein at intersection of reactivated D_{3B} shear and amphibolite unit. Galena -quartz-siderite Consols type vein cuts orebody in the British Mine	Reactivation or continuation of D_{4A}
Isochemical metamorphism and grainsize coarsening in orebodies	Grainsize coarsening of gangue and sulphides. Annealing crystallisation throughout orebodies	Extensive silica metasomatism of ore and wall rocks in sheared parts of the deposit	Completion of shear offset of 2L and 3L in the North Mine area (Fitzpatrick orebody and 2K)	Intrusion of fine-grained dolerite dykes into mineralisation along NW planes	Chloritic, puggy and sericitic fracture planes with deformation of D_{4A} features
Coarse knots and bundles of fibrolite developed in pelitic rocks in the northern part of the deposit	Extensive mechanical and fluid phase sulphide mobilisation in the orebodies	Development of dropper orebodies within select shear planes and attenuated regions	Completion of the attenuation of 2L and 3L between the 29 and the 32 levels of the North Mine	Minor mechanical sulphide mobilisation in ore, dolerite dykes dismembered	Chloritic faults, shears, pug zones and milled ore
Banding in lode pegmatite?	Fluid phase sulphide migration into rhodonite-bustamite margins and wall rocks (mainly garnet sandstone and garnet quartzite)	Minor F_3 folds develop in zones of transposition. Needle-like sillimanite characteristic	Offset of D_{3A} Thompson shear by British shear in Browne Shaft area	Minor hydrothermal activity in orebodies - garnet alteration of dolerite dykes	Secondary calcite lining vughs
	Differentiation of sulphide constituents into Pb-Ag-Au-As-W (Cu)–rich fluid phase and Zn-Fe-Cu–rich fluid phase	Attenuation of F_2 folded geometry of 2L and 3L between 29 and 32 levels in the North Mine		Minor fluid phase sulphide mobilisation (pyrrhotite, chalcopyrite and minor galena mobilisation). Mobile sulphides impregnate dyke fragment margins in ore	Jointing and faulting throughout the deposit
	Structural influence on galena distribution in 3L in North Mine	Start of shear offset of 3L and 2L between 32–34 levels in the North Mine (Fitzpatrick area)		White quartz veining and silicification of some pegmatite. Wall rock bleaching - silicification, sericitisation and coarse muscovite in wall rocks	Pyrite along fault planes, vughs and joints
	Fracturing/brecciation in GQH Siliceous metasomatism, veining and stockworks - within rocks on 3L-2L margins in North Mine	WAL offset from ALL by 250 m movement of BL Dropper shear WMIN offset from WAL?		Gentle refolding of line of lode on NW axis	
		Silicification and sericitisation of stratabound pegmatite			
Associated Mineralogy					
rhodonite, knebelite, fluorite, calcite, quartz	rhodonite, bustamite, quartz, hedenbergite, wollastonite	hedenbergite, wollastonite metasomatic quartz (veining)	actinolite, cummingtonite, sturtite, sericite	garnet, manganocalcite, siderite carbonate alteration	chlorite and/or secondary calcite and/or pyrite

grade and therefore the most significant sulphide mobilisation within the Broken Hill orebodies took place during D_2. This conclusion is supported by the textures and lithological relationships of mobilised sulphides, primary silicates and calcite within the orebodies.

Two processes of sulphide mobilisation operated during D_2. The first process was dominated by the mobilisation and transport of sulphides in solution (or possibly as melts) which were then deposited in favourable sites (fluid-phase mobilisation). The second process was dominated by the in situ recrystallisation during flow of the sulphide and gangue components of the mineralisation (mechanical mobilisation).

Metasomatically-altered mineralisation

Metasomatically altered mineralisation forms a small but varied category which has been altered in situ by the introduction of material from fluids, especially silica. This style overprints all stratiform and most mobilised styles of mineralisation.

