

A REVIEW OF METALLIFEROUS BASINS IN NEW SOUTH WALES

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Introduction

New South Wales (NSW) is characterised by significant marine basins that are host to a variety of Pb–Zn±Ag±Cu±Au metal deposits, many of which were deposited during basin-forming volcano-sedimentary processes. Examples of these deposits described in NSW cover most of the spectrum of volcano-sedimentary base metal deposits, including reduced sedimentary exhalatives, carbonate-hosted types, and volcanic associated massive sulfide (VAMS) deposits (Downes et al. 2011a). A major revision of the Geological Survey of NSW's mineral deposit database (MetIndEx), and a new mineral system classification (Lewis & Downes 2008; Downes et al. 2011b) has allowed a more comprehensive evaluation of the relative economic importance of these mineral systems and their host provinces.

Herein, the major Pb–Zn±Ag±Cu±Au bearing basins of NSW (central Tasmanides) are revisited to document their deposit types, geodynamic setting, known endowment (production & resources) and mineral potential. Using Broken Hill, the grand master of base-metal deposits as a pre-Tasmanides blueprint, known metal-bearing basins of the NSW Palaeozoic Era are examined (Girilambone District, Cobar Basin, Siluro-Devonian eastern Lachlan basins), as well as poorly-endowed basins with base-metal potential (Ponto Group, the Ordovician Jindalee Group, and Devonian to Permian basins in the New England Orogen).

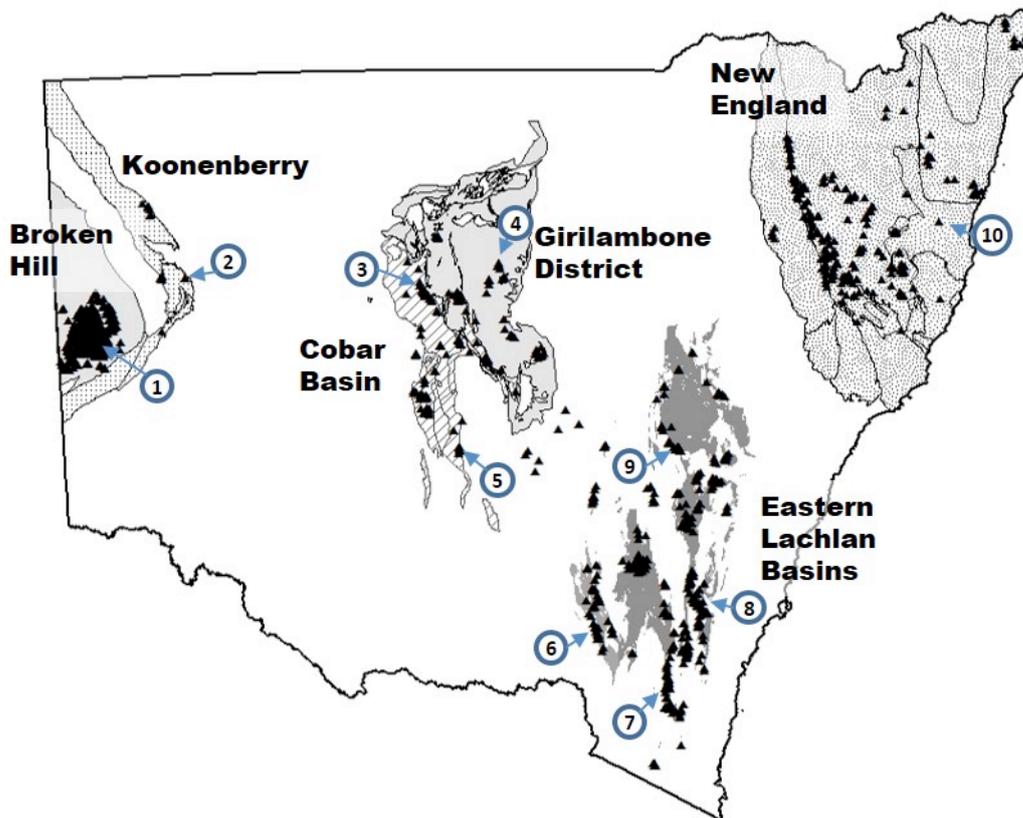


Figure 1. NSW metalliferous basins described in the text. Black triangles = 1909 volcano-sedimentary deposits and occurrences. 1) Broken Hill line of lode 2) Grasmere 3) Major Cobar-type deposits 4) Tritton 5) Browns Reef 6) Basin Creek 7) Captains Flat 8) Woodlawn 9) Lewis Ponds 10) Halls Peak.

Broken Hill

The Broken Hill basin contains one of the largest Pb–Zn–Ag deposits ever discovered, and serves as a useful NSW test-case to examine the character of giant volcano-sedimentary base metal deposits. The sheer size of the deposit (Table 1) and its enigmatic setting has triggered a vast amount of research into its genesis, with over 2100 research papers/reports and over 350 university theses produced that are relevant to the ore body and its regional setting (Greenfield 2003). A summary of the key mineral system parameters for the main Broken Hill deposit are shown in Table 2.

The basin is also host to a wide range of mainly sub-economic syn-sedimentary exhalative base-metal deposit types (Barnes 1988; reclassified by Downes & Fitzherbert 2014; Fitzherbert et al. 2014), including the following Pb, Zn, Ag or Cu bearing types:

- Pb–Ag–Zn VAMS bimodal felsic dominated (Broken Hill type): 507 occurrences, 33 small, 11 medium, 10 large, 10 very large deposits; accounts for most of the Pb–Zn–Ag–Au endowment shown in Table 1
- Pyrite–Cu–Co Great Eastern type (i.e. structurally controlled base metal): 274 occurrences, 4 small deposits, 40t estimated production for 4t Cu
- Fe–Cu–Co Sisters type (including volcanic-related BIF): 67 occurrences, 3 small deposits, 726t actual production for 70t Cu

Of the 3834 mineral occurrences and deposits in MetIndEx within the Broken Hill Domain, over 900 are related to syn-sedimentary or volcanogenic mineralisation (Barnes 1988). Apart from historic copper won from the Copper King and Copper Blow mines, the known Pb–Zn–

Ag–Cu–Au endowment across the Broken Hill Basin is completely dominated by the Broken Hill line of lode (Table 1).

