

Proterozoic stratiform sediment-hosted Zn–Pb–Ag deposits

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EXPLORATION MODEL

Examples

Mount Isa Pb–Zn–Ag, Hilton, George Fisher, Century, Lady Loretta, HYC, Dugald River

Target

- Large deposits are characteristic (average for Australian deposits is about 100 Mt @ >> 10 wt% Zn+Pb).
- May contain structurally controlled higher grade zones (> 30 wt% Zn +Pb).
- Zn/(Zn+Pb) ratios vary between about 40 and >90.
- Often with high Ag credits (e.g. Mount Isa 150 ppm, HYC 60 ppm).

Mining and treatment

- Tabular form and uniform grades allow relatively easy assessment and mining.
- Some fine-grained ores create treatment difficulties.
- Coarser (metamorphosed and/or recrystallised) ores are easier to treat.
- Smelter penalties can be a problem, owing to high but variable As, Sb, Bi, Cd, Hg, In and Tl.
- Mn in solid solution in sphalerite can cause treatment problems (e.g. Dugald River).

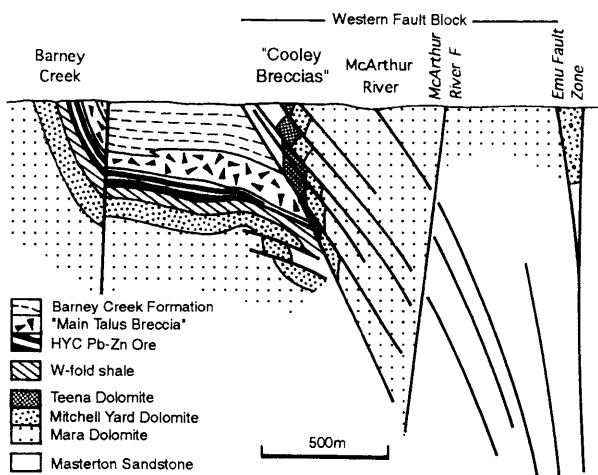


Figure 1. HYC geology section at 182900 mN (from Hinman 1995).

Regional geological criteria

- Intracontinental rift or rifted margin (marine) basins.
- Unmetamorphosed to greenschist–amphibolite transition.
- Continental basalts and felsic volcanics and intrusives form an important part of the underlying (older) rift fill.
- Diverse sedimentary host lithologies deposited in terrestrial, peritidal and deep marine settings; in part evaporitic; includes black, grey, brown and red rocks.
- All major deposits lie within a few kilometres of major long-lived regional-scale fault systems (e.g. Emu Fault, Mount Isa Fault, Termite Range Fault).
- Regional host sequence is often the latest sag phase fill of a series of rift-sag cycles.
- 'Carpentaria Zinc Belt' deposits are in rocks of 1660–1590 Ma.
- Evaporites may be needed for high-salinity ore fluids.

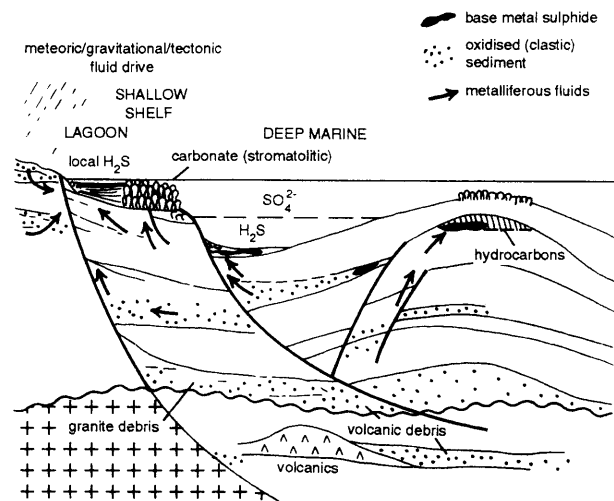


Figure 2. Schematic section showing possible sites for stratiform deposits and sources of metals and fluids

Local geological criteria

- Host sediments and ores are essentially coeval in most deposits, i.e. syngenetic (exhalative) or early diagenetic timing for the introduction of base-metal-bearing fluids (Century may be an exception).
- Host rocks are carbonaceous and/or pyritic black and grey (dolomitic) siltstone, mudstone and shale, often with a significant clastic carbonate (dolomite) component, i.e. the most 'reduced' parts of the local sequence.
- Turbidite and/or tempestite facies are commonly present.
- The water depths in which the sediments were deposited are different in different deposits (shallow/emergent to sub-photic zone and sub-storm wave base).
- Coarse-grained debris flows (breccias) in some deposits indicate local syn-sedimentary faulting.
- Fine-grained tuffaceous component is the only indication of (distal) coeval volcanic activity.