Siliceous metasomatism was widespread at the margins of the orebodies and within adjoining wall rocks during D_2 and D_{3A} (Webster, 1993, 1994a, b, 1996b). The interaction between siliceous fluids, carbonate and manganese silicates within the ore lenses formed a suite of distinctive styles of mineralisation containing variable amounts of hedenbergite, wollastonite, knebelite, bustamite, quartz and garnet. Silicification was also strongly developed within garnet quartzite in association with stockwork vein formation, and clastic metasediments were intensely silicified at ore–wall rock contacts, especially in the northern part of the deposit.

Siliceous metasomatism was strongest in the northern part of the deposit during D_2, especially in the North mine and was also strongly developed along the attenuated margins of 2L, 3L, 1LU and 1LL during D_{3A} in the Southern Operations. Extensive zones of metasomatic mineralisation were developed within lithostructural sites in the GQH adjacent to the orebodies, particularly within F_2 folds and within D_{3A} shears.

In Pasminco's Northern Operation, 3L and 2L are associated with a well developed metasomatic alteration zone consisting of pale creamy pink garnet-quartz rock known locally as 'GO' rock, particularly on their up dip margins, which reflects metasomatism along the orebody margins during D_2 folding (D F Larsen, personal communication, 1993; Lips, 1994; White *et al*, 1995; D F Larsen and A E Webster, unpublished data, 1996). Extensive metasomatic silicification and sulphide mobilisation have also strongly affected the clastic metasedimentary wall rocks along the margins of 2L and 3L and within the zone between the two orebodies. This process has formed large zones of low to high grade mineable siliceous blue quartz lode. Fluid-phase mobilised sulphides penetrated the silicified metasediment to produce zones of low to high grade mineralisation which were not originally part of the orebodies. Metasedimentary banding within adjacent clastic metasediment can be traced by mapping from unaltered metasediment into the blue quartz lode zones. Similar low grade siliceous mineralisation was also developed on the contacts of 2L and 3L in the Southern Operations but generally in association with zones of D_{3A} transposition. In such zones, the siliceous blue quartz mineralisation is observed to overprint the banded texture of transposed metasediments.

The styles of mineralisation formed during siliceous metasomatism lie at the contacts of the orebodies, especially where they have been highly attenuated. Saccharoidal quartz and/or calc-silicate mineralisation may be the only constituent of the orebodies in severely attenuated regions of 2L, 3L, 1LU and 1LL (Webster, 1993, 1994a, b). Significant calc-silicate components are only found within orebodies with a significant calcite and/or rhodonite content.

Within the orebodies at Broken Hill, wollastonite, hedenbergite, bustamite and the suite of less common calc-silicates are the products of intense but localised syndeformational and structurally controlled metasomatism and largely post-date F_2 folding.

STRUCTURAL EVOLUTION OF THE DEPOSIT

The relationships of the three styles of mineralisation and the fabrics they define and preserve show that two major phases of deformation took place during a single regional metamorphic event at granulite to upper amphibolite facies in the Olarian Orogeny. A later phase of deformation, associated with the Delamerian Orogeny, also affected the deposit and is recorded in the mineralisation. The structural history of the Broken Hill deposit is summarised in Table 1.

Several important observations can be made about the relationship of mineralisation and structure:

1. All orebodies preserve gangue-defined stratification and layering which predate all deformation. Such features are concordant with the surrounding stratigraphy of the lode horizon. The relationships between the GQH, CLH and mineralisation were established before deformation.
2. F_2 folds developed throughout the deposit during granulite grade regional metamorphism, transgressing the linearity of the lode horizon. There is no relationship between the linear form of the deposit and fold structure. Folding cut across the orebody at approximately 20° to its original trend.
3. There has been no large scale movement of mineralisation into fold hinges during fold development.
4. Two planes of intense sinistral, west block up shearing and transposition, with 200 to 300 m of movement, developed during upper amphibolite grade retrograde metamorphism. F_2 folds were severely attenuated and reoriented in the shear planes.
5. The deposit was affected by the Delamerian Orogeny, with fault zones developing in which hydrothermal activity took place (Webster, 1994a, 1996a, b), including the development of the ABH Consols quartz-siderite vein. Gentle refolding of the orebody along a NW axis may also have taken place (Webster, 1996a).

