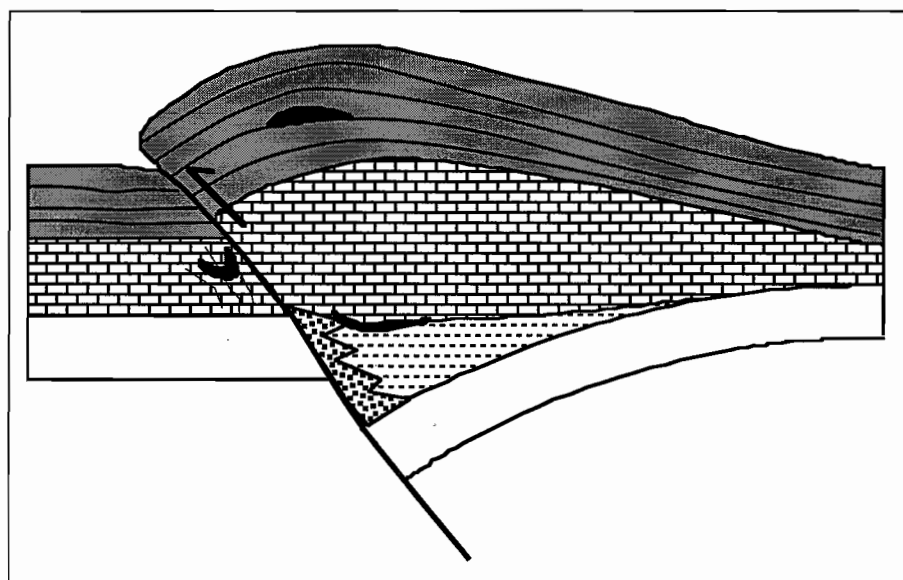


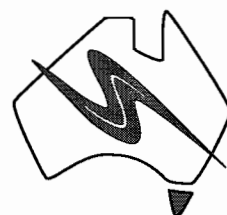
Sediment-hosted base metal deposits

Project Outcomes Report



AMIRA/ARC project P384A

Final Report
December 1998



CODES SRC

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Introduction

Project objectives P384A

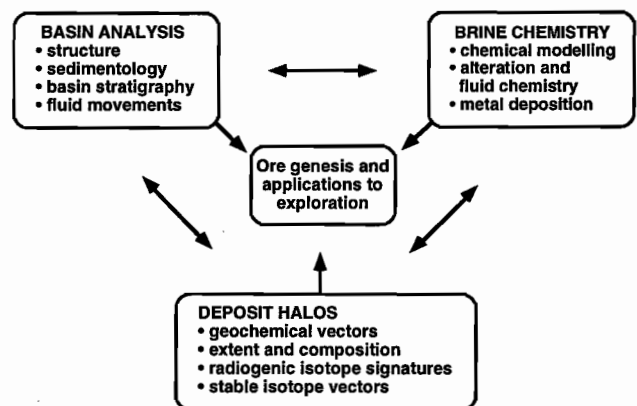
There were four principal objectives of P384A as outlined in the original project proposal and in the November 1996 synopsis:

- To determine the primary geological, geochemical and structural controls on the location and timing of base metal mineral deposits in sedimentary basins, and to develop and refine ore deposit models applicable to exploration.
- To investigate the chemical processes controlling brine compositions and metal sulfide accumulation during fluid movements in sedimentary basins, including the relationships between copper and lead-zinc deposition
- To investigate the physical and hydrological processes involved in the evolution and movement of metalliferous fluids in sedimentary basins
- To develop geological and geochemical vectors to a variety of styles of sedimentary base metal mineralisation that may be used in the exploration for large tonnage deposits.

Research framework

This project utilised a multidisciplinary approach incorporating geophysics, sedimentology and structure, lithogeochemistry, and physical and chemical fluid modelling. For convenience, the research programme for the original P384 project and the P384A project extension, has been run as three separate, but related modules (see figure below). As the original P384 project progressed, this

distinction began to break down, resulting in the presentation of several integrated studies in the final report. This integration of research disciplines has carried over into the P384A project extension, and the studies presented here in the final report routinely overlap more than one module.



Achievements of the project

Module 1 : Basin Analysis

1. Interpretation of regional gravity and magnetic data has been extended through the Camooweal and Dobbyn 1:250,000 sheets to include 5 sections across the Mount Isa and Cloncurry region. Structures and sequences from the western Mount Isa Basin are consistent with those previously described from the Mt Drummond and Lawn Hill sheets. Indications are that the major mafic sequence interpreted across the region is a correlate or extension of the Eastern Creek Volcanics.