Mineralisation features

- Stratiform (stacked) lenses are common.
- Individual lenses have a sheet-like aspect ratio.
- Base-metal sulphides can be finely laminated and are interbedded with or form infillings in clastic sedimentary layers.
- Pyrite is abundant in most deposits, but in detail there is no simple relationship between pyrite and base-metal sulphide abundance.
- Pyrrhotite is only common in metasomatised/metamorphosed deposits (e.g. Mount Isa).
- Wide range of Zn/(Zn+Pb), but most deposits and most parts of individual deposits Zn > Pb.
- Only minor Cu (500–5000 ppm)
- Weak (Cu) > Pb > Zn zonation in some deposits.
- Barite is usually not present (except Lady Loretta and Grevillea).

Alteration

- Footwall alteration ('feeder') pipes are not recognised in Australian deposits.

- Carbonates in host sequences become richer in Fe and Mn closer to mineralisation.
- Ankerite and/or siderite halos are recognised in several deposits, e.g. HYC (Lambert & Scott 1973); Lady Loretta (Large & McGoldrick 1997); Century (Waltho et al. 1993).
- In low-grade metamorphic deposits, the organic matter associated with the ores is more thermally mature than organic matter in surrounding host rocks.

Deposit geochemical criteria

- Host sequences are anomalous in Zn, Fe, Mn and Tl.
- Fe and Mn content of carbonates in host sediments increases towards ore lenses in some cases, e.g. HYC (Lambert & Scott 1973).
- Ores contain high but variable Ag, As, Sb, Bi, Cd, Hg, In and Tl, but very low Au.
- Se, low; S/Se ratios of base-metal sulphides and pyrite are high.
- Sulphur isotope signatures of base-metal sulphides and pyrite are heavy and highly variable within and between deposits.
- Lead isotopes in the ores are (mostly) non-radiogenic and have model ages consistent with the ages of the host sequences.

Surficial geochemical criteria

- All deposits crop out at the surface.
- All (except Century) have prominent gossans.
- Rock chip and soil samples from the vicinity of all deposits return anomalous base-metal values.
- Soil geochemistry (Pb, Zn) has assisted in targeting drilling.

Geophysical criteria

- Processed regional potential field data can be used to define basement structures, basin margins, the nature and thickness of basin fill (depocentres) and other (?syn-sedimentary) structures.
- Density contrast between ores and host rocks may be recognisable from detailed gravity surveys.
- Ores are generally poor electrical conductors and non-magnetic (pyrrhotite-bearing ores are an exception).
- Airborne and ground electromagnetic surveys can locate carbonaceous and pyritic sedimentary host facies.

Fluid chemistry and source

- Limited direct evidence from fluid inclusions, e.g. Walford Creek fluids were 150–180°C (Rohrlach et al. 1996).
- Indirect evidence from fluid modelling, Au geochemistry, O isotopes, and (possible) ore-fluid aquifer characteristics indicates base-metal transporting fluids were:
 - high salinity (5–25 wt% NaCl eq.);
 - low to moderate temperature (100–200°C);
 - weakly oxidised ($\text{SO}_4^{2-} \gg \text{H}_2\text{S}$).
- Base-metal fluid source was basinal brines.
- Sulphide generation and base-metal sulphide precipitation caused by thermochemical and/or biogenic sulphate reduction.

Comments on genesis

Most existing models for these deposits invoke an exhalative process and a syngenetic timing for their formation in which sulphides accumulate as (chemical) sedimentary layers at the sediment–water interface (Stanton 1972). Mineralising fluids are thought to be relatively hot and reduced, carrying all the ingredients for precipitating pyrite and base-metal sulphides contained in the orebodies (Russell et al. 1981). However, textural, sedimentological and isotopic evidence from some deposits, notably HYC (Williams 1978a,b, Rye & Williams 1981, Logan 1979, Eldridge et al. 1993, Hinman 1996), has been used to support a model in which base-metal sulphide mineralisation forms in unconsolidated sediments during diagenesis and significant amounts of pyrite form independently of the base-metal sulphides. The genetic model presented here has some elements of both earlier models, but an important difference is that cool, oxidised fluids are invoked as the likely base-metal transporting fluids (McGoldrick & Keays 1990; D.R. Cooke, CODES, pers. comm. 1994). Oxidised fluids moving through or out of the sediment pile will precipitate base-metal sulphides if their dissolved sulphate undergoes reduction to sulphide or if they encounter another source of reduced sulphur. This could happen in several ways:

- exhalation into an anoxic and/or organic matter-rich water body (e.g. HYC, part of Lady Loretta);
- reaction between transient oxidised brines and organic matter or diagenetic Fe sulphides in porous sediments in the shallow sub-surface before significant burial (e.g. part of Lady Loretta);
- reaction between transient oxidised brines and organic matter accumulations (?petroleum) in the deep sub-surface (e.g. Century).

An alternative model, developed for the Mount Isa Zn–Pb–Ag deposits, suggests they formed by hydrothermal replacement of lithified and deformed pyritic sedimentary rocks (Grondijs & Schouten 1937, Perkins 1990, Laing 1990, Myers et al. 1996). This model cannot be extended to less deformed and unmetamorphosed deposits elsewhere.

Introduction

Late Palaeoproterozoic rocks in northwest Queensland and the Northern Territory (the 'Carpentaria Zinc Belt' of Sweet et al. 1993) host five world-class stratiform sediment-hosted Zn-Pb-Ag orebodies (Mount Isa, Hilton, George Fisher, Century and HYC) and two smaller, but significant deposits (Lady Loretta and Dugald River). The gossanous outcrop of the Mount Isa Zn-Pb-Ag lodes was found in 1923 by Campbell Miles, a prospector, and since World War 2, geological exploration by mining companies has resulted in a significant discovery in every decade except the 1970s. The discoveries were the Hilton deposit at MIM's 'Northern Leases' in 1948, HYC in 1956, Lady Loretta in 1966, Hilton North (now renamed George Fisher) by MIM in the early 1980s, and Century in 1990. All these deposits had gossanous outcrop or, in the case of Century, a strong soil geochemical signature. No world-class deposits are known from other Australian Proterozoic sedimentary basins.

Discoveries in the Carpentaria Zinc Belt during the last decade (e.g. Century, George Fisher and Grevillea) hold promise for new major deposits in this region and in similar Proterozoic sedimentary basins elsewhere. The following discussion emphasises geological and geochemical features relevant to understanding ore genesis and developing better exploration models.

Main features of the deposits

The important geological features of the Carpentaria Zinc Belt deposits are summarised in Table 1. The deposits comprise multiple or single lenses of laminated to massive sphalerite, galena, Ag-bearing sulphosalts and pyrite. In the larger deposits the mineralisation has sheet-like aspect ratios and consists of multiple stacked lenses with individual lenses up to several hundred metres across and several tens of metres thick. At Mount Isa, more than thirty Zn-Pb-Ag ore lenses are present in the upper 650 m of the Urquhart Shale Member of the Mount Isa Group; at McArthur River the HYC mineralisation occurs as seven ore lenses in 80 m of the Barney Creek Formation, and at Century there are two mineralised zones in a 40 m thick sequence of Member 4 of the Lawn Hill Formation.

Geological setting

The immediate host lithologies to all the Carpentaria Zinc Belt deposits are fine-grained carbonaceous (i.e. organic matter-rich) siltstones and shales. However, local and regional facies relationships for individual deposits indicate a wide variety of sedimentary settings. For instance, the Lady Loretta host sequence is thought to have been deposited in a shallow evaporitic restricted water body on a partly emergent carbonate shelf (Dunster 1996, McGoldrick et al. 1996). By contrast, sedimentary and geochemical halo features in the Barney Creek Formation can be traced more than 20 km from HYC and indicate that a substantial water body existed at the time of mineralisation (Large et al. 1996). Furthermore, the Barney Creek Formation is thickest at HYC and the mineralised sequence was probably deposited in the most rapidly subsiding (and deepest?) part of an elongate graben adjacent to the Emu Fault Zone (Neudert & McGeough 1996). Microfossils from the ore sequence indicate deposition below the photic zone (Oehler & Logan 1977). At Mount Isa, Neudert (1983) interpreted the Urquhart Shale, a dolomitic pyritic carbonaceous siltstone, as a ('deeper-water') shelf-slope facies of a large perennial lake. In contrast, the Lawn Hill Formation, host to Century, is a siliciclastic-dominated sandstone-mudstone unit deposited in a mid to outer shelf or deeper (marine) setting (Andrews 1996).