Broken Hill Basin endowment (tonnes)	Pb - t	Zn - t	Ag - t	Cu - t	Au - t
Production	16,304,634	13,857,121	21,618	88	22
Resources	3,005,168	3,547,252	5,210	14,000	7
Total	19,309,802	17,404,373	26,828	14,088	29

Table 1. Broken Hill basin endowment figures, based on GSNSW MetIndEx and unpublished data. Apart from copper, these numbers mainly reflect production and resources on the Broken Hill line of lode.

Basin	Broken Hill
Deposit	Broken Hill line of lode (VAMS bimodal felsic dominated [Broken Hill type])
Endowment	Contained metal in Table 1; Tonnage estimations vary (see Webster 2006), Burton (1990) calculated 279 Mt of pre-mining ore
Geodynamic setting	Inferred Palaeoproterozoic intracontinental rift or far-field back arc, half-graben basin. Peak rifting, mafic intrusion and an elevated geotherm coincident with main ore-forming hydrothermal activity (references within Greenfield 2003)
Within-basin setting	Vent-proximal to major eastern growth/discharge fault, ore position along transition between basin rift and sag phases, on the flank an inferred volcanic centre
Key lithologies	Hosted in strongly-altered clastic sediments with intercalated Fe-rich tholeiitic sills and felsic volcanoclastics in the footwall stratigraphy. Albitised rocks in footwall
Heat source	Elevated geotherm provided by mafic underplating, and within-basin bimodal volcanics including tholeiitic sills in near-ore or footwall stratigraphy and felsic plutonic/volcanic activity
Fluid source	Deep crust/upper mantle is favoured, with late input from basin leaching
Fluid type	Reduced, slightly acidic, saline, low $\Sigma[H_2S]$; $\Sigma metal > \Sigma sulphur$; rich in Si, Ca, Mn, Fe, S, P, Ag, Zn, Pb
Alteration	<ul style="list-style-type: none"> • Distal diffuse alteration halo featuring stratabound garnet-sillimanite in aluminous country rocks • Proximal envelope of fine-grained Fe-Mn garnet quartzite • Distinct Fe-Ca-K-Mn-F-P REE 'skarn-like' enrichment of ore zone • Na-depletion common in the alteration halo
Metal deposition	Long-lived period (~5-6 myr) of deposition with ~9 abrupt pulses of inhalative \pm exhalative ore lens deposition (Parr et al. 2004)
Preservation factors	Inferred high energy depositional environment would have been difficult to preserve exhalative mounds. Early diagenetic inhalative mineralisation would have aided preservation. Sealed by felsic volcanoclastics and sag-phase turbidite deposition. Ore body remained within alteration halo following high grade metamorphism and deformation
References	Greenfield 2003, Webster 2006 and references therein

Table 2. Mineral system characteristics of the main Broken Hill deposit.

Mineralisation in the Broken Hill basin was dominated by exhalative and inhalative (replacement) processes active during the rift phase of basin development. There are several basin-scale features which are fundamental to the endowment of the Broken Hill Basin and provide a blueprint for gauging the mineral potential of the younger Palaeozoic basins of the Tasmanides, including the importance of:

- an extensional geodynamic setting with an elevated geotherm related to magmatic underplating (Plimer 1985; Sawkins, 1989)
- rift-stage bimodal volcanics, tholeiitic mafic-ultramafic magmas (Stevens et al. 1988)
- master growth faults controlling major fluid discharge conduits (Plimer 1979)
- a hydrothermal fluid surge during the transition from basin rift to sag depositional phase (Plimer 1985)
- mineralisation during late diagenetic sedimentation, allowing 'inhalative' replacement within permeable units (Large 2003; Parr et al. 2004).

Ponto Group, Koonenberry Belt

The Ponto Group in northwest NSW comprises an oceanic basin containing pelagic mudstone and siltstone, interbedded with minor sandstone, laminated felsic tuff, quartz-magnetite beds and tholeiitic mafic igneous rocks of the Bittles Tank Volcanics (Mills 2010). The basin is interpreted to be part of a fore-arc package that has been thrust onto the pre-Cambrian continental margin during the Delamerian Orogeny (Greenfield et al. 2011). This has resulted in the strike-extensive Ponto Group confined to a narrow belt extending for over 300 km, from the Koonenberry Belt (northeast of the Broken Hill Domain) folding about the Grasmere Knee-zone, and extending along the southeast margin of the Broken Hill Domain. Imbricate thrust faulting has intercalated the Ponto Group units, masking the original basin architecture, however it's likely that the Ponto Group lithologies are representative an early rift stage of oceanic basin development.

The basin is host to two syn-sedimentary exhalative pelitic–mafic-hosted (Besshi-type) Cu–Ag–(Au–Zn) deposits, best represented by the small Ponto copper mine and the large Peveril-Grasmere deposit (Gilmore 2010, Figure 1, Table 3).

