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**FINAL  
REPORT**

**AMIRA**  
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**Proterozoic Sediment-Hosted  
Base Metal Deposits**

**- P384 -**



CENTRE FOR ORE DEPOSITS AND EXPLORATION STUDIES  
UNIVERSITY OF TASMANIA



Centre for Ore Deposit and Exploration Studies



## PROJECT OUTCOMES REPORT

A summary of the outcomes of the  
three-year AMIRA/ARC research project P384 on  
**Proterozoic sediment-hosted base-metal deposits**

### Research Team

Ross Large — Project Leader  
Peter Mc Goldrick — Deputy Leader, halo studies  
Stuart Bull — sedimentology  
David Cooke — chemical modelling  
Garry Davidson — alkali alteration  
Nathan Duhig — alteration vectors  
Richard Keele — structure  
David Leaman — regional geophysics  
Jamie Rogers — structure

### AMIRA/ARC Project P384 Final Report



UNIVERSITY OF TASMANIA

June 1995

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## Introduction

### Project Objectives: P384

1. To determine the primary geological, geochemical and structural controls on the location and timing of base metal deposits in sedimentary basins.
2. To understand the chemical and hydrological evolution of metalliferous brines in selected Proterozoic sedimentary basins of Australia.
3. To develop basin metallogenic models and specific ore deposit models that may be used in the exploration for large-tonnage base-metal ore deposits.

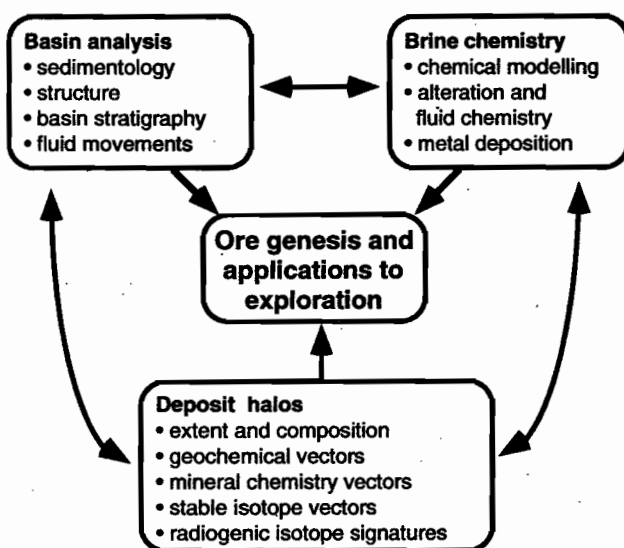
### Research framework

This research project involves a multi-disciplinary approach using regional geological, geophysical and structural studies, brine chemical modelling and geochemical and isotopic halo studies to provide a foundation on which to build a network of exploration criteria and ore deposit models for major sediment-hosted base metal deposits.

The project consists of three research modules as outlined in the figure.

### This report

This report summarises the achievements of the AMIRA/ARC Collaborative Project P384 on Proterozoic sediment-hosted base-metal deposits. An executive summary of each component of the three research modules is presented, with reference to previous reports which provide details for follow-up. This is followed by a listing of summaries of all individual papers in the eight reports from November 1992 to June 1995.



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Ross Large  
Director

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## Module 1: Basin architecture

### Regional geophysics

Regional geophysical data accumulated by AGSO (BMR) have been used to generate a preliminary interpretation of primary structure in the McArthur Basin. This work represents the first large scale quantified analysis of the entire basin sequence. The interpretation has evolved from an initial study of the "Batten Trough" region (Report 1: 1-34). The quantitative modelling techniques employed were based on long experience in the region and recognition that potential field treatments could be made reliable and consistent (Criteria paper, Report 2: 49-64). Primary basin research also suggested that magnetic sources within a basin section could be distinguished from basement variations — the normal presumption for simple (standard) interpretation of such data (Volcanic piles, Report 7, appendix).

The initial Batten region work shattered many of the presumptions of previous workers to suggest that significant Isa Orogen type sequences may exist in the Basin. The former are well known and include very thick volcanic sequences. This work suggested that the Batten Trough was not a true trough, simply an illusion generated by persistent uplift of a basement core displaying onlapped sequences and better local exposure as a consequence. This view implied that major sequences were not exposed but were concealed in covered rift basins up to 20 km thick/deep. The possibility that different styles and compositions of cover mineralisation were related to rejuvenated ancient structures was first mooted in this context.

Instead of detailing the Batten region interpretation, as originally proposed, the primary evaluation was extended across the entire southern

half of the McArthur Basin in order to confirm the initial view, define gross structural relationships, and assess the basin form since the structure was clearly larger than previously assumed.

The "Batten Trough" analysis was first extended south towards Wallhallow (Report 2: 15-26). Some additional maps were provided for the Bauhinia Downs region (Report 2: 1-14) after it was realised that isopach maps of interpreted intervals offered considerable information on the evolution of the basal sequences. Subsequent work considered the supposed "shelves" for the Batten Trough, as defined in the literature, to show that prior to the McArthur Group these regions were not fundamentally different - only less actively structured throughout their post rift stage history (Wearyan shelf, Murphy Inlier, Report 2: 65-100); Bauhinia Shelf, Report 4: 1-16).

The confirmation of large volcanic sequences led to discussion of possible correlation with the Isa region (e.g. Report 2: 101-114). Possible ties of interpreted horizon positions to the limited reflection seismic data available near the central McArthur Basin were also discussed in Report 2: 1-14. Reflection events could be crudely interpolated into the potential field interpretation.

The possible relationships between the McArthur Basin and the Isa Basin led to a linking interpretation, and revision of the earlier Murphy Inlier interpretation. This has shown that the two zones do possess similar structural and content styles and that this entire view can be linked to credible seismic data (in the Lawn Hill region) to show that the deep elements are thinned and have onlapped the Inlier as predicted. (Report 7: 1-36).

While the findings and interpretation can be considered generally valid in style and form the



evolutionary nature of the work, the findings and the implications now require a complete reworking for a proper integration and development. This has not been possible within the schedules and budgets of this project but a preliminary integration has been attempted (Final Report: 1–36) which allows an evolutionary view of the basin and its contents. This suggests a cell-like early rift phase — including very thick felsic and mafic volcanic piles, major uplifts and considerable localised erosion — to a relatively thin cover phase including the Tawallah Group and the McArthur Group.

The preliminary integration also provides some definition of the principal basement and basin structures, as well as zones of activity during basin evolution. Since the analysis covers a large area, including the HYC and Century deposits, it is possible to compare structures, patterns and igneous relationships with other work at Hilton and Mount Isa itself and so suggest a number of factors which might control selection of mineralised sites in crustal or structural terms (Final Report: 25–36). Any review of site controls is clearly at an early stage but sufficient has now been learnt about the architecture of the region to suggest that it may be possible to discriminate critical zones and so focus exploration activity. The ramifications of any possible correlations between the McArthur Basin and the materials and history of the Isa Basin, including discussion of supporting structural and stratigraphic evidence is discussed in a joint report (with R.A. Keele, Final Report: 37–60).

The current view of the architecture of the McArthur Basin is preliminary but probably adequate for a worthwhile assessment of likely heat flow patterns, hydrology and fluid flow regimes — including consideration of different fluid source or brine volumes, within the basin. As such, the interpretation represents fundamental and essential background information which must be fully developed and incorporated into concepts of chemical evolution and mineral deposition.

**Research Contact: David Leaman**

## Structure and basin analysis — McArthur Basin

### Introduction

From the outset, it was agreed that a 'bottom up' approach would be the most appropriate course of action to follow when analysing basin structures, since (a) some of the best structures (and exposures) in the southern McArthur Basin are to be found in the Tawallah Group and (b) access to the mineralised structures of the McArthur Group was limited. It was argued that if the initial, pre-mineralised rift could be adequately defined, then it would be a simple matter to fit the structures of the McArthur Group 'sag' phase into this framework. Understanding the pattern of basin fluid flow *prior* to deposition of the rocks hosting mineralisation was considered essential for predicting fluid charge zones and their sites of subsequent discharge, via basinal faults. The structural work has satisfied the original aims of the project by establishing: (1) a deformation hierarchy (2) the existence of a number of generations of basinal faults, from syn-depositional through to late-stage uplift, (3) the persistent reactivation of some faults over others and (4) the relative timings of the various movements on some 1st order faults. In particular, the integration of geophysical and structural data in the Batten Fault Zone has enabled the nature and true extent of the Tawallah Rift to be determined.

### Deformation hierarchy

D<sub>1</sub> is an E–W compression that caused uplift prior to deposition of the Wunnumantyal Sandstone, principally in the region of the Tawallah Fault (Mid-Tawallah Inversion, Report No. 4: 24). D<sub>2</sub> is a NW–SE compression that set up sinistral strike slip movements along N-trending faults and is equivalent to the Batten Subgroup inversion of M. Hinman. D<sub>3</sub> is the post-Roper NE–SW compression related to folding and dextral strike slip movements across the whole basin (Final Report: 79–111).

### Tawallah Rift

Studies on uplift in the Northwest Batten Fault Zone have indicated that the Urapunga Ridge formed the shoulders to a 200 x 150 km rift that was initiated

during Yiyintyi times (Final Report: 118, Fig. 3). From a restricted graben lying between the Four Archers and Tawallah Faults, this rift spread rapidly to encompass a broad region of 50–100 km linear volcanic 'troughs' by late-Tawallah times: the way these two faults are linked suggests a sinistral wrench component to this extension. The broad outline of the rift, which is principally defined by fault activity rather than volcanic thicknesses, indicates: (1) the HYC Pb/Zn  $\pm$  Cu mineralisation lies towards its eastern margin (2) copper occurrences lie along its southern margin (e.g. Kilgour Cu).

An important conclusion of this study concerns the nature of uplift during the Tawallah in the Northwest Batten Fault Zone (Report No. 4: 70–72; Final Report: 54). This uplift accompanied rifting and was due to vertical, isostatically-controlled, movements on the major faults from mid-Tawallah times onwards. In detail the uplift along the north-western margin of the Batten Fault Zone has been shown to have involved a combination of east-side-up movement on the Four Archers Fault during Tawallah times, and W-directed thrusting, during pre- and post-Roper compressions: broad E-W arching also contributed to this uplift, e.g. Scrutton Inlier. The Warrapirrmantila Dome was an unusual 'high stand' feature during Tawallah times that involved a combination of NW–SE and NE–SW extension, the first of which is related to the extension and uplift along the margins of the Yiyintyi rift.

#### Dynamo-thermal events

Detailed studies in the Warrapirrmantila Dome (Final Report: 48) show that haematite breccias  $\pm$  quartz veining were related to: (1) the Tawallah uplift, (2) Batten Subgroup inversion, and (3) post-Roper inversion. Three movements in all were recorded on the Lorella fault, one pre-dating and the others post-dating the Roper Group. The syn-depositional deformation of the Sly Creek Sandstone (Final Report: 49, Fig. 5B) is possibly the first of its kind to be described in the McArthur Basin.

#### Palaeo-stresses

Calculations of stress tensors from fault striations (Final Report: 71, 80–88) give two principal stress fields (and six stress states) for the southern McArthur Basin: these were an early sub N–S compression —

the Umbolooga–Batten inversion recorded at HYC by M. Hinman — and a late ENE–WSW compression equivalent to the Mount Isa Orogeny (i.e. D<sub>3</sub> and D<sub>4</sub>). The essentially pre- and post-Roper age for these stress fields is supported by data from the Four Archers Faults (Final Report: 77). Detailed mapping in the northern Mallapunyah Dome has shown this feature to be a 'pop-out' caused by dextral wrenching and thrusting on the Tawallah and Mallapunyah Faults.

#### Lawn Hill Platform

Early growth faulting has been identified on the eastern margins of the Lawn Hill Platform where preliminary structural work has shown that a NW–SE compression — similar to the early event in the McArthur Basin related to the I<sub>2</sub> palaeo-magnetic inflexion — occurred between the Lady Loretta Formation and Shady Bore Quartzite (Report No. 7: 41, Fig. 1). The implications for mineralisation are fundamental because the Pb/Zn (like HYC) may be related to a major basin-wide inversion.

#### Implications for exploration

The relevance of structure to exploration lies in the role played by faults in helping to focus the discharge of metal-rich brines from the basin. Whether these faults were the actual conduits for the fluids or whether they acted as screens that compartmentalised fluid flow into discrete cells, is a matter of scale and degree. The important discovery is that significant Pb/Zn/Cu mineralisation is located at the margins of the Yiyintyi–Tawallah Rift: for example, HYC occurs within 20–25 km of the margins of a rift that is 150 km across. Any potentially successful targeting programme should, therefore, need to incorporate the following parameters: (1) the outlines of the underlying volcanic rift, (2) all first-order faults that were active during development of this rift. Nominally, the width of influence of the underlying rift would be specified as a 25–30 km wide band in from the margin, although this could be varied according to conditions and circumstances. The HYC deposit would rate a high chance of discovery if these parameters were integrated with the outline and thicknesses of the overlying sag phase carbonates.



## Further work

An extension to the project involves a model for early copper mineralisation in the Lawn Hill/Lady Loretta region in which metalliferous brines are suggested to have been expelled outwards from the centre of the basin towards the Gordon Arch. The shallow-dipping unconformity surface (sub-Torpedo Creek Quartzite) was able to focus escaping brines into a suitable structural trap such as the steep basinward-facing faults located on the northern flank of the uplift, e.g. Mammoth Cu Mines (see "Geology of the sub-Torpedo Creek Quartzite unconformity in the Riversleigh Fold Belt: implications for Cu mineralisation" prepared for the proposed project extension). This model, if further developed, has the advantage of being better able to predict the likely fluid pathways for the nearby Lady Loretta Pb/Zn bodies. Field work has already suggested the following areas as suitable for further structural and sedimentological studies: (1) the Leopard Fault, north of Lady Loretta; (2) the Mount Gordon Fault Zone, particularly where Myally Subgroup is in contact with Surprise Creek; and (3) the Termite Range Fault, near the Fiery Creek and Komarga Domes.

**Research Contact:** Richard Keele

## Structure and sedimentology of the Tawallah Group

The Tawallah Group has the potential to record all of the major structural events that have affected the southern McArthur Basin and in consequence, was the primary target for field based studies in the basin analysis module. Detailed structural mapping was integrated with facies based sedimentological analysis, as sedimentary facies and palaeocurrent patterns will reflect the palaeo-basin architecture and its principle controlling structures. The basal unit of the McArthur Group, the Masterton Sandstone, was included in the sedimentological study because it represents the last regionally extensive and thick clastic unit (?aquifer) to be deposited prior to the mineralised McArthur Group carbonates. Detailed structural studies involved the reconstruction of palaeostress orientations using fault-slip data in the

Batten, Scrutton and Tawallah Ranges. This analysis suggests a southern McArthur Basin structural hierarchy comprising three main tectonic phases.

Brittle structures developed during E-W horizontal compression are attributed to the initial tectonic event recognised in the region ( $D_1$ ; previously referred to as the Mid-Tawallah Inversion; J. Rogers, Report 4: 17-31; S. Bull, Report 4: 33-53). The  $D_1$  fault pattern is developed only in pre-Wununmantlyala Sandstone stratigraphy exposed in the Batten Range. Substantial regional uplift associated with  $D_1$  is reflected in the presence of basement-derived (Scrutton Volcanic) clasts in coarse-grained Wununmantlyala Sandstone deposits, and is responsible for the abrupt change from subaqueous (Aquarium Formation) to subaerial (alluvial/fluvial; Wununmantlyala Sandstone) depositional environments. Provenance data indicates that the Wununmantlyala Sandstone was predominantly derived from erosion of the lower Tawallah Group cores of the Batten and Tawallah Ranges. In combination with palaeocurrent measurements (which are consistently directed away from the lower Tawallah Group range cores; S. Bull, Report 4: 33-53), this indicates that  $D_1$  uplift occurred along the western margin of a N-S-trending Tawallah Fault. Similar palaeocurrent and provenance patterns occur in the overlying Masterton Sandstone, suggesting that elevation persisted in this area until at least lower McArthur Group times.

The second tectonic event recognised in the southern McArthur Basin ( $D_2$ ) is a NW-SE compression. Secondary Fault geometries associated with  $D_2$  are best developed in the Batten and Tawallah Ranges where left-lateral strike-slip displacement on the Lorella and Tawallah Faults clearly post-dates Tawallah group deposition.  $D_2$  is correlated with the NW-SE transpressional event documented at HYC by Hinman et al. (1994), which resulted in uplift of the Western Fault Block to source the talus breccia lithofacies of the upper Barney Creek Formation.

The primary structural elements of the present day southern McArthur Basin geometry developed during a NE-SW horizontal compression that post-dated Roper Group deposition ( $D_3$ ). The characteristics of the  $D_3$  event are dextral strike-slip deformation adjacent to NNW- to N-trending primary structures (Tawallah and Lorella Faults) and horizontal shortening above major NW-trending

faults (Bauhinia Fault). A fluid inclusion study was carried out for barren hydrothermal mineralisation in D<sub>3</sub> hydraulic fault breccia samples (J. Rogers, Report 5: 65–86). Results indicate that the Tawallah Fault and associated secondary structures had seen moderate to high temperature (160°–210°C), saline (8–13 eq wt.% NaCl) and oxidising fluids. Fluids of this type have excellent potential for base metal transport (D. Cooke, Report 4: 111–129).

The results of integrated structural and sedimentological studies of the Tawallah and lower McArthur Groups have several major implications for exploration strategies and mineralisation models for the McArthur Basin:

The D<sub>1</sub> basin inversion event provided the regional structural framework and resultant facies architecture that would have controlled basin-scale fluid flow in the clastic aquifers for much of the basin history. Since the topography generated in D<sub>1</sub> persisted into McArthur Group times, it had the potential for ongoing control on local fault and sediment facies geometries. These geometries will ultimately control aquifer and “trap” unit patterns in the overlying mineralised carbonate succession.

The relative timing of NW–SE compression, during deposition of the Barney Creek Formation implies that the kinematic characteristics of the D<sub>2</sub> event are important considerations in any exploration model for HYC-type sub-basins. The development of WNW- to NW-trending growth faults are a distinct possibility, and an intersection of these with major N–S structures, as at HYC (Hinman et al., 1994), would represent highly a prospective target for thick Barney Creek Formation successions and associated base metal mineralisation.

The recognition of potential ore-forming fluids in D<sub>3</sub> structures suggests the possibility for epigenetic mineralisation to occur throughout the entire basin stratigraphy, particularly where these fluids could interact with reduced (graphite or pyrite bearing) “trap” sediments.

**Research Contacts: Jamie Rogers and Stuart Bull**

## **Sedimentology of the Barney Creek Formation and adjacent units**

The Barney Creek Formation is a dolomitic siltstone-dominated succession which hosts the HYC and associated mineralisation in the McArthur River area. It has been the focus of sporadic sedimentological studies since the early 1960s, some of which have incorporated regional sections, and others which have been focused on the unit close to the mineralisation. Overall, two contrasting depositional models have evolved, one invoking sub-wave base accumulation in a relatively large water body, and the other lacustrine sabkha deposition. Other studies have proposed a combination of these two end member depositional models. Contrasting models have also been proposed for the architecture of the basin system in which the Barney Creek Formation accumulated, with different orientations proposed for the controlling syn-sedimentary structures.