Sedimentary breccias at HYC (Walker et al. 1977) and Walford Creek (Rohrlach et al. 1996) indicate local syn-sedimentary faulting contemporaneous with deposition of the mineralised sequences. These faults may have been conduits for mineralising fluids (Williams 1978a, Rohrlach et al. 1996). Other

deposits (e.g. Mount Isa, Century) are close to major regional faults, but the host rocks do not contain sedimentary facies consistent with nearby syn-sedimentary faulting. These regional structures may have exerted fundamental control on early basin architecture and later basin inversion, and hence may have been important in controlling (or focussing) hydrothermal fluid flow.

Deformation and metamorphism

All the deposits have been deformed, but the intensity of deformation varies greatly between deposits. High metal-grade zones in some deposits may be due to deformation effects. Syn-sedimentary deformation of unconsolidated ores is recognised at HYC (Hinman 1995); and late brittle structures disrupt both HYC and Century (Coultts 1996, Waltho & Andrews 1993, Waltho et al. 1993). Although some galena and sphalerite at HYC and Century show indications of recrystallisation, much of the mineralisation preserves primary depositional textures (Broadbent & McKnight 1993, Eldridge et al. 1993, Hinman 1996, Large et al. 1996). In other deposits, fine-grained pyrite retains primary textures, but the base-metal sulphides are mostly recrystallised. The Dugald River Main Lode, a shoot-like body of slate-sulphide breccias up to 30 m thick, is interpreted to have formed during folding by remobilisation of lower grade mineralisation (Newbery et al. 1993). The highest grade parts of the Lady Loretta orebody are strongly deformed and form the 'keel' of a canoe-shaped orebody corresponding to the hinge of a local D_2 syncline (Hancock & Purvis 1990, Aheimer 1994). The highest grade parts of the Hilton orebodies also display strong structural control (Valenta 1994). The Mount Isa orebodies occur in the west limb of a regional upright D_2 anticline and galena-rich ores show spectacular smaller scale disharmonic folds. These folds are tectonic and formed in response to D_2 and D_3 deformation (McClay 1979).

Century and HYC are essentially unmetamorphosed, although slightly higher organic matter maturity in the immediate vicinity of HYC suggests a local thermal perturbation (Crick 1992). Although a spaced axial plane cleavage is present in more argillaceous host rocks at Lady Loretta, peak metamorphic conditions are not constrained, but were probably sub-greenschist grade. The host sequences at Mount Isa (and Hilton) are generally ascribed a lower greenschist metamorphic grade on the basis of mafic mineral assemblages in older metavolcanic rocks near the mine, and phyllosilicate minerals in the Urquhart Shale. However, the metavolcanics are in faulted contact with the Urquhart Shale, and 'metamorphic' phyllosilicates in the mine may be products of mineralisation-related hydrothermal alteration (Finlow-Bates & Stumpfl 1979). Some phyllosilicate-rich zones can be related with certainty to the silica-dolomite metasomatic process (Swager et al. 1987, Waring et al. 1998). The Dugald River deposit has been metamorphosed at upper greenschist to lower amphibolite grades (Newbery et al. 1993).

Timing of mineralisation

Timing of the formation of the base-metal sulphides in Carpentaria Zinc Belt deposits has been a major point of contention. The Mount Isa lodes were originally interpreted as hydrothermal replacement deposits (Grondijs & Schouten 1937, Blanchard & Hall 1942), but with the acceptance of syngenetic concepts in the 1950s and 60s, Mount Isa and HYC were reinterpreted as syngenetic-exhalative deposits (Murray 1961, Stanton 1962, Croxford 1962, Mathias & Clark 1975). The first descriptions of the HYC mineralisation assumed a syngenetic-exhalative origin for the deposit (Croxford & Jephcott 1972, Lambert 1976). Later, Williams (1978a,b) used textural and geochemical evidence from HYC and nearby minor deposits (Ridge and Cooley) to suggest that the HYC mineralisation formed some unspecified distance (centimetres? metres?) below the sediment-water interface, from fluids sourced from the direction of the Emu Fault Zone. He argued that the formation of the HYC stratiform mineralisation was an epigenetic process (using the definition of

Table 1. Important geological features of northern Australian Proterozoic stratiform sediment-hosted Zn-Pb deposits.