2. Interpretation of the gravity data in the southern McArthur Basin has been used to infer thickness of the dense, dolomite-dominated McArthur Group and revise the overall setting around HYC.
3. Detailed interpretation of the gravity, magnetic and radiometric data from around the Lady Loretta deposit has also been carried out. It indicates a WNW-oriented syndepositional structure extending from Lady Loretta to the Mount Gordon Fault Zone along the Redie Creek Fault trend, and a magnetic low beneath the ore body that could represent a sub-basin or zone of alteration.
4. Mapping and integrated structural and sedimentological analysis of key areas of McArthur Group in the southern McArthur Basin, has confirmed that the mineralised succession, comprising the Barney Creek Formation and adjacent units, was deposited during a period of tectonically-generated sub-basin formation. This is reflected by rapid lateral facies changes from depocentres to marginal areas that render the current layer cake stratigraphic scheme inadequate for detailed studies.
5. Structural mapping and sedimentological sectioning around the mineralised stratigraphic level along the sinuous Tawallah and Hot Springs Faults, using the Coxco Dolomite as a stratigraphic marker, indicates an apparently systematic structural control on sedimentation, and hence basin formation. Basinal facies deposits like those that host HYC occur in accommodation space generated adjacent to NNW-trending fault segments by extension and growth faulting on parallel structures. In contrast, there are often no basinal facies present in areas adjacent to N-NNE-trending fault segments, where sedimentation records sustained shallow water conditions indicating no accommodation space was generated.
6. Detailed mapping of the Myrtle Basin, an area situated some distance from the major N-NNW-trending structures where the original basin geometries have been masked by major wrenching and associated transpressional folding has provided the first constrained field evidence that E-W-trending faults and folds are syn-Barney Creek Formation structures. Sub-basin formation and deposition of potentially mineralised Basinal Facies deposits was optimised where these structures intersect the NNW-trending faults, and occurred in two distinct transgressional cycles. Work in this region has also given insight into the potential significance of spectacular heterolithic carbonate megabreccias similar to the breccias in the Barney Creek Formation around HYC.
7. In the Mount Isa Basin, integrated structural and sedimentological analysis of the basal McNamara Group units in the Kamarga Dome and Lady Loretta areas of the Lawn Hill Platform, indicates that they represent a phase of active tectonism (~rifting). This event established the structural template which controlled mineralisation in the overlying "sag" phase carbonates and clastics.
8. The Lady Loretta deposit occurs in the tectonically quiescent "sag" phase of the McNamara group, that is characterised by the deposition of peri-tidal platform carbonates. The host rocks are indistinguishable from the formation regionally, and there is no evidence that the mineralising event was associated with active tectonism and sub-basin formation. However, the mineralised site is located adjacent to a growth fault in the subsurface that was active at lower McNamara, illustrating the importance of understanding the rift-phase architecture of mineralised basin settings. This situation is similar in some respects to that of the Century deposit.
9. Sedimentological analysis concurs with geophysical interpretation that the growth fault adjacent to Lady Loretta was a northwestern continuation of the Redie Creek Fault. In the area of the deposit, this structure appears to have been cut/offset by a number of relatively

closely spaced, roughly orthogonal faults (?transfers). These were subsequently re-activated during the Isan Orogeny to produce the present day structural complexity of the Lady Loretta area, suggesting that other areas of equivalent structural complexity in the Lawn Hill Platform could be prospective for base metal mineralisation.

Module 2 : Brine Chemistry and Fluid Flow

10. Based on the results of chemical modelling, two brine types have been identified that are capable of precipitating stratiform sediment-hosted Pb-Zn mineralisation, which should form in distinct tectonostratigraphic environments. McArthur-type brines can form in basins dominated by oxidised sedimentary lithologies, such as the northern Australian Proterozoic basins. These oxidised brines can transport high concentrations of Pb, Zn, Cu and (depending on pH) Fe and Mn, but will not carry Ba, Au or Sn. Selwyn type brines have reduced and acidic compositions, and form in reduced basinal environments. They can carry elevated Pb, Zn, Ba, Fe, Mn and in some cases Au or Sn, but are unlikely to carry high concentrations of Cu.
11. Numerical simulations of ore deposition have identified that fluid mixing is the most viable mechanism for Pb-Zn sulfide deposition in the Northern Australian basins. Mineralising brines can potentially mix with seawater or hydrocarbon reservoirs and precipitate their base metal loads. In general, water-rock interaction is predicted to precipitate base metal sulfides associated with complicated gangue assemblages, unless only one or two reactive components are present in the host lithology.
12. Several discrete episodes of alkali metasomatism have been documented in the sedimentary and volcanic lithologies of the McArthur and Tawallah Groups. Low-temperature alkali metasomatism resulted in leaching of base metals from the Tawallah Group dolerites, and the resultant metal-rich brines had potential to become involved in base metal mineralising processes elsewhere in the basin.
13. In parallel to P384A, a preliminary hydrogeological study of the southern McArthur Basin has been undertaken with funding from CODES SRC. This involved numerical modelling by Grant Garven, of an east-west section through the Batten Fault Zone in the area of the HYC deposit. The section was constrained using open file geophysical and field-based data from the Basin Analysis Module of the original P384 Project. The results confirm that large fault zones exert a major control on flow patterns in both density- and topography-driven hydrothermal systems, and that the upper Tawallah Group sandstones provide a significant strata parallel aquifer system for the focus of deep basinal brines.
14. Petrographic, lithogeochemical and FTIR studies in the McArthur Basin have defined a pattern of K-Al silicate distribution, which is considered to result from diagenesis and fluid evolution related to basin-wide fluid migration. This work, when integrated with hydrologic modelling, and structural/sedimentological studies, has the capacity to focus exploration into high priority fluid discharge sites related to stratiform mineralisation.

