Structural evolution of the mineralised system at Broken Hill

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Introduction

The mineralised system at Broken Hill was not unlike a broaching porpoise in that it was just breaking the topographic surface when discovered by Charles Rasp in 1883. Very little of the line of lode had been exposed at surface at the time of discovery, and only 1.7-3 million tonnes of the low-grade, mineralised rocks fringing the orebodies had been lost to erosion (Webster, 2004, 2006).

A rich zone of secondary oxidised mineralisation lay just beneath the Broken Hill ridgeline but was hidden from most prospectors by a thin and mainly barren manganiferous carapace. It was the swing of the sledgehammer by Harry Campbell on the southern end of Block 12 in 1885 (a previously unprospected part of the hill) that released the real wealth of the field. Campbell discovered the richest, near-surface ore ever found at Broken Hill, consisting of kaolinitic, silver-rich mineralisation. His discovery became Knox Shaft, and paid the capital costs of the subsequent BHP mine development (e.g. Bridges, 1920). Campbell was the Aboriginal horse master for William Jamieson.

The configuration of the main orebodies produced by successive deformations was the prime factor controlling the outcrop pattern of the mineralised system, the topography of the ‘broken hill’, and the geology of the near-surface, oxidised zone (Webster, 2004, 2006). This abstract seeks to summarise the structural events that produced the outcrop geometry of the Broken Hill mineralised system, and which ultimately led to the topography of the long, low ridge for which it was named. To achieve this objective, information from the shallow parts of the field is integrated with observations from the deeper exposures in mine workings to the northeast and southwest of the surface expression of the mineralisation (Webster, 2004, 2006; Webster and Wilde 2008).

Structural history of the mineralised system at Broken Hill

The present geometry of the mineralised system at Broken Hill is the product of four deformational events (Figure 1, Table 1). To varying degrees, three of these events have left their effects in the geometry of the mineralised system (Figure 1), and in the textural and structural fabrics preserved by those rocks. The first event is relatively insignificant, in terms of the geometry of the mineralisation but had some textural and mineralogical effects, as well as being associated with pegmatite intrusion. The second and third events are of greatest significance and are responsible for most of the post-depositional modification of the geometry of the mineralised system.