Deposit	Size & grade	Mineralisation	Host rocks	Age (Ma)	Metamorphism / Deformation	Evaporites	Oxidised sediments	Zoning	Hosts	References
HYC	8 ore lenses in ~70 m; global res. 227 Mt @ 9.2% Zn, 4.1% Pb; current project 104 Mt @ 14.1% Zn, 6.1% Pb and ~60 g/t Ag.	Stratiform, f.g. py, sp, minor ch, marcasite, arsenopy, primary textures well preserved.	Barney Creek Fm-HYC Pyritic Shale; pyritic, organic matter-rich (up to 7% TOC), dolomitic siltstones; coarse sedimentary breccias; minor tuffaceous component.	1640±3	Essentially unmetamorphosed, basin inversion, but no penetrative deformation.	Important parts of sequences above and below HYC Pyritic Shale are evaporitic.	W-Fold Shale (immediate f/w to mineralisation) shows extensive patchy reddening; Ennu FZ; various units elsewhere in McArthur and Tawallah Gps.	Small very Cu-rich zone in north; general (Cu-Pb)-Zn.	Py, TI regionally; Fe, Mn in carbonates.	Logan et al. 1990, 1993 & references therein; Crick 1992.
Walford Creek	No published reserves; several ore-grade intersections (Cu, Zn, Pb) of a few metres; covers area 6 x 1.5 km.	3 stacked lenses of stratiform massive py with sp & g as matrix in pyritic beds; primary textures preserved.	Fickling Gp-Mt Les Siltstone; dolomitic shale (regionally), highly carbonaceous, dolomitic and pyritic shales and local talus breccias.	1640±7	Sub-greenschist; relatively flat-lying, but bounded by major regional structure (Fish River Fault).	Pseudomorphs after gp in Mt Les Siltstone.	Cu-rich, late stage mineralisation near Fish River Fault.	Py	Rohliach et al. 1996; Page et al. 1994; Sweet et al. 1981.	
Century	2 main ore zones in 40 m mineralised sequence; 118 Mt @ 10.2% Zn, 1.5% Pb, 36 g/t Ag.	Stratiform sp, py (5-10%), g, zch (minimale association with organic matter and authigenic sil; primary textures preserved.	McNamara Gp-Lawn Hill Fm-unit Pmp4; siliciclastic, carbonaceous (TOC 1-5%), sideritic, shale & siltstone; minor tuffaceous component.	1595±6	Sub-greenschist; open folding, faulted ore contacts; stylolitic layering developed in ore sequence.	Not known.	Not known.	Highest Zn grades transgress mineralised sequence from SE to NW.	Py envelope; intense siderite development in siltstone.	Walther & Andrews 1993; Walther et al. 1996; Page et al. 1994.
Lady Loretta	Single high-grade lens with reserves of 8.3 Mt @ 18.4% Zn, 8.5% Pb, 125 g/t Ag; mineralised horizon ~50 m thick, recognisable over several km ² .	Stratiform py, sp, g, tetrahedrite, ba, si, tr, he; some primary textures preserved.	McNamara Gp-Lady Loretta Fm: carbonaceous, pyritic, dolomitic, sideritic siltstone & shale.	1647±4	?Sub-greenschist; open-tight synclinal (?D2) structure locally, more open folding regionally.	Gp moulds from ore horizon; sulphate evaporites important in lower McNamara Group (Paradise CK Fm, Gunpowder Creek Fm).	Not known.	Pb-Zn core to Zn-Ba flanks of main mineralisation.	Py, siderite, Mn, TI.	Hancock & Purvis 1990 (& references therein), McGoldrick et al. 1996.