As a result of these disparate models for economically important Barney Creek Formation, the rationale behind this study was two-fold. Firstly to undertake a detailed sedimentary facies based examination of a well preserved, open file drill core intersection. The aim was to determine a well constrained depositional model for the unit at one locality which would be used to investigate the sedimentary controls on selected geochemical parameters. A second aspect of this study involved the examination of intersections through the unit in a widely spaced network of sections from within the central Batten Fault Zone, to determine the validity of extending the depositional model regionally. Facies and thickness patterns within this section network would also be used, in combination with the regional depositional model, to test previously proposed configurations for the basin architecture of the system.

The Barney Creek Formation intersection chosen for detailed study was DDH BMR McArthur 2 stored at the AGSO core shed in Canberra. In addition to being well preserved and ideal for sedimentological logging, analysis of open file geochemical data indicated that although the hole was collared 23 km SW of the McArthur River Mine, it was within the outer extremity of the halo associated with the HYC mineralisation (R. Large & P. McGoldrick, Report 3: 63–126). As a result, facies based sedimentological



logging was carried out in conjunction with further geochemical sampling for detailed studies of the deposit halo. A summary of the major results of the sedimentological aspects of this study (S. Bull, Report 7: 97–114; S Bull, Final Report: 133–158; S. Bull & R. Large, Final Report: 159–182) are as follows:

- The intersection in DDH BMR McArthur 2 comprises the Barney Creek Formation (W-Fold Shale and HYC Pyritic Shale Members) overlain, with a gradational transition, by the Reward Dolomite. The succession can be considered in terms of four facies, all of which were deposited entirely within a quiet, reduced sub-wave base environment. There is no direct relationship between the two dominant sedimentary facies present and the alteration index, although organic carbon-rich samples generally give relatively high  $AI_3$  values.
- Reconnaissance examination of a network of sections through the Barney Creek Formation, suggests that this depositional model can be applied throughout the central Batten Fault Zone, with the possible exception of the McArthur River area in the immediate vicinity of the HYC mineralisation. However, mass flow units of intraclastic dolomitic sandstone in the upper part of the Barney Creek Formation intersection in DDH BMR McArthur 2 clearly indicate the presence of a co-existing agitated shoreline environment. Similar deposits have been described locally in the overlying Reward Dolomite, suggesting that this unit may represent the shoreline facies at some localities and is, therefore, at least partially time equivalent to the Barney Creek Formation.
- The restriction of key facies to discrete stratigraphic levels within the DDH BMR McArthur 2 intersection, allows the succession to be subdivided into five sections which reflect subtle variations in palaeoenvironmental conditions, chiefly water depth, during deposition. Two of these sections within the Barney Creek Formation (at around the base and top of the HYC Pyritic Shale Member and its equivalents) are interpreted to represent periods of water depth maxima. These key “deep water” facies can be recognised in the majority of intersections in the section network, suggesting that the Barney Creek Formation depositional system was linked throughout the central Batten

Fault Zone. Within this extensive depositional system, there is no progressive change in thickness and/or facies association in the HYC Pyritic Shale Member and equivalents, westward from the anomalously thick accumulation in the McArthur River area. This distribution is consistent with models for the structural architecture which propose that the syn-sedimentary faults trended E–W, but does not provide active evidence supporting this proposal.

**Research Contact: Stuart Bull**

## Module 2: Brine chemistry

### Fluid chemistry and alteration

Research in the brine chemistry module of AMIRA/ARC project p384 has focussed on three main topics:

- (i) Numerical simulations of transport and depositional processes from high and moderate temperature saline brines.
- (ii) Field- and laboratory-based studies of hydrothermal alteration in the Settlement Creek Volcanics (Report 6: 13–27, 29–31; Final Report: 183–226).
- (iii) Theoretical investigations of fluid-mineral equilibria relationships to determine likely mineralising solution compositions and conditions favourable for siderite formation (Report 5: 55–64; Report 7: 149–158; Final Report: 345–370).

Initial research concentrated on numerical simulations of hypothetical brine compositions. These calculations revealed that at 250°C, significant base metal transport can occur in oxidised, and acidic, reduced 10 eq. wt. % brines (Report 4: 111–130). At 150°C, oxidised 10 wt % solutions were still capable of carrying significant metals in solution, but reduced fluids could only transport Pb and Zn at low pH values. The calculations showed that hematitic sandstones provide excellent aquifers for oxidised metalliferous brines, and that potassic and/or propylitic assemblages will form when brines interact with mafic volcanics. In the trap environment, the simulations showed that mixing of metalliferous brines with anoxic seawater is an excellent mechanism for producing Zn-Pb-rich massive sulfide mineralisation. Mixing of the same brines with oxidised seawater produces siliceous Cu-Ag-rich exhalites. Interaction of reduced, acidic brines with pyritic dolomitic sediments results in the precipitation of

simple Zn-Pb-rich sulfide mineralisation. More complex silicates are produced together with the base metal sulfides when the replacement process involves oxidised brines.

Field and follow-up laboratory studies of regional-scale potassic alteration in the McArthur Basin was conducted to provide constraints for the numerical simulations. This work documented evidence for the leaching of major and trace elements and base metals from dolerites of the Upper Tawallah Group by basinal brines. Geochemical studies demonstrated that the brines were low temperature (100°C), oxidised, saline, hydrocarbon-bearing and derived from a meteoric and/or seawater source. The fluids responsible for potassic alteration essentially stripped the base metals out of the volcanic pile. The resultant metalliferous brines could have transported base metals significant distances from the site of leaching, provided they passed along a suitable regional aquifer. This work confirmed the presence of oxidised metalliferous brines in the stratigraphy under HYC.

Recognition of siderite and ankerite alteration halos in the deposit halo studies of Large and McGoldrick led to fluid-mineral equilibria calculations to establish what conditions are favourable for the formation of siderite in stratiform sediment-hosted Pb-Zn environments. This work showed that siderite will form from low temperature oxidised fluids when Fe/Mg, Fe/Ca ratios and/or  $\text{CO}_2$  (aq) concentrations are high. This modelling led to the development of a preliminary chemical model for two classes of sediment-hosted Pb-Zn deposits: McArthur-type, which form in oxidised carbonate-evaporite rift basins; and Selwyn-type, which occur in reduced, turbidite-dominated siliciclastic basins (Final Report: 345–370).



With regards to exploration implications, the numerical simulations demonstrated that the barren massive quartz-hematite veins that occur throughout the Tawallah Group could have formed from metal-rich brines, with the metals only precipitating if a reduced lithology or fluid was encountered during cross-stratal fluid flow. This opens up the possibility for epigenetic-style base metal mineralisation throughout the McArthur Basin, and syngenetic mineralisation wherever the appropriate sedimentary environment coincided with expulsion of brines by fault movements. The potassic alteration study highlighted the potential for proximal Redbank-style breccia-hosted Cu around Mallapunyah Dome, and recognised that Pb-Zn mineralisation probably lies distal to the altered volcanics. The calculations of siderite stability and general fluid-mineral equilibria led to the development of exploration models for McArthur-type and Selwyn-type deposits, recognising that the trap environments for reduced metalliferous brines in siliciclastic basins should differ from those necessary for base metal deposition from oxidised brines in carbonate-evaporite basins.

The brine chemistry module has begun to define the chemical conditions necessary for base metal transport and deposition in a variety of sedimentary basins. In the project extension, this work will continue by presenting refined numerical simulations based on the final results of the initial project. More specific modelling needs to be done at Lady Loretta to establish likely fluid compositions and chemical processes in the trap environment. More research on regional brine migration is required to establish the chemical nature of brines in the sandstone- and carbonate-dominated parts of the McArthur and Lawn Hill Platform sequence. The siderite modelling will be continued by incorporation of Cu, Fe and Mn solubility studies. This will provide the framework for establishing unified chemical models for the origins of base metal mineralisation in sedimentary basins. The project extension will conclude with further numerical simulations, which will generate new exploration targets for base metal mineralisation using the results from 5–6 years of detailed structural, sedimentological and geochemical investigations.

**Research Contact: David Cooke**

## **Alkali metasomatism of volcanoclastic and clastic rocks in the McArthur Group, with emphasis on the HYC Zn–Pb deposit**

A detailed study of alteration in tuffaceous units within the McArthur Group provides significant information on episodes of alkali metasomatism in the McArthur Basin (Final Report: 227–272). In the McArthur Group of the McArthur Basin, feldspathised beds are common in both carbonate- and shale-dominated units, and larger scale K-metasomatism is identified by the aeroradiometric response of some units, specifically the Stretton Sandstone, and the Lynnott, Barney Creek and Tooganinie Formations. Most massive feldspathised beds have Ti/Zr distinct from their host sediments, are laterally extensive, contain euhedral zircons and resorbed phenocrysts, and in places preserve vitriclast fabrics. These are identified as original volcanoclastic beds, divided into primary airfall and slump-redisminated varieties. Alkali metasomatism around some volcanoclastic beds extends into the adjacent sediment, in places altering significant thicknesses of clastic beds that are associated with evaporitic successions. Petrography, XRD and whole rock  $\text{SiO}_2/\text{SiO}_2+\text{Al}_2\text{O}_3$  of 0.75–0.94 indicate that quartz, microcline, albite, calcite, dolomite, ankerite  $\pm$  illite are the dominant metasomatic phases in the volcanoclastic rocks. Microcline–quartz  $\pm$  calcite is the prevailing assemblage in the central McArthur Group, whereas close to bounding structures such as the Emu Fault, albite–quartz also occurs.  $\delta^{18}\text{O}_{\text{wholerock}}$  of HYC volcanoclastic beds has strong linear correlations with  $\text{Al}_2\text{O}_3$ ,  $\text{SiO}_2$  and  $[\text{Na}_2\text{O}+\text{K}_2\text{O}]$ , permitting modelling of the replacement process as equilibrium precipitation of quartz and feldspar from a fluid with  $\delta^{18}\text{O} = -5$  to  $-15\%$ , at  $25 \pm 11^\circ\text{C}$ , implicating a cool, saline, meteoric fluid. The diagenesis of these beds mainly preceded alteration by HYC fluids, and with some exceptions was isotopically unaffected by them.

McArthur Group alkali metasomatism occurred in several phases. Basinward of major faults such as the Emu Fault Zone, gravity driven meteoric-evaporitic brines descended from adjacent shelves and were focussed by the faults into adjacent deeper water clastic successions, forming zoned albite-

microcline assemblages with elevated B contents. HYC ore fluids later added disseminated ankerite, adularia and basemetal sulphides to some feldspathised beds.

A second early diagenetic alkali metasomatism was associated with descending and advecting brines generated within and above porous aeolian and shelf sand bodies. The K-rich brines evolved when seawater was evaporated to gypsum/halite saturation (salinity > 35 wt %) in supratidal to lagoonal settings, as occurs in the Donnegan Member of the Lynott Formation, and the overlying Yalco Formation.

The most aerially extensive K-feldspar metasomatism post-dated early diagenetic albite alteration at Glyde River, but is otherwise unconstrained in time. Widespread vitriclastic fabric destruction suggests that it was preceded by texturally destructive illite, as is common in bentonites, and its mineralogic uniformity indicates that it accompanied basin-wide fluid migration, speculatively during basin inversion (1640–1430 Ma) following the McArthur Group deposition. This hypothesis can only be tested with radiometric dating.

The exploration implications are: (1) The alteration assemblages in the volcanoclastic rocks are mainly not associated with base-metal-bearing fluids. (2) Subtle indicators of base-metal alteration are Pb-Zn and ankerite replacement of more feldspathic beds. (3)  $MnO_D$  has potential as a halo indicator in volcanoclastic beds, sedex AI requires further assessment, whereas Zn content and  $Al_3$  are definitely not useful. These criteria earmark the southern Glyde sub-basin as a particularly base metal prospective succession.

**Research Contact: Garry Davidson**



## Module 3: Deposit haloes

### Geochemical halo to the Lady Loretta deposit

Detailed sampling and analysis of the host sediments to the Lady Loretta deposit in the small syncline area, Lawn Hill Platform, led to the development of a geochemical halo model for the deposit (Report 3: 63–90). This study showed that the Pb-Zn ore lens at Lady Loretta was surrounded by an inner siderite halo and outer dolomite halo (Fig. 1). The siderite halo exhibits enrichment in Zn, Pb, Ba, Fe, Mn, Sr and Tl, and depletion in CaO, MgO and Na<sub>2</sub>O. The outer dolomite halo shows enrichment in Mn and Tl only. Based on the whole rock analyses, a marked increase in MnO content of the dolomite (MnO<sub>D</sub>) was interpreted in the footwall dolomitic sediments approaching the ore zone. Subsequent microprobe studies of the carbonate chemistry at Lady Loretta (Report 7: 69–76) confirmed the high Mn content of the dolomites approaching the ore, and revealed a good correlation between calculated MnO content of dolomite (MnO<sub>D</sub>) using whole-rock analyses, and the microprobe values determined on mineral grains. This study also revealed that dolomites in the zone surrounding the siderite halo varied in iron content from Fe-poor dolomite to ankerite, with an ankerite-bearing zone surrounding the siderite zone (Fig. 1). Carbon and oxygen isotope studies of carbonates in the halo (Final Report: 289–302) revealed that the siderite zone has a distinctly heavy δ<sup>18</sup>O signature, indicating formation from a moderate temperature evolved basinal brine. In contrast, the outer dolomites display isotopic values which suggest equilibration with low temperature meteoric waters.

**Research Contacts: Ross Large, Peter McGoldrick**

### Development of geochemical halo vectors for stratiform Pb-Zn deposits

One of the most exciting outcomes of P384 has been the development of a series of geochemical criteria which allow discrimination of potential host horizons to stratiform Pb-Zn deposits, and which can be used as vectors to target deposit locations. The criteria and vectors were initially developed at Lady Loretta and have been shown to work well at HYC, Mt Isa and Hilton.

Based on the Lady Loretta study (Report 3: 78–87), the following vectors were defined:

Alteration Index =

$$\frac{100[10\text{MnO} + \text{FeO}]}{[\text{MgO} + \text{Na}_2\text{O} + 10\text{MnO} + \text{FeO}]}$$

MnO content of dolomite, MnO<sub>D</sub> =

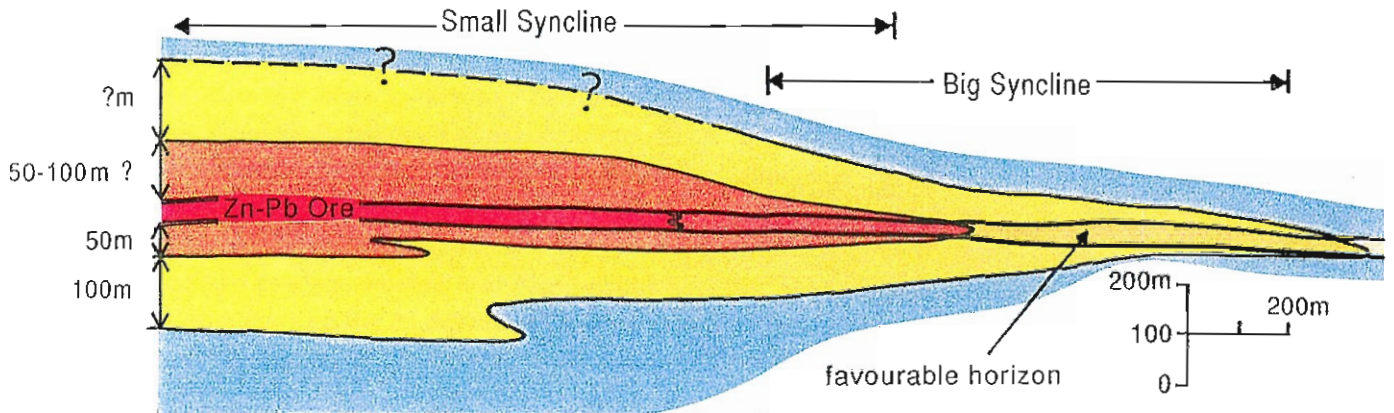
$$\frac{\text{MnO}_{\text{WR}} \times 30.41}{\text{CaO}_{\text{WR}}}$$

MnO content of siderite, MnO<sub>S</sub> =

$$\frac{\text{MnO}_{\text{WR}} \times 62.01}{\text{FeO}_{\text{WR}} - \text{FeO}_{\text{Py}}}$$

AI was shown to increase from 30 to 95 approaching ore both along strike and across strike, and MnO<sub>D</sub> increased from 0.2% to over 1% approaching ore from the footwall side. Zinc and Tl were found to be generally more erratic and needed to be used in conjunction with AI and MnO<sub>D</sub>.

### LADY LORETTA HALO MODEL



	Zn	Pb	dominant Carbonate	Tl	MnO	CaO	Sr	K <sub>2</sub> O
Zn-Pb ore	>5%	>1000ppm	siderite	>50ppm	0.01-0.4%	0-1%	100-1000 ppm	↑ no pattern ↓
Siderite zone	100ppm to 5%	10-1000	siderite	2-50	0.01-1%	0-1%	10-500	
Ankerite halo	20-200ppm	<70	ankerite	2-50	0.01-0.4%	1-30%	<100	
Dolomite background	<50ppm	<30	dolomite	<4	<0.02	1-30%	<100	

### LADY LORETTA HALO MODEL

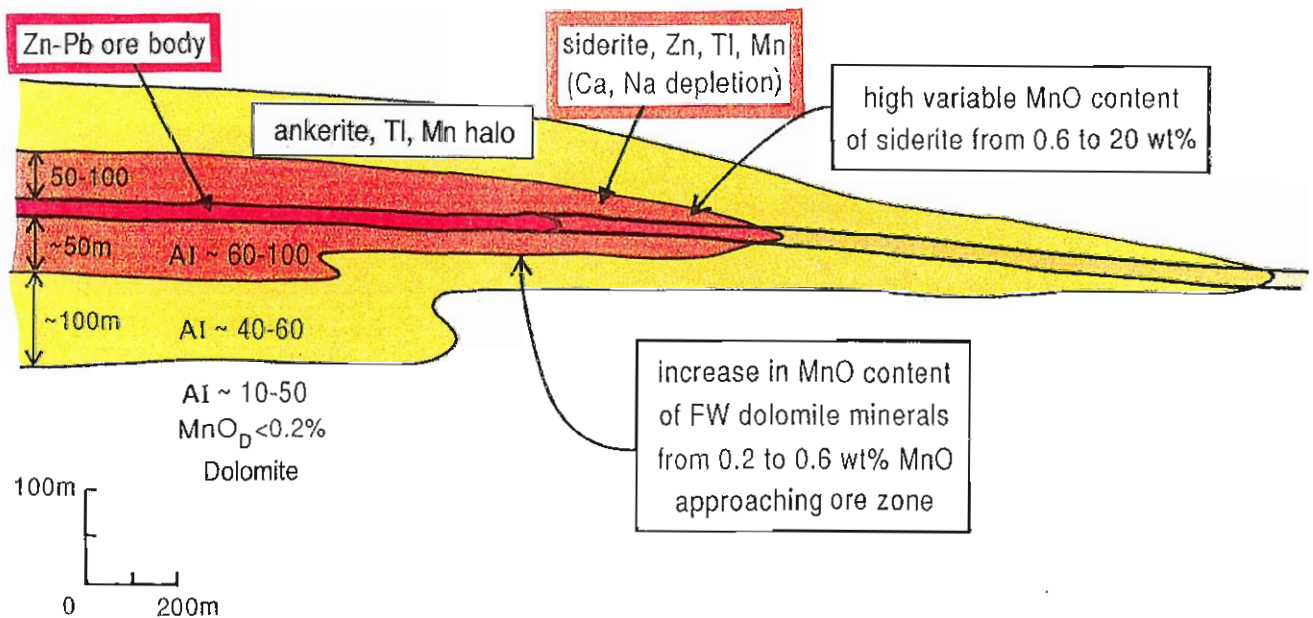


FIG. 1 — Diagrammatic representation of the carbonate halos surrounding the Lady Loretta Deposit (modified from Large & McGoldrick 1993, Duhig 1994).