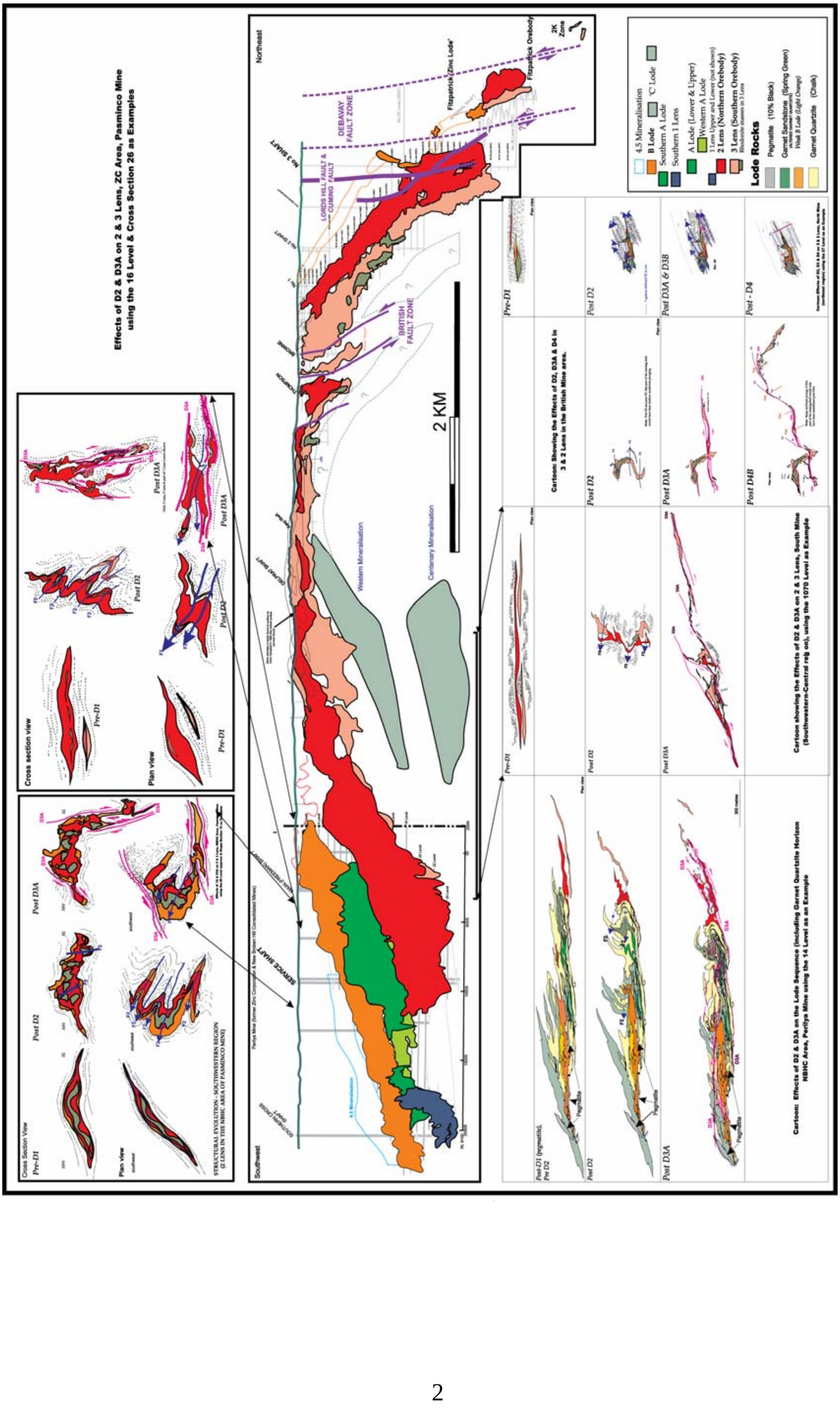

Figure 1. Effects of D2 and D3A on 2 and 3 Lens, ZC Area, Pasminco Mine, using the 16 Level and Cross Section 26 as examples.

First Deformation (D1)

The first deformation (D1) reported to have affected the mines area by Laing et al. (1978) has left few effects in the orebodies, companion lithologies or the surrounding volcano-sedimentary succession (Figure 1, Table 2). D1 manifests as a weak, bedding-parallel sillimanite-biotite foliation (S1) and variable development of bedding/S1 parallel, to weakly-transgressive, pegmatite dykes and quartzofeldspathic melt segregations. Large, weakly-transgressive, pegmatite dykes intruded the orebodies and Lode Sequence strata at the southwestern end of the mining field. In the northeastern part of the field, larger stratabound pegmatites and melt segregations occur at lithological contacts within clastic metasedimentary rocks and adjacent to quartzofeldspathic gneiss units.

Table 1. Comparison between the structural events identified in the mineralised system at Broken Hill (Webster, 2004, 2006) and the generally accepted structural model of the mining field (Laing et al., 1978).

Regional Metamorphic Event	Syntectonic features identified in the mineralised system (Webster, 2004, 2006)		Laing et al. (1978)
OLARIAN (M1)	**D1**	Lode Pegmatite intrusion Bedding parallel S1 foliation in metasedimentary rocks (and possibly banding in pegmatite), Grainsize annealing.	D1
	D2/D3A	Tight-isoclinal folding (F2), S2 (ore and wallrocks), initiation of early retrograde shearing. High-grade attenuation/metasomatism, transposition and local F3 folds/S3.	D2
	D3B	Biotite-muscovite shear zones Minor folds in shear zones	D3
DELAMERIAN (M2)	**D4A**	Fault systems and localised high temperature hydrothermal activity (alteration of ore and wallrocks). Dolerite intrusion into orebodies, and then dismembered and altered.	F4?
	D4B	Late, brittle chloritic faulting and milling of ore.	

Within the orebodies, the banded fabric of the sulfide-silicate-carbonate rocks was annealed, and equigranular rhodonite was formed. There does not appear to have been any significant D1 structural fabric developed in the mineralised rocks.

Second Deformation (D2)

The second deformation (D2) had the most important and far-reaching effects within the mineralised system. It was predominantly a folding event, characterised within the Mine Sequence, in the mines area, by an asymmetric set of south-verging, macroscopic and mesoscopic F2 folds with variable style. F2 folds in the orebodies are parasitic, lying on the northern limb of a major regional F2 antiform located south of the mining field; the Airport Antiform (Webster, 2004, 2006). This structure previously has been interpreted to be the Broken Hill Synform (Andrews, 1922; Laing et al., 1978).

F2 folding in the mining field area was most intense in the region northeast of the British Mine, and was associated with extensive transposition and differentiation of orebody constituents. F2 folds in this region were developed at all scales, from macroscopic structures, to parasitic folds

Table 2. Summary of the main effects of D1 within the rocks of the mineralised system and the Mine Sequence at Broken Hill. Each of these features is discussed in detail in the following sections.