Grevillea	No published reserves; several ore-grade intersections (Zn, Pb, Ba).	Stratiform massive py & ba; sp & g in pyritic beds.	McNamara Gp-Riversleigh Siltstone; siliciclastic carbonaceous mudstone & sandstone.	>1636 and <1652	? Sub-greenschist steep, westerly dip, fault-bounded.	Pseudomorphs of mush-textured gp.	Sandstone interbeds, and basal Shady Bore Quartzite.	Not known.	Py, siderite, Mn, TI.	Coolgardie Gold Annual reports.
Mount Isa	30 stacked (en echelon) ore lenses in ~1000 m (most in upper 650 m); pre-production reserves of ~150 Mt @ 7% Zn, 6% Pb, 150 g/t Ag.	Stratiform py, sp, g, tetrahedrite ± po, rare mt; ores show locally intense deformation, but some primary textures preserved.	Mount Isa Gp-Urquhart Shale; carbonaceous (now g), pyritic, dolomitic siltstones; 'tuffaceous' component.	1652±7	(Lower) greenschist facies; D1-D3.	Pseudomorphs of do after gp in Urquhart Shale; halite casts in siltstone unit above Urquhart Shale.	Basal Mt Isa Gp; Surprise Creek Fm (beneath and possibly laterally equivalent to Mt Isa Gp).	(Cu-Pb)-Zn.	Py, TI; ?Fe, Mn enrichment in carbonates.	Forrestal 1990 & references therein, McKirdy & Powell 1974; Page et al. 1994.
George Fisher	11 stacked ore lenses; 108 Mt @ 11.5% Zn, 5.4% Pb, 93 g/t Ag.	As for Mt Isa.	As for Mt Isa.	As for Mt Isa.	As for Mt Isa.	Carbonate pseudomorphs in orebodies interpreted as after primary sulphates.	As for Mt Isa.	Not known.	Py.	MIM 1995 Annual Rpt.
Hilton	7 stacked ore lenses; approx. 120 Mt @ 10.2% Zn, 5.5% Pb, 100 g/t Ag.	As for Mt Isa, but with higher grade and more Cu-rich fault-related ore.	As for Mt Isa.	As for Mt Isa, but locally more structurally complex.	As for Mt Isa, but locally more structurally complex.	As for Mt Isa.	As for Mt Isa.	Upper o/s most Cu-rich; (Cu-Pb)-Zn moving up-dip.	Sideritic siltstone.	Valenta 1994, Mathias et al. 1973, Forrestal 1990.
Mount Novit	Single py lens up to ~20 m thick; strike length 5 km; no calculated resource, several intersections of >10% Zn+Pb.	Stratiform/stratobound (massive) coarse py, po, mt ± sp, g.	(Lower) Mt Isa Gp-Moondarra Siltstone; dolomitic, pelitic schists.	Probably 1660-1650; i.e. slightly older than Urquhart Shale.	Greenschist/amphibolite transition; D1-D3, but complex due to faulting.	Not known.	As for Mt Isa.	Not known.	Siderite in mineralisation	Russell 1978, MIM unpublished data.
Dugald River	40 m thick lode; 38 Mt @ 13.2% Zn, 2.1% Pb, 32 g/t Ag.	Stratobound py, sp, po, g, tr, ch, pyrrhotite, arsenopy, tetrahedrite; mostly recrystallised, but some rare primary textures.	Dugald River Slates (Shear Zone); black, f.g. carbonaceous slates; stratigraphic position not well constrained.	Uncertain, but probably older than Mt Isa Group.	Greenschist-amphibolite transition; D1-D3, refolded isoclinal folds with mineralised sequence overturned; Mt Isa mineralisation has mylonitic contacts.	Corella Fm in stratigraphic footwall is scapolite-rich; pseudomorphs after ?shortite from the mineralised sequence.	(?Post-D3) homatisation of Corella Fm in the stratigraphic footwall.	(Cu-Pb)-Zn & S isotopes.	K, Li, Rb, TI, Pb, Sr, Ag, & Sr enrichment enhancement in hanging wall & footwall.	Newbery et al. 1993, Dixon & Davidson 1996, Muir 1983.