Basin	Ponto Group, Koonenberry Belt
Deposits	Pelitic–mafic-hosted (Besshi-type) Cu–Ag–(Au–Zn): Ponto, Grasmere
Endowment	<ul style="list-style-type: none"> • Ponto Copper Mine: resource (1973-01-01) 3400t inferred for 170t Cu; 50t actual production for 9.25t Cu • Grasmere Copper deposit: resource (2006-07-31) 5.75Mt inferred for 13.225t Ag, 0.29t Au, 60000t Cu, 20125t Zn; 500t actual production for 100t Cu • 15 related mineral occurrences
Geodynamic setting	Suprasubduction setting: deep oceanic fore-arc basin
Within-basin setting	Tholeiitic mafic sills in the footwall and hosted by altered phyllite. Nearby quartz-magnetite ± hematite ± pyrite ± pyrrhotite exhalative units
Heat source	Elevated geotherm generated by subducting slab
Alteration	Bleached phyllite envelope, silica cap present at Grasmere Copper deposit
Metal deposition	Inferred seafloor exhalative
Preservation factors	Interbedded laminated cherty tuff, mudstone and exhalative units suggests low energy environment of deposition may have been an important preservation factor
References	Gilmore (2010), resource data from MetIndEx

Table 3. Mineral system characteristics of the Ponto Group pelitic–mafic-hosted (Besshi-type) deposits.

Girilambone District, Lachlan Orogen

The Early to Middle Girilambone Group is located to the west of the Macquarie Arc, and comprise micaceous, quartzose and quartz-lithic turbidite, chert, minor polymictic conglomerate, siltstone, quartzite, as well as mafic igneous rocks (Scheibner & Basden 1998). Strongly deformed and metamorphosed up to biotite grade in the Benambran Orogeny, the group is characterised by north-south trending thrust-bound packages that separate Early (Narrama Formation) and Middle (Ballast and Lang formations) Ordovician parts of the basin (Gilmore 2014). In terms of basin development, the Early Ordovician Narrama Formation hosts the bulk of the mafic igneous units, coarser-clastics, quartz-magnetite units and mineralisation, probably representing the early stage of basin development. The majority of the mafic units are interpreted to be sills of MORB-affinity that have intruded into unconsolidated turbiditic sediments (Burton 2014).

The Girilambone Group hosts VAMS pelitic–mafic-hosted (Besshi-type) Cu–Ag–(Au–Zn) deposits in the Narrama Formation, including the very large Tritton deposit, and 12 small to large deposits in the Budgerygar, Collierina and Tottenham districts (Gilligan & Byrnes 1995, Jones 2012). Recent field mapping by the Geological Survey of NSW (e.g. Gilmore 2014) has defined a 200 km long, narrow N-S trending fairway of mineralisation along the eastern margin of the Girilambone Group that links these districts, with a consistent host package of footwall MORB basalt, hanging wall silica-magnetite units, and distal hanging wall quartzite (Gilmore 2014).

There is a second small district of pelitic–mafic-hosted deposits at Canbelego, in the western Narrama Formation, close to the Cobar Basin, that includes one medium sized deposit (Canbelego copper mine) and two small deposits (Burra and Mt Boppy Block 51).

All the Girilambone Group deposits are hosted in the Narrama Formation. The eastern districts are close to the faulted contact with the Macquarie Arc, with a series of alpine-style ultramafic units in between, suggesting that these deposits may have been formed in the earliest phase of rift basin development.

South from the Girilambone Group, the strongly sheared and fault-bound early- to mid-Late Ordovician Jindalee Group is interpreted to be a strongly sheared equivalent of the Girilambone Group (Basden 1990). It consists of distal turbidite with interbedded slate, Mn-bearing chert, quartzite, quartz-magnetite units and tholeiitic mafic to ultramafic rocks (Basden 1990). Three small VAMS pelitic–mafic-hosted (Besshi-type) and mafic setting-hosted (Cyprus-type) deposits and several occurrences associated with mafic and ultramafic (Coolac Serpentinite) rocks have been identified (Ashley 1974, Basden 1986). This is a much underexplored, strongly deformed rock package that has been overlain by the Siluro-Devonian Tumut Trough.

Girilambone Group endowment (tonnes)	Cu - t	Ag - t	Au - t
Production	760,946	18.5	0.45
Resources	309,298	0	0
Total	1,070,154	18.5	0.45

Table 4. Endowment figures for VAMS deposits hosted in the Girilambone and Jindalee Groups, based on GSNSW MetIndEx data and updated resource data for Tritton Mine (Straits Resources website).

Basin	Girilambone District
Deposits	VAMS pelitic–mafic-hosted (Besshi-type): Tritton, Tottenham, Canbelego, Bonnie Dundee, Budgery
Endowment	10 small, 2 medium, 7 large, 1 very large deposit (see Table 4), 34 occurrences
Geodynamic setting	Deep oceanic basin; Back arc to Ordovician Macquarie Arc (Scheibner & Basden 1998)
Within-basin setting	Consistent mineralisation package from footwall basalt, silica-magnetite units, and distal hanging wall quartzite (Jones 2012, Gilmore 2014)
Heat source	Magmatic underplating, local mafic sills powering hydrothermal convection beneath deposits (Gilmore 2015)
Alteration	Proximal Fe-chlorite to distal Mg-chlorite in the footwall, silicification of the ore zone, and carbonate-altered hangingwall assemblages (Jones 2012)
Metal deposition	Minor exhalative onto seafloor, inhalative replacement of pore spaces within unconsolidated sediments by mafic-derived ore fluids (Gilmore 2015)
Preservation factors	A lack of barium and manganese associated with the deposits suggest a subseafloor replacement model for the bulk of the ore (Gilmore 2015)

Table 5. Mineral system characteristics of the Girilambone Group deposits.