The key factor in the use of the Alteration Index vector relates to the increase in Fe and Mn in carbonate minerals approaching mineralisation and the concomitant decrease in MgO (and CaO). Approaching the orebody dolomite is replaced by ankerite and in the extreme case (eg. Lady Loretta) by siderite. Secondary factors that cause an increase in AI, are increasing pyrite content of sediments and increases in the shale to dolomite ratio in the sediments.

Subsequent studies showed that Na<sub>2</sub>O could be easily eliminated from the AI definition (Report 5, 1-17) without changing the effectiveness of the vector, thus leading to the development of Sedex AI.

$$\text{Sedex AI} = \frac{100[10\text{MnO} + \text{FeO}]}{[10\text{MnO} + \text{FeO} + \text{MgO}]}$$

A second modification was made to the AI vector by introducing Al<sub>2</sub>O<sub>3</sub> in the denominator (Report 7: 45-68). This was found to be necessary for shale-rich sequences containing low levels of carbonate, which gave anomalous Sedex AI values independent of their relationship to Pb-Zn mineralisation. Consequently a new alteration index was defined:

AI Mark 3, AI<sub>3</sub> =

$$\frac{100[10\text{MnO} + \text{FeO}]}{[10\text{MnO} + \text{FeO} + \text{MgO} + \text{Al}_2\text{O}_3]}$$

AI<sub>3</sub> increases with increasing Fe, Mn content of carbonates and increasing pyrite content of sediments, but is not effected by the shale/dolomite ratio. This vector was found to be very robust for both carbonate-rich and shale-rich sequences, but it is recommended that both Sedex AI and AI<sub>3</sub> be used together with MnO<sub>D</sub> for the most effective results.

A summary of the geochemical criteria used to identify favourable stratiform Pb-Zn horizons, based on our studies is given in the Final Report: 159-182, and shown in Figure 2. This diagram emphasises that no single parameter should be used alone. For example Zn, Pb analyses by themselves may identify mineralisation in sediments, but the exact nature of the mineralisation may not be revealed until after many further drill holes and considerable expenditure. However by utilising a matrix of vectors

— Sedex AI, AI<sub>3</sub>, MnO<sub>D</sub>, Fe+Mn/Mg molar ratio in carbonate, and Tl, it is possible to clearly distinguish the halo of a major stratiform Pb-Zn deposit from Pb-Zn mineralisation of another style. This was demonstrated by the case studies (summarised below) where the halo vectors to the major ore deposits at HYC, Lady Loretta, Mt Isa and Hilton are shown to be similar to one another but are very different from those to the lesser mineralisation at Kamarga and Walford Creek.

The results from this project indicate the potential to apply litho-geochemistry in the search for giant stratiform Pb-Zn-Ag deposits in an analogous way to the use of stratigraphic drilling and source rock studies in oil exploration (Report 3: 78-125; Report 7: 56). The new approach suggested involves a two-stage drilling program.

1. Litho-geochemical stratigraphic drilling (LSD) of discrete sub-basins to determine the presence or absence of potential horizons for giant Pb-Zn-Ag deposits (Fig. 2). One drill-hole through the carbonate-shale facies stratigraphy may be sufficient to test a sub-basin of diameter up to 10-20 km.

If no horizons with anomalous alteration index (Sedex AI and AI<sub>3</sub>), MnO<sub>D</sub> or thallium are identified, then the sub-basin may be considered barren of giant Pb-Zn-Ag deposits.

2. Litho-geochemical Vector Drilling (LVD). If an horizon or horizons with Sedex AI, AI<sub>3</sub> and/or MnO<sub>D</sub> are identified in the first LSD drill-hole, follow-up drilling at 2 km spacings may be used to determine the vector toward ore.

Increasing MnO<sub>D</sub> and AI<sub>3</sub> values, coupled with their relationship to sedimentary facies will provide information on the placement of step-out and in-fill drilling. This exploration approach "takes off the blinkers" in that emphasis is placed on litho-geochemistry rather than the assumed "preferred stratigraphy".

**Research Contacts: Ross Large, Peter McGoldrick**



## Geochemical halo and vectors to the HYC Deposit

Published data on the HYC geochemistry was initially compared with the halo model developed for Lady Loretta (Report 3: 91–126). This comparison revealed remarkable similarity between the Lady Loretta halo and HYC halo. However, the HYC manganese halo was found to be far more extensive (up to 23 km along strike) and siderite was lacking from the district. The geochemical vectors (AI and  $MnO_D$ ) developed at Lady Loretta were found to be directly applicable to HYC. For example,  $MnO_D$  in the footwall sediments increases systematically towards the favourable horizon from a background of 0.5 wt % up to 1–12 wt %  $MnO_D$  over about 50 m.  $AI_3$  increases along strike towards the deposit, over 25 km, from values of 30–40 to 70–100. Factors contributing to the alteration index were studied in a series of mixing models (Report 7: 45–68) which reproduced the trends shown in the HYC ores and wall rocks.

Further sampling and sedimentological studies of DDH BMR 2 and DDH Barney 3 in the McArthur Basin showed a relationship between sedimentary facies and the alteration indices (Report 7: 99–114; Final Report: 159–182) which allowed the formulation of a relationship between sedimentary facies and mineralising events (Final Report: 371–408). Microprobe analyses of carbonates from DDH BMR 2 (Final Report: 283–288) confirmed that the whole-rock calculations of  $MnO_D$  were justified and closely correlate with the microprobe analyses of mineral chemistry. Studies utilising the XPLOR® program enabled the distinction between dolomite and ankerite in the HYC drill holes, and showed the presence of an extensive halo of ankerite-bearing sediment surrounding HYC (Final Report: 273–282). Although the  $MnO_D$ ,  $AI_3$ , ankerite and zinc halos at HYC overlap, they have important spatial and chemical differences which all contribute to the overall halo model and alteration vectors developed for HYC (Fig. 3).

**Research Contact: Ross Large**

## Application of the geochemical alteration vectors to other deposits

Following development and refinement of the stratiform sediment hosted Zn-Pb alteration vectors for Lady Loretta and HYC, test case studies of other northern Australian Zn-Pb deposits were undertaken. The deposits chosen for this work were the Mount Isa and Hilton Zn-Pb-Ag ores and the sub-economic Kamarga and Walford Creek mineralisation.

A case study of the Mount Isa and Hilton deposits was presented in Report 7: 115–140. The data used at Mount Isa were derived from three different 'public domain' sources. Analysis of the data confirm that alteration vectors ('Sedex Alteration Index', 'Alteration Index Mk 3' and ' $MnO_D$ ') provide useful indications of these giant deposits. More specifically, mine sequence samples from Mount Isa indicate that unmineralised inter-ore beds carry strongly anomalous AI and  $MnO_D$  signatures and that thallium is elevated in the Isamine samples. The Hilton deposit has a similar geochemical signature to the Isamine deposits. Using an older, poorer quality, data set reveals that elevated AI and  $MnO_D$  persist for hundreds of metres along strike from economic mineralisation. This study also has important implications for the genesis of the Mount Isa deposits and is good evidence that Mount Isa and Hilton belong to the same class of deposit as HYC and Lady Loretta.

The second case study was the Kamarga strata-bound Zn prospect (Report 5: 41–54; Final Report: 319–332). Two geochemical data sets from this large low-grade Zn resource were used for this study. These were core-grind samples reported in Doug Jones' (1986) PhD, and a new set of grab samples from three diamond drill holes sampled by Jones (one in the main mineralised zone, a second in a fringe mineralisation position and a third distal to the main mineralisation). Both data sets revealed AI and  $MnO_D$  signatures that were quite distinct from the patterns associated with the stratiform deposits at HYC, Lady Loretta and Mount Isa. The Kamarga mineralisation and host rocks are not associated with anomalous AI and  $MnO_D$  trends, and even Zn-rich samples have low values of these indices. Use of these geochemical vectors could have been used to argue for substantial down-grading of the prospect

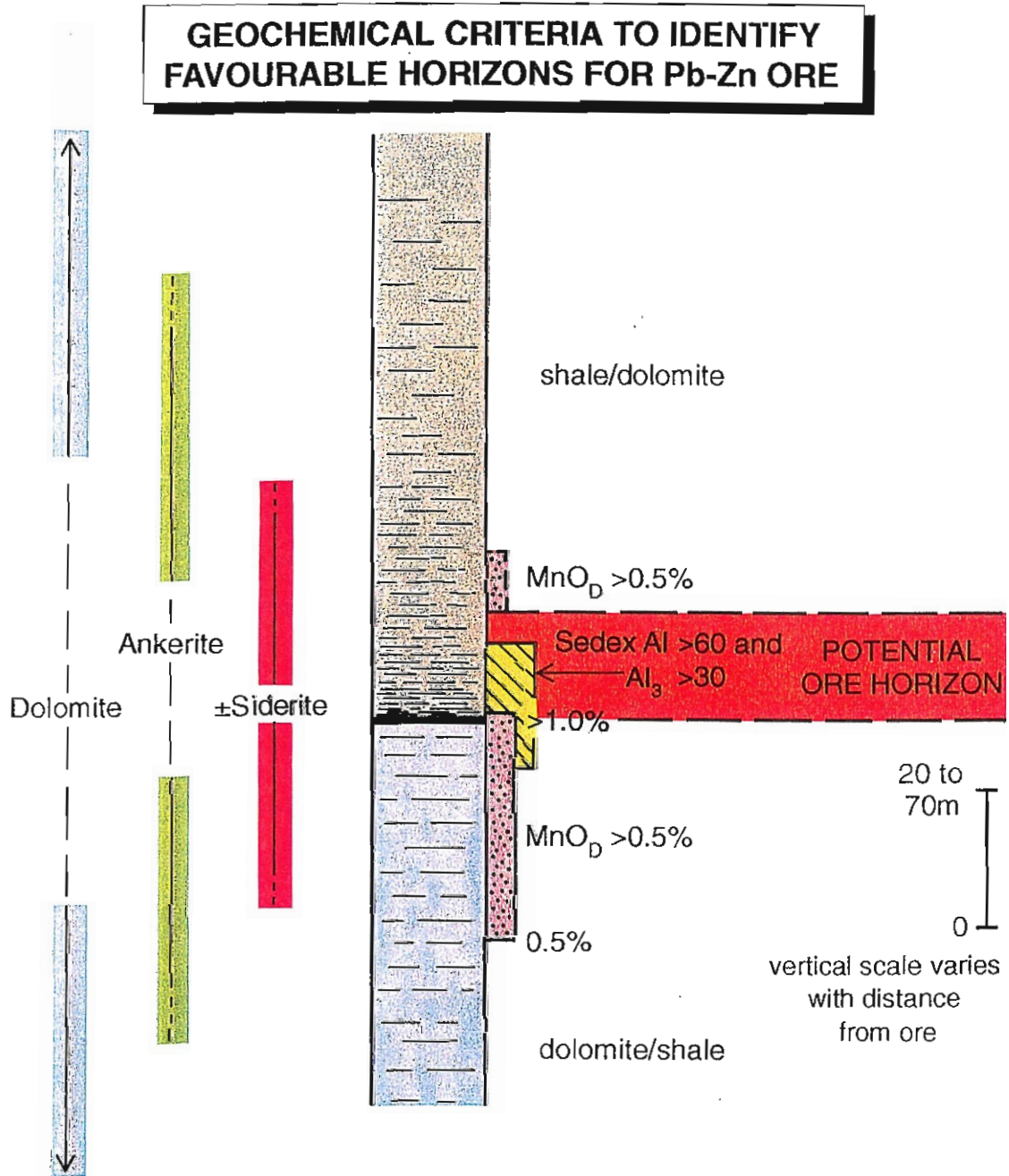


FIG. 2 — Geochemical criteria developed to identify favourable horizons for Pb-Zn ore (from Report 3: 78-126; Report 5: 1-17; Report 7: 45-68; Final Report: 159-182, 273-282). The siderite zone may not be present in all cases (e.g. HYC).



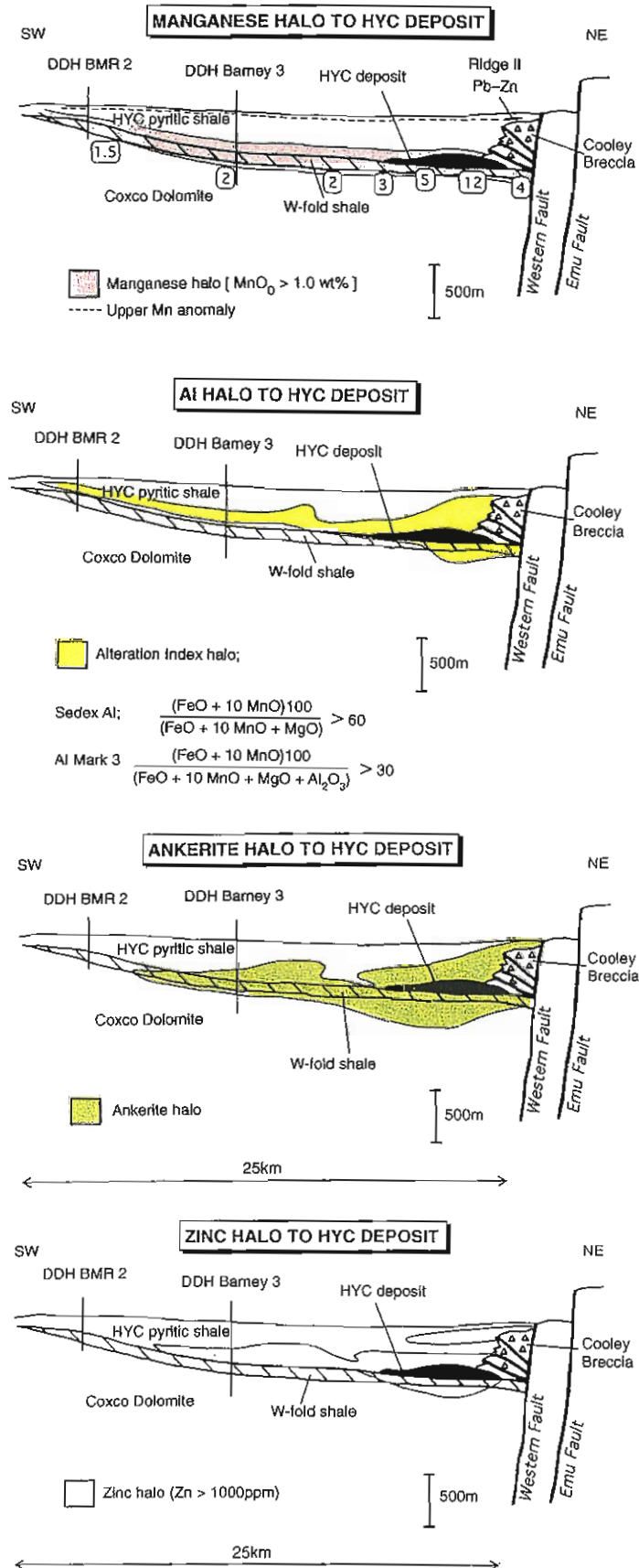


FIG. 3 — Halo model for the HYC deposit, McArthur Basin, based on studies in Report 3: 78–126 and the Final Report: 159–182, 273–282.



at an early stage of exploration. Fluid inclusion work reported in Jones (1986) implicates a hot, reduced, acid fluid as the base-metal carrier, and although such a fluid would carry substantial Fe and Mn, these two metals are clearly not enriched in the Kamarga host rocks by the mineralising process. This observation has important implications for the nature of the ore-forming fluids in the large stratiform deposits and the type of processes involved in metal transport and deposition.

The final case study involved samples from four drill holes through Fickling Group at the Walford Creek prospect. A significant base metal resource is present in the largest of three syngenetic pyrite lenses adjacent to the Fish River Fault. Base-metal mineralisation formed as a diagenetic overprint within the pyrite lenses. Samples were collected from two drill holes proximal to the pyrite lenses and two from several kilometres distance. New geochemical data from these holes indicate that neither the base metals nor Al and MnO<sub>2</sub> indices can be used to infer the presence of the Walford Creek mineralisation. Samples from a low-carbonate siltstone stratigraphically above the uppermost pyrite lens in two of the four drill holes are highly anomalous in Mn; this Mn enrichment may indicate a major syngenetic hydrothermal input elsewhere in the basin at this time.

**Research Contact: Peter McGoldrick**

### The geochemical database

The primary source of geochemical data used in this part of the project was over 350 new, high quality geochemical analyses (mainly by XRF at the University of Tasmania). These data were supplemented with data from the literature for some of the southern McArthur Basin work. An Excel™ macro, XPLOR®, has been developed to aid data analysis. The new data have been supplied to sponsors on request as the analyses became available, and a compilation of all the new data, a copy of XPLOR® and a users manual will be provided to sponsors at the final project meeting. The sample set will form the basis for ongoing geochemical investigations in the project extension.

**Research Contact: Peter McGoldrick**

### Sulfur isotope stratigraphy

Studies on sulfur isotope stratigraphy form an ongoing part of this study (Final Report: 333–344). Biogenic sulfate reduction processes can lead to heavy δ<sup>34</sup>S signatures in pyrite both at the scale of individual deposits, and more regionally if the water bodies involved become closed or partially closed. An important aim of this module was to develop a better understanding of the S isotope systematics of the northern Australian stratiform deposits and their host rocks. To this end the stable isotope laser probe facility at the University of Tasmania was used to generate over a hundred new precise S isotope measurements of pyrite in samples from the McNamara Group. Most of the samples were from the Lady Loretta mine area and from near the Kamarga prospect. The new data from Lady Loretta confirmed and extended the trend to heavy pyrite δ<sup>34</sup>S up sequence described by Carr & Smith (1977). Furthermore, multiple measurements in individual bands revealed wide within-band δ<sup>34</sup>S variations down to the sub-millimetre scale. These large and small variations were interpreted to indicate closed system biogenic sulfate processes operated for all the time represented by the 150 m of sampled sequence. Approximately 430 million m<sup>3</sup> of water with 'average seawater S content' would have been needed to supply the S now present in the Lady Loretta 'Ore Horizon' in both the Big and Small Synclines.

In the Kamarga samples and in the Lady Loretta Formation 90 km north of the Lady Loretta mine, two types of pyrite were distinguished on the basis of their S isotope signatures, one contains light and variable S and the other a generally tight range of heavy δ<sup>34</sup>S values for any given sample. The two types are also texturally distinct and the latter group were interpreted to have formed through complete *in situ* reduction of co-eval sulfate, and hence, their S isotope signature was inferred to represent the basin water sulfate signature at the time of sediment deposition. These data were used to refine the seawater sulfate S isotope evolution curve for the Proterozoic presented in Strauss (1993). Implications of this work to stratigraphic correlations in the lower McNamara group were discussed.

This preliminary study has immediate exploration implications in that syndiagenetic pyrite with heavy



$\delta^{34}\text{S}$  signatures may indicate extensive closed system sulfate reduction has operated. Furthermore, the continued refinement of secular sulfate isotopic curves may assist with distinguishing mineralisation related pyrite from 'normal' syndiagenetic pyrite. This latter work will be continued in the project extension.