CONCLUSIONS ABOUT THE STRUCTURAL HISTORY OF THE DEPOSIT

It is concluded that there are no structural guides to the location of the Broken Hill lead-zinc-silver deposit. It is a part of the sedimentary succession in which it lies and has been deformed and metamorphosed along with the other rocks with which it is interlayered. The controls and indicators of the Broken Hill orebodies are mostly syngenetic stratigraphic features and all of the evidence preserved by the Broken Hill deposit shows that it formed subaqueously as a linear series of chemical sediment bodies within the lode horizon.

The linearity and stratification of the orebodies and GQH predate deformation, metamorphism and pegmatite formation. The internal stratification of ore lenses, particularly ALL, 3L and 2L, are preserved throughout their strike length, even in the northern part of the deposit where D_2 deformation was most intense and internal sulphide mobilisation was pervasive. The orebodies have not been moved from their stratigraphic positions on a mass scale by deformation nor were they formed as a result of syntectonic epigenetic processes. The depositional system which produced the Broken Hill deposit can be determined, in some detail, from its present form.

Detailed structural reinterpretation has led to a more complete understanding of the relationship of the stratigraphy of the deposit to its structure. This work has suggested that the Western A lode (WAL) segment of ALL is truncated by west block up, sinistral shearing to the west of the D_2 WAL synform. The mineralised position may continue to the NW of WAL and exploration potential exists between this position and the Western–Centenary mineralisation below the City of Broken Hill. Sinistral, west block up shearing may place the continuation of ALL to the south and above its last known position on the 19 Level of the Southern Operations, a location that would not be highlighted by previous structural models.

Given the multitude of exploration models proposed and tested in the district, and the large exploration expenditures, it is interesting to note that no new major Broken Hill deposits have been found. It can only be concluded that they are not there, or at least not within the detection limits of current technology.

MINE EXPLORATION DEVELOPMENTS 1988–1996

NORTH MINE

Relatively little has been published on the geology of North Mine since the 1950s, the most recent being by Leyh and Hinde (1990).

Fitzpatrick orebody and the 2K mineralisation

In the late 1960s, North Broken Hill geologists realised that 2L and 3L were truncated at depth by the Globe–Vauxhall shear zone. Exploration was successful in locating a fault offset extension to the NE named the Fitzpatrick orebody (Widdop, 1983; Figs 1 and 2), which was mined from 1982 to 1993. In the lower levels the Fitzpatrick orebody cut out or was attenuated in the Western shear. Exploration for the extensions continued for several years.

Mineralisation was identified on the NW side of the Western shear after a very costly diamond drilling program and named the 2K in recognition of its two kilometre depth below surface (Figs 1 and 2). Downhole electromagnetic surveys were undertaken (Bishop and Morland, 1994; J R Bishop, unpublished data, 1991, 1992) and an Inferred Resource of 0.6 Mt grading 18.0% lead, 350 g/t silver, and 17.0% zinc was estimated (Pasminco Mining, unpublished data, 1992). Work on 2K was stopped prior to mine closure due to the high cost of exploration, perceived high mining costs if exploration were successful, timing issues and the relatively small size of the mineralisation. The orebody is open at depth.