ba, barite; ch, chalcopyrite; g, galena; ex, gypsum; he, hematite; mt, magnetite; po, pyrrhotite; py, pyrite; si, silica; sp, sphalerite; TOC, total organic carbon; tr, trace.

'epigenetic' proposed by Tourtelot & Vine 1976).

Nevertheless, the timing of formation of base-metal sulphides was broadly 'syn-sedimentary' (i.e. early to late sedimentary diagenesis before lithification and porosity occlusion). Detailed textural and structural studies by Hinman (1995, 1996) demonstrated that the bulk of base-metal mineralisation was present in the sequence before consolidation of the Barney Creek Formation muds, and he favours a replacement process occurring at a shallow depth below the basin floor to account for the base-metal sulphide and pyrite textural relationships. Recent reinterpretation of these textures by Large et al. (1996) as a 'layer by layer' paragenesis suggests individual base-metal sulphide-rich bands formed at the sediment-water interface, hence, mineralisation may again be termed 'syngenetic-exhalative'.

The Lady Loretta deposit is hosted by sediments deposited in a shallow to emergent restricted (lagoonal?) setting (Dunster 1996) and mineralisation probably formed both in the water column and in the shallow sediment subsurface by replacement and porosity infilling (McGoldrick et al. 1996). Sulphur isotope data (Carr & Smith 1977) suggest that large amounts of reduced S were generated by biogenic and/or thermochemical sulphate reduction processes associated with oxidation of reactive carbonaceous matter. High organic C contents preserved in fine-grained host rocks to the Lady Loretta deposit suggest a sedimentary-diagenetic environment rich in reactive carbonaceous matter.

By contrast, at the Century deposit, Broadbent et al. (1996) have described metal zoning, distinctive ore textures, and an intimate association of base-metal sulphides with degraded hydrocarbons, which, they argue, indicate that mineralisation formed in the deep subsurface during late diagenesis, owing to the interaction of separate sulphate- and base-metal-bearing fluids. The hydrocarbons were thought to have been generated in situ from organic matter deposited with the siltstones, and the mineralisation event coincided with the onset of basin inversion.

Neudert (1983, 1984) argued on sedimentological and textural grounds that the Mount Isa Zn-Pb-Ag ores formed below the sediment-water interface after early diagenesis of the Urquhart Shale. Evidence presented included the observation that siltstones with early carbonate cements are unmineralised, and base-metal sulphides occur preferentially in coarser grained, current-deposited beds.

A radically different genetic model for Mount Isa Zn-Pb lodes extends Perkins' (1984) syntectonic model for the Mount Isa Cu deposits (Waring et al. 1998) to include the Zn-Pb-Ag ores. Perkins (1990, 1995), Laing (1990) and Myers et al. (1996) have argued that the Zn-Pb-Ag deposits formed after the major D_2 upright folding of the Mount Isa Group, during the same fault-controlled metasomatic event(s) responsible for forming the 'silica-dolomite' hosts to the Cu mineralisation. The Mount Isa Cu and Zn-Pb-Ag lodes in their model are structurally controlled, cogenetic, syntectonic, zoned hydrothermal replacement deposits. If this interpretation is correct, then 'Mount Isa style' Zn-Pb-Ag mineralisation is a distinct deposit type and should not be grouped with the other Carpentaria Zinc Belt stratiform deposits.

This model has yet to gain wide acceptance and the abundant similarities between the deposits described here support a common, syn-sedimentation to late diagenetic origin for all the deposits, rather than a separate genesis for Mount Isa, Hilton, and George Fisher. Additional independent evidence for a common genetic process for all the 'Carpentaria Zinc Belt' deposits comes from Pb isotope data, which indicate that the Pb in each major deposit has a model age very similar to the depositional age of the host sequence (Page et al. 1994). Hence, Pb mineralisation at Mount Isa is unlikely to have formed during D_2 , which occurred several tens of millions of years after sedimentation.

Chemical constraints on ore genesis

Metal transport

New thermodynamic modelling indicates that several types of near-surface saline hydrothermal fluids can carry sufficient base metals to form large orebodies if they are focussed into a suitable trap site (D.R. Cooke, CODES, pers. comm. 1994). Hot ($>>250^\circ\text{C}$) fluids can carry Fe, base metals and reduced S together in solution. Cool fluids, however, must be quite acid to carry metals and reduced S together. Oxidised, near-neutral, high-salinity fluids can carry large quantities of base metals, even at quite low temperatures ($<<150^\circ\text{C}$), but, by definition, cannot carry reduced S.

Apart from recent work at Walford Creek (Rohrlach et al. 1996), fluid-inclusion studies of these deposits have not provided direct evidence of the physico-chemical character of the hydrothermal fluids responsible for base-metal transport. At Walford Creek, fluids at $150\text{--}180^\circ\text{C}$ precipitated sphalerite and galena in primary porosity inside syn-diagenetic pyrite mounds (Rohrlach et al. 1996).