**Research Contact : Peter McGoldrick**

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## Integrated studies

### Genetic models for the HYC deposit, McArthur Basin

The McArthur River (HYC) ore deposit is the largest known example of a stratiform sediment hosted Zn–Pb–Ag deposit, with a geological resource of 237 million tonnes grading 9.2% Zn, 4.1% Pb, 41 g/t Ag and 0.2% Cu (Gustafson & Williams, 1981). However, although considered the type example of its class, the opinions on the genesis of the deposit vary from sedimentary exhalative (sedex) to syn-diagenetic replacement. The results from this AMIRA project P384 have shed new light on a number of aspects of the McArthur basin geology which have allowed a re-evaluation of the previous genetic models. New information which was incorporated into the model includes basin architecture research by Leaman (Report 1: 1–34; Final Report: 1–24), sedimentology by Bull (Report 7: 99–114; Final Report: 133–158, 159–182), structure by Keele & Rogers (Final Report: 37–60, 79–112), halo studies by Large, McGoldrick & Duhig (Report 3: 91–26; Report 7: 45–68, 99–114; Final Report: 273–282) and chemical modelling by Cooke (Report 1: 63–75; Report 4: 111–139; Report 7: 149–158).

A review of previous research on the HYC ore deposit, combined with new contributions from this project resulted in the revised genetic model for HYC presented in the Final Report: 371–408. The key elements of the revised model are:

- the HYC Pyritic Shale was deposited in a “deep-water” setting rather than a shallow sabkha environment;
- the extensive Mn halo to the deposit is a function of Mn exhalation, accompanying basin deepening, with Mn concentration in the oxic/anoxic sedimentary facies prior to base-metal introduction;
- the sedimentary breccia–ore cycles are linked to deep seismic events related to basin extension;
- layering in the sulphides is related to rapid pulsing of the basinal brine release, caused by over pressured crack-seal cycles;
- sulphide deposition occurs when the dense, oxidised bottom-hugging brines from each pulse sink into organic dolomitic muds on the basin floor;
- the Py1-Py2–base-metal textural and isotopic paragenesis is a cyclic layer-by-layer paragenesis rather than an orebody-wide paragenesis;
- the ore fluids are cool, neutral pH, oxidised basinal brines rather than hot, acid, reduced brines, and have a much greater metal-carrying capacity than previously considered;
- the source of the ore fluids are basinal brines from the lower McArthur Group which have penetrated deep into the basin to leach metals from the thick felsic and mafic volcanic packages of the Tawallah Group and lower sequences.

**Research Contact: Ross Large**



## Ore deposit models for Lady Loretta and its geochemical halo

During AMIRA Project P384 the Lady Loretta deposit was the focus of geochemical and isotopic studies aimed at defining vectors to base metal mineralisation (Report 3: 31–48, 63–126; Report 7: 69–76; Final Report: 409–446). Detailed regional and local scale sedimentological studies of the Lady Loretta Formation were commenced in 1994 (Dunster, work in progress), and detailed macroscopic and microscopic investigations of the mineralisation are reported in Mark Aheimer's honours thesis.

The new information has led to a re-interpretation of the sedimentary setting of the deposit and a new synsedimentary genetic model for the base metal mineralisation and its associated primary dispersion halos (Final Report: 409–446).

The host sediments, including the mineralised sequence, are interpreted to have been deposited in a small, shallow, evaporitic restricted water body. Relic textures in the ores indicate early (in part syngenetic) formation of base metal sulfides. The low Au tenor of the ores and O isotope features of ferroan carbonates in the halo of the mineralisation indicate cool, oxidised fluids supplied the base metals. Geochemical modelling (Report 4: 111–130) indicates cool oxidised fluids are excellent solvents for base metals. Sulfur isotopes in the mineralised sequence indicate closed system biogenic sulfate reduction supplied sulfide for pyrite, and may have (indirectly) provided sulfide for base metal sulfides.

Principal features of the new genetic model involve a cool, oxidised metal bearing hydrothermal fluid moving into unconsolidated carbonaceous and pyritic sediments and displacing connate pore fluids. Early (base-metal-poor) hydrothermal activity promotes copious microbial activity which on burial decompose to cause sulfate reduction and biogenic pyrite formation. Some of this hydrothermal fluid reaches the sediment–water interface. More oxidised fluids are base metal-rich and these react with reduced S in the sediment and the overlying water column to precipitate base metal sulfides. New (ferroan) carbonates are also produced within the sediment by this reaction. Primary mineralogical, geochemical and isotopic halos are caused by the interaction of the hydrothermal fluid with the unconsolidated sediments and the metal sulfide

precipitation mechanism which promotes local carbonate dissolution and re-precipitation.

Exploration implications of the Lady Loretta model are discussed in the Final Report.

**Research Contact: Peter McGoldrick**

## Two classes of stratiform sediment-hosted Pb–Zn deposits

Chemical modelling combined with basin and deposit studies have resulted in the formulation of a new classification scheme for stratiform Pb–Zn deposits (Final Report: 345–370). In the past, several subdivisions have been proposed within the large group collectively known as stratiform sediment-hosted Pb–Zn deposits. We propose a new two fold genetic subdivision based on fundamental differences in the chemistry of the base metal transporting fluids responsible for forming the mineralisation. Furthermore, we argue that fluid composition is controlled by the type of sedimentary basin from which the ore fluids are derived. The two deposit classes are called the *Selwyn-type* and the *McArthur-type*. Selwyn-type deposits form from reduced, acid brines, whereas base metals in McArthur-type deposits are transported to the site of mineralisation by (relatively cool) oxidised, near-neutral fluids. Selwyn-type fluids are basinal brines produced from sedimentary basins dominated by siliclastic turbidites and carbonaceous shales. McArthur-type fluids are generated in basins dominated by carbonate-evaporites, oxidised clastics and carbonaceous shales. Most brines sampled from young sedimentary basins are oxidised and several are known to contain elevated levels of base metals. Fluid chemical modelling demonstrates, for geologically reasonable conditions, there are two potential base metal transporting regions in  $f_{(O_2)}$ –pH space. The first region is reduced and acid and would correspond to Selwyn-type fluids, the second is oxidised and near-neutral to alkaline and would correspond to McArthur-type fluids. Controls on metal-sulfide deposition will be fundamentally different for the two fluid types. Temperature decrease and pH increase will be important for Selwyn-type fluids, whereas reduction processes will be important for McArthur-type fluids.

**Research Contact: David Cooke**

**Summaries of individual papers  
from Reports 1-8**



## Report 1 — November 1992

### Introduction

This is the first major progress report on the project and covers the six-month period from May to October 1992. Very good progress has been achieved in all three modules.

#### M1: Basin Analysis

- David Leaman reports on a regional geophysical analysis of basic architecture in the Southern McArthur basin, surrounding the HYC deposit.
- Richard Keele and Jamie Rogers provide a preliminary report on structural mapping in the Southern McArthur Basin.

#### M2: Deposit Halos

- Peter McGoldrick reports on progress to date in the geochemical study of the Lady Loretta halo.

#### M3: Brine Chemistry

- David Cooke has undertaken initial computer modelling on fluid geochemistry of sedimentary brines to simulate potential ore-forming conditions for sediment-hosted Pb-Zn deposits.

Important data and conclusions are already emerging from this project which have significant implications for exploration and will be discussed in detail at the November meeting. Progress in the first six months of the project has been very encouraging and I would like to acknowledge the excellent work by the CODES research team and the cooperation provided by the BMR and sponsor companies.

### Regional geophysics — basin architecture: 1. Batten Trough region

D. E. Leaman

Initial work in the Batten Trough within the McArthur Basin has shown that much structural and architectural information can be extracted using a combination of standard and unconventional geophysical interpretation procedures. Fundamental thickness and structural relationships for all parts of the section can be inferred regardless of any limitations in assumptions about rock properties or complex interactive effects within the potential field data used. The interpretation provided is indicative of regional relationships and not intended to provide detailed information on any part of the sequence.

The interpretation has shown, however, that the apparent dominance of sub N-S trends and faults indicated by surface mapping is not a true representation of underlying structural or basin patterns — merely the effect of the most recent uplifts and compressions.

Fundamental structures in the region trend NE, NW and sub E-W as well as NNW. The relationship of deeper volcanic sequences, such as the Scrutton Volcanics, and previously unrecognised variations in mafic units, either deep within the Tawallah Group or a variation of the Scrutton Volcanics, to these fundamental trends has not been described previously.

Growth relationships are evident across many major faults, most of which display reversal of displacements with time. Initial review of the relationships between mineralisation, deep basement trends, deep basin trends, growth patterns and distribution of particular volcanic compositions would seem to suggest that copper shows reflect the presence of thick (>3 km) mafic piles in half grabens while other base metals may be associated with active margins which display substantial thickness variations in units older than the Tawallah Group.

Initial results imply direct relationships between the loci of known mineralisation and marginal structures which have been active in the long term.

## Structures in the southern McArthur Basin

R. A. Keele and J. Rogers

The regional geological setting of sediment-hosted base metal deposits within Australian Proterozoic sedimentary basins is at present, poorly understood. Those studies which have been undertaken have placed minimal emphasis on regional basin structure.

In the southern McArthur Basin, deposition of sediments that host base metal mineralisation has primarily been structurally controlled. Furthermore, mineralising fluids have been focussed along major structures at many localities. In consequence, the primary aims of the present research are to investigate:

- the structural evolution of the basin.
- relationships between basin structure and sedimentation.
- relationships between basin structure and the generation and movement of Pb-Zn mineralising fluids.

Understanding these factors will result in the determination of a set of criteria that can be used to recognise faults which acted as conduits for fluid flow. This could ultimately lead to the establishment of possible fluid pathways for mineralising fluids within the southern McArthur Basin.

These problems are being addressed by mapping selected fault structures within the southern McArthur Basin. Particular attention is being paid to fault attitudes, kinematics and any evidence for fault rotations and reactivations.

The areas chosen for detailed regional investigation this season were the Batten Ranges and the Mallapunyah Dome. The Tawallah Ranges were also targeted for investigation, however access to the area was denied by the local property owners (Billengarah Station). Mapping was conducted at 1:25 000 and 1:10 000 respectively using a topographic base of 1:25 000 air photographs.

## Deposit Halos

### 1. Lady Loretta geochemical studies: preliminary results

Peter McGoldrick

#### Summary

Work at Lady Loretta commenced in May this year. This report summarises progress to date on documenting geochemical and isotopic halos associated with the Zn-Pb-Ag mineralisation. A brief review of Lady Loretta geology is provided and some new geological observations are presented and discussed. The sampling strategy and planned analytical program are described. A preliminary set of over one hundred multi-element geochemical analyses of siltstones and shales are presented. Some preliminary discussion of these data will be presented at the forthcoming meeting.

#### Introduction

The Lady Loretta Zn-Pb-Ag deposit (Hancock and Purvis, 1990 & references therein) was selected as the initial focus for deposit halo studies. The deposit makes an excellent case study for a number of reasons:

- a 20-year exploration and development history with extensive drill core material from the orebody and its environs; this comprises over 24 km of surface drilling and about 14 km of underground drilling, most of which is stored on site and still accessible
- the deposit is a small (8.3 Mt at 18.4% Zn, 8.5% Pb and 125g/t Ag) example of the larger stratiform SHBM deposits of north Queensland; hence, it is possible to sample the deposit and host sediments fairly comprehensively in three dimensions
- the mineralisation and host rocks have been described in detail by previous workers (esp. Carr, 1981 & subsequent papers), and a large geochemical data set from the underground drilling is available
- the host rocks are an (apparently) monotonous group of grey-black pyritic, carbonaceous siltstones and shales
- previous chemical (Zn, Pb, Cu, Ag, Cd, Hg, Fe and Ba) and mineralogical dispersion studies of samples from the surface drilling program (Carr, 1981, 1984) provide an excellent framework for further multi-element and isotopic halo studies

This report briefly describes the geology of the deposit, discusses the sampling strategy used for geochemical



halo samples, and presents a preliminary data set of 104 partial analyses of Lady Loretta host siltstones and shales.

## Deposit Halos

### 2. Sulphur isotopes: status report

Peter McGoldrick

#### Lady Loretta

At the time of writing no S isotope analyses have been carried on Lady Loretta samples, however, material collected for geochemical analysis (esp. pyrite samples) will be used for future work. Sulphur isotopes may reveal the source of S in the ores and the bedded pyrite, and also provide insights into the mechanisms involved in generating the sulphide needed for ore formation (e.g. Davidson's abstract in this volume).

Carr (1981, 1986) reports a small number of S isotope determinations from the Ore Horizon and from bedded pyrite in the Cyclic Unit above the ores. His work demonstrates a variation in  $\delta^{34}\text{S}$  values from 4 to 22‰ in the ores and up to a 10‰ variation in individual pyrite beds. Only limited inferences can be made from these data, but they suggest both closed and open system sulphate reduction processes were operating on a small scale.

For the planned work at Lady Loretta the new laser ablation S isotope facility in the Central Science Laboratory at the University of Tasmania will be used to analyse individual 100  $\mu\text{m}$  sized areas. This capability should help resolve the sampling difficulties inherent in using conventional techniques on isotopically variable samples and lead to new insights into the ore forming process. It is worth noting that the conflicting interpretation of a large set of conventional S isotopic analyses from HYC was not resolved until the ion microprobe was used to analyse individual mineral generations *in situ* (Eldridge, Econ. Geol., in press).

## Sedimentology/basin analysis

Peter McGoldrick

### 2. Lady Loretta Sedimentology PhD Proposal — The sedimentary setting of the Lady Loretta Zn–Pb–Ag deposit, northwest Queensland

Recent detailed investigations of the sedimentary host rocks of the Mount Isa and HYC deposits (Neudert, 1983 (PhD, RSES-ANU) reprinted 1986; Logan, var) have contributed to a fundamental re-interpretation of the geological setting and genesis of these deposits. Similar work has not been carried out at Lady Loretta, although, following a short visit in 1987, M. Neudert recommended that detailed sedimentological work should be undertaken.

Research work is being carried out at Lady Loretta as part of the AMIRA Project 384, and with mining activity "on hold", an opportunity exist for a detailed sedimentological analysis of the Lady Loretta Formation in the vicinity of the deposit. Drill core from the last twenty years is stored on site, and is, for the most part, reasonably well preserved and accessible. Costeans and surface exposure in the vicinity of the mine have been mapped at quite large scales. These materials provide an excellent background for detailed sedimentologic studies.

The work proposed has the potential to add substantially to our understanding of Proterozoic sediment hosted base metal deposits, and provide important background information to the geochemical halo studies currently underway at Lady Loretta. The project would address a number of questions with important exploration implications. These include, on a local scale:

- is there a small scale facies control on the position of the ore horizon (OH) in the Small Syncline?
  - was the OH in the Big Syncline deposited in the same sedimentary environment as in the Small Syncline?
  - what was the palaeogeography of the Lady Loretta sub-basin?
  - can a plausible palinspastic reconstruction combining the Big Syncline and Small Syncline sequences be deduced?
- and more regionally:
- can the sedimentary facies observed in proximity to the mine be recognised elsewhere in the Lady Loretta Formation?

- what elements of the sedimentary package mandatory for base metal mineralisation?
- can the Lady Loretta OH be identified regionally?
- can a sequence stratigraphy approach (i.e. interpreting sedimentary rocks in terms of basin scale events and cycles) be applied to the Lady Loretta Formation and/or McNamara Group?
- what are the tectonic controls on these sequences and how do these relate to the geological evolution of the Lawn Hill Platform, and what do these imply for basin scale fluid movements?

The initial work for this project would be twofold:

- (i) detailed logging of underground and surface drill-core with the emphasis on sedimentary features; this would be complimented by lab studies of sample mineralogy and geochemistry
- (ii) mapping of nearby measured sections and costeans to relate surface outcrop to the data from core.

The field work would require a three- or four-month field season in 1992.

Pending logistic support and availability of suitable drill-core material, later work would extend beyond the immediate Lady Loretta area.

## **Brine Chemistry: Sulfide solubilities and depositional processes in sedimentary brines: preliminary modelling results**

David R. Cooke

Geological and geochemical controls on ore transport and deposition in Proterozoic stratabound/stratiform environments are currently being investigated using thermodynamic computer modelling techniques. Preliminary work has involved updating and modifying the thermodynamic database SOLTHERM for use in this project. Initial calculations are now focusing on the metal-carrying capacity of reduced and oxidised sedimentary brines under a variety of geologically reasonable conditions. These calculations are an essential prerequisite for investigations of fluid-rock and fluid-fluid interactions in sedimentary/hydrothermal environments. Preliminary examples of fluid-buffered depositional processes are also presented to demonstrate what is planned upon completion of the solubility calculations.



## Report 2 — May 1993

### **Regional geophysics and basin architecture**

David Leaman

This report describes further advances in the regional basin architecture study

Some revisions and refinements of previously reported material within the Battern Trough are included. The extension of the interpretation southward into the Wallhallow region and eastward onto the Wearyan Shelf is also described. This new work generally confirms the implications of the original study and suggests that the Battern Trough has had a long and complex history. The first two stages of its evolution include large-scale volcanism and irregular extension and uplift. The structural environment of the Wearyan Shelf is shown to be distinct.

Most refinements of the Batten Trough study relate to additional peripheral studies, either reported here or under way, and involve small variations in presented diagrams or additional diagrams. The latter include one omitted from the original report and a detailed version of the distribution of basement granitoids. The few seismic sections available have also been reviewed in light of the implications of the gravity-magnetics interpretation and found consistent with it.

Some readers of the first report were concerned that the inferences concerning substantial, differentiated and concealed volcanic piles might be suspect. Since this pre-Tawallah Group aspect of the interpretation may ultimately prove crucial to an understanding of the basin, its evolution and its mineralisation, it is necessary to demonstrate that feasible alternatives do not exist. An example of such analysis is included here. This shows that the potential field data do not leave much conceptual uncertainty although many details remain to be worked out. Thick, deep volcanic sections do exist in the McArthur Basin.

Others have noted that some interpretation fits were less than ideal and that as a consequence the entire interpretation might be suspect. Lack of fit perfection may result from the nature of the regional data sets and their subsampling for evaluation purposes, the scale of the analysis, and the amount of time actually spent on each analysis. Irrespective of any deficiencies in these factors, an outline of the very rigorous interpretation criteria actually used is included. This outline, and the discussion of volcanic piles, shows that any imperfections are not of consequence at the scale of this study and any refinements are either not justified or not meaningful.

The implications of these findings have yet to be appraised and the significance of the Battern Trough, its margins and structures such as the Emu Fault await completion of interpretation across the Bauhinia Shelf. This study will be described in the next report.

However, it is evident that a coherent history for the basin and its deep volcanic sequences is evolving. The stratigraphic implications are contrasted with the observed relationships in the nearby Isa Inlier. A future study will test the possible correlations across the Murphy Inlier, South Nicholson Basin and Lawn Hill Platform.

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## Regional geophysics — basin architecture: 2. Batten Trough region — update and further analysis

D.E. Leaman

A detailed analysis of the Batten Trough region of the McArthur Basin was provided in Report 1 for the project (Leaman, 1992).

Some minor errors were overlooked during preparation of that report and one figure was replaced by another.

The report also referred to BMR seismic data in the region. Full panels of this data have now been inspected and compared with the implications of the gravity and magnetic interpretation.