North Mine Zinc lode

After an extensive exploration effort Zinc lode was mined from the Fitzpatrick area from late 1991 (Fig 2). The ore was dominated by coarse grained marmatite and galena with a

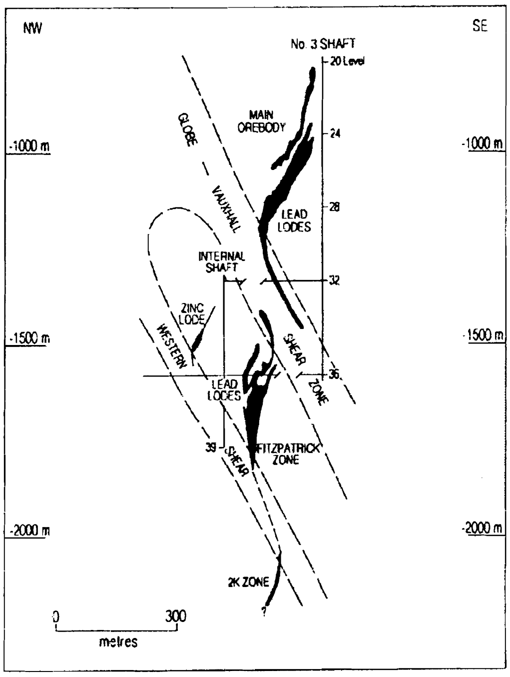

FIG 2 - Composite cross section, looking SW, of the lower levels of North Mine, looking NE (modified from Widdop, 1983).

gangue of quartz, blue quartz, gahnite and garnet with lesser bustamite, manganhedenbergite, calcite and fluorite. The high silver content is in galena. Whereas the Zinc lode is within a similar stratigraphic position to those at the Southern Operations some 5 km away, it is debatable as to which, if any, it directly relates to.

In 1992 an extensive surface diamond drilling program was undertaken to test for the development of Zinc lodes associated with 2L and 3L in the upper part of North Mine (D F Larsen and P Jackson, unpublished data, 1993), because minor Zinc lode–type mineralisation had been identified in Number 1 open cut. Eleven drill holes were completed with associated downhole geophysical measurements but no economic mineralisation was identified.

SOUTHERN OPERATIONS

C lode and droppers

The CL orebody is extensive in its distribution, being at least 2.6 km long with a maximum horizontal width of 130 m and a vertical extent of 250 m. It is a garnetiferous spotted psammopelite with blue quartz–gahnite lode rocks and lode pegmatites. Overall it is poorly mineralised with marmatite, galena and pyrrhotite (Mackenzie and Davies, 1990).

A breakthrough in the understanding of the distribution of the higher grade parts of CL was made early in the 1990s (J Stockfeld, unpublished data, 1993; A Wilson, unpublished data, 1994) when it was recognised that the higher grade pods of mineralisation within CL are in fact BL which was mobilised into the overlying CL sequence during D_{3A} shearing. BL sulphides were mobilised as upward droppers along a D_{3A} shear zone that is closely associated with the hinge of the D_2 Western antiform (A E Webster, unpublished data 1995). This helps to explain why the mineralisation style in the droppers is so different from most of CL, is more akin to BL, and also why the ore shoots are discordant to the stratigraphic sequence. It is characterised by sulphide-quartz-actinolite ore with the presence of coarse-grained sphalerite to 5 cm, clear vein quartz, galena, actinolite as coarse crystals or knots of needles, pyrrhotite, arsenopyrite and chalcopyrite in order of decreasing abundance.

CL sensu stricto is uneconomic except when the droppers are mined in conjunction with it. In 1996 the +10% lead plus zinc Measured and Indicated Resource stood at 1.3 Mt grading 5.0% lead, 50 g/t silver and 10.5% zinc (R Morland, unpublished data, 1996). It is currently being mined and exploration is ongoing.

Western A lode

The WAL orebody is defined as the ALL lower position to the west of the hinge of the D_2 Western antiform (Fig 3). The mineralisation is more discontinuous than the rest of ALL and many geologists had tried to unravel its internal geometry and lack of homogeneity without success. Recent improved understanding (J Moore, unpublished data, 1992; M Hudson, unpublished data, 1994) has led to mineralisation being defined and stopes being developed in WAL. In 1996 the resource using a +10% lead plus zinc cutoff was 3.2 Mt grading 3.9% lead, 37 g/t silver and 14.3% zinc (S O Stansfield, unpublished data, 1996).