Cobar Basin, Lachlan Orogen

The latest Silurian to Early Devonian Cobar Basin in central-western NSW represents marine deposition in an intracontinental rift basin, developed on a weathered basement of Ordovician turbidite and Silurian granite. Recent work by GSNSW in the Nymagee area has refined the timing of basin development, magmatism and mineralisation (Downes et al. in prep.). Subsidence was initiated during trans-tensional extension, and was associated with thermal underplating, expressed in the early basin rift fill as latest Silurian to early Devonian I-type granites and related high-K calc-alkaline volcanics (Downes et al. submitted), coeval with siliciclastic deposition of the lower Amphitheatre Group (Glen 1990). The northern, deeper part of the basin developed as an eastern-facing half-graben along a master growth fault (Rookery Fault), whereas to the south, the narrow Mt Hope and Rast troughs developed as symmetrical grabens (David 2006). To the east, the smaller-scale Canbelego-Mineral Hill Rift Zone also developed as an east-facing half-graben along the Coonarra Fault. Carbonate shelves developed on the basements highs, as isolated reef mounds along the eastern margins (Kopyje Shelf, Walters Range Shelf) and patchy reef limestone on the western margins (Winduck Shelf). Deposition of siliciclastic turbidite of the upper Amphitheatre Group marks the onset of the sag phase of basin deposition.

Basin mineralisation resulted in a combined value of Cu-Zn-Pb-Au-Ag endowment at ~\$33.7b in 2009 Australian dollars (based on MetIndex figures in Table 6).

Cobar Basin	Cu - t	Zn - t	Pb - t	Au - t	Ag - t
Production	1,104,747	2,128,843	1,025,952	120	1,857
Resources	903,827	2,416,463	1,710,395	76	4,419
Total	2,008,574	4,545,306	2,736,347	196	6,277

Table 6. Cobar Basin endowment figures (in tonnes), based on GSNSW MetIndEx and some unpublished data (Perks & Downes in prep.).

The mineral deposits are dominantly structurally-controlled high-sulfide base metal (Cobar type) and hosted in the rift-phase and carbonate shelf sequences of the basin, with the largest deposits (CSA, The Peak, Perseverance, New Occidental) developed along a narrow corridor west of the Rookery Fault (Figure 1). The Cobar Basin experienced strong deformation and greenschist facies metamorphism during the Middle Devonian Tabberabberan Orogeny, and the Cobar type deposits are structurally controlled within linear pipe-like high strain zones associated with that orogenic event (Lawrie & Hinman 1998). Structurally-controlled high-sulfide base metal (Cobar type) deposits are therefore interpreted as syn-tectonic, with mineralisation being synchronous with post-peak deformation (Stegman 2001). However a hybrid model of syn-sedimentary mineralisation followed by mechanical (and local chemical) remobilisation of the ore into structural sites is favoured by Gilligan & Byrnes (1995) and David (2006) explain the genesis of some Cobar type deposits. Recent work by the GSNSW (Downes et al. in prep.) using lead- and sulfur-isotope data has shown that structurally-controlled high-sulfide base metal deposits in the Nymagee are derived from a combination of basinal and basement derived fluids.

Other deposit types include VAMS (e.g. Great Central Mine) which are located in the southern parts of the basin, associated with latest Silurian volcanics, and carbonate-hosted stratabound (MVT type) deposits that formed by replacement and/or cavity infill of patchy carbonate units on the western margin of the basin (e.g. Manuka— formerly Wonawinta). In the north of the basin, the Zn-Pb-Ag Elura deposit is interpreted as a vent-proximal Irish type deposit by David (2008), although Downes et al. (2008) defined it as a reduced sedimentary exhalative system. At Elura, mineralisation occurs within unconsolidated carbonate units (and fine-grained clastics) close to a fluid discharge-growth fault. Typical of deposits in the basin, the original Elura mineralisation was subsequently remobilised into seven large cylindrical pods during basin inversion in the Tabberabberan Orogeny.

Basin	Cobar Supergroup
Deposits	<ul style="list-style-type: none"> structurally-controlled high-sulfide base metal (Cobar type): 42 occurrences, five small, four medium, six large, five very large (CSA, The Peak, Perseverance, New Occidental, Browns Reef) deposits Reduced sedimentary exhalative system: one very large deposit (Endeavor/Elura) Carbonate-hosted stratabound Zn–Pb (MVT type): 2 occurrences and one very large (Wonawinta/Manuka) deposit VAMS: 43 occurrences, six small, two medium (e.g. Great Central Mine) deposits
Geodynamic setting	Intracontinental transtensional rift setting, heat inferred to have been generated by distal subducting slab (trench to the east)
Within-basin setting	Majority of deposits located either in the rift phase volcano-sedimentary package or on the shelf margins
Heat source	Local heat sources provided by latest Silurian to early Devonian volcanic centres
Alteration	Proximal Mg-rich chlorite (Downes et al. submitted), carbonate silica and albite
Metal deposition	Syn-sedimentary mineralisation important in early rift phase, structural remobilisation important during basin inversion
Preservation factors	Along the Rookery Fault, dextral transpression during basin inversion facilitated remobilisation of ore into steep north-plunging pipes parallel to stretching lineation (Stegman 2001). Carbonate replacement/cavity infill in MVT deposits provided protective ‘jackets’, combined with lower strain on basin margins helped to protect deposits.

Table 7. Mineral system characteristics of the Cobar Basin deposits.

Silurian basins of the Eastern Lachlan Orogen

In the mid to late Silurian, rollback of the west-dipping subduction zone to the east of the current Lachlan Orogen resulted in the development of back arc rift basins on thinned Cambro-Ordovician oceanic and continental crust. These are named the Tumut Trough, Goulburn Basin, Hill End Trough; and coeval basin margins including the Canberra-Yass Shelf, Mumbil Shelf and Capertee Rise (Scheibner & Basden 1998, Thomas & Pogson 2012) that host a significant VAMS province, with a combined value of volcano-sedimentary Cu-Zn-Pb-Au-Ag deposits of ~\$13.1b in 2009 Australian dollars (Table 8) based on the production and/or resources of over 100 deposits (Table 9).