This report is in two parts. The first presents the omitted diagram and discussion of the available seismic data with particular reference to implications of the potential field interpretation. Several other diagrams have been represented with minor updates as a result of a comprehensive study of the Wearyan Shelf to the east. The Wearyan study will be reported when complete.

The second part extends the analysis of the Batten Trough south across the Wallhallow 1:250 000 map sheet.

## Issues in interpretation — McArthur Basin. Do thick volcanic piles really exist?

D.E. Leaman

Following presentation of a comprehensive regional gravity and magnetics interpretation for the Batten Trough Region in Progress Report 1 some have expressed concern that:

1. alternatives may exist in respect of many elements,
2. thick volcanic piles may not exist,
3. pile and granite assumptions may lead to mass cancellation,
4. generally poor fits were presented for the models,
5. the use of potential field methods for sub-horizontal structures may not be valid or lack resolving power,
6. the criteria used to evaluate the results are not adequately explained,
7. shallow volcanic units known to be present may explain all effects.

It is important that these issues, queries and doubts be resolved.

This note aims to show that such concerns are unfounded from two perspectives.

From a geophysicist's point of view it is desirable to have a perfect profile fit. But is it feasible, realistic or even relevant in terms of this project or the data available to it?

From a geologist's viewpoint the real issue is whether the solution gives a true indication of unit relationships while remaining furry on details. It is important that the reader feel comfortable that a wide range of geological options has been tested and that this relationship is established regardless of perceived imperfections in fit, property or other assumptions.

The example chosen for discussion has been taken at random from the Wearyan Shelf investigation currently in progress. All the intermediate files saved have been accumulated and presented to indicate some of the options tested and the quite strict limitations imposed by them. Each stage displayed reflects an evolution of at least ten variations within a chain of ideas and checks.



The suite of diagrams illustrates the power of the interpretation criteria as well as the focus generated on what is really feasible geologically. They provide a clear and proper perspective about what really counts during the interpretation process.

### **Interpretation criteria**

D.E. Leaman

The interpretation of the Batten Trough described in Progress Report 1 for AMIRA Project P384 included a brief discussion of the criteria used to apply rigour to, and assessment of, the analysis described.

Reference was made in that report to the original presentation of the arguments concerning the criteria at a meeting of the European Association of Exploration Geophysicists in Paris in June 1992. A short paper was published at that time.

A complete text has since been submitted to *First Break* (published by the EAEG) for review and publication and a copy of that paper is appended here. I believe that this paper makes some crucial points about data analysis by modelling which are apparently self evident but are far from as transparent as they seem and which are almost never heeded in practice.

They provide a means whereby interfering aspects of the geology can be included in a model and assessed reliably since the base level factor forces consideration of both subtler intervening sources or interference effects between strongly magnetised or volumetrically large sources.

These criteria are also referred to in the accompanying discussion about the evaluation of the existence of thick volcanic piles.

### **Criteria for evaluation of potential field interpretations**

D.E. Leaman

Five criteria are described which can enforce a degree of rigour in potential field interpretation and allow the methods to be used to the limit of their resolution. These criteria relate geological input, geometric and contrast validity, multi-facet treatment of the data and observation base levels. The criteria are relevant to all model-based interpretations. Their use by interpreters and reviewers alike can remove much potential ambiguity, discriminate faulty solutions and provide more detailed results or appraisal.

Recognition of true base levels and possible inherent interference effects, and their effect on modelling, is shown to be a crucial element in sound interpretation which can lead to unique interpretation styles with detailed internal resolution limited only by the data set.

### **Regional geophysics — basin architecture: 3. The Wearyan Shelf and Murphy Inlier**

David Leaman

Examination of potential field data across the Wearyan Shelf within the McArthur Basin of northern Australia has shown that the stable platform style which has dominated the region since the onset of the Tawallah Group deposition is the result of limited disruption of the basement granitic complexes and massive blanketing by thick mafic volcanic suites which preceded normal basin deposition.

The region has remained rigid and moved only as a large block. Negligible tensile, and consequent uplift, forces have been applied since the onset of rifting in the region which controlled the disposition of felsic volcanics which unconformably overlie the basement complex directly. This uplift effect was re-inforced by the rifting and extension of the Batten Region resulting in reduced sedimentation in the Wearyan Region. No major structural heterogeneities exist north of the Murphy Inlier until about 50 km east of the Emu

Fault Zone. At this easting the proportions and continuity of the volcanic pile changes rapidly and this zone must mark the limit of the mobile Batten Zone. The active margin trends N-S within a gross framework which is NW-SE. These orientations are fundamental and reflected in basement granite patterns. Other fracture systems, such as those which trend ENE or NE are superimposed and related to early basin developments.

All units up to upper members of the Tawallah Group onlap the basement rocks of the Murphy Inlier. The deep volcanic piles also thin or disappear along the inlier but are locally very thick near it. Long-lived activity is indicated. The present disposition of the inlier, however, is quite different. It forms part of a major low angle detachment which has transferred the northern plate southward. The possible displacement may exceed 30 km. The Fish River Fault Zone marks the site of the detachment. The entire block of the Wearyan Shelf has been carried as an entity. The increased dips near the inlier reflect the local stresses approaching the detachment which steepens toward the Fish River Fault.

The detachment must predate the deposition of the McArthur or Fickling Groups since these unconformably onlap all older units and the fault zone along the inlier.

Faulting across the shelf appears to be very minor and displacements greater than 250 m are difficult to demonstrate. This contrasts with the Batten Trough region and also with the nature of faults which preceded onset of the two deep volcanic piles.

Known mineralisation can be linked with the general distribution and thickness of the volcanic piles but the region would not appear to possess the same active history or potential for fluid circulation offered by the region west of the Foelsche River. Dolomitic units are also generally absent. Any connate or confined circulation would have been largely restricted to the rocks west of the shelf margin since these are thicker, could pressurise more fluid and were almost certainly more permeable overall.



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## Report 3 — October 1993

### Introduction

This is the third major report on the project and outlines results to date on the Deposit Halos module. A comprehensive account of deposit halo mineralogy and geochemistry is presented for Lady Loretta and HYC. The results have major implications regarding mineral exploration and ore genesis for giant stratiform Pb-Zn deposits.

A further report (No. 4), covering work on the Basin Analysis and Brine Chemistry modules, will be distributed to sponsors at the November 29-30 meeting.

It is now 18 months since the commencement of this project and research progress in all aspects of the work has been very pleasing. Acknowledgement, for our progress to date, is due to the excellent work by the CODES research team and the close cooperation provided by the sponsor companies, AGSO and the NTGS. In particular, for the Deposit Halos module, we would like to acknowledge Mel Jones and Pancontinental for their support and encouragement on the Lady Loretta study.

### Geology of the Lady Loretta deposit: review, new developments and implications for ore genesis.

Peter McGoldrick

This reports reviews the regional geology of the Lady Loretta formation and its sedimentary setting. The geology of the host sequence at Lady Loretta mine is described along with some new observations (evaporite pseudomorphs, desiccation cracks and delicate stromatolites) consistent with a very shallow water to emergent setting for the mineralized sequence. Three macroscopic varieties of pyrite types are present in the mine sequence. The most abundant pyrite type is thought to form from decomposing microbial mat in the shallow sub-surface during diagenesis. An external source (?low temperature hydrothermal fluid) for Fe is probably required to form thick Fe sulphide accumulations.

The genesis of the Lady Loretta base metal mineralisation is discussed using three genetic models:

- (i) an exhalative-syngenetic model: base metal sulphides and pyrite precipitate from hydrothermal solutions escaping to the water column and deposit as sedimentary layers during times of (relatively) low sedimentation rates;
  - (ii) syn-sedimentation — early model: base metal sulphides post-date diagenetic Fe sulphides and form within the soft sediment a few centimetres or decimetres below the basin floor;
  - (iii) syn-sedimentation — late model : base metal sulphides form late in the burial-compaction history of the sediment pile from metalliferous solutions passing through large thicknesses of sediment; thick diagenetic pyrite accumulations are not directly related to the mineralizing event
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## **Sampling and whole rock analyses for the Lady Loretta deposits**

Peter McGoldrick

This report documents the sampling program carried out at Lady Loretta in May 1992. Complete analyses for 30 major and trace elements for 104 sediment samples are presented. All samples were analysed at the University of Tasmania, and a summary of the techniques used for geochemical analysis is provided. These analyses provide the basic data for developing the geochemical halo models presented in Large and McGoldrick, (1993). Appendix 4-i presents an assessment of commercial ICP-ES data for the same group of samples. Appendix 4.11 describes the XRF technique used for measuring TI and compares the XRF data with commercial graphite furnace-AAS analyses.

## **Primary geochemical halos related to Proterozoic sediment hosted Pb-Zn deposits and applications to exploration**

Ross Large and Peter McGoldrick

The purpose of our research in the geochemical halo module of AMIRA Project P384, is to develop a model for geochemical dispersion associated with Australia Proterozoic stratiform Pb-Zn deposits that is applicable to mineral exploration. In this report, primary halos around the Lady Loretta deposit are documented and discussed in detail, based on the sample collection and analysis programme outlined in the previous paper by McGoldrick (1993). The halo model developed for Lady Loretta has two components: (1) an inner siderite halo with anomalous zinc and lead which surrounds the orebody and extends up to 1km along strike; (2) an outer dolomite halo with anomalous Mn and TI which surrounds the siderite halo and extends further along the ore horizon. Within the nested halos vectors towards ore have been defined using a metal index, an alteration index and the MnO content of carbonate phases.

In light of the model developed for Lady Loretta, previously published data on geochemical dispersion surrounding the HYC deposit has been re-evaluated, leading to the formulation of a halo model and ore vectors for stratiform Pb-Zn deposits throughout the McArthur Basin. The ultimate outcome of this research is the development of a new approach to litho-geochemistry applied to stratiform Pb-Zn exploration, which is analogous to the use of stratigraphic drilling and the source rock/trap rock approach to oil exploration.



## Report 4 — November 1993

### Introduction

This is the fourth major report on the project and outlines results to date on the Basin Analysis and Brine Chemistry modules. A summary of research findings from the 1993 honours field program is also provided. The structural and sedimentological evidence for early (mid- and late-Tawallah) inversion events in the McArthur Basin documented here has major implications for understanding fluid flow regimes during McArthur Group (HYC) times. Investigations into the origin(s) of alkali alteration, metal transport and ore depositional processes from sedimentary brines are also of significance in understanding regional-scale alteration and mineralisation features in the McArthur Basin.

The results presented here are derived primarily from the 1993 field season. The extensive field program mounted by the CODES research team could not have been achieved without the close cooperation and logistical support of the NTGS. In particular, we would like to acknowledge Paul Le Messurier, Barry Pietsch, Peter Haines, David (Rowdy) Rawlings and Brian Atkins.

### Regional geophysics — basin architecture: 4. The Bauhinia Shelf

David Leaman

Interpretation of regional gravity and magnetic data in the Tanumbirini and Hodgson Downs regions, otherwise known as the Bauhinia Shelf with respect to the Batten Trough of the McArthur Basin, has shown that the region had a moderately stable history during Tawallah and McArthur Group times but has been very active subsequently. Proterozoic to Mesozoic deposition, including all units from the Roper Group to Cretaceous cover sequences, has been substantial but patchy.

The region possesses a largely granitic basement overlain by two massive volcanic sequences; the earlier one essentially felsic and the younger predominantly mafic. These gross associations have now been recognised across the entire McArthur Basin west of the Murphy Inlier and are inferred to continue SE beneath the inlier. Examination of structural relationships involving these associations suggests that each was controlled by primary basin faulting to yield asymmetric wedges of material but that considerable erosion occurred before and after each sequence. Each association can be defined magnetically and the older, less magnetic or more variable package is much more patchy. This may be a primary pattern or it may reflect extended erosion and uplift. The overlying mafics-dominated association is much more consistent in thickness but it, too, is variable — much more variable than on the facing Wearyan Shelf — although the maximum estimated thicknesses are comparable. There is every possibility that this sequence formed a large, continental sheet of flood basalts. Thickness variations are related to primary basin forms or subsequent local uplift and erosion.

These volcanic sequences have been tentatively linked to the Leichhardt-Argylla and Haslingden Group packages of the Isa Inlier in previous reports.

Substantial uplift and erosion has occurred prior to deposition of the Roper Group since these rocks may be inferred to directly overlie the mafic association in many parts of the region at depths up to 6 km. Either the Tawallah and McArthur Groups were never deposited in these zones or the units have been eroded. Either circumstance implies continuing tectonism across the Bauhinia Shelf but of different style to that within the Batten Trough or Wearyan Shelf regions.

Regional NW, NE and E-W trend systems are evident in the raw data and explained upon analysis to reflect proportions of the volcanic associations and the balance between cover and basement patterns. Major structures can be traced into the Batten Trough zone and some can be extended to the Murphy Inlier across the Wallhallow region. Depositional and erosional controls on the felsic suites is different north and south of the Hodgson Downs-Tanumbirini sheet boundary but the controlling structure seems only to have limited deposition or later uplift in terms of the mafic suites. Is this a compressional axis complementary to the Murphy and Urapunga zones?

No mineralisation is known in this region due to thickness and extent of cover sequences and none is yet known within the cover sequences themselves. The results, however, are of value in that they allow, when assembled in a basin-wide view, a comprehensive assessment of the shear couples acting throughout the early history of the McArthur Basin. A dextral wrench system acting NW-SE could generate the NE-trending extensional basins and the sub E-W compressional axes implied by all lower associations.

### **The structural setting of the Tawallah Group, southern McArthur Basin, Northern Territory: Implications for an early tectonic event**

Jamie Rogers

Detailed Structural mapping and fault sense determination in the Tawallah Group and lower McArthur Group of the Batten, Scrutton and southern Tawallah Ranges has recognised at least three distinct compressional tectonic events; a NE-SW compression

(Post-Roper inversion), a NW-SE compression and an early E-W compression (Mid-Tawallah Inversion). A four-stage tectonic model is proposed for the study area invoking a complex structural history of large-scale block faulting and high-level brittle deformation for the southern McArthur Basin.

### **Progress report: Sedimentology and volcanology of the southern McArthur Basin**

Stuart Bull

Detailed sedimentological and palaeocurrent data have been collected from the Masterton Sandstone at twelve localities in and around the Batten Trough. Two main facies associations have been identified, a conglomeratic basal sequence which is not always present and is very variable in thickness, overlain by a widespread fine to medium-grained sandstone succession. These are provisionally interpreted as coarse grained alluvial fan deposits developed on a deeply dissected palaeosurface, and associated finer grained, high-energy braidplain or braided fluvial deposits respectively. These uniformly high-energy clastic deposits are thought to have accumulated in fan or apron systems, and they interfinger with lower-energy/more distal fluvial and lacustrine or shallow marine deposits at some localities.

Provisional observations on the provenance of the basal conglomerates suggests that, in the Scrutton, Batten and Tawallah Range areas at least, they are derived from the lower Tawallah Group sandstone-dominated units, the Yiyinti and Sly Creek Sandstones. These units form the cores of each range, and the clear implication is that these Tawallah Group cores were lithified and subsequently uplifted by a major basin inversion event prior to the onset of McArthur Group sedimentation. This previously unrecognised syn- or post-Tawallah tectonic event has important implications for the development of southern McArthur basin, in that it indicates that the system could represent multiple generations of rift-phase/sag-phase couplets. In addition, an important implication for ore genesis models is that the proposed syn- or post-Tawallah basin inversion provides the potential for the existence of gravitationally driven,



basin-wide meteoric fluid flow systems during the deposition of the mineralised McArthur Group.

The upper volcanic units of the Tawallah Group have been examined in the Mallapunyah Dome and Scrutton Ranges areas. The lower unit, the Settlement Creek Volcanics, consists dominantly of massive, medium-grain mafic material at both localities, and mafic peperitic textures have been described in the Gold Creek Volcanics in the Scrutton Ranges. A provisional depositional model has been proposed in which the bulk of the volcanic units represent mafic sills. Those of the Settlement Creek Volcanics were emplaced as largely coherent bodies at the base of the Wologorang Formation, and those of the Gold Creek Volcanics breached this unit and intruded into unconsolidated sediments at a higher stratigraphic level. The whole sequence was later cut by rhyolite dykes. One of the main implications of this model for the analysis of southern McArthur Basin system is that if both volcanic units are largely intrusive in character, then their distribution will be independent of the topographic control exerted in subaerial basaltic terrains. Care therefore needs to be taken when using these units as regional stratigraphic markers.

### **The histories of some faults in the southern McArthur Basin: Evidence for an End-Tawallah uplift and a preliminary analysis of stresses related to post-McArthur and post-Roper compressions**

Richard Keele

Structural work has focussed on the northern part of the Southern McArthur Basin in the Tawallah and Costello Ranges. A combination of field work, interpretation of existing geological maps and drawing up cross-sections has produced evidence for an end-Tawallah tectonic event that involved uplift and erosion of the underlying Tawallah Group rocks prior to the deposition of the Masterton Sandstones. A reconstruction of the geology at the time indicates that there was (1) a series of eastward facing tilt blocks (e.g. Four Archers-Hermit Fault block & Rosie-Emu Fault block, and (2) a hanging block or dome which has exposed the Tawallah Group down as far as the Sly Creek Sandstone (Warrapirrmanitla Dome).

This may be explained by extension of the lithosphere during simple shear normal faulting in the lithosphere after a model proposed by Wernicke. This tectonic event at the end of the Tawallah may have been the driving force for uplift: in this scenario the Tawallah Group would be pre-rift, the Nyanantu syn-rift and the Masterton the post-rift sequence.

### **Alkali alteration in the McArthur Group with particular reference to volcanoclastic materials: a progress report**

Garry Davidson

This is a progress report on a study of the behaviour of alkali elements in the saline-alkaline McArthur Group, with special reference to base metal mineralisation. The bulk of this report is a review of previous work on this topic. Feldspar-dominated alkali replacement of glassy volcanoclastic rocks can occur during low-temperature saline diagenesis, or can characterise the passage of higher temperature saline fluids; the latter fluids can also be associated with Pb-Zn-Ag deposits in sedimentary basins. There is a clear need to discriminate the similar metasomatic products of these diverse processes.

A review of McArthur Basin data indicates (1) K-feldspar is an intimate part of the HYC ore assemblage; (2) albite forms the outermost alteration shell at HYC within tuff, surrounding an albite+K-feldspar zone; (3) tuff in regional BCF west of HYC consists of K-feldspar, whereas tuff in the Clyde sub-basin is dominated by albite. Oxygen isotope geochemistry separates Clyde sub-basin from HYC sub-basin volcanoclastics with similar Pb+Zn contents. Further work on the oxygen isotope interpretation is required, but the method has potential as an ore halo tool. Core samples of high-K tuff from west of HYC have been obtained and are presently being geochemically analysed.

## Transport and deposition of base metals from high temperature (250°C) and low temperature (150°C) sedimentary brines

David Cooke

Numerical simulations of transport and depositional processes for high temperature (250°C) moderate salinity (10 eq. wt. % NaCl) sedimentary brines have revealed that significant base metal transport can occur in acidic oxidised, alkaline oxidised, and acidic reduced brines. Moderate salinity, alkaline, reduced brines are not capable of carrying sufficient quantities of base metals to be important in sediment-hosted base metal deposit formation.

Hematitic sandstones provide excellent aquifers for oxidised metalliferous brines. In contrast, significant alteration to potassic and/or propylitic assemblages will occur when brines interact with mafic volcanics. High temperature mineralised brines can migrate significant distances along faults without dumping their base metal load, provided the fluids do not interact significantly with the surrounding wallrocks. Cooling and/or boiling of these metal-rich fluids during cross-stratal transport will produce barren quartz veins.