Several lines of indirect evidence suggest that hot reduced fluids were not responsible for base-metal transport in these deposits. These include:

- the very low Cu tenor of the Zn-Pb ores;
- the lack of well-developed Cu-rich feeder zones; although minor chalcopyrite is associated with the ores;
- the lack of indication that boiling occurred in deposits hosted by shallow-water sediments;
- the extremely low Au tenor of these deposits (McGoldrick et al. 1996).

Nor is it likely that acid fluids could survive transport through the carbonate-rich sedimentary substrate without being neutralised. In basins hosting the Australian deposits, cool, relatively oxidised, near neutral, saline fluids would be common connate brines, and are the favoured fluids for transporting base metals (and possible S as sulphate) to the site of mineralisation in these deposits (McGoldrick & Keays 1990).

Sulphur source(s) and base-metal sulphide precipitation

Sulphur isotopes and S/Se ratios indicate that the pyrite and base-metal sulphides in these deposits contain S from a 'seawater' (or evaporitic) S source, and do not contain magmatic S (Stanton 1972, McGoldrick 1986). Pyrite $\delta^{34}\text{S}$ values are heavy and variable, suggesting biogenic sulphate reduction under closed-system or partly closed-system conditions (e.g. Lady Loretta; Carr & Smith 1977). At temperatures over about 80°C thermochemical reduction of sulphate is a viable alternative to biogenic reduction and Painter et al. (1996) have advocated this mechanism for sulphide in fine-grained pyrite at Mount Isa. Base-metal sulphide S isotope signatures are similar to, and overlap, the pyrite values, but are usually more tightly clustered and suggest additional S may have been introduced with the mineralising fluid (Painter et al. 1996, Large et al. 1996). The wide range in calculated temperatures from sphalerite-galena pairs indicates isotopic disequilibrium for the mineralisation, consistent with a low-temperature ($<200^\circ\text{C}$) mineralising process.

Current genetic model

The general ingredients needed to form a stratiform sediment-hosted Zn-Pb-Ag deposit are a base-metal transporting fluid (relatively oxidised, near-neutral basinal brines), and a fluid drive which focusses this fluid into a sedimentary environment conducive to biogenic or thermochemical sulphate reduction. Base-metal sulphide precipitation occurs in response to redox changes. Cooling or mixing with less-saline fluids will not promote base-metal sulphide precipitation (D.R. Cooke, CODES, pers. comm. 1994).

The variety in sedimentary settings inferred from host-rock facies reflects the diversity of organic matter-rich sedimentary facies (e.g. shallow lagoonal carbonates at Lady Loretta, deeper water clastic carbonates at HYC, open shelf marine siliciclastics for Century). The timing of introduction of metal-carrying fluids into these settings can vary from syn-sedimentation (e.g. syn-genetic-exhalative mineralisation at HYC and Lady Loretta), to syn-diagenesis (e.g. parts of Lady Loretta formed in the shallow sediment subsurface; Mount Isa Zn–Pb–Ag ores may have formed at quite some depth in the subsurface, after significant compaction and cementation), to syn-early basin inversion (e.g. Century mineralisation). Fluid drive and focussing mechanisms are not well understood, but the association of some deposits with major structures suggests that pre-existing structural grain is an important control on fluid movement. Seismic effects may cause intermittent high flow rates (e.g. Large et al. 1996). Deep convective circulation, which would involve fluid interaction with older basement rocks, is favoured by some workers (e.g. Solomon & Heinrich 1992), but topographically driven flow in shallow aquifers may be a viable alternative (e.g. Garven 1995).

Key exploration tools

Because of the diversity shown by these deposits, there is no single set of exploration techniques that can be used in the search for new deposits. At the basin scale, understanding the structural architecture (past and present) and the distribution of organic-rich sedimentary facies can help to define areas of interest. Remote field geophysical data will elucidate basin structures and distribution of other rock types hidden beneath the sedimentary cover.

At the prospect scale, geological mapping of structures and sedimentary facies is important. Airborne and ground EM surveys may be used to locate pyritic and/or carbonaceous facies in the subsurface. Surface geochemical surveys and gossan studies give useful information, but spurious anomalies and broad Zn dispersions can make interpretation difficult (e.g. Broadbent 1995). Detailed gravity surveys (e.g. Duffett 1996) can reveal the presence of high-grade Zn–Pb mineralisation at depths of several hundred metres.

Lithochemical techniques applied to fresh outcrop and drill-core samples can provide vectors to hidden mineralisation (Lambert & Scott 1973, Large & McGoldrick 1997).

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