Main features of D1 in the Broken Hill Mining Field (Olarian Orogeny)
Pegmatite intrudes Lode Sequence
- Separation pegmatites in Garnet Quartzite Horizon at the southwest end of mining field. *S1(?)* banding in larger lode pegmatite bodies?
- Widespread stratiform dykes at margins of psammite and quartzofeldspathic units in the northern leases
- Bedding-parallel and stratiform melt segregations in clastic metasedimentary rock, especially at the margins of pelitic and psammitic layers
Biotite-sillimanite foliation (S1), parallel to bedding in metasedimentary rocks of the Mine Sequence
Bedding-parallel sillimanite-biotite foliation (S1 of Laing et al., 1978)
Coarse knots & bundles of fibrous sillimanite developed in pelite in the northeast region (wrap pyrite in places)
Early structural/metamorphic features of the ore lenses (pre-or syn-D1)
Isochemical metamorphism, annealing and grainsize coarsening in orebody sulfides and gangue
Calcitic Orebodies
- Pegmatites in 2 Lens
Siliceous Orebodies
- Pegmatites in B Lode and in the zones between B Lode and underlying A Lodes

of wavelengths less than 20cm, and were associated with the development of a galena-defined S2 fabric in the orebodies. The S2 fabric in ore is not observed in other regions of the field. To the southwest, and particularly in the South and Perilya Mines, folding was less intense, F2 folds were more cylindrical, and pre-D2 features of the orebodies were more conspicuously preserved; particularly within the Lode Sequence. In the Southwestern Domain, in the Perilya Mine, F2 folds were associated with the formation of silicate-sulfide veins and stockworks formed within particular horizons, particularly the Garnet Quartzite Horizon, and in the massive rhodonite zones within 2L and ALL. Massive rhodonite layers within 2L were dismembered during D2 (Webster, 1993, 1994).

In the generally accepted structural model of the mining field (Laing et al., 1978), the Hangingwall Succession is considered to be a structural repeat of the Footwall Succession; requiring a F2 Broken Hill Antiform in a position in the footwall of the orebodies to produce the repetition. The structural repeat model does not stand up to close scrutiny, however, as the majority of folds that affect the orebody geometry are F2 in age (Webster, 1993, 1994), whereas Laing et al. (1978) interpret them to be F3, and to refold the F2 Broken Hill Antiform. There is no room in the underwall zone of the Footwall Succession to accommodate the Broken Hill Antiform beneath the orebodies. The minor marker units in this area, such as calcsilicate horizons, amphibolites, banded-iron formations and magnetic pelites, are not repeated, truncated or attenuated, nor do they exhibit a symmetrical distribution. There are also significant differences between key marker units in the Hangingwall Succession and the Footwall Succession. Neither is there any observable evidence of a D2 slide occupying the F2 antiform position in the footwall rocks, where exposed in the workings. Instead, there is a continuous, unbroken stratigraphic succession from the Footwall Quartzofeldspathic Gneiss to the Hangingwall Quartzofeldspathic Gneiss.

Third Deformation (D3)

The demarcation between D2 (Table 3) and D3A (Table 4) is difficult to define, and the two events are considered to be transitional. It is probable that all F2 folding included some degree

Table 3. Summary of the features of the first significant phase of deformation (D2) within the mineralised system and the Mine Sequence at Broken Hill (Webster, 2004, 2006).

Summary of the features of D2 (Olarian Orogeny)