In the trap environment, mixing of metalliferous brines with anoxic seawater is an excellent mechanism for producing Zn-Pb-rich massive sulfide mineralisation. Mixing of the same brines with oxidised seawater produces siliceous Cu-Ag-rich exhalites. Interaction of reduced, acidic brines with pyritic dolomitic sediments results in the precipitation of simple Zn-Pb-rich sulfide mineralisation. More complex silicates are produced together with the base metal sulfides when the replacement process involves oxidised brines.

At 150°C, similar depositional products are predicted for aquifer and cross-stratal transport, and for depositional processes. However, 10 wt % brines are mostly incapable of carrying sufficient base metals to form economic base metal mineralisation, unless the fluid is oxidised and/or acidic enough. High CO<sub>2</sub> (aq) contents (1 wt %) in the initial brines stabilises siderite as a depositional product in several low-T simulations, suggesting that sedimentary brines must be sufficiently overpressured to retain high CO<sub>2</sub> levels

in solution. Reasonable water depths (several hundred metres) would be required to maintain such pressures (you'd definitely get your feet wet).



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## Report 5 — June 1994

### Introduction

This is the fifth major report on the project and comes at the end of just over two years of research. In this report emphasis is given to further development of the lithogeochemical halo studies and their application to exploration for stratiform lead-zinc deposits. In this regard a database of lithogeochemistry for the McArthur Basin sediments has been established and background distributions for alteration vectors have been determined for the major stratigraphic units. The alteration index approach to exploration has been tested in a number of case studies; including several sub-basins in the McArthur Basin and the Kamarga Prospect on the Lawn Hill Platform. The results of this work are very exciting and confirm the importance of lithogeochemistry in exploration for sedex deposits.

In parallel with our applied studies on alteration vectors we report on the results of more fundamental research on iron carbonate formation and its relationship to ore genesis, and fluid flow studies along the Tawallah Fault.

This work will be presented at the mid-year field meeting in Darwin on 14-15 June followed by a field trip through the McArthur basin to visit areas relevant to the previous and on-going research program.

Particular thanks are extended to AMIRA, the sponsor companies, NTGS and AGSO for their continued support in the planning and execution of this research program.

### Refinement of the Sedex Alteration Index and $MnO_D$ vectors

Ross Large and Peter McGoldrick

Refinements to the alteration index defined by Large and McGoldrick (1993) have been undertaken in order to improve its value as an exploration tool for stratiform lead-zinc deposits. By combining alteration index with the manganese content of dolomite ( $MnOD$ ) in the same graphical plot it has been possible to establish criteria to set priorities on particular data sets from either surface rock samples or drill core samples. Four priority zones have been set up from zone 1 — immediate priority to zone 4 — low priority.

### Background data on Sedex AI and $MnO_D$ for McArthur Basin sediments

Ross Large

A database for lithogeochemistry of sediments in the McArthur Basin has been established using the previously published data sets, which comprise in total 470 surface samples and 246 drill core samples. Analysis of the data base indicates that the background alteration index varies from 0 to 40 and the background  $MnO_D$  varies from 0.02 to 0.5 wt% for samples with  $CaO > 1$  wt%. The dolomite content of the "background" sediments has a considerable influence on the calculated alteration index, such that pure dolomites have a mean of around 10, and weakly dolomitic shales have a mean of around 40. Using AI vs  $MnO_D$  plots for the database it has been possible to assess the various stratigraphic units in the McArthur Basin in terms of their potential to host stratiform Pb-Zn deposits. This procedure indicates that, in addition to the Barney Creek Formation, the Lynott Formation has a very high potential to host lead-zinc ore deposits.

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## Case Studies: Application of the Alteration Index to selected areas in the McArthur Basin

Ross R. Large

Application of the refined alteration index procedure to three sub-basins in the McArthur Basin has indicated the potential for further stratiform Pb–Zn deposits remote from the HYC deposit. Two favourable horizons identified in the BMR 2 area, 25 km SW of HYC, are confirmed by our recent sampling, however the AI and  $MnO_p$  anomalies are considered to relate to HYC rather than more proximal deposits. Evaluation of previous sampling (Brown et al., 1969) in the Top Crossing area (60 km SW of HYC) indicates the presence of a favourable horizon with high potential for lead–zinc mineralisation, down plunge, adjacent to the Tawallah Fault. In the Glyde Sub-basin (80 km S of HYC), drill hole lithochemical sampling by Shell Metals indicates a favourable horizon with anomalous alteration character intersected in one of the ten drillholes.

## Application of the Alteration Index to the Kamarga zinc–lead deposit: preliminary report

Peter McGoldrick

This report reviews the geology of the large, low-grade, sub-economic, stratabound Kamarga deposit, and presents an assessment of existing core grind whole-rock geochemical data (Jones, 1986) using the Alteration Index (AI) and  $MnO_p$  index developed for Lady Loretta and HYC by Large & McGoldrick (1993). The Kamarga data *do not* have patterns like those from the stratiform deposits. Hence, application of the AI could have substantially down-graded the prospectivity of the deposit at an earlier stage of drilling (the data presented here are from four of eighteen diamond drill holes through the Kamarga mineralisation).

## Progress report: Conditions of formation for siderite and ferroan carbonate — implications for the formation of sediment hosted base metal deposits

David Cooke, Ross Large and Peter McGoldrick

Our recent research has emphasised the importance of siderite and ferroan dolomite in the halo to stratiform sediment-hosted zinc–lead deposits. Thermodynamic modelling of siderite and ferroan dolomite stability places important constraints on the genesis of these deposits. This work demonstrates that  $CO_2$  fluid concentration is probably the dominant control on hydrothermal carbonate formation. Siderite and ferroan dolomite are stabilised at high  $\Sigma C$  and low  $\Sigma S$  concentrations. Lower temperatures will stabilise siderite at constant  $a_{CO_2}$ . Ferroan carbonates that form under relatively oxidised to oxidised conditions in association with pyrite or hematite are favoured by lower temperatures and/or high  $\Sigma S$  concentrations, and have the potential to be associated with base metal-rich solutions.

Our calculations indicate that for siderite to form with lead–zinc by exhalation, then at least 250–500 m water depth is required to prevent fluid boiling. Alternatively siderite can form by subsurface replacement of dolomitic sediments below the palaeowater table.



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**Analysis of fluid flow during late stage wrenching of the Tawallah Fault system, southern McArthur Basin, Northern Territory: a fluid inclusion approach**

Jamie Rogers

A fluid inclusion study of the quartz-hematite hydraulic breccias along the Tawallah Fault system indicates that hot (~210°C), saline, oxidised fluids passed through the fault during late-stage wrench movements associated with post-Roper deformation. Enthalpy-chlorite plots suggest that the hot fluids were boiling, and mixing with colder fluids during hematite-quartz deposition. High-heat-producing granites are proposed as a heat source for the fluids, as the system was active well after rifting and volcanism had ceased.

The presence of hot, saline, oxidised fluids lend great potential for mineralisation throughout the entire history of the southern McArthur Basin along the Tawallah Fault and similar fault systems where reduced (graphite and/or pyrite bearing) sediments are juxtaposed against the structure. The results may also provide an insight into processes that occurred along the Emu Fault system during the formation of base metal mineralisation at McArthur River.

**Alteration vectors applied to the Mount Isa Pb-Zn system: a review of existing data**

Peter McGoldrick

This presentation will review some of the published available whole rock geochemical data for the Mount Isa mineralised sequence and associated Mount Isa Group sedimentary rocks.

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## Report 6 (Field Meeting)— June 1994

### Structures in the NW Batten Fault Zone, southern McArthur Basin

Richard Keele

The purpose of this short report, together with the accompanying field guide, is to present the results of structural mapping from three areas: the Four Archers Fault near Nathan River homestead (Stops 1, 2), the Lorella Fault at Lorella Springs (Stop 3) and the Coppermine Creek Fault at the Coppermine Creek prospect (Stop 4). The NW part of the Batten Trough was originally mapped by Plumb & Paine (1964) but has recently been remapped by Rawlings et al. (1993) and Haines et al. (1993). This excellent database has enabled the project to focus in on areas of special structural and sedimentological interest in the Tawallah Group. Our research has concentrated on the basal rather than middle or upper sequences, because the processes and evolution recorded here have important ramifications for the McArthur Basin as a whole. A detailed description of one of the localities (Lorella Springs) has already been given in Report 4, otherwise many of the aspects of the structure discussed here are new and have not been reported before. Work is continuing in all three areas.

### Kilgour copper mine

David R. Cooke

Kilgour copper mine is located 2 km west of Kilgour waterhole, and is hosted by the Amelia Dolomite of the Lower McArthur Group. This unit conformably overlies the Mallapunyah Formation, and is thought to have been deposited in a broad marginal sabkha setting (Muir, 1979).

Kilgour copper mine yielded 125 tons of ore during sporadic production from 1913 to 1955 (Plumb & Rhodes, 1964). Malachite and minor azurite, bornite, cerussite and barite occur in solution collapse breccias,

along bedding planes and in cross-cutting fractures in stromatolitic and massive Amelia Dolomite. Remnants of a steeply plunging massive copper-hematite gossan are present; the gossan dies out suddenly at a depth of 5 m (Plumb & Rhodes, 1964). Analysis of one gossan sample revealed 16% Cu (Jackson et al., 1987).

Jackson et al. (1987) claimed that extensive weathering and erosion exposed the Amelia Dolomite during the late Proterozoic, prior to the deposition of the Cambrian Bukalara Sandstone. Erosion produced an irregular karst land surface, and the Bukalara Sandstone partially filled the solution or collapse features that now host Cu mineralisation (Jackson et al., 1987).

### Section of the Barney Creek Formation and adjacent units in the Top Crossing area

Stuart W. Bull

The often recessive sediments of the McArthur Group are relatively well exposed in the Top Crossing area. The general aim of this traverse is to examine the sedimentological characteristics of the Barney Creek Formation in the field at some distance from the HYC deposit. No sedimentological work has been done on the unit at HYC itself in the course of this project, however, core from HYC will be reviewed on Day 4 and some comparisons can therefore be made.

The contact relationships with the adjacent underlying Coxco Dolomite Member and overlying Reward Dolomite will also be examined in this traverse, as will part of the Lynott Formation which is the basal unit of the overlying Barren Subgroup.



## **Structure and sedimentology of the Tawallah and Lower McArthur Groups, Batten Range**

Stuart W. Bull and Jamie R. Rogers

The Batten Range, located approximately 50 km west of the McArthur River deposit, is bounded by the Tawallah Fault along its eastern margin. The Tawallah Fault has been reactivated several times during its history, so that the oldest sedimentary package (Tawallah Group) and parts of the basement (Scrutton Volcanics) are currently exposed along its western side. In the Batten Range, the lowermost units of the Tawallah Group up to and including the Settlement Creek Volcanics are exposed, which are in turn directly overlain by basal McArthur Group sediments.

The fault block that includes the Batten Range was a positive topographic feature during the early evolution of the southern McArthur Basin, being structurally emplaced by the "Mid-Tawallah" basin inversion event (Rogers, 1993). The extensional phase that followed saw the uplifted block acting as a source for clastic alluvial/fluvial sediments of the upper Tawallah Group and lower McArthur Group (Bull, 1993; Rogers, 1993), and was associated with bimodal and felsic volcanism (Settlement Creek and Gold Creek Volcanics, Tanumbirini Rhyolite). With the cessation of extension (perhaps during a NW-SE directed compressional event at some stage during McArthur Group time; Keele, 1993), suppression of relief led to continued deposition of the carbonate-dominated McArthur and Nathan Groups in a sag-type environment (Bull, 1993). The uppermost unit of the McArthur Basin, the sandstone dominated Roper Group, may have developed in response to another, as yet unrecognised, compressional tectonic event (Bull, 1993). The major structural event to affect the southern McArthur Basin was a NE-SW directed compression post-dating all sedimentary deposition and may represent final basin closure. This event, termed the Post-Roper Inversion (Rogers, 1993), saw the reactivation of early segmented basinal structures to wrench or thrust fault geometries (depending on initial orientation), the former being the case for the Batten Range.

In summary, the Batten Range has undergone a complex structural history involving multiple periods of high-level brittle deformation, with dextral wrench faulting associated with the Post-Roper Inversion particularly well recorded.

Two traverses will be completed in the Batten Range. The morning traverse provides an examination of the major structure in the area, the Tawallah Fault and its effects on a lower Tawallah Group unit, the Sly Creek Sandstone. The aim of the afternoon traverse is to investigate the transition from Tawallah Group to McArthur Group, providing structural and sedimentological field evidence for the "Mid-Tawallah" basin inversion.

## Report 7 — November 1994

### Introduction

This report covers work over the past six months (June–November 1994) and is the seventh report for P384. During this period our research has advanced on a number of fronts: in particular the geophysics and structure of the Riversleigh Fold Belt (formerly Lawn Hill Platform) and further refinement of the alteration halo vectors and their relationship to sedimentary facies in the McArthur Basin.

Coordination of the team results outlined in this report into a series of preliminary integrated models on basin architecture and ore deposit halo formation will be presented at the sponsors meeting on November 24–25. A final P384 report which brings together all our research advances will be presented to the sponsors in May 1995.

### Regional geophysics — basin architecture: 5. The Lawn Hill Platform

David Leaman

This report presents an interpretation of regional gravity and magnetic data in the Calvert Hills, Westmoreland, Lawn Hill and Mt Drummond regions, otherwise known as the Lawn Hill Platform, South Nicholson Basin and Murphy Tectonic Ridge with respect to the McArthur Basin and Isa Inlier, has shown that the region has had a continuously active history and that all relationships are consistent with a single basin evolution sequence.

The terms Murphy Tectonic Ridge, South Nicholson Basin and Lawn Hill Platform should be discontinued since they are misleading in regional terms and based only on near surface perspectives.

The uplifted block, which has been renamed the Murphy Inlier (McConachie *et al*, 1993), has been

active throughout the basin's history since all pre-Tawallah Group rocks appear to thin and onlap it and Tawallah Group rocks are deformed by uplift. Post Tawallah rocks have also been controlled by continued activity and the rocks of the South Nicholson area reflects this.

The region possesses a largely granitic basement overlain by two massive volcanic sequences; the earlier one essentially felsic and the younger predominantly mafic. These gross associations have now been recognised across the entire McArthur Basin west of the Murphy Inlier and are now shown to continue SE beyond the inlier toward Kamarga where thick mafic members of the Haslingden Group are actually exposed. Examination of structural relationships involving these associations suggests that each was controlled by primary basin faulting to yield asymmetric wedges of material but that considerable erosion occurred before and after each sequence. Each association can be defined magnetically and the older, less magnetic or more variable package is much more patchy. The maximum estimated thicknesses within the area studied are much less than have been identified within the McArthur Basin but thickness does increase southward to levels comparable with measured values for the Eastern Creek Volcanics of the Haslingden Group of the Isa region. There is every possibility that this sequence formed a large, continental sheet of flood basalts. Thickness variations are related to primary basin forms or subsequent local uplift and erosion. These volcanic sequences are correlated with the Leichhardt–Argylla and Haslingden Group packages of the Isa Inlier.

Substantial uplift and erosion has occurred prior to deposition of the South Nicholson Group. The persistent uplift of the Murphy Inlier may be related to the granitoid balance to north and south. At least three granitic rocks can be defined regionally and geophysically; a more dioritic form north of the inlier



and a more granitic form south of it. A lower density phase intrudes both of these batholith complexes and an example penetrates some of the central basin elements at Kamarga.

Regional NW, NE and E-W trend systems are evident in the raw data and explained upon analysis to reflect proportions of the volcanic associations and the balance between cover and basement patterns. Major structures can be traced across the entire region. Particular foci for fracture systems, and substantial variations in cover sequences of all ages, have been recognised near the eastern exposure of the inlier and also a little west of Kamarga.

A major change in basement composition has also been defined. The boundary is oriented NNW and can be traced southward across the region at the longitude of Doomadgee.

Few mineralised sites are known in this region due to thickness and extent of cover sequences. Known mineralisation, of all types, can be associated with the foci recognised as anomalous structural features. The Silver King - Century zone is associated with fundamental basement features and substantial changes in unit thicknesses. The Termite Fault represents a late rejuvenation of a complex primary structure. Many of the defined elements are comparable with those described near HYC in an earlier stage of this study. Other, similar, anomalous zones are rare in this region. Given the substantial cover sequences (Cambrian and younger) this may be important information with considerable ramifications for exploration.

## **A preliminary structural analysis of the Riversleigh Fold Belt (formerly Lawn Hill Platform) with special reference to structures around the Lady Loretta deposit**

Richard A. Keele

Preliminary studies of the Leopard Fault suggests that it was active during the McArthur extension. Minor inversions along this fault represent pre-cursors to the main orogenic event (Mount Isa - D1) in which the sub E-W basinal faults became thrusts. Subsequent upright folding (Mount Isa - D2) has preserved a section through one such a fault. Fault striae analysis in the Lawn Hill Platform gives results that are consistent with the variable effects of the nearby orogen (Mount Isa Orogeny). An early basin-wide pre-orogenic pulse which involved brittle-style wrenching at the end of sag phase sedimentation is probably related to Pb-Zn mineralisation at Lady Loretta. It is followed by thrusts during Isa D1 and shear bands during Isa D2. Partitioning of the regional strain in the Platform suggests that 'indent tectonics' may have been active during the main phase of orogeny.

## **Modelling the relationship between sedimentary facies and Alteration Index and resolution of the "shale factor"**

Ross R. Large

A study of sediment mixing models for the HYC and Lady Loretta areas has enabled the development of a refined alteration index called AI Mark 3 ( $AI_3$ ) which utilises  $Al_2O_3$  wt%, in addition to FeO, MnO and MgO wt%. This refined geochemical index vector reduces the "shale-factor" that was prevalent in the Sedex AI, which gave high priority to low carbonate bearing shales, but could not discriminate between barren shales and potentially fertile shale host rocks. Further testing of  $AI_3$  will be required to assess its full potential as a robust exploration vector.

## Microprobe analysis of carbonate phases at Lady Loretta

Nathan Duhig

Carbonates from dolomitic and sideritic sediments at Lady Loretta were analysed by microprobe to test the validity of the calculated MnO distributions in the carbonates. A good correlation was obtained between the actual and calculated MnO values. The study also revealed that ankerite, not dolomite, is the dominant carbonate away from the siderite halo. There is varying substitution between Mg and Mn with Fe and Zn (where Zn is available) in the siderites. Further probing and cathode luminescence studies may aid in determining the paragenesis of the carbonate phases and hence the origin of the siderite (and ankerite?) halo.

## Petrology and tectonic setting of the Tawallah Group igneous rocks

Jamie Rogers

This paper aims to describe geochemical traits of the Tawallah Group igneous rocks with respect to the tectonic processes that were active during their emplacement. Variations in immobile element compositions allow for geochemical characterisation of the different igneous units and their identification as continental within-plate tholeiites. The latter conclusion enables comparison with tholeiitic basalts and andesites of the Lower Cretaceous Paraná CFB province. Zr/Nb, Y/Nb and REE relationships suggest that the Settlement Creek and Gold Creek Volcanics are derived from a more enriched mantle source (T-type to P-type MORB) than the Seigal Volcanics (T-type MORB). This is interpreted to reflect increased input of relatively enriched deep mantle into sub-continental lithospheric source regions or, alternatively, suggests progressive involvement of a deep mantle source region as the plume system relaxes to depth. In either case, the entire system appears to relax and suggests that rifting in the southern McArthur Basin failed at an early stage.