East Lachlan Basins	Pb - t	Zn - t	Ag - t	Cu - t	Au - t
Production	652,157	1,151,057	395	194,769	19
Resources	833,232	1,303,476	3,334	321,995	29
Total	1,485,389	2,454,533	3,729	516,764	48

Table 8. Endowment figures (in tonnes) for Silurian volcano-sedimentary deposits of the East Lachlan Orogen, based on GSNSW MetIndEx data.

VAMS deposits are located along basin margins within the exposed syn-rift phase volcano-sedimentary units, and localised clusters of ~10 deposits in ~50 km wide zones are characteristic around discrete volcanic centres (Ramsden 1982). There are subtle changes in the geological setting of the deposits, e.g. recent GSNSW metallogenic mapping in the Bathurst region (Downes et. al. 2013, Downes 2013) has seen a reclassification of some VAMS deposits in the Hill End Trough as siliciclastic–felsic-hosted (Iberian-type), recognising a lack of mafic volcanic rocks associated with these deposits (e.g. Lewis Ponds, Burruga, Sunny Corner). This contrasts with the bimodal felsic-dominated (Kuroko-type) deposits that characterise the Goulburn Basin further south, highlighted by the Captains Flat and world-class Woodlawn deposits that are associated with felsic and mafic volcanic rocks within the Hoskinstown and Mount Fairy groups respectively (Fitzherbert et al. 2010).

Other deposit types in the province have only minor economic significance. In the far southern Lachlan (southernmost occurrences in Figure 1), limestone and mudstone units of the Quidong Basin hosts stratabound pyrite-rich base metal deposits that are distal to known volcanic centres and have been interpreted to be Irish type by McQueen (1989). In the Brindabella district of the Canberra-Yass Shelf, the Late Silurian Cooleman Limestone hosts brecciated galena, pale sphalerite and chalcopyrite bearing orebodies that have zoned textures suggesting open-space cavity fill, and have been classified as MVT type by Gilligan (1973).

Basin	Late Silurian basins of the Eastern Lachlan: Tumut Trough, Goulburn Basin, Hill End Trough; and coeval basin margins: Canberra-Yass Shelf, Mumbil Shelf, Capertee Rise
Deposits	<ul style="list-style-type: none"> • VAMS bimodal felsic-dominated (Kuroko-type) and siliciclastic–felsic-hosted (Iberian-type): 316 occurrences, 63 small, 18 medium, 12 large, three very large deposits (Woodlawn, Captains Flat, Lewis Ponds) • VAMS pelitic–mafic-hosted (Besshi-type) & mafic setting-hosted (Cyprus-type): 43 occurrences, 11 small deposits (e.g. Tumut Trough) • Carbonate-hosted stratabound (Irish type): five occurrences (Quidong) • Carbonate-hosted stratabound (MVT type): seven occurrences (e.g. Brindabella)
Geodynamic setting	Distal back-arc marine basins developed on rifted Cambro-Ordovician oceanic and continental crust
Within-basin setting	VAMS deposits spatially associated with the margins of bimodal volcanic centres adjacent to basin margin syn-volcanic and intra-basin discharge faults; carbonate-hosted stratabound (MVT type) located on carbonate shelf regions
Heat source	Heat inferred to have been generated by distal subducting slab (trench to the east); Silurian I-type magmas intruded thinned Ordovician basement beneath basins (e.g. Thurrallilly Suite under Goulburn Basin)
Alteration	Distal (100-300 m) silicic-sericitic halo; Proximal Mg-rich chlorite and talc common
Metal deposition	Inferred deep water seafloor exhalative (e.g. Captains Flat) and/or sub-seafloor inhalative (e.g. Currawang) into siliciclastic fine-grained sediments or volcanoclastics above volcanic centres.
Preservation factors	Rapid burial of VAMS deposits by volcanoclastic or turbiditic deposition. Carbonate replacement/cavity infill in MVT deposits provided protective ‘jackets’, combined with lower strain during deformation on basin margins.
References for table	Gilligan 1973, Fitzherbert et al. 2010, Deyssing & Fitzherbert 2014, Downes et al. (submitted)

Table 9. Mineral system characteristics of the volcano-sedimentary deposits of the Late Silurian Eastern Lachlan Orogen.

Southern New England Orogen

Pb–Zn–Ag–Cu–Au metallogeny of the Devonian–Carboniferous accretionary complex and Permian extensional basins in the southern New England Orogen (Figure 1) is dominated by magmatic deposits. Volcano-sedimentary deposits account for only ~AUD\$49 million out of the total ~AUD\$7 billion Pb–Zn–Ag–Cu–Au endowment value for the region (based on 2009 Australian dollars and figures in Table 10).

S. New England Orogen	Pb - t	Zn - t	Ag - t	Cu - t	Au - t
Production & Resources (volcano-sedimentary)	556	670	1.44	2889	0.77
Production & Resources (total for region)	68,987	77,703	2,359	72,772	130

Table 10. Endowment figures (in tonnes) for Southern New England (NSW) volcano-sedimentary deposits, compared to total Pb–Zn–Ag–Cu–Au endowment value for the same area based on GSNSW MetIndEx and some unpublished data (Perks & Downes in prep.).