F2 Folds	Alteration	Structural fabric
Asymmetric south verging F2 folds that traverse the orebodies at c20° to their original strike. Second order F2 folds: SXS, ZCA, NBHCS SMA, CMA, CMS, BHPS, B14A, BA, BS, NMA, WKS etc. Isoclinal style in the NE and central mining field; tight folds in SW. Formation of the initiation points of droppers (small scale F2 synformal folds). First order F2: HWS, IRS, MBA, RHS, Airport Antiform (Broken Hill Synform). Initiation of B Lode Shear and related D3A structures? **Northeast Region** Intense D3A transposition in the northeastern region is closely associated with complex isoclinal folding and the distinction between F2 folding and D3A shearing is much less obvious that in the southwest. Very tight to isoclinal F2 folding with some transposition of ore lenses at margins and dislocation of stratigraphic markers (e.g. epidosite layers). Silicification of metasedimentary rocks on 3L-2L margins in North Mine - intense silicification of wallrocks at orebody contacts (formation of GO rock).	Extensive mechanical and fluid phase sulphide mobilisation in orebodies. Includes fluid phase sulfide migration into rhodonite-bustamite margins and wallrocks (mostly garnet sandstone and garnet quartzite). Wallrock silicification at orebody contacts (silica metasomatism), especially on margins of 3L in North Mine. Differentiation of sulfide constituents into Pb-Ag-Au-As-W(Cu) - rich fluid phase and Zn-Fe-Cu - rich fluid phase. Extensive development of siliceous, saccharoidal mineralised breccias, vein systems and stockworks in Garnet Quartzite in tightly infolded F2 folds, especially within A Lode Lower in the hinge of the NBHCS and ALL in the WKS. Process continues into D3A. Quartz-hedenbergite vein stockworks and breccias & alteration of garnet quartzite to garnet sandstone on vein walls. Including extensive sulphide mobilisation and garnet recrystallisation in veins and wallrocks. Silicification and mineralisation of metasedimentary rocks, pegmatite and pegmatitic segregations at most orebody contacts, especially in clastic metasedimentary rocks Siliceous alteration of wallrocks most strongly developed in North Mine, especially at margins of 3L, to form low grade siliceous, blue quartz mineralisation, often mined as ore (originally wallrock metasedimentary rocks in many cases). Smaller and weaker occurrences developed at orebody margins in PerilyaMine. Vein Brecciated Manganese Silicate Mineralisation (AL Lower). Pegmatitic sulfide veining and coarse sphalerite veining within ore lens horizons and adjacent garnet quartzite. Abundant vein quartz-hosted mobilised mineralisation in North Mine compared with relatively minor in the southwest region.	Grainsize coarsening of gangue & sulfide. Annealling crystallisation throughout orebodies. Formation of varied styles of fibrolite bundles within pelitic rocks S3 axial plane foliation defined by galena distribution in 3L in North Mine Extreme recrystallisation of rhodonite at margins of rhodonite masses in 2L.

of high-grade shearing and localised transposition, particularly in fold limbs and at the boundaries of large masses of more competent lithologies. This interpretation is based on the observation that there is usually a close association between the limbs of F2 folds and D3A shearing (including dropper shears and the C Lode Fault), and because D2 and D3A deformations produced texturally different, but mineralogically similar, fabrics in the orebodies. D3A shears were initiated during F2 folding and then became the predominant style of deformation in the mineralised system.

The effects of D3A were unevenly distributed throughout the mining field and it had its greatest effects within the British-Junction and North-eastern Regions (Figure 1). In this part of the field, the Thompson Shear produced a 250-300 metre offset of 2L and 3L, strongly attenuating the orebodies and suppressing the F2 folded geometry. A similar style of high grade D3A shearing caused the attenuation of 3L and 2L and the dislocation of the Fitzpatrick Orebody from the main orebodies below the 30 Level of North Mine. The dislocation of the Fitzpatrick Orebody predates the development of the more obvious quartz-muscovite-biotite fabric, which is associated with the D3B Globe-Vauxhall Shear system. D3A shears were also a major influence on orebody geometries in the lowest levels of South Mine and the Perilya Mine, where some F2 folds were almost destroyed by shearing. D3A shears were more localised within the Lode

Sequence in the Perilya Mine, forming relatively narrow shear zones, such as the B Lode Shear.
D3B (Table 5) was a continuation of D3A, and is characterised by the development of a series of biotite-muscovite-quartz shear zones throughout the mining field area. Most D3B shear planes are localised within, or closely associated with, earlier D3A structures, but separate developments are also seen. D3B shears were the first type of retrograde shear to be recognised in the BH district (e.g. Andrews, 1922; Vernon and Ransom, 1971) and are the most easily distinguished. The northeastern region of the mining field is most severely affected by D3B shearing, and it produces the important Globe-Vauxhall-Western Shear System, which is prominent along the northern periphery of the mining field.

Table 4. Summary of the features of the early retrograde (D3A) deformation in the mineralised system and the Mine Sequence at Broken Hill (Webster, 2004, 2006).

Summary of the features of D3A (Olarian Orogeny)