## Depositional attributes of the Barney Creek Formation in DDH BMR McArthur 2

Stuart Bull

Detailed sedimentological examination and geochemical resampling of DDH BMR McArthur 2 has been carried out to provide a new geochemical data set and to study the effects of sedimentary facies on the alteration index. The sedimentological studies indicate that: (1) The Barney Creek Formation, which comprises the bottom 97 m of the core, was deposited in a quiet (ie. below wave base), anoxic subaqueous environment via hemi-pelagic suspension deposition interrupted by periodic, small volume mass flows. (2) The upper 25 m of core record gradually shoaling conditions interpreted to represent a gradational contact with the overlying Reward Dolomite. (3) The presence of mass flow beds of peloidal sandstone throughout the Barney Creek Formation, which are similar in composition to sub-tidal peloidal sandstone deposits described from the Reward Dolomite, suggests that the two units are at least partly time equivalent.

With respect to the alteration index, there is no direct relationship to sedimentary facies (which are defined on the basis of dominant depositional mechanism and probably also organic carbon content and are independent of dolomite content), apart from the "shale effect" which has been addressed by creating AI3. There is a crude relationship between AI3 and sulphur content (occurring as pyrite). This results in black (ie. carbonaceous +/- pyritic) mudstone-rich samples giving relatively high AI3 values, however, not all samples of this type give high AI3 values. In fact, three of the five samples with high AI3 values which define the AI3 peak in DDH BMR McArthur 2 are from the main facies present which is less carbonaceous and pyritic than the black mudstone facies.



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### **Application of the Alteration Index and $MnO_D$ to the Mount Isa and Hilton zinc-lead-silver deposits**

Peter McGoldrick

This report describes an assessment of the applicability of geochemical vectors to mineralisation developed for Lady Loretta and HYC to the giant Mount Isa and Hilton Zn-Pb systems. Several old public domain data sets have been used for this purpose. The data analysis indicates that the 'Sedex Alteration Index' (Large and McGoldrick, 1994), the 'Alteration Index Mk3' (Large, this volume),  $MnO_D$  (Large and McGoldrick, 1993) and TI (McGoldrick, 1986) are all potentially useful vectors to the Mount Isa and Hilton deposits.

### **The geochemistry of 'barren' late Palaeoproterozoic sediments from the McNamara Group: background values for the 'SEDEX AI', 'AI Mk3' and $MnO_D$**

Peter McGoldrick

This preliminary report presents geochemical data for 43 samples collected from four stratigraphic drill holes through McNamara Group sediments in the Lawn Hill Platform/Riversleigh Fold Belt (McConachie et al., 1993). The geochemical vectors refined by (Large and McGoldrick, 1994) and Large (this volume) are calculated for these samples and the results are used to confirm 'background' values for these indices. This analysis supports intuitive arguments that these samples represent 'typical' compositions for unmineralised fine grained sediments in the McNamara Group.

### **Conditions of formation for siderite and barite from sedimentary brines: implications for the formation of sediment-hosted base metal deposits**

David Cooke

This report presents results of the continuing study into controls on siderite deposition from low-moderate temperature hydrothermal fluids. Some brief comments on siderite deposition from low temperature (50°C) brines are provided prior to a discussion of the relationships between barite, siderite and metalliferous brines. The report concludes with a discussion of preliminary chemical models for sediment-hosted base metal deposits.

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# Final Report — June 1995

## Introduction

This is the final report for project P384 coming at the end of three years of research, involving a team of seven research scientists, one PhD student and three honours students. The report is a combination of over-view papers which summarise data and conclusions over the three-year program, plus a series of papers which cover results in the past six months of the project. All papers are grouped in the order: basin analysis, brine chemistry, deposit haloes and integrated studies.

## Architecture of the McArthur Basin, northern Australia

D. E. Leaman

Quantitative regional geophysical analysis of the McArthur Basin in northern Australia has shown that the basin includes sequences which have a total thickness in excess of 20 km. Little of the deep section, which includes thick volcanic and rift sequences, is exposed due to the limited general uplift or deformation but the implied stratigraphy is consistent, and may be grossly correlated, with the adjacent western sequence of the Mt Isa Basin. Thick basal felsic and covering flood basalts can be inferred within the primary rift structures. These active rift sequences account for about two thirds of the basin section everywhere.

Thinner cover sequences, including the predominantly siliclastic Tawallah and dolomitic McArthur Groups, are variably developed in subsidiary basins controlled by underlying basin and crustal structures. The overlying Roper Group is much thicker and more widespread.

The geometric relationships between all sequences indicate substantial erosion or local uplift and

subsidence activity throughout the evolution of the basin. Major erosive events are recognisable across the basin.

Most tectonic activity has been focussed in the zone known as the Batten Trough although this name is not appropriate; the region has been largely uplifted throughout its history. Uplifted zones such as the Murphy Tectonic Zone tend to be oriented sub E-W. The basin has evolved from a series of rift cells which were not simply connected but which were overtopped and the covering sequences have interlinked. No clearly defined ultimate limits have been recognised for the basin which appears to be an extension of the Mt Isa Basin to the southeast. An original crustal grain may have been oriented NW-SE and NNE-SSW. Many structures have been rejuvenated and impressed and some may still be active.

Mineralisation within the basin appears to be related to regions where rift or rift cell margins have been persistently uplifted and known mineralised sites lie on the rim horsts.

## Considerations on the regional setting of mineralised sites in northern Australia

D. E. Leaman

The structural and crustal settings of the large sediment-hosted Pb-Zn deposits of northern Australia have been reviewed using available mapping and geophysical data and several common elements have been identified.

Mineralisation at HYC, Hilton, Century and Mount Isa has been focussed near sites which possess an increased fracture density through the crust and all sites lie adjacent to very active rift structures. No site is located within the active rift segment; all



were marginal and persistently elevated within the gross basin setting. Each site is located within 25 km of a young granitoid which may be of an age comparable to the ore formation and the lower basin cover sequences are dominated by bimodal volcanic suites.

NNW, NW and ENE trend systems are regionally important.

Few other sites can be identified in the McArthur Basin with these characteristics and many are now inaccessible.

### **Structures in the Northwest Batten Fault Zone, southern McArthur Basin, Northern Territory: with reference to tectonic uplift during Tawallah times**

Richard A. Keele

The volcano-sedimentary sequences of the southern McArthur Basin that were subject to erosion at the time of Masterton Sandstone deposition, ranged from lower to upper Tawallah Group in age, i.e. from Sly Creek Sandstone to Warramana Sandstone. Uplift commenced during deposition of the Sly Creek Sandstone and ceased with the Warramana Sandstone, the greatest amount being in the central and northwestern parts of the region and the least in the east and south. The Tawallah Range, Lorella, Rosie and Four Archers Faults were all active during this period, controlling the variable amounts of uplift throughout the region. The Warrapirmantila Dome, a NW-trending structural high whose core comprises the oldest rocks exposed at this time, is mantled by basal McArthur Group sag-phase sediments (Masterton Sandstone and Mallapunyah Formation). These draped units have an asymmetry with respect to the dome whose formation was principally due to: (1) differential uplift in Tawallah times, and (2) gentle folding during the post-Roper ENE-WSW compression. Uplift along the western margin of the Batten Fault Zone involved a combination of east-side-up movements on the Four Archers Fault in Tawallah times and W-directed thrusting during subsequent pre- and post-Roper compressions. Other events that also contributed to uplift (e.g. Scrutton Inlier) included broad-scale post-Umbolooga

Subgroup/pre-Roper E-W arching of the basement. The Northwest Batten Fault Zone and the neighbouring Urapunga Ridge, to which the latter is joined, occupied the shoulders of an extensive region of rifting that was centred to the south and east of the study area. Uplift during Tawallah times is thought to have been achieved without significant crustal shortening.

### **Analysis of some fault striae in the Proterozoic southern McArthur Basin, Northern Territory: with reference to the Mallapunyah Dome and Four Archers Fault**

Richard A. Keele and John V. Wright

Stress tensor calculations, derived from an analysis of fault striation data, yield two fundamental stress fields and six related stress states: an early N-S compression in wrench mode was followed by an ENE-WSW compression that incorporated thrust and wrench components. The northern Mallapunyah Dome, lying at the intersection of the Mallapunyah and Tawallah Faults, resulted from an uplift that was accomplished by a combination of dextral wrenching, SW-, and W- to E-directed thrusting that caused a 'pop-out' to form, giving the dome its characteristic N-S elongation. This process may have been aided by early (pre-Masterton) east-side-up movements on the Tawallah Fault. The Four Archers Fault records both pre- and post-Roper stresses that are related to this secular change in the regional stress patterns.

The extensional stress states, responsible for normal faulting at Mallapunyah and on the Four Archers Fault, share common directions with the compressions. They are considered to be due to a rebound effect or stress relaxation in the crust following each compression. Similar effects have been noted in the Mount Isa Inlier. As a consequence, the fault striation method is not capable of directly identifying the normal fault activity during basin extension, because of its very close relationship to the compression events. Although two principal stress fields, due to an early N-S compression and

late ENE–WSW compression, can be correlated across the basin, the stress tensors may not always provide a clear distinction between these events. The fault striation method works best with data sets of 200 or more; however, fewer data (<15) may be used to adequately define the palaeo-stress tensor as long as fault orientations are optimised.

### **Brittle deformation events in the western McArthur River region, southern McArthur Basin, Northern Territory**

**Jamie Rogers**

Fault-slip data gained from primary and secondary brittle structures in the Batten, Scrutton and Tawallah Ranges have been analysed by the inverse palaeo-stress method. Reconstruction of palaeostress orientations suggests that the structural architecture of the study region has developed in response to three main compressional events. The initial event,  $D_1$ , is defined as an E–W horizontal compression and was associated with significant uplift along the Tawallah Fault prior to Wunnumantyalu Sandstone deposition.  $D_2$  is characterised by secondary fault patterns generated during NW–SE compression and left-lateral strike-slip motion on N–S-trending primary structures (Tawallah/Lorella Faults). This tectonic phase is correlated with the transpressional event of Hinman et al. (1994) that was active during Barney Creek Formation deposition. The final tectonic phase,  $D_3$ , post-dates Roper Group sedimentation and is defined by a NE–SW compression. Brittle deformation associated with dextral motion on the Tawallah and Lorella Faults and NE-directed reverse motion on the Bauhinia Fault characterise this event. Both primary and secondary structures have seen moderate to high temperature (160°–210°C), saline (8–13 eq wt.% NaCl) and oxidising fluids during  $D_3$  (Rogers, 1994). This lends great potential for base metal mineralisation throughout the entire southern McArthur Basin stratigraphy where reduced (graphite or pyrite bearing) sediments are juxtaposed against primary  $D_3$  structures.

### **Evolution and tectonics of the North Australian Zinc Belt — the Southern McArthur Basin and Lawn Hill Platform**

**D.E. Leaman and R.A. Keele**

The development of early felsic and mafic volcanic sequences in the southern McArthur Basin was controlled by a N–S crustal extension in which sinistral dislocations along fractures related to the NW-trending basement grain and local NE-trending rifts played a prominent role. The rifts have a distinct cell-like character with all subsequent units onlapping their margins or uplift axes; sub-E–W elements of uplift are a persistent and widespread feature between cells across much of the basin (e.g. Murphy Inlier) and are an isostatic response to the main stress field. In the Batten Fault zone, the Yiyintyi–Tawallah Rift Cell is 100 km × 150 km in extent. The distribution of contemporary fault activity and the sub-radial pattern of volcanic troughs indicate the plume-like nature of the thermal pulse. The irregular E–W boundaries of the McArthur Group are onlap features derived from the sag phase in which the Emu and Tawallah Faults acted as transform or partitioning faults. A general concordance of lithotypes within each rift suggests that gross sequence styles in the McArthur and Mount Isa basins may be correlated with each other, although they may not be exact time equivalents.

All faults have been active for long periods and in some cases they change their polarity several times. The Emu Fault had a long and complex history from earliest volcanic times through to Roper sedimentation. During the period covering Pb/Zn mineralisation, thick McArthur Group carbonate sequences were deposited between the (E-side-down) Hot Springs and (W-side-down) Emu Faults, with HYC lying on the NE flanks of this thick prism of sediments. HYC lies within 25 km of the margins of the underlying Tawallah rift, further emphasising its unique position in the McArthur Basin.



## **Towards a regional depositional model for the Palaeoproterozoic Barney Creek Formation, southern McArthur Basin, Northern Territory**

Stuart W. Bull

The 122 m-long diamond core DDH BMR McArthur 2 was collared in Reward Dolomite approximately 23 km SW. of McArthur River Mine. It intersected 25 m of Reward Dolomite and was terminated in the underlying Barney Creek Formation, comprising 97 m of grey to black dolomitic siltstones and shales which are undifferentiated in this area. Facies and geochemical characteristics suggest that the lowermost 15 m of the intersection represent the upper part of the W-Fold Shale Member, and the overlying 82 m has a close affinity to the HYC Pyritic Shale Member.

Sedimentary facies based analysis of the DDH BMR McArthur 2 intersection indicates that the entire succession accumulated in a quiet, reduced, sub-wave base environment. However, the restriction of key facies to discrete stratigraphic intervals indicates subtle fluctuations in environmental conditions, chiefly water depth, during deposition. A schematic relative water depth curve has been constructed which identifies two periods of increasing water depth (one from the W-Fold Shale Member into the lower part of the HYC Pyritic Shale Member, and one in the upper part of the HYC Pyritic Shale Member), and two periods of shallowing and/or shoreline transgression (one in the middle/upper part of the HYC Pyritic Shale Member and one at the top of the hole, representing a gradational contact between the Barney Creek Formation and the Reward Dolomite).

Reconnaissance examination of five additional intersections of the Barney Creek Formation (three diamond drill holes and two field sections), indicates that the sub-wave base depositional model for the unit can be extended throughout the central Batten Fault Zone, with the possible exception of the McArthur River area in the vicinity of the HYC and associated mineralisation. Thickness and facies distribution patterns within the unit in the section network show no consistent westward change in the central Batten Fault zone, outside the anomalously thick accumulation in the McArthur River area. This

is consistent with, but provides no positive evidence for, syn-sedimentary activity on E-W trending normal faults. These patterns also indicate that although some form of sub-basin control appears to have existed during deposition, as is suggested by the anomalously thick accumulation in the McArthur River area, the depositional system was linked throughout the central Batten Fault Zone.

## **Sedimentology, geochemistry, alteration patterns and C/O isotope chemostratigraphy, DDH BMR McArthur 2, McArthur Basin, NT**

Stuart Bull and Ross Large

A comparison of sedimentary facies and geochemistry in DDH BMR 2 indicates a correlation between selected sedimentological and geochemical parameters at the outer extremity of the HYC deposit halo (23 km distant).

Trends in calculated content of sedimentary dolomite, based on CaO analyses, have proved to be a successful "first pass" indicator of water depth in the McArthur Basin. They support the sedimentological interpretation that two periods of basin deepening occurred during Barney Creek times. The main "deep water" facies corresponds to the down hole interval 60–106 m. It is characterised by an increase in the thickness and abundance of units of a massive carbonaceous  $\pm$  pyritic mudstone facies, intercalated with the dominant thinly-bedded dolomitic sandstone/siltstone/mudstone facies.

Al<sub>3</sub> and MnOD anomalies are well developed in this interval and define the favourable horizon for Pb–Zn mineralisation between 78 to 106 m down hole. The zone also shows above average total organic carbon, with a weak positive correlation observed between Al<sub>3</sub> and % organic carbon in the sediments. Sulphur-carbon and down hole DOP (degree of pyritization) variations indicate that the basin bottom waters varied from oxic to anoxic. Periods of anoxia correspond to the black mudstone facies, with evidence of pyrite formation due to both diagenetic and syngenetic processes.

The base of the favourable horizon is marked by an increase in % MnO in dolomite (MnO<sub>D</sub>), which

corresponds to a decrease in the dolomite/shale ratio related to basin deepening. Dolomite-rich facies which have  $MnO_D < 0.5$  wt % are indicative of "shallow water" environments (e.g. 40–60 m down hole) and correspond to low potential zones for stratiform Pb–Zn–Ag mineralisation. Zinc and lead have become decoupled in DDH BMR 2, with minor Zn concentration in sediments above the favourable horizon. No correlation was found between carbon and oxygen isotopes of carbonate and patterns in sedimentary facies or alteration indices down the drill hole.

### **Potassic alteration in the Settlement Creek and Gold Creek Volcanics, McArthur Basin, Northern Territory — implications for base-metal mineralisation**

David R. Cooke, Stuart W. Bull and Serena Donovan

This report documents evidence for the leaching of base metals from dolerites of the Upper Tawallah Group by oxidised, saline brines, and discusses implications for the formation of base metal mineralisation in the McArthur Basin. The petrographic and chemical characteristics of potassic and chlorite–orthoclase altered dolerites are documented, and mass-balance calculations are used to quantify the chemical changes resulting from the potassic alteration event. Stable isotopic and fluid inclusion data indicate that the fluids responsible for metal leaching and potassic alteration were low temperature, oxidised, saline, hydrocarbon-bearing and derived from a meteoric source. The metals acquired by these brines could have been transported significant distances through a suitable aquifer (e.g. hematitic sandstone) and were potentially important for the formation of stratiform Pb–Zn, MVT and breccia-hosted Cu deposits in the upper Tawallah and McArthur groups. The mafic volcanics are concluded to be a more likely source for base metals than the red bed horizons, or the piles of felsic volcanics and basement granites inferred by the geophysical modelling of Leaman (1992).

### **Alkali metasomatism of volcanoclastic and clastic rocks in the McArthur Group, with emphasis on the HYC Zn–Pb deposit**

Garry J. Davidson

Low to moderate temperature alkali metasomatism characterises shallow evaporitic basins and the adjacent sedimentary successions around the world. In the McArthur Group of the McArthur Basin, feldspathised beds are common in both carbonate- and shale-dominated units, and larger scale K-metasomatism is identified by the aeroradiometric response of some units, specifically the Stretton Sandstone, and the Lynnott, Barney Creek and Tooganinie Formations. Most massive feldspathised beds have Ti/Zr distinct from their host sediments, are laterally extensive, contain euhedral zircons and resorbed phenocrysts, and in places preserve vitriclast fabrics. These are identified as original volcanoclastic beds, divided into primary airfall and slump-re-sedimented varieties. Alkali metasomatism around some volcanoclastic beds extends into the adjacent sediment, in places altering significant thicknesses of clastic beds that are associated with evaporitic successions. Petrography, XRD and whole rock  $SiO_2/SiO_2 + Al_2O_3$  of 0.75–0.94 indicate that quartz, microcline, albite, calcite, dolomite, ankerite  $\pm$  illite are the dominant metasomatic phases in the volcanoclastic rocks. Microcline–quartz  $\pm$  calcite is the prevailing assemblage in the central McArthur Group, whereas close to bounding structures such as the Emu Fault, albite–quartz also occurs.  $\delta^{18}O_{\text{wholerock}}$  of HYC volcanoclastic beds has strong linear correlations with  $Al_2O_3$ ,  $SiO_2$  and  $[Na_2O + K_2O]$ , permitting modelling of the replacement process as equilibrium precipitation of quartz and feldspar from a fluid with  $\delta^{18}O = -5$  to  $-15\%$ , at  $25 \pm 11^\circ C$ , implicating a cool, saline, meteoric fluid. The diagenesis of these beds mainly preceded alteration by HYC fluids, and with some exceptions was isotopically unaffected by them.