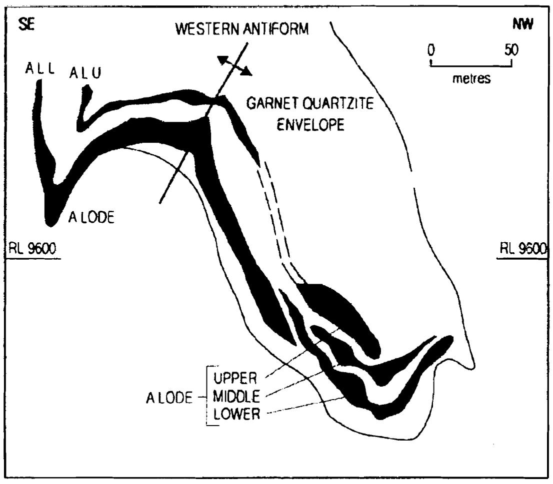

FIG 3 - Longitudinal projection of the Broken Hill orebody, viewed from the SE.

The main body of ALL is a series of relatively thin (less than 8 m wide) lenses of marmatite and galena with a distinctive band of rhodonite, quartz and hedenbergite (Haydon and McConachy, 1987). WAL has been divided into three major mineralised horizons (lower, middle and upper) within the unmineralised garnet quartzite envelope. Primary sulphides are marmatite and galena with accessory pyrrhotite, arsenopyrite, pyrite and chalcopyrite. The principal gangue minerals are quartz, rhodonite, bustamite, hedenbergite and garnet sandstone, with minor garnet quartzite, gahnite, cummingtonite, garnet, biotite, apatite and staurolite (M Hudson, unpublished data, 1994; Bottrill, 1984). The upper limb is also enriched in pyrrhotite locally as an envelope within the surrounding rhodonite, probably replacing it.

Previous interpretations were based on drill hole data but only recently has mapping of underground exposure validated and enhanced them. The western termination of the orebody, recently exposed, indicates a structural end of the orebody and thus offers hope in the search for additional ore.

4.5 mineralisation

Exploration drilling is underway to provide more data on the 4.5 mineralisation. This hosts the Potosi orebody to the north (Morland and Leevers, this publication) but its prospectivity in the south has never been fully evaluated.

The southern termination of the orebodies

A major underground diamond drill campaign has been under way since 1993 aimed at testing for the extension of the Broken Hill orebodies, in particular BL. Previous exploration, based on knowledge at the time, was aimed too deep and the prospective ground, the Southern Extensions (Fig 3), was untested (R Morland, unpublished data, 1992). To July 1996 a total of 13 191 m has been drilled in 21 holes in fans on sections 200 m apart. A consistent stratigraphic and structural picture has developed (L G Reid, unpublished data, 1996; S O Stansfield, unpublished data, 1996) and the southern termination of the orebody has been clearly identified.

Exploration drill hole data and the reassessment of the stratification and structure of the orebodies within the Southern Operations have shown that BL, SAL and S1L diminish in size and strength to the south as GQH dies out. Mineralised positions persist for several tens of metres beyond the end of the GQH and eventually peter out into scattered mineralisation, within a linear position, which has been observed throughout the prospective sequence for over 1 km strike length. This mineralisation is thin and impersistent both along strike and down dip. Spotted psammopelite–hosted C lode–style mineralisation within the CLH dominates the lode horizon on the Southern Leases and contains common 1 to 2 m widths of mineralisation, but none of economic significance at present. Currently the only potential seen is for the mineralisation to remake within the lode horizon further down plunge to the south. This is currently being investigated.

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