Formation of BOA Shear System and the Thomson Shear.	**D3A Effects on F2 Folds**	**Associated Styles of Mineralisation & Alteration**	**D3A Structures & Fabrics.**
250-300m sinistral movement, northwest block up (reversed). Intersect F2 fold axes at approximately 20° to 35° to their strike. - Channel Shear, Central Mine Shear, - Main Shear, Western Zone of Shearing in Perilya Mine. - Development of the B Lode Shear and related structures near hinge of ZCA. - Staurolite zone on upper limb of ALL and within distal B Lode (CL). - 250m sinistral NNE trending, west block up displacement of 3L and 2L in the Browne Shaft area (Thomson Shear).	- F2 folds geometries are accentuated by shearing along southern & northern margins of 2L (and to a lesser extent 3L) to produce the 'limbs' of the orebody. Final geometries of the ZCA, NBHCS, SMA, CMA established. - Dissection of the BHP Synform and shearing in the north and south limbs of the Block 14 Antiform. Central Mine Synform attenuated and mostly destroyed. - Dislocation and dismemberment of 2L throughout the Central and British-Junction regions of the mining field. - Dissection and dislocation of the hinge of the ZC Antiform. GQH dissected in rollover position. CL offset from BL by 250m movement of B Lode Shear. - The main part of the final geometry of the Western Keel Synform established in 2L. Offset of hinge of WKS in ALL from that in 2L. - Structural dislocation of the keel of Southern Cross Synform by Prograde Main Shear. - Intense D3A transposition in the northeastern region is closely associated with complex isoclinal folding and the distinction between F2 folding and D3A shearing is much less obvious that in the southwest. - Dislocation of competent infolded garnet quartzite blocks within the keel of the NBHCS, associated with sulfide mobilisation and silicification. Also well developed adjacent to the ZCA (commenced in D2?) - Development of the droppers in association with Main Shear adjacent to 2L and 3L in the Perilya Mine and in the South Mine. - Extreme attenuation of 3L segments in lower mine levels focussed mainly in the Central Mine Antiform. - Attenuation of F2 folded geometry of 2L and 3L between 29 and 32 Levels in the North Mine. Shear	- Bustamite, wollastonite, hedenbergite crystallisation within calcic mineralisation in sheared sections of 2L. - Continued development of breccias and stockworks within the garnet quartzite, and zones of saccharoidal silicification within sheared parts of the orebodies, started during D2. Continued development of the metasomatic, siliceous alteration of clastic metasedimentary wallrocks initiated during D2, which probably reached a culmination during D3A. Forms siliceous styles of low grade mineralisation adjacent to ore lenses in shear zones. - Silicification and alteration of lode pegmatite, especially southwest of the GQH. - Intense silicification of thinned peripheries of the orebodies at contacts with clastic metasedimentary rocks, especially 1LL (e.g. 20 Level sill, Perilya Mine) and S1L. - Early phases of the development of irregular patches of fibrous and acicular cummingtonite within some fractures on orebody margins and as patches of skeletal crystals within the matrix of saccharoidal siliceous sulfide ore. Also developed in association with saccharoidal quartz, in strongly attenuated parts of B Lode on the 16 & 17 Levels of the Southern Cross area of the Perilya Mine. See D3B. - Well formed garnets (gem) within siliceous, galena-rich veining within ore horizons (e.g. A Lode lower on the 17 Level). - Development of Axial Plane Orebodies in B Lode Shear. Staurolite formation.	Complex isoclinal F3 folds develop in shear zones, especially where shear planes merge. - S3 sillimanite is characteristically needle-like in habit and parallel to F3 axes. - An S3 biotite-defined schistosity is developed in clastic metasediments of the northern leases and is characterised by the reorientation of S1 fibrolite to form the flame shaped and ragged S1/S3 fibrolite bundles.

	offset of 3L and 2L between 32-34 Levels of North Mine (Fitzpatrick Orebody).		

Droppers and the C Lode Fault

Dropper is an archaic mining term that did not originate in Broken Hill. It was defined by Davies (1901) as “a course of ore leaving the lower side of a lode”. Emmons (1908) described how miners considered droppers intersecting the footwall of a main lode (i.e. to drop from the footwall) to 'bleed' or ‘rob’ a lode of its grade.

Shear-hosted lenses and sheets of sub-ore-grade to ore-grade mineralisation that project both above and below the main orebodies are widespread throughout the entire field. They vary from the apparently pendulous droppers that are particularly well known in the Perilya Southern Operations, where they can crosscut the Mine Sequence stratigraphy at a low angle (e.g. King and O’Driscoll, 1953; Maiden, 1972; Ogierman, 1984; Stockfeld, 1993; Webster, 1994, 2004, 2006), to the 32 Level of the North Mine where the folded geometry of both 2 Lens and 3 Lens is so severely attenuated and sheared that it can be interpreted to be shear-hosted.

Table 5. Summary of the features of the second phase of the third deformation (D3B) within the mineralised system and Mine Sequence at Broken Hill (Webster, 2004, 2006).