McArthur Group alkali metasomatism occurred in several phases, none of which fit a classic model of alkali mineral zonation toward an evaporitic basin centre. Basinward of major faults such as the Emu Fault Zone, gravity driven meteoric–evaporitic brines descended from adjacent shelves and were focussed



by the faults into adjacent deeper water clastic successions, forming zoned albite-microcline assemblages with elevated B contents. At HYC this represented the prevailing ambient fluid flux, punctuated by episodic release of deeply sourced metal-bearing brines from the Emu Fault Zone. HYC ore fluids added disseminated ankerite, adularia and basemetal sulphides to some feldspathised beds.

A second early diagenetic alkali metasomatism was associated with descending and advecting brines generated within and above porous aeolian and shelf sand bodies. The K-rich brines evolved when seawater was evaporated to gypsum/halite saturation (salinity > 35 wt. %) in supratidal to lagoonal settings, as occurs in the Donnegan Member of the Lynott Fm, and the overlying Yalco Fm.

The most aerially extensive K-feldspar metasomatism post-dated early diagenetic albite alteration at Glyde River, but is otherwise unconstrained in time. Widespread vitriclastic fabric destruction suggests that it was preceded by texturally destructive illite, as is common in bentonites, and its mineralogic uniformity indicates that it accompanied basin-wide fluid migration, speculatively during basin inversion (1640–1430 Ma) following the McArthur Group deposition. This hypothesis can only be tested with radiometric dating.

The exploration implications are: (1) The alteration assemblages in the volcanoclastic rocks are mainly not associated with base-metal-bearing fluids. (2) Subtle indicators of base-metal alteration are Pb-Zn and ankerite replacement of more feldspathic beds. (3)  $MnO_2$  has potential as a halo indicator in volcanoclastic beds, sedex AI requires further assessment, whereas Zn content and  $Al_3$  are definitely not useful. These criteria earmark the southern Glyde sub-basin as a particularly base metal prospective zone.

Lastly, in terms of the AMIRA extension, the following fruitful directions could be pursued: (1) feldspathised beds have great potential for identifying episodes of fluid movement, but only radiometric dating will discriminate alternatives; (2) one conclusion that the AGSO sequence stratigraphy project will quickly reach is that far more can be achieved for correlation using the abundant volcanoclastic beds, particularly with phenocryst melt inclusions and immobile element geochemistry;

CODES could collaborate with them on this. (3) Review of previous work by Logan (1979) on illite crystallinity shows that it has great potential for mapping fluid flow, and should be applied more widely to the McArthur Group. (4) Carbonate oxygen/carbon isotopes in feldspathised beds will provide more information on post-feldspathisation fluid movement. (5) Further detailed  $\delta^{18}O$  wholerock isotopes on the Myrtle, Glyde and Bing Bong and Donnegan Member feldspathised beds will constrain their conditions of formation.

### **Ankerite halo to the HYC deposit**

Ross Large and Nathan Duhig

The distribution of ankerite in the Barney Creek formation surrounding the HYC deposit has been determined using the XPLOR® computer program. The program enables the calculation of (Fe+Mn)/Mg molar ratios in dolomite and ankerite from the whole rock analyses. This study demonstrates that ankerite forms a halo around the deposit, up to 400 m thick, and laterally extensive along the base of the favourable horizon for at least 15 km from HYC. Carbonates within the halo are a mixture of ankerite and dolomite, while outside the halo the dolomites are iron-poor.

The Mn-halo and ankerite halo at HYC are broadly coincident, however, the ankerite halo shows greater across-strike extent and the Mn-halo greater along-strike extent. The most iron-rich ankerites occur in the ore zone and/or favourable horizon, however, the most Mn-rich carbonates occur at the top of the W-Fold Shale.

## A microprobe study of carbonates from DDH BMR McArthur 2

Nathan Duhig

A microprobe study of carbonates in 12 samples from DDH BMR McArthur 2 was undertaken to test the validity of the  $\text{MnO}_p$  and molar (Fe+Mn):Mg (the 'ankerite ratio') values, derived from processing the whole rock geochemical data. The microprobe results show very good agreement with these values. The fine grained nature of the samples and the pervasive silica/alkali feldspar alteration meant that it was not possible to attribute the Mn distribution to any particular phase(s) of carbonate. Future work may include a similar study closer to HYC, and detailed diagenetic studies to integrate the carbonate paragenesis with the mineral chemistry.

## Variation of carbon and oxygen isotopes in the alteration halo to the Lady Loretta deposit — implications for exploration and ore genesis.

Ross Large, Paul Kitto and Peter McGoldrick

Carbon and oxygen isotope analyses of carbonates were measured on twenty-nine sediment samples within the geochemical halo of the Lady Loretta stratiform sediment-hosted Pb-Zn-Ag deposit. Previous research indicates that the sediments in the inner halo are siderite-bearing and pass outwards to ankerite-bearing and then dolomite-bearing further from the deposit.

This isotope study shows that the inner zone siderites are distinctly heavier in oxygen isotopes ( $\delta^{18}\text{O}_{\text{sid}} = 23.2$  to  $28.3\text{‰}$ ) and lighter in carbon ( $\delta^{13}\text{C}_{\text{sid}} = -1.9$  to  $-3.2\text{‰}$ ) than the outer zone dolomites;  $\delta^{18}\text{O}_{\text{dol}} = 16.5$  to  $18.2\text{‰}$  and  $\delta^{13}\text{C}_{\text{dol}} = -0.9$  to  $-1.5\text{‰}$ . Equilibrium fluid calculations suggest that the siderite halo formed at temperatures near  $100^\circ\text{C}$  from a fluid with  $\delta^{18}\text{O} = +6\text{‰}$  and  $\delta^{13}\text{C} = -6\text{‰}$ , having the characteristics of an evolved basinal brine. In contrast, the outer dolomite sediments formed in equilibrium with a lower temperature ( $\sim 50^\circ\text{C}$ ) fluid, with  $\delta^{18}\text{O} = -11\text{‰}$ ,  $\delta^{13}\text{C} = -5\text{‰}$ , suggesting either a meteoric or evaporated seawater origin.

The data also suggest that C/O isotopes on carbonates have the potential to be an exploration indicator of favourable stratigraphy for Pb-Zn-Ag mineralisation. For example, within a given district, carbonate sediments which show the heaviest  $\delta^{18}\text{O}$  values and lightest  $\delta^{13}\text{C}$  values, are most likely related to the halo of a lead-zinc deposit. Also, within the ankerite halo to a deposit,  $\delta^{18}\text{O}$  values increase with proximity to the deposit, and a general positive linear correlation between  $\delta^{18}\text{O}$  and alteration index ( $\text{AI}_3$ ) is to be expected.

## Geochemical vectors to stratiform sediment-hosted base metal deposits at the Walford Creek prospect, northwestern Queensland

Peter McGoldrick

This report describes the results of a geochemical investigation of four diamond drill holes through the Fickling Group proximal and distal to the Walford Creek pyrite lenses. The largest of the pyrite lenses contains significant base metal (mainly Pb and Zn) mineralisation, although no resource calculation is available to date (Webb & Rohrlach, 1992). The pyrite lenses are syngenetic and may have had some synoptic relief; base metals occur as impregnations in the pyrite lenses and formed when warm saline fluids moved through the pyrite lenses during diagenesis.

The data indicate that neither the base metals nor the chemical vectors developed for large stratiform deposits can be used to infer the presence of the Walford Creek mineralisation.

The inferred chemistry of the base metal mineralised fluids (Rohrlach, pers. comm.) indicates they would have been good Fe and Mn solutes. Hence, the lack of Alteration Index and  $\text{MnO}_p$  effects cannot be ascribed to mineralising fluid chemistry. More likely movement of the mineralising fluid was restricted to the permeable pyrite mounds, thereby minimising interaction with the host sediments.

Samples from a low-carbonate siltstone above the uppermost pyrite lens in two of the four drill holes are highly anomalous in Mn; this Mn enrichment may indicate a major syngenetic hydrothermal input elsewhere in the basin at this time.



## The Alteration Index and $MnO_D$ at Kamarga (re-visited): new geochemical data

Peter McGoldrick

For this study three diamond drillholes from the epigenetic Kamarga Zn prospect were re-sampled for whole rock geochemical analysis. The data from these samples are compared to an existing set of analyses based on continuous core-grinds (Jones, 1986). The new data confirm the trends in Alteration Index (AI) and  $MnO_D$  described from the old data by McGoldrick (1994).

The Kamarga mineralisation is not associated with anomalous AI and  $MnO_D$  trends, and even Zn-rich samples have low values of these indices.

Fluid inclusion work by Jones (1986) implicates a hot, reduced, acid fluid as the base metal carrier, and although such a fluid would carry substantial Fe and Mn, these two metals are clearly not enriched in the Kamarga host rocks by the mineralising process.

Use of the AI and  $MnO_D$  vectors at an early stage of drilling at Kamarga would have substantially down-graded the prospectivity of the Gunpowder Creek Formation in the area.

## Stratigraphic variations in sulfur isotopes in late Palaeoproterozoic sediments from the McNamara Group, northwestern Queensland

Peter McGoldrick

This report presents the results of over 100 new precise laser probe S isotope measurements from samples from the McNamara group in northwest Queensland. Most of the samples are from the Lady Loretta mine area and from near the Kamarga prospect. The new data from Lady Loretta confirm and extend the trend to heavy pyrite  $\delta^{34}S$  up sequence described by Carr & Smith (1977). Furthermore, multiple measurements in individual bands reveal wide within-band  $\delta^{34}S$  variations down to sub-millimetre scale. These large and small variations are interpreted to indicate closed system biogenic sulfate processes operated for all the time represented by the 150 m of sampled sequence. Approximately 430 million cubic metres of water with 'average

seawater S content' would have been needed to supply the S now present in the Lady Loretta 'Ore Horizon' in both the Big and Small Synclines.

In the Kamarga samples and in the Lady Loretta Formation 90 km north of the Lady Loretta mine, two types of pyrite can be distinguished on the basis of their S isotope signatures, one contains light and variable S and the other a generally tight range of heavy  $\delta^{34}S$  values for any sample. The two types are also texturally distinct. If the latter group form through complete *in situ* reduction of co-eval sulfate then their S isotope signature may represent the basin water sulfate signature at the time of sediment deposition. These data are used to refine the seawater sulfate S isotope evolution curve for the Proterozoic presented in Strauss (1993). Implications of this work to stratigraphic correlations in the lower McNamara group are discussed.

## Two classes of stratiform sediment hosted Pb–Zn deposits

David R. Cooke, Ross R. Large,

Peter J. McGoldrick and Stuart W. Bull

In the past, several subdivisions have been proposed within the large group collectively known as stratiform sediment-hosted Pb–Zn deposits. We propose a new two fold genetic subdivision based on fundamental differences in the chemistry of the base metal transporting fluids responsible for forming the mineralisation. Furthermore, we argue that fluid composition is controlled by the type of sedimentary basin from which the ore fluids are derived. The two deposit classes are called the *Selwyn-type* and the *McArthur-type*. Selwyn-type deposits form from reduced, acid brines, whereas base metals in McArthur-type deposits are transported to the site of mineralisation by (relatively cool) oxidised, near-neutral fluids. Selwyn-type fluids are basinal brines produced from sedimentary basins dominated by siliclastic turbidites and carbonaceous shales. McArthur-type fluids are generated in basins dominated by carbonate-evaporites, oxidised clastics and carbonaceous shales. Most brines sampled from young sedimentary basins are oxidised and several are known to contain elevated levels of base metals

(Kharaka et al., 1987). Fluid chemical modelling demonstrates, for geologically reasonable conditions, there are two potential base metal transporting regions in  $f_{(O_2)}$  – pH space. The first region is reduced and acid and would correspond to Selwyn-type fluids, the second is oxidised and near-neutral to alkaline and would correspond to McArthur-type fluids. Controls on metal-sulfide deposition will be fundamentally different for the two fluid types. Temperature decrease and pH increase will be important for Selwyn-type fluids, whereas reduction processes will be important for McArthur-type fluids. Exploration implications of the new classification are discussed.

### **Review of genetic models at HYC: constraints from new sedimentology, alteration halo studies and fluid chemical modelling**

Ross Large, Stuart Bull, David Cooke and Peter McGoldrick

A review of previous research on the HYC ore deposit, combined with new studies on the basin architecture, sedimentology, alteration halo and chemical modelling of Pb–Zn fluids, indicates that a “deep-water” exhalative model for HYC is compatible with all the available data.

The key elements of the model are:

- the HYC Pyritic Shale was deposited in a “deep-water” setting rather than a shallow sabkha environment;
- the extensive Mn halo to the deposit is a function of Mn exhalation, accompanying basin deepening, with Mn concentration in the oxic/anoxic sedimentary facies prior to base metal introduction;
- the sedimentary breccia–ore cycles are linked to deep seismic events related to basin extension;
- layering in the sulphides is related to rapid pulsing of the basinal brine release, caused by over pressured crack-seal cycles;
- sulphide deposition occurs when the dense, oxidised bottom-hugging brines from each pulse sink into organic dolomitic muds on the basin floor;

- the Py1–Py2–base-metal textural and isotopic paragenesis is a cyclic layer-by-layer paragenesis rather than an orebody-wide paragenesis;
- the ore fluids are cool, neutral pH, oxidised basinal brines rather than hot, acid, reduced brines, and have a much greater metal-carrying capacity than previously considered;
- the source of the ore fluids are basinal brines from the lower McArthur Group which have penetrated deep into the basin to leach metals from the thick felsic and mafic volcanic packages of the Tawallah Group and lower sequences.

Integration of these key elements has led to a model of ore genesis which has major implications for mineral exploration in Proterozoic terrains.

### **The Lady Loretta zinc–lead–silver deposit: primary dispersion halos, sedimentology, ore textures, stable isotopes, and metal distributions — towards a genetic model**

Peter McGoldrick, John Dunster and Mark Aheimer

This report summarises the results of several integrated parallel investigations of the Lady Loretta Zn–Pb–Ag deposit and its host rocks. During AMIRA Project P384 the deposit was the focus of geochemical isotopic studies aimed at defining vectors to base metal mineralisation (McGoldrick, 1993; Large and McGoldrick, 1993; Duhig, 1994; Large et al, this volume). Detailed regional and local scale sedimentological studies of the Lady Loretta Formation were commenced in 1994 (Dunster, work in progress), and detailed macroscopic and microscopic investigations of the mineralisation are reported in Aheimer (1994).

The new information has led to a re-interpretation of the sedimentary setting of the deposit and a new synsedimentary genetic model for the base metal mineralisation and its associated primary dispersion halos.

The host sediments, including the mineralised sequence, are interpreted to have been deposited in a small, shallow, evaporitic restricted water body. Relic textures in the ores indicate early (in part syngenetic) formation of base metal sulfides. The



low Au tenor of the ores and O isotope features of ferroan carbonates in the halo of the mineralisation indicate cool, oxidised fluids supplied the base metals. Geochemical modelling (Cooke, 1993) indicates cool oxidised fluids are excellent solvents for base metals. Sulfur isotopes in the mineralised sequence indicate closed system biogenic sulfate reduction supplied sulfide for pyrite, and may have (indirectly) provided sulfide for base metal sulfides.

Principal features of the new genetic model involve a cool, oxidised metal bearing hydrothermal fluid moving into unconsolidated carbonaceous and pyritic sediments and displacing connate pore fluids. Early (base metal poor) hydrothermal activity promotes copious microbial activity which on burial decompose to cause sulfate reduction and biogenic pyrite formation. Some of this hydrothermal fluid reaches the sediment-water interface. More oxidised fluids are base metal-rich and these react with reduced S in the sediment and the overlying water column to precipitate base metal sulfides. New (ferroan) carbonates are also produced within the sediment by this reaction. Primary mineralogical, geochemical and isotopic halos are caused by the interaction of the hydrothermal fluid with the unconsolidated sediments and the metal sulfide precipitation mechanism which promotes local carbonate dissolution and re-precipitation.

Exploration implications of the Lady Loretta model are discussed.

#### Appendix

### **Stable isotope evidence for thermochemical sulfate reduction in a stratabound shale-hosted zinc-lead deposit: Dugald River, Australia**

Grant Dixon and Garry J. Davidson

*In press: "Chemical Geology"*

This study examines the along-strike and down-dip sulfur isotopic variation of the mid-Proterozoic Dugald River stratabound shale-hosted zinc-lead ore deposit, Australia. Although the metal grade of the Dugald River deposit has been substantially increased at its southern end by tectonism, geological relationships indicate that mineralisation was emplaced

during early diagenesis, probably in an organic-rich, shallow water to evaporitic setting (Muir, 1983). Cu, Cu/(Cu+Pb+Zn) and Pb/(Pb+Zn) decrease in the mineralisation northwards independent of the main structural thickening, and so are likely to represent a pre-deformational primary geochemical dispersion.

Average  $\delta^{34}\text{S}$  values in pyrite and sphalerite are zoned from  $\sim -1\%$  in the south, coincident with the highest copper content of the ores, to  $\sim +8\%$  in the north, accompanying mineralisation thinning. In contrast, adjacent footwall and hangingwall iron-sulfide does not exhibit isotopic zonation, and has a  $\delta^{34}\text{S}$  peak between +3 and +4‰ (n=33), with some values as light as  $-14.5\%$ , whereas overlying dolomites contain  $\delta^{34}\text{S}_{\text{py}} = +5.5$  to  $+17.5\%$ ; each population is attributed to varying degrees of closed-system biogenic sulfate reduction. Two populations of carbonate carbon-isotopes are present. The first ( $\delta^{13}\text{C} = -5$  to  $-11\%$ ) mainly characterises graphitic Footwall Limestone of the Lady Clayre Dolomite, and is interpreted to reflect the metamorphic equilibration of carbonate and organic carbon isotopes. The second ( $\delta^{13}\text{C} = -15$  to  $-25\%$ ) characterises the mineralisation and its immediate sediment host, and is only consistent with formation by the oxidation of organic carbon.

Thermochemical sulfate reduction (TSR) by organic matter is preferred to account for the  $\delta^{34}\text{S}$  zonation, because of (1) mass-balance calculations; (2) the  $\delta^{13}\text{C}$  values of ore and near-ore carbonate; (3) the high temperatures likely for ore formation ( $150^\circ$ – $250^\circ\text{C}$ ), which would have prevented biogenic sulfur reduction but promoted TSR, and; (4) the trend toward  $\delta^{34}\text{S}_{\text{seawater}}$ . The proposed mineralisation model involves two main sulfur sources. An  $\text{H}_2\text{S}$ - and metal-bearing fluid with  $\delta^{34}\text{S} \sim -3$  to  $0\%$  ascended into the Dugald basin in the south, and permeated laterally northward through carbonaceous sediments, below an evaporitic to shallow marine carbonate platform. These fluids reacted with organic matter and sulfate to form  $^{34}\text{S}$ -rich sulfide by thermochemical reduction. Reaction was catalysed by deep sourced  $\text{H}_2\text{S}$ , biogenic  $\text{H}_2\text{S}$  and  $\text{H}_2\text{S}$  evolved by hydrothermal-cracking of organic matter. The sources of sulfate for the reaction were two-fold: (1) evaporites locally within the sequence; (2) dissolved sulfate diffusing from surface-waters into the diagenetic zone.