Most of the volcano-sedimentary mineralisation occurs in the Tablelands Complex of the Devonian–Carboniferous accretionary complex in two distinct fairways. The first is a line of 11 small Cu–Mn rich mafic setting-hosted (Cyprus-type) deposits hosted by basaltic rocks (in sheared contact with chert or jasper, Brown 1995) within the Siluro–Devonian Woolomin Group, centred on the Bingara Gold Field, extending north-south from Warialda in the north to Woodsreef in the south, east of the Peel Fault (Gilligan et al. 1987, Brown et al. 1992, Stroud & Brown 1998). Further along strike from these deposits are numerous occurrences of manganese- or pyrite-rich exhalatives hosted in chert, slate or jasper of the Woolomin Group (Gilligan et al. 1987). These deposit types are prospective along strike to the north of Warialda where the Woolomin Group disappear undercover.

The second fairway consists of two small deposits and 10 occurrences hosted in the Devonian to Carboniferous Sandon Association, extending broadly east-southeast from Bundarra to Greengate, north of Armidale (Brown et al, 1992). These deposits also associated with scattered occurrences of manganese- or pyrite-rich exhalatives hosted within chert and jasper of the Sandon Association. Numerous other occurrences of manganese- or pyrite-rich exhalatives hosted mainly in chert or jasper occur throughout the Tablelands Complex in linear arrays that are broadly parallel to strike (e.g. Gilligan et al. 1992; Brown 2015). Chert- and carbonate-hosted stratiform gold occurrences in the Coffs Harbour Block are unusual and require further investigation (Henley et al. 2001). These exhalative occurrences can host various Cu–Pb–Zn sulfides and be associated with mangiferous rocks (Gilligan et al. 1992). They may serve as exploration vectors to more substantial volcano-sedimentary mineralisation.

In the early Permian, back-arc extension associated with the termination of the Devonian–Carboniferous convergent margin, experienced S-type magmatism that may have provided a heat engine for volcano-sedimentary mineralisation in early Permian marine basins. The best example is the Halls Peak VAMS bimodal felsic-dominated (Kuroko-type) deposit (Degeling 1978, Figure 1), which was mined from ~1916 to the 1970s to produce 58t Cu, 1.4t Ag, 556t Pb and 670t Zn from five small deposits (Gilligan et al. 1992). The deposit is hosted in coherent andesitic volcanics and rhyolitic pyroclastics of the shallow marine to emergent Halls Peak Volcanics and represents mineralisation in the early rift phase of basin development (Degeling 1978).

Summary

NSW metalliferous basins host a spectrum of volcano-sedimentary deposits, with world-class endowment in the Broken Hill, Cobar, and East Lachlan basins. The total value of the Pb–Zn–Ag–Cu–Au endowment for the volcano-sedimentary basins in NSW is ~AUD\$125b, compared to the total Pb–Zn–Ag–Cu–Au basin endowment of ~AUD\$323b (2009 Australian dollars, MetIndex and unpublished data from Perkins & Downes).

The majority of Pb–Zn±Ag±Cu±Au volcano-sedimentary mineralisation in NSW occurred during long-lived extension associated with trench-distal back-arc basins, initiated by roll-back from an episodically retreating subduction system. A key discrimination between these back arc settings is whether the basin was developed on an oceanic substrate (e.g. Girilambone district) or continental substrate (e.g. Cobar & eastern Lachlan basins). The oceanic rift settings host smaller VAMS pelitic–mafic-hosted (Besshi-type) and mafic setting-hosted (Cyprus-type) districts that are copper-dominant and lack clear discharge fault zones, whereas the continental rift settings host intermediate-felsic volcanism and magmatism providing distinct fault zones, rapid facies changes, and local heat engines for focused and longer-lived mineral systems. The crystalline basement substrate also allowed the development of carbonate-rich shelves and felsic volcanism on the basin margins that provided further mineralisation opportunities, including the development of carbonate-hosted stratabound (MVT type) and reduced sedimentary exhalative system deposits. The Broken Hill basin itself has been interpreted as a far-field continental back-arc basin (Giles et al. 2003), which could help to explain the extraordinary heat flow generated during basin evolution, although the basin substrate was clearly ensialic, and mineralisation occurred during the basin rift-sag transition.

In contrast, most deposits described here are located in the lower rift phase rock packages of the basins. VAMS deposits dominate in terms of the number of deposits and occurrences which explains the large endowment of the ‘hotter’ metals such as Cu and Au, although overall, endowment is completely dominated by the Broken Hill line of lode. Carbonate-hosted stratabound (MVT type) and reduced sedimentary exhalative system deposits are rare in NSW, which may say something about the lack of availability of key lithologies exposed in the described basins, such as (extensive) carbonate platform rocks and reduced graphitic sag-phase clastic rocks. This may in-turn hint at the dynamic tectonic regime that characterised the development of these basins, they were relatively short-lived, not allowing lower temperature mineral deposits time to accumulate.

In contrast, the Tablelands Complex in New England hosts minor exhalative mineralisation in an accretionary wedge setting. The limited size of the known endowment may reflect the difficulty in preserving syngenetic basin mineralisation in such a dynamic setting, however the apparent strike extents of the deposits and exhalative occurrences provide encouraging vectors for further exploration. The value of characterising volcano-sedimentary deposits is that further exploration is generally pursued in the host lithologies along strike. In NSW there is clear along-strike potential in the Mount Hope Trough, Jindalee Group and Koonenberry Belt extensions of the Ponto Group in the Koonenberry and Loch Lilly–Kars belts.