Summary of the features of D3B (Olarian Orogeny)

Quartz-Muscovite-Biotite Shear Zones	**D3B Effects on Earlier Structural Features.**	**Associated Styles of Mineralisation and Alteration**	**D3B Structures and Fabrics**
D3B shears seem to have two distinct phases: - *Early biotite-rich phase* - *Later muscovite-rich phase* They tend to be focussed along major stratigraphic contacts, particularly the contacts of the Garnet Quartzite Horizon in the SW part of the mining field. The main development of D3B shearing is in the northeastern part of the mining field. Important D3B shears are: - Retrograde Main Shear (NBHC & SX), - Termination Schist Shear & early phases of the Central Fault. - Major phase of development of the: - Globe-Vauxhall and Western Shear System and associated structures. - Early phase of the DeBavay Shear System (?), - Later phases of Potosi Shear? - Early phase (quartz-muscovite-biotite schist) of Lords Hill Fault. - Final stages of B Lode Shear development (fracturing of clasts and actinolite formation?) - Retrograde (later) part of the Dropper & B Lode Shears. ***Lower amphibolite-greenschist grade***	Extensive development of quartz-muscovite-biotite shear zones within the D3A subordinate planes of the BOA. Retrograde quartz-muscovite-biotite schist zones developed in the planes of the D3A Thomson Shear. Modification of the D2-D3A geometry of 3L and 2L in the North Mine, between the 26 and 29 Levels and completion of the attenuation of 2L and 3L between the 29 and the 32 Levels of North Mine Completion of shear offset of Fitzpatrick Orebody components of 2L and 3L from the main orebodies by the Globe-Vauxhall Shear in North Mine. Dislocation of the Fitzpatrick Orebody and 2K Mineralisation (northeastern continuation of 2L and 3L) by the Western Shear. Structural dislocation of Centenary Mineralisation from the Western Mineralisation by Globe Vauxhall Shear Zone (Haydon and McConachy, 1987)	Later elements of the dropper shears hosting mineralisation, including quartz-muscovite-biotite shear fabrics on dropper ore contacts and within the D3A shear fabric of the dropper wall rocks. Actinolite in fractures in quartz veining and wallrocks (in D3A zones with dropper mineralisation) Amphibole filled fractures in - bearing quartz veins, Cummingtonite in deformed quartz veins and infiltrating ore; particularly in mineralisation associated with garnet quartzite that has been overprinted by silicification. Muscovite alteration of pegmatite dykes and other wallrocks.	Quartz-muscovite-biotite schist belts from centimetre to hundreds of metres in width. Extensive development of quartz-muscovite biotite shears and retrograde schistosity on major lithological contacts (particularly competent units like garnet quartzite, psammite and quartzofeldspathic units). Pervasive retrogression of all S1 (fibrolite bundles) /S2/S3 sillimanite throughout pelite in much of the northeastern part of the mining field, including the North Mine. Pervasive muscovite-biotitic foliation throughout attenuated areas of the Perilya Mine (particularly the ZC area) Needle-like sillimanite in early phases? Quartz-muscovite-biotite margins and actinolite growth within clear quartz veining on margins of earlier D3A droppers. Pervasive Retrogression in later phases (sericitised)

The C Lode Fault (defined as the B Lode Shear by Webster, 2004, 2006) is one of this type of D3A structure. Its character differs from many other planes of intense D3A shearing, however, because it is strongly influenced by the nature of the Lode Sequence wallrocks in which it developed. Garnetite (garnet quartzite), unlike the more ductile clastic metasedimentary rocks and sulfide-dominated rocks of the ore lenses, behaved in a brittle-ductile manner at the peak and early waning stages of metamorphism; related folds (D2) and shears (D3A) provided sites for the redeposition of remobilised fluid-phase sulfides and syntectonic wallrock alteration. Garnetite and the adjacent, weakly mineralised stratiform component of C Lode were most intensely deformed where they were folded in the hinges of two adjacent, very tight to isoclinal folds (F2), in particular, the formation of the ZC Antiform and the NBHC Synform (Webster (2004; 2006). The orientation, dip and mineralogy of the syntectonic alteration and veins of the C Lode Fault and in adjacent deformed wallrocks are similar to other subordinate planes of the BOA Shear System (Webster, 2004, 2006).

Fourth Deformation (D4)

M2 affected the orebodies during the Delamerian Orogeny, and locally exceeded greenschist grade. M2 was associated with a fourth period of deformation (D4). Within the orebodies, it caused the reactivation of Olarian D3A-D3B shears, and produced a generation of brittle fault systems, associated with localised belts of F4 folding. Transgressive dolerite dykes intruded the ore system in three main belts and were subsequently dismembered and weakly garnet-altered within ore. D4 had particularly widespread effects in the northeastern part of the mines area, being mainly manifested as brittle-ductile to brittle deformation, which is most commonly represented by the development of extensive fault, joint and fracture systems. D4 structural features overprint Olarian structures within the orebodies.