Module 3 : Deposit Halos

15. Detailed lithogeochemical halo models have been developed for the following seven Australian Proterozoic stratiform Zn-Pb-Ag deposits: Lady Loretta, HYC, Mt Isa, Century, Mt Novit, Walford Creek and Grevillea, and one strata-bound deposit (Kamarga). Lithogeochemical vectors for these deposits have been tested on samples from the Sullivan deposit in Canada.

Each model includes a description of the geochemistry and mineralogy of the halo and a set of criteria and vectors that are useful for regional and mine scale exploration.

16. A basket of exploration indices has been developed which can be applied in the identification of favourable horizons for stratiform Zn-Pb-Ag deposits within carbonate-bearing sedimentary basins.

17. Specific studies of lithogeochemistry in the Lawn Hill region surrounding Century have identified the potential for several mineralised horizons within the Lawn Hill Formation. This research has shown that, in addition to unit Pmh 4, there are three other stratigraphic levels with potential for stratiform Zn-Pb-Ag mineralisation.
18. Carbon and oxygen isotope chemostratigraphy has been undertaken in a number of locations throughout the McArthur Basin to establish the background and anomalous isotope patterns. This work has identified an extensive C/O isotope halo surrounding the HYC deposit, of similar character to the isotope halo previously defined at Lady Loretta in P384. This work has also revealed that the isotope trends within the halos at HYC and Lady Loretta are unique, and very different to carbonate isotope patterns associated with other carbonate replacement deposits (MVT, skarn, carlin-type and Renison-style replacement deposits).

North Exploration
Pancontinental Mining
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Thanks also to Buka and Brenton Grant for continued access to Lady Loretta. To Damien Nihil at McArthur River Mining for access to drill core and underground exposures at HYC. To Andrew Allen and Ian Matheison at North Limited for supporting honours projects and allowing access to their Bloodwood Bore prospect, and to Ian Garsed at MIMEX for allowing continued access to the Kamarga Dome area. To Coolgardie Gold and Andrew Allen again for allowing access to the Grevillea Prospect. To Dave Wallace and Tony Hespe at Aberfoyle for allowing access to their Lawn Hill drilling. To Cominco for allowing sampling of Sullivan and Sheep Creek. To Lesley Wyborn for access to the AGSO Rock Chem data base and for providing the delightful fruit cakes at the sponsors meetings. To John Dunster, Peter Winefield & Mark Duffett for unstinting contributions to the overall research program. To the NABRE team for fruitful discussions and access to gamma log data. To the NTGS for field equipment (sorry about the fridge Neils). To the high quality analysis team (Phil, Nilar and Katie) for the geochemical data. And last, but not least, to Mike Blake and June (Pongratz Productions), without whom the compilation of this report would have been impossible.

This report

The Final Report for P384A is divided into three volumes:

- Volume 1: Summary of Outcomes
- Volume 2: Research results for 1998
- Volume 3: Publications from AMIRA P384 (1992 to 1995)

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Architecture of the McArthur and Mount Isa Basins, northern Australia

David Leaman

Centre for Ore Deposit Research

Summary

The enormous sedimentary hosted Pb-Zn ore deposits of northern Australia are located within sequences which, in several instances, have not been markedly deformed nor altered since formation. Further, the host sequences generally lack evidence of intensive tectonism or volcanism at the time of deposition - hints of tuffs or local faulting notwithstanding. While the rocks of the Mount Isa region have been folded, thrust and eroded, but not significantly metamorphosed, those of the McArthur Basin are much less altered.

The large HYC deposit, placed in this setting, poses a fundamental question: what could have controlled mineralisation processes within this part of the basin at that time and in that, not apparently special, host sequence?

The answer to such a question has widespread ramifications both for appraisal of other deposits now in less pristine settings and for exploration.

The regional geophysical and basin evaluation undertaken was designed to suggest either the answer or constraints upon it.

Data and methods

Regional gravity and magnetic data, as compiled in 1991-2 were used throughout the study. Deficiencies and variations in both cover and reliability were known to exist (and which have since been claimed to have been resolved — Leven *et al*, 1998) but the forward modelling of a large, interlocking line array (ultimately about 160 profiles) was able to identify most problems and check consistency of implied solutions. All solutions were required to satisfy both

data sets and defined, objective criteria (Leaman, 1994a) which, while not establishing veracity in detail, do indicate the most likely *style* of solution. This study represents the first comprehensive, large scale, quantitative analysis of the data sets in the region.

These methods soon revealed geological implications not countenanced previously — namely that sequences including volcanics were common and of a scale comparable with those in the adjacent Mount Isa Basin. This topic was canvassed in Leaman (1996) and the actual nature of the methods and results were described in Leaman (1997a).