References

- Ashley, P.M., 1974. Stratabound pyritic sulphide occurrences in an ophiolite rock assemblage near Tumut, New South Wales, *Journal of the Geological Society of Australia*, 21:1, 53-62.
- Barnes, R.G., 1988. Metallogenic Studies of the Broken Hill and Euriowie Block, NSW, 1. Styles of Mineralisation in the Broken Hill Block. *Geological Survey of NSW Bulletin* 38 (1, 2), 1-116.
- Basden, H., 1986. Mineral deposits in the Tumut 1:100 000 sheet area. *Geological Survey of NSW*, GS1986/106.
- Basden, H., 1990. *Geology of the Tumut 1:100 000 sheet 8527*. Geological Survey of NSW. 275pp.
- Brown R.E., 1995. Mineral Deposits of the Bingara, Croppa Creek, Gravesend and Yallaroi 1:100 000 sheet areas. *Quarterly Notes of the Geological Survey of NSW*, 98.
- Brown R.E., Krynen J.P. and Brownlow J.W., 1992, *Manilla-Narrabri 1:250 000 Metallogenic Map*, 1st edition. Geological Survey of New South Wales, Sydney.
- Brown, R.E. (compiler) 2015, *Warwick-Tweed Heads 1:250 000 Metallogenic Map SH/56 2 and SH/56-3: metallogenic study*. Geological Survey of New South Wales, Maitland.
- Burton, G.R., 1990. Pre-Mining Tonnage of the Individual Ore Lenses of the Broken Hill Main Lode. *Geological Survey of NSW Report*, GS1990/0322.
- Burton, G.R. 2014. Interpretation of whole rock geochemical data for samples of mafic schists from the Tottenham area, Central New South Wales. *Geological Survey of New South Wales report* GS2014/0215.
- David, V., 2006. Cobar Superbasin metallogenesis. *AIG Bulletin No. 46: Mines & Wines 2007*, 12pp.
- David, V., 2008. Structural–geological setting of the Elura-Zn–Pb–Ag massive sulphide deposit, Australia. *Ore Geology Reviews*, v.34, 3, 428–444.
- Degeling, P.R., 1978. The geology and ore potential of the Faints-Firefly silver-lead-zinc-copper area, Halls Peak, New South Wales. *Geological Survey of NSW Report*, GS1978/384.
- Deysing, L.J. and Fitzherbert, J.F., 2014. Controls on mineralisation and architecture of the southern Goulburn Basin (poster). *Geological Survey of NSW Report*, GS2014/0941.
- Downes, P.M., Blevin, P.L., Forster, D.B., Whitehouse, J., Lewis, P., and Barnes, R.G., 2011. Mineral systems of NSW, version 4 (poster). *Geological Survey of NSW, Report* GS2010/0917.
- Downes, P.M., and Fitzherbert, J.F., 2014. Development of the 1:250 000 scale Broken Hill Special Metallogenic map, concepts and methodology. *Geological Survey of NSW, Report* GS2015/0001.
- Downes P.M., Blevin P., Reid W.J., Barnes R.G. & Forster D.B. 2011a. Metallogenic map of New South Wales — 1:1 500 000 Map. *Geological Survey of NSW, Department of Industry & Investment, Maitland, Australia*.
- Downes P.M., Blevin P.L., Forster D.B., Whitehouse J., Lewis P. & Barnes R.G. 2011b. Mineral systems of New South Wales version 4 — 2011. *Geological Survey of NSW, Report* GS2010/0917.

- Downes P.M., Colquhoun G.P., Blevin P.L., Forster D.B., Rutledge J.M. & Pogson D.J. 2013. Bathurst 1:250 000 Metallogenic Map (2nd edition). Geological Survey of New South Wales, Maitland, Australia.
- Downes P.M., 2013. Development of the second edition 1:250 000 scale Bathurst metallogenic map, concepts and methodology. Geological Survey of NSW, Report GS2013/1609.
- Downes P.M, Tilley D.B., Fitzherbert J. & Clissold M.E. (submitted). Regional metamorphism and the alteration response to selected Silurian to Devonian mineral systems in the Nymagee area, Central Lachlan Orogen, New South Wales — a HyLogger™ case study. GSNSW Quarterly Notes.
- Downes P.M., Blevin P.L., Simpson C.J., Armstrong R., Sherwin L., Tilley D.B. & Burton G.R. (in prep). Towards a greater understanding of the Central Lachlan — the Nymagee mineral systems study. GSNSW Quarterly Notes.
- Fitzherbert J., Deysing L., Thomas O., Simpson C. and Bodorkos S. 2010. Poster: Lockhart Igneous Complex: Plutonic links with volcanism during Silurian rifting, eastern Lachlan Orogen, southeastern Australia. Australian Earth Sciences Convention, Canberra, 4-8 July 2010. Geological Survey of NSW, GS2010/0467.
- Fitzherbert J.A. & Downes P.M. 2015. Geological history of the Broken Hill 1:250 000 Special Metallogenic Map. Quarterly Notes 143(2), 29–43.
- Fitzherbert J.A., Downes P.M., Colquhoun G.P., Blevin P.L. & Forster D.B. 2014. Broken Hill 1:250 000 Special Metallogenic Map. Geological Survey of New South Wales, Maitland, Australia.
- Giles, D., Betts, P. G., Lister, G. S., 2003. Tectonic environment of shale-hosted massive sulfide Pb-Zn-Ag deposits of Proterozoic northeastern Australia. Economic geology and the Bulletin of the society of economic geologists. Monash Univ, Sch Geosci, Australian Crustal Res Ctr, Wellington Rd, Melbourne, Vic 3800, Australia. 98, 3, 557-576.
- Gilligan, L.B., 1973. Possible Mississippi Valley-type deposits at Coleman, southeastern NSW. Quarterly Notes of the Geological Survey of NSW, 10.
- Gilligan L.B., Brownlow J.W. and Cameron R.G., 1987, Tamworth-Hastings 1:250 000 Metallogenic Map, 1st edition. Geological Survey of New South Wales, Sydney.
- Gilligan L.B., Brownlow J.W., Cameron R.G. and Henley H.F., 1992, Dorrigo - Coffs Harbour 1:250 000 Metallogenic Map. 1st edition, Geological Survey of New South Wales, Sydney.
- Gilligan L.B., and Byrnes, J. G., 1995. 1:250 000 Cobar SH5514 Metallogenic Map - Metallogenic study and mineral deposit data sheet. Geological Survey of New South Wales, Sydney.
- Gilmore, P.J., 2010. Mineral Systems. In: Greenfield J.E., Gilmore P.J. & Mills K.J. (compilers) 2010. Explanatory notes for the Koonenberry Belt maps. Geological Survey of NSW, Bulletin 35, 400-424.
- Gilmore, P.J. 2014. Exhalative horizons and volcanic-associated massive sulfide (VMS) deposits in the Ordovician Girilambone Group, NSW (poster). Geological Survey of NSW Report, GS2014/0939.
- Gilmore, P.J. 2015. Exhalative horizons and volcanic-associated massive sulfide mineralisation in the Ordovician Girilambone Group, New South Wales. Unpublished thesis, Masters of Economic Geology, University of Tasmania, Hobart.