There were at least two distinct phases in the fourth deformation (D4A and D4B; Table 6). D4A was a relatively high-grade phase that reached lower amphibolite grade in places and locally higher grades in some faults. It was associated with hydrothermal activity, dolerite intrusion and local folding. D4A faults were associated with localised ductile deformation, in the form of F4 folds, and caused the major reversal in F2 plunges in the central mining field. Within the mines area, the most significant belts of D4A deformation are the British and DeBavay Fault systems, multiple planed, north-striking zones that traverse the mines area in the British Junction Region of the field and to the north of North Mine.

F4 folds were closely associated with complex D4A fault zones, such as the British Fault System, and refold the main orebodies. Pegmatite veins developed in F4 hinges (e.g. Laing et al., 1978). Mechanical sulfide mobilisation dismembered dolerite dykes within 2L and 3L (e.g. Webster, 1996). Hydrothermal activity along D4 faults produced alteration within mineralisation, including sulfide mobilisation and impregnation on the margins of the dykes. It was also associated with the formation of hydraulic breccias, laminated vein systems, tension vein systems, wallrock alteration in gangue, and in localised areas around fault and vein margins (e.g. 2L and amphibolite adjacent to the Consols Lode).

D4B was a subsequent phase of relatively low temperature brittle deformation (Table 6), which was possibly a distinct reactivation event. It produced widespread, relatively minor, joint, fault and fracture systems throughout the mining field.

Conclusions

An understanding of the structural history and geometric development of the mineralised system at Broken Hill reveals that it is not scrambled by deformation and metamorphism but is largely intact and in place.

Table 6. Summary of the features of the fourth deformation (D4) within the mineralised system and Mine Sequence at Broken Hill (Webster, 2004, 2006).

Summary of the features of D4A (Delamerian Orogeny)	**Summary of the features of D4B (Delamerian Orogeny)**
Brittle, hydrothermally Active Fault Systems and Associated Drag Folding. D4 faults have exploited several significant D3A shear zones and systems (reactivated) including: - British Fault System - Most significant(?) phase of the DeBavay Fault System - Lords Hill Fault (merges into F4 folding in lower levels of North Mine) - Prograde Main Shear and similar structures in southwest - The early stages of the development of the Central and Flat Faults. ***Structures*** Forms hydraulic breccias, laminated vein systems, tension vein systems and alters wallrocks and gangue in localised areas around fault and vein margins (e.g. 2L and amphibolite adjacent to the Consols Lode). Offset of the NE region by British Fault System – approximately 500-750m. Offset of D3A Thompson Shear in Browne Shaft Area ***Intrusion of fine-grained dolerite dykes into mineralisation along NW-SE planes.*** Minor mechanical sulfide mobilisation in ore – dolerite dykes dismembered. ***F4 folding*** traverse mining field in the Block 14 and British Mines (especially). F4 gently refolds the mining field and all previous structures on NW-SE axis. Pegmatite veins develop in F4 hinges. F2 folds in Mine Sequence are now SW plunging at SW end, NE plunging at NE end of deposit. Undulations elsewhere may also be F4. ***Alteration & mineralisation*** - Hydrothermal activity along faults produces laminated veins. - Rhodonite, bustamite (including fibrous & crustiform varieties), hedenbergite and rhodocrosite form as cavity fills in some faults and cavities during hydrothermal activity. - Hydrothermal veining and gangue mineral alteration in 2L in Perilya Mine and 3L in North Mine associated with carbonate and sturtitic alteration of rhodonite- bustamite near fault systems. - Formation of ABH Consols siderite-silver vein at intersection of D3B fault splay and Consols Amphibolite units. Galena-quartz-siderite veins in lower levels of British Mine. - Minor hydrothermal activity in orebodies - garnet alteration of dolerite dykes and sulfides impregnate dolerite fragment margins. Minor fluid phase sulfide mobilisation (pyrrhotite, chalcopyrite and minor galena mobilisation). - White quartz veining and silicification of some pegmatite. Wallrock bleaching-silicification, sericitisation and coarse muscovite in wallrocks of veins and faults. - Manganocalcite-bearing angular fault breccias, with fracture associated amorphous hydrous manganese silicate (sturtite) alteration of rhodonite in 2L. Some silicification of rocks adjacent to fault zones ***D4A: Locally lower amphibolite grade & possibly higher in hydrothermal systems?***	**Late-stage faulting, joint and fracture systems** Reactivation or continuation of D4A. ***Structures*** - Late-stage faulting with chloritic, brittle and puggy stages of movement (e.g. later stage of movement on the Flat Fault and Central Faults in the Perilya Mine, which were the most significant fault sets, in terms of ground conditions, in much of the 2L mining area). - Pug-lined joint and fracture systems. Jointing throughout the deposit. - D4B faults often exploit and overprint D4A faults and tend to be focussed in pre-existing shear zones, generally destroying or milling D4A features. However, they may crosscut all other structural fabrics. - Diffuse joint and fracture sets may exploit lithological boundaries forming slabby ground. Probably the cause of the extremely poor ground conditions in the Fitzpatrick Orebody. ***Associated minerals.*** - Chloritic, puggy and muscovite altered fracture planes, with deformation of D4A features - Some schistose (sheared) sulfides - Some milled ore - Chloritic faults, shears, pug zones and milled ore. - Secondary calcite (often dogs tooth) lining vughs and cementing fragments. - Pyrite along fault planes, vughs and joints - Jointing and faulting throughout the deposit. ***D4B: Greenschist grade.***