Although the analysis was based on regional compilations and coarsely-sampled profiles (in order to evaluate long wavelength effects and minimise data quality variations and shallow spike sources) it has been claimed since that many long wavelength effects were artifacts of non, or inappropriate, levelling of the data sets (magnetic) (Leven *et al*, 1997). While there may have been inadequacies in the compilations, or their presentations, as used the interlocking array solution based on rigorous criteria and use of both gravity and magnetic data sets not only identified such problems but allowed general separation of sources of error. This is not a valid criticism of the final results which are only claimed to have indicative and regional validity at this stage. Additionally, Leaman (1997a) showed that intra basement source variations (now offered as an alternative explanation by Leven *et al*, 1997) are not likely to produce the long wavelength responses sought and do not satisfy line array solutions. It may be concluded that a thick basin sequence including an extensive, wedged sequence including volcanics is required.

The limited seismic data available are wholly

consistent with the interpretations provided (see Leaman, 1994b) regardless of whether some units are within "acoustic" basement or not. magnetic and gravity responses are not restricted by such concepts.

Conclusions from the first part of the project (P384) were published as Leaman (1998d). Most work has focussed on structural conditions north and west of the Murphy Tectonic Zone and the Lawn Hill Platform; that is, the McArthur Basin (Leaman, 1993a, b, c, d, 1994b). Some less detailed extension of this analysis was completed in order to test some implied correlations and allow some comparison with setting of mineralisation near Mount Isa (Duffett, 1996; Leaman 1997b, 1998c).

Geological implications

The interpretation provides information on several aspects of the basin; namely its basement, its contents, location of major rift structures and an indication of fault history.

The basement is composed largely of granitic rocks. A range in composition is implied by gravity responses but few magnetic contrasts can be detected or confirmed. This suggests that granodiorites, diorites and monzonites are either not dominant or the plutons are too deeply buried for any response pattern to emerge from relatively subtle contrasts. Many lesser plutons intrude the basement complex and some may penetrate the lower members of the main basin sequence. Metamorphic complexes are not physically significant and are essentially non magnetic. Metamorphic basement east of the Murphy Ridge, and east of the Gorge Creek Fault, is much denser than that to the west. This axis may represent the junction between the Isa and Cloncurry terranes and, near the Murphy Ridge, this trends NNW. Granitic basement is increasingly disrupted to the north and west of HYC and this may indicate greater extension overall in that direction.

The main basin sequence consists of at least two, deeply buried and very thick volcanic suites; an upper, thin volcanic suite; a dense, dolomitic sequence and all are overlain by a thick siliceous sequence. Although there has been considerable debate concerning the possible correlation or identification of these geophysically-defined packages it seems certain now that the lower members

are correlates of either the Eastern Creek Volcanics or the Argylla Formation and the Eastern Creek Volcanics. Other packets represent the Tawallah Group volcanics, McArthur Group and Roper/Abner Group. Non magnetic units of average or background density cannot be specified although their likely thickness can be suggested.

The two deeper 'volcanic' suites — both demonstrably magnetic and denser than sedimentary background are variable in thickness and distribution. The interpretation can only describe the sequences crudely as they 'appear' today but the lower sequence is much more patchy or piled although up to 5 km thick and there are regions in which the material is absent; either eroded or never deposited.

The upper sequence, denser and more magnetic is clearly mafic and contained in half graben with a thickness of up to 11 km. Again, there are regions in which the material is absent but erosion following persistent uplift is implicated in this case and it is likely that the volcanism was very broadly spread. In one region within the Tawallah Ranges near Bauhinia Downs both sequences have been removed. Although the summation of work completed up to 1995 (Leaman, 1998d) suggests that the lower sequence is "felsic" more recent analysis (e.g., Leaman, 1997b, 1998c) has led to some review. Although one can argue that parts of the Scrutton (or Clifffdale) Volcanics might possess the appropriate properties, so do the rocks of the Argylla Formation. The massive thicknesses are a problem in terms of sustaining magnetic contrasts and it is likely that the lower unit either consists of mafic rocks diluted by quartzites or other sedimentary rocks at about 50:50 proportions. The upper volcanics are likely to contain >80 : <20 proportions of volcanics to sediments and the tie line models connected to the main Isa-Cloncurry type sections shows that the upper volcanics are undoubtedly direct correlates of the Eastern Creek Volcanics.

The lower part (typically 2–3 km) of the Cromwell Member of the Eastern Creek Volcanics of the Mount Isa region is less magnetic (by about 50%) than the upper part and both parts of this member are less magnetic than the overlying Pickwick Member - which is thinned by erosion throughout the Isa Basin. The entire known ECV package is up to 8 km thick and the Cromwell Member may account for 6 km of

this. It is possible that the interpretation of the McArthur Basin has identified both members and fully estimated representative thicknesses of the Pickwick Member (or its equivalent) (Leaman, 1998c, d). See also Scott *et al* (1997).

Although detailed review in the Tawallah Ranges and Mount Young region shows that thick sequences, either of Westmoreland Conglomerate or Yiyintyi Sandstone, can be mapped adjacent to the major fault systems the effective geophysical markers within the Tawallah Group are volcanics (Leaman, 1992, 1993c). The Tawallah Group rocks have been deposited upon a major erosional surface with local basin developments being much more restricted. It is at this stage of development that the, so-called, Batten Trough becomes evident due to persistent uplift within the ranges and Murphy Inlier.

The McArthur Group is similarly framed within local structures and some have been grossly defined by density differences reflecting dolomitic proportions in the sequence (Leaman, 1992, 1998e). More detailed examination of these relationships when correlated with drilling and geological sections in the HYC region shows that pre McArthur Group contributions can erratically swamp local density variations. Zones containing sulphides above background levels are unambiguously defined in gravity surveys where data coverage is wide enough to sample both the anomalous region and the more normal rocks (Leaman, 1999e).

The overlying Roper Group is readily discriminated by density contrast and thickens westward where some structures preserve up to 6 km of the group.

Structures

Many structural trends associated with pre-Tawallah Group rocks are not evident in presentations of the gravity and magnetic fields. Detailed magnetic data, in particular, tends to map or represent very shallow, post Roper character and gravity definition is much more limited overall. Interpretations within 2–5 km sampling cells does allow recognition and definition of primary structures including fault zones and rift margins. The dominant fracture trends are NNE, NNW, NE and N-S and, near the Murphy Inlier,

ENE. Many of these are recognisable throughout the entire 21 km established thickness of deposition in some areas (Leaman, 1998d; Leaman & Keele, 1995).

Rift margins tend to preserve N-S, NNE and NW orientations but critical zones, especially those uplifted, are approximately E-W. Most persistent uplift is focussed in the region of the Murphy Tectonic Zone (trending ENE) and this is arguably still active. Lesser uplift (N-S) extends along the Tawallah Range. Total uplift in each zone during basin history may be as much as 20 km although onlapping and depositional thinning may have been contemporaneous at all stages. These uplifted zones, always tectonically active, must have constrained or restricted fluid flow as discussed by Leaman (1998a).

Rift cells and patterns generated during the volcanic-extension phase of basin development can be mapped regionally. Subsequent Tawallah/McArthur, and Roper Group developments could be expected to have been influenced or controlled by some of these elements and there is every suggestion, for example, that the modern Calvert Fault, is such a rejuvenation. Similarly stresses to yield the early basins imply sub N-S compression. Similar stresses apply today (Winefield *et al*, 1997; Davidson, 1997). The Emu Fault fits a part of this stress field.

Fault/fracture histories compiled for the HYC area (Leaman, 1992, 1998d) indicate a complex, interwoven pattern on all major structures. The fundamental structures trend NW or NE; the Calvert, Mallapunyah and Lagoon Creek Faults are derived from the former and the Emu East, Tawallah and southeast sections of the Lagoon Creek Faults are derived from the latter. Other faults divide this conjugate (~NNW). At each intersection and at each time-range of formation the NNW-trending structures change sense of displacement and, probably, style of movement. Continuous activity is implied on all elements at all times. Packets of NE-trending shears indicated by regional analysis are both defined and confirmed by other change-overs. HYC lies at one such junction and the zone of anomalous sulphide distribution lies directly east of the intersection (within the precision of the methods and sampling employed) (Leaman, 1998e). A small granitoid which penetrates lower sequences of the basin succession occupies the area directly west of this same intersection. Such a conjunction is not likely

to be random and must be significant in terms of heat and fluid flow (also Leaman, 1998a).

Settings of mineralised sites

Most information about architecture and fracture history has been collected for the HYC region although areas about the Century, Hilton and Mount Isa deposits may be compared generally. All sites appear to be located within the most active rift element of an active zone but within 5 km of the uplifted margin and not within the subsiding cell. Fluid circulation may have been enhanced by this marginal aspect. The sites are at extreme conjunctions of long-lived regional fracture systems. Transforms and shears are indicated. A relatively young penetrative granitoid is nearby in each case but the role of the intrusion is uncertain and its effect may be thermal, circulatory or structural.

There is no evidence for any margins to the McArthur Basin and it was clearly not a simple, linear and narrow structure. The entire "basin" appears to have been made up of sets of thermal, subsiding cells in which activity was never consistently focussed in the region of any particular cell (Leaman, 1998a).

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Review of interpretation of McArthur Group near HYC

D.E. Leaman

Centre for Ore Deposit Research

Introduction

Leaman (1992, Fig 13) presented an interpretation of the thickness of at least part of the McArthur Group. It was suggested initially that the upper (Batten Sub Group) was denser overall and that the difference was recognisable in gravity analysis of regional data. The inference was then extended to the entire group due to the common and extensive occurrence of dolomitic rocks which are clearly denser than other groups. The interpretation was dependent upon establishment of a regional structural view at basin scale. This view allowed an assessment of that portion of the gravity field which was not readily explained; a gross association between deviations and distribution of the McArthur Group was then noted.

The data used for this early analysis were treated consistently (see criteria of Leaman, 1994 which establish feasibility of solution) but were lacking in resolution due to station spacing and sample spacing for regional analysis. The approach was acceptable for a primary regional study. New data were acquired in late 1997 by Codes (M. Duffett observer) and supplemented by detailed coverage near the HYC deposit (courtesy MIM). Although the amended coverage is variable it has been possible to revise discussion of gravity field character near HYC, to sample in a more detailed manner and hence to revise the overall interpretation in the region.

This revised interpretation has been coupled with an updated compilation of the geology of the region. A new basemap derived from Smith et al. (1964), Pietsch et al. (1991) and a number of CODES projects undertaken as part of AMIRA P384 has been compiled by S. Bull.

Comments on the gravity field

The previous interpretation demonstrated that the features of the gravity field were a complex integration of sources and structures and that shallow (< 2 km) sources were dominated by substantial deeper elements; the principal basin fill and basement granitoids in particular. This conclusion has been reinforced by relationships which can be more sharply defined by the new compilations.

There are very few direct correlations between the gravity field and exposed geology. Three evident upon inspection are the local, relatively positive peak near HYC (radius of 3–4 km), and two negative features within the Abner Range. The first response is associated with the pyritic host sequences in the ore zone while the second is associated with pockets of Bukalara Sandstone within the Abner Range structure. There are also very minor negative correlations with exposures of Tawallah Group rocks and examples may be noted near Mallapunyah and along the northern section of the Tawallah Fault. The response at Mallapunyah is relatively minor and very local. The Tawallah Fault block response is also subtle but can be distinguished from a much larger negative effect further south.

All large scale features, whether broad patterns or gradients, express no association with any mapped structure, unit or group of units.

There is a single sweep of gradient from east of HYC, where there is no suggestion of pre Roper Group formations, and across the Calvert Fault-Emu Fault-Hot Springs Fault-Mallapunyah and Tawallah Fault systems. This gradient which curls from N-S to E-W displays no noticeable deflection (with existing data coverage) at any fault or at any formation

boundary in this region. Part of smoothing of response may be due to cover of Bukalara Sandstone. Some changes have been observed elsewhere in the area where either Roper Group or Bukalara Sandstone abut faults or produce other marked boundaries. Such changes are to be expected given the known density contrast between these formations and the older McArthur and Tawallah Group rocks.

Much finer survey coverage may be required southeast of Myrtle Basin in order to evaluate the existence or significance of any responses due to these materials.

The gradient defined above marks the eastern and southern limits of a belt of relatively positive Bouguer anomalies which extends from north of HYC through Myrtle Basin to the Mallapunyah Dome area. The Emu Fault zone only partly modifies the response pattern and most of the change can be linked to Roper Group further east.

The negative anomaly centred a little east of the junction of the Abner and Tawallah Faults cannot be explained by any exposed unit or structure. Gradients associated with this feature, as with the larger regional gradient described above, tend to be normal to any geological pattern - including the principal areas of exposure of the McArthur Group.

Regional interpretation (Leaman, 1992) implied that the negative anomaly was related to granitoids while the main eastern gradient was due to an interplay of volcanic piles and granitoids. The distribution of Tawallah and McArthur Group rocks can not explain either anomaly.

Review

The ten regional sections-profiles which were used to generate the original concept (Fig 13, Leaman, 1992) were re-calculated using more detailed gravity profiles and with regard to more detailed geological compilations (at 100 000 rather than 250 000 scale). These sections have been supported by some additional profiles in order to improve general definition.

The interpretation remains difficult and would, on a single section basis, be considered ambiguous and uncertain. This situation reflects the interplay between sources and only the interlocking aspects of

a line array method allows adequate resolution of the gross sources — allowing subtler aspects to be treated. It should also be noted that the primary regional view, modified here, was also supported by magnetic data analysis and few changes have been made which affect the magnetic field in any way. The emphasis in this review has been directed toward extraction of the contribution *possibly* due to McArthur Group.

Even this subset source study is complex and uncertain since it presumes

- (a) validity of the underlying basin model (acceptable and not especially critical)
- (b) knowledge of density contrasts in McArthur Group rocks (uncertain)
- (c) knowledge of sectional proportion of dolomites (not really known areally)
- (d) adequate indications of other near surface source densities (fair)

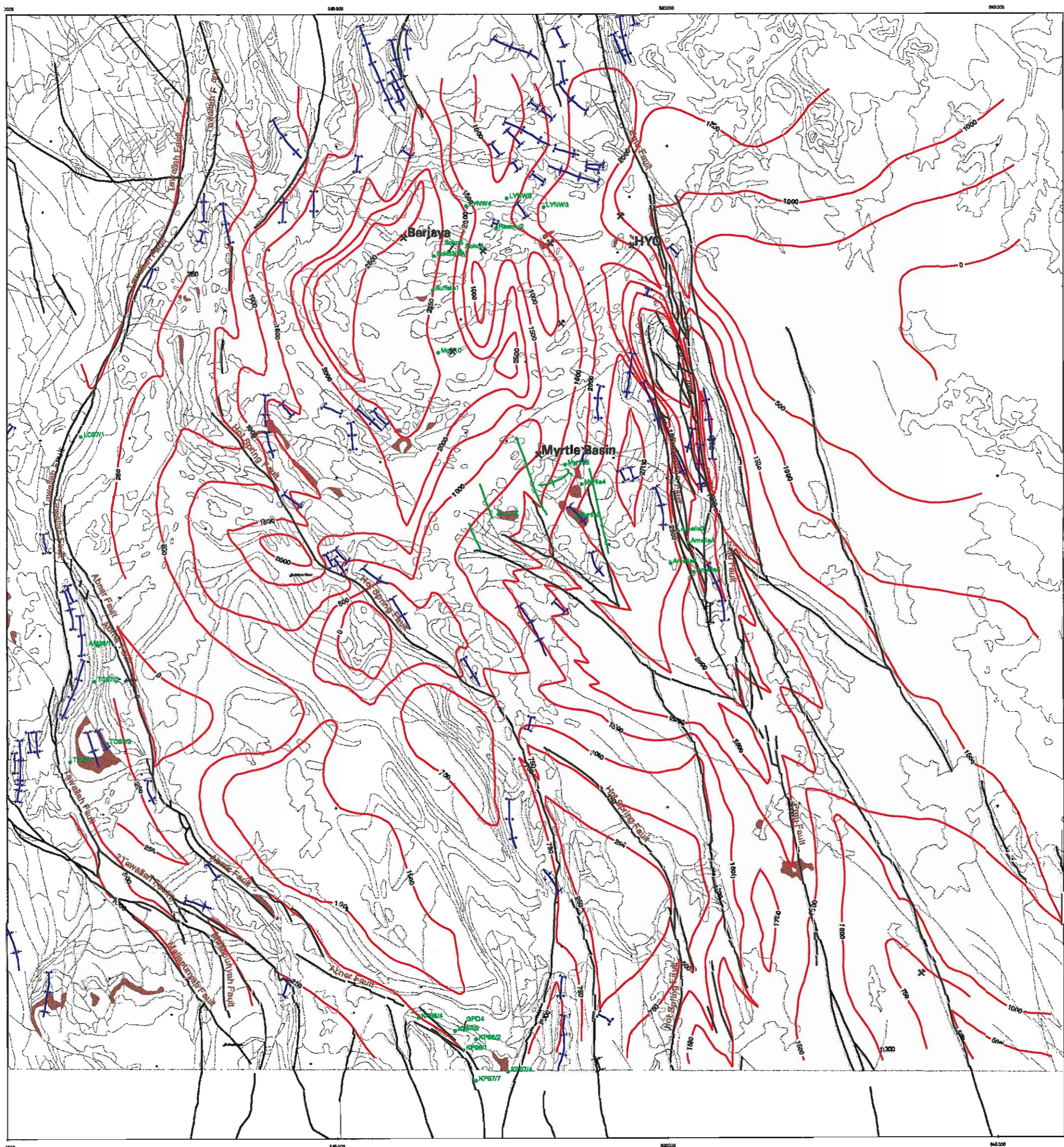
The original interpretation was prepared within these limitations and the present review has also been similarly constrained but rendered more reliable by many more recent interpretations and compilations.

The interpretation now provided should be considered only as a guide to group thicknesses since it presumes a marked contrast (0.03 to 0.05 t/m³) between McArthur Group and Tawallah Group. The contrast with Roper Group and younger rocks is at least 0.15 to 0.18 t/m³ and this is much more convincingly established. There have also been places where adjustment of the form of the underlying granites affects this study - especially near the Tawallah Fault and northwest of Mallapunyah. Since the new data have sharpened definition of these bodies some review of their shape was also completed.

The results are shown in Figures 1 to 4. Figure 1 presents a compilation of both the geology and the revised view of the gravity interpretation (at A3 size, 1:200 000). Figures 2 and 3 present samples of the revised sectional models and Figure 4 suggests the distribution and general thickness of the McArthur Group. The relationships shown in section are little varied from those presented in the original interpretation. The assigned thickness contour values shown in Figure 4, however, should be treated as



McArthur Group Thickness



Survey + Renewed outcrop

Jersey Creek Formation

Cell size 100m

Isobars labelled in metres

Geology from NTGS Southia Downs 1:250K, BMR McArthur Basin 1:1M, David Selley

Geophysical interpretation by David Leaman

GIS by Mark Duffett and Mike Black

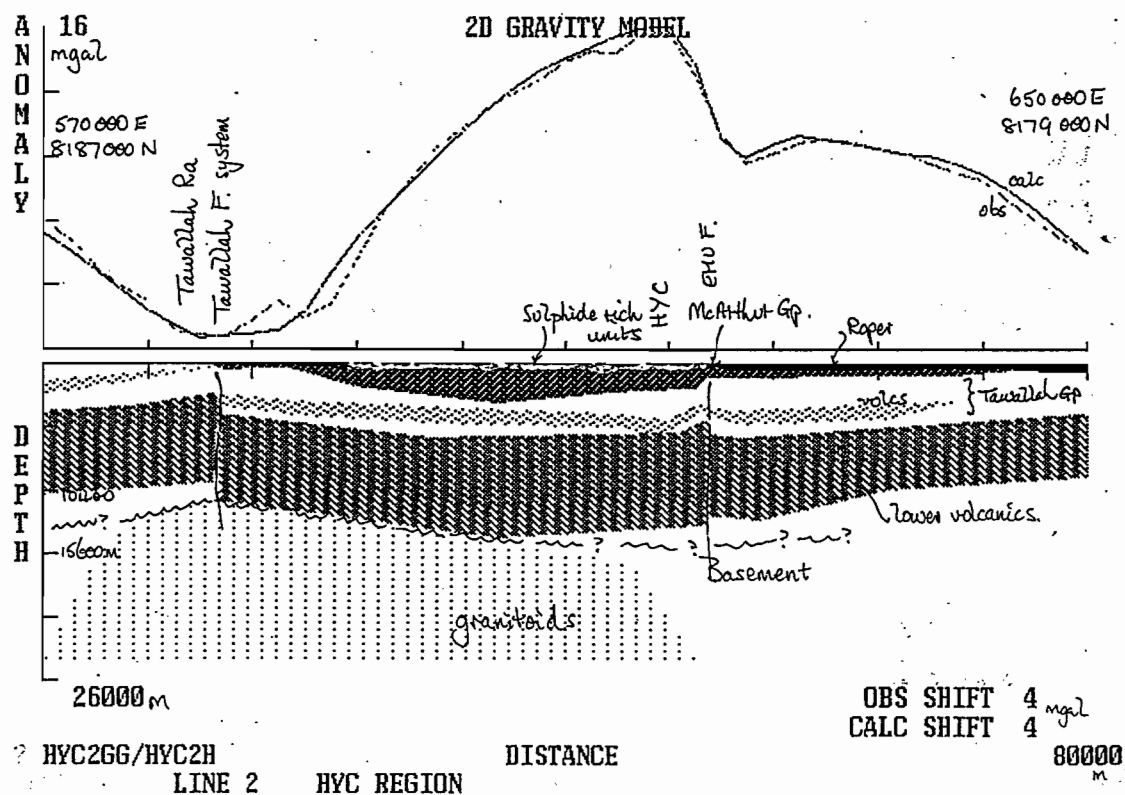
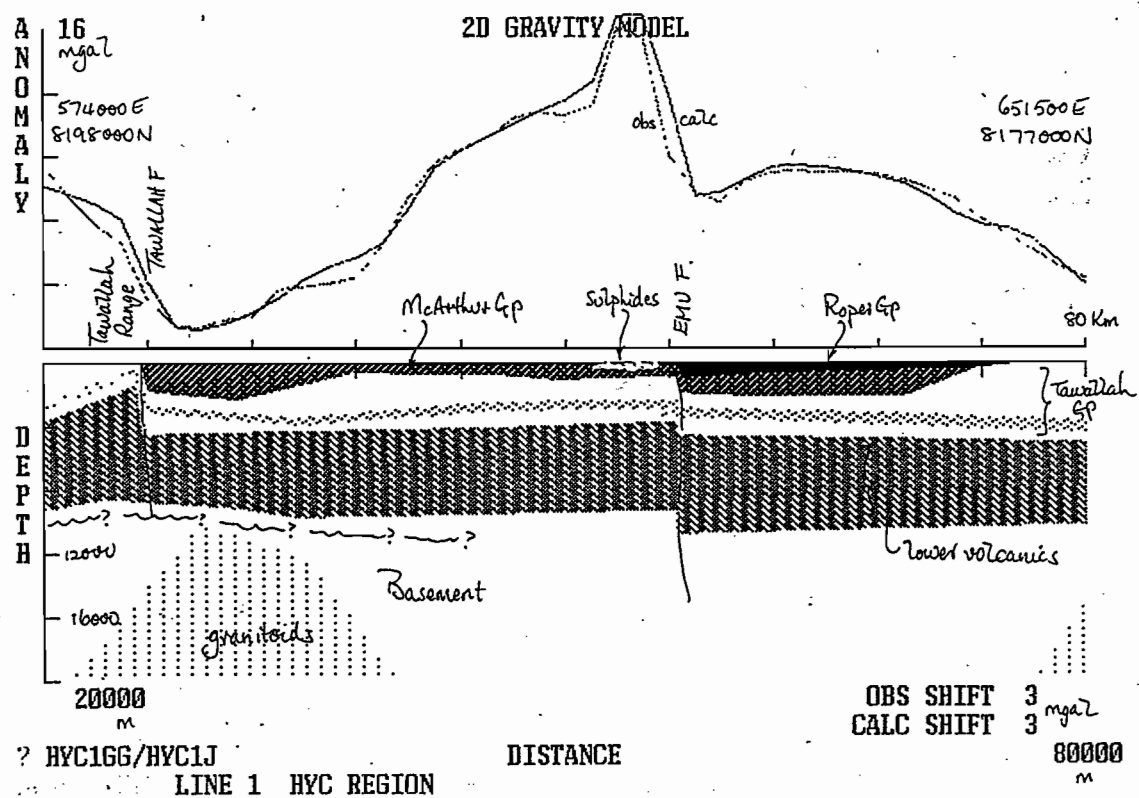


Figure 2