- Glen, R.A., 1990, Formation and inversion of transtensional basins in the western part of the Lachlan Fold Belt, Australia, with emphasis on the Cobar Basin. *Journal of Structural Geology*, 12(5/6), p601-620.
- Greenfield, J.E., 2003. A critical review of Broken Hill Ore System models. CSIRO Exploration and Mining Report 1154R, Geological Survey of NSW Report GS2012/880. 191 pages.
- Greenfield, J.E., Musgrave, R.G., Bruce, M., Gilmore, P.J., Mills, K.J., 2011. The Mount Wright Arc: A Cambrian subduction system developed on the continental margin of East Gondwana, Koonenberry Belt, eastern Australia. *Gondwana Research* 19, 650–669.
- Henley H.F., Brown R.E., Brownlow J.W., Barnes R.G. and Stroud W.J., 2001, Grafton-Maclean 1:250 000 Metallogenic Map, 1st edition. Geological Survey of New South Wales, Sydney.
- Jones P. 2012. Tritton copper mine: mineralisation and host sequence. In: Post-conference field excursion; Geology and mineralisation of the Cobar–Nyngan region. Cobar Regional Mining and Exploration Conference. Geological Survey of NSW report GS2012/695.
- Large RR, 2003. BHT deposits: part of the spectrum of stratiform sediment hosted Zn-Pb-Ag deposits. Peljo, M., Proceedings of Broken Hill Exploration Initiative 2003 Conference, July 7-9th, Broken Hill. *Geoscience Australia Record* 2003/13, 4. p93-96.
- Lawrie, K, and Hinman, 1998. Cobar-style polymetallic Au-Cu-Ag-Pb-Zn deposits. *AGSO Journal of Australian Geology and Geophysics*. 17(4), p169-187.
- Lewis & Downes, 2008. Mineral Systems and Processes in New South Wales: a project to enhance understanding and assist exploration. *Quarterly Notes of the Geological Survey of NSW*, 128.
- McQueen, K.G. 1989. Sediment geochemistry and sulphide base metal mineralisation in the Quidong area, southeastern NSW, Australia. *Mineralium Deposita*, 24, 100-110.
- Mills, K. J., 2010. Ponto Group. In: Greenfield J.E., Gilmore P.J. & Mills K.J. (compilers) 2010. Explanatory notes for the Koonenberry Belt maps. Geological Survey of NSW, Bulletin 35, 75–98.
- Parr, J.M., Stevens, B.P.J., Carr, G.R., Page R.W. in press. Sub-seafloor origin for Broken Hill Pb-Zn-Ag mineralization, New South Wales, Australia. *Geology*, 32, 589-592.
- Plimer IR, 1979. Sulphide rock zonation and hydrothermal alteration at Broken Hill, Australia. *Institution of Mining and Metallurgy. Transactions/Section B*. 88, November, pB161-B176; 15 fig, 87 ref, 4 tables.
- Plimer IR, 1985. Broken Hill Pb-Zn-Ag deposit - a product of mantle metasomatism. *Mineralium Deposita*. 20(3) July, p147-153.
- Ramsden A. R., 1982. Distribution of stratiform zinc-lead-copper mineralisation in the eastern part of the Lachlan Fold Belt, central western New South Wales: *Pacific Geology*, v. 16, p. 1-6.
- Sawkins FJ, 1989. An orogenic felsic magmatism, rift sedimentation, and giant Proterozoic Pb-Zn deposits. *Geology*. 17(7) July, p657-660.
- Scheibner, E. and Basden, H. ed. 1998. *Geology of New South Wales – Synthesis. Volume 1 Structural Framework*. Geological Survey of New South Wales, *Memoir Geology* 13 (1), 295pp.

- Stegman, C. L., 2001. Cobar deposits: Still defining Classification. SEG Newsletter. No.44, p15-25.
- Stevens BPJ, Barnes RG, Brown RE, Stroud WJ, Willis IL, 1988. The Willyama Supergroup in the Broken Hill and Euriowie Blocks, New South Wales. Precambrian Research. 40/41, October, p297-327.
- Stroud W.J. and Brown R.E., 1998, Inverell 1:250 000 Metallogenic Map, 1st edition. Geological Survey of New South Wales, Sydney.
- Thomas O.D. Pogson D.J., 2012. 1:250,000 Geological Series, Explanatory Notes Goulburn sheet SI55-12. Geological Survey of New South Wales, Maitland.
- Webster, A.E., 2006. The geology of the Broken Hill lead-zinc-silver deposit, New South Wales, Australia. ARC Centre of Excellence in Ore Deposits, University of Tasmania, CODES Monograph No. 1.