Primary features of the mineralised system can be recognised (Table 7). The elongated geometry, and stratification of the mineralised system and its host Lode Sequence, preserves syndepositional textures, internal stratification and layered gangue mineral distributions that predate pegmatite intrusion and F2 folding. The orebodies are conformable with the surrounding units of the Mine Sequence, even in the most intensely deformed areas and despite sulfide mobilisation in places.

The present geometry of the mineralised system is the result of the interaction between the original elongate, lens-shaped geometry of the ore lenses and their companion lithologies, and the deformations that have modified that geometry. Of particular importance to the geometry of the exposed region were F2 folds, D3A shears and the plunge reversal produced by D4 refolding and faulting of the field.

Table 7. Summary table of the recognisable primary features of the mineralised system at Broken Hill.

Primary Features of Broken Hill Mineralisation - Orebody Scale

2L, 3L, 1 Lens Lower, 1 Lens Upper	A Lode Lower, A Lode Upper, B Lode, Southern A Lode (?), Southern 1 Lens (?)
Calcite-silicate-apatite-fluorite-sulfide banding (2L, 1LU and 1LL). Fluoritic horizon in 2L (southwest end). Fluorite as a component of calcitic banding. Apatite-rich bands also form a component of calcitic banding.	Quartz-sulfide banding (ALU, ALL, BL)
Rhodonite layers (2L; 16-21 Levels, Perilya Mine, southwest end; and 3L in ML 15 and north-eastwards (particularly the British Mine and middle levels of North Mine)	Rhodonite layer (banded) (ALL)
Quartz-sulfide banding in 3 Lens and 1LU/1LL	Pyrrhotite zone in ALU/WAL (?)
Disseminated fluorite, quartz-rich and rhodonite layers (rhodonite in NE only) in 3 Lens (Northeast and southwestern ends of deposit)	Stratification of the BL orebody (the B Lode Complex)
Calcitic ore (2L style) development on northern limb of 3L, near southwestern termination (Perilya Mine)	Calcsilicate (hedenbergite) layer (originally calcite-rich zone?) in A Lode Lower
Rhodonite, fluorite and quartz distribution in North Mine 3L	Lenticular cross section of ore lenses (i.e. Linear mounds).
Layered galena (lead grade) distribution in British Mine and North Mine 3L (modified by D2).	Linearity of ore lenses (less affected by shear attenuation than 2L and 3L)
Lenticular (mound shape) cross sections of ore lenses.	Bulk geochemical differences of ore lenses as reflected in gangue mineral assemblages; decrease in calcium and manganese content of mineralisation from 2L-1L to BL.
Linearity of ore lenses (accentuated by shearing in 2L and 3L)	Increase in quartz content within sulfides upwards from ALL & especially from AL Upper.
Garnet quartzite (progenitor) , 3L (NE and SW end terminations and footwall).	Diminishing lead content from 2L to BL.
Pyrrhotite zone on northwestern margin 2L, South Mine to Perilya Mine	Relatively uniform percentage of zinc deposition as weight percentage of total mineralisation deposited in each lens (i.e. each ore lens has a similar volume of zinc).
Clastic metasedimentary tongues and interdigitation with 2L and branches (1 Lens) between 17 & 19 Levels Perilya Mine	
Fitzpatrick Zinc Lode (affinities uncertain but probably dislocated 3L segment)	
Possible association with underwall zone calcium-rich lithologies (southwest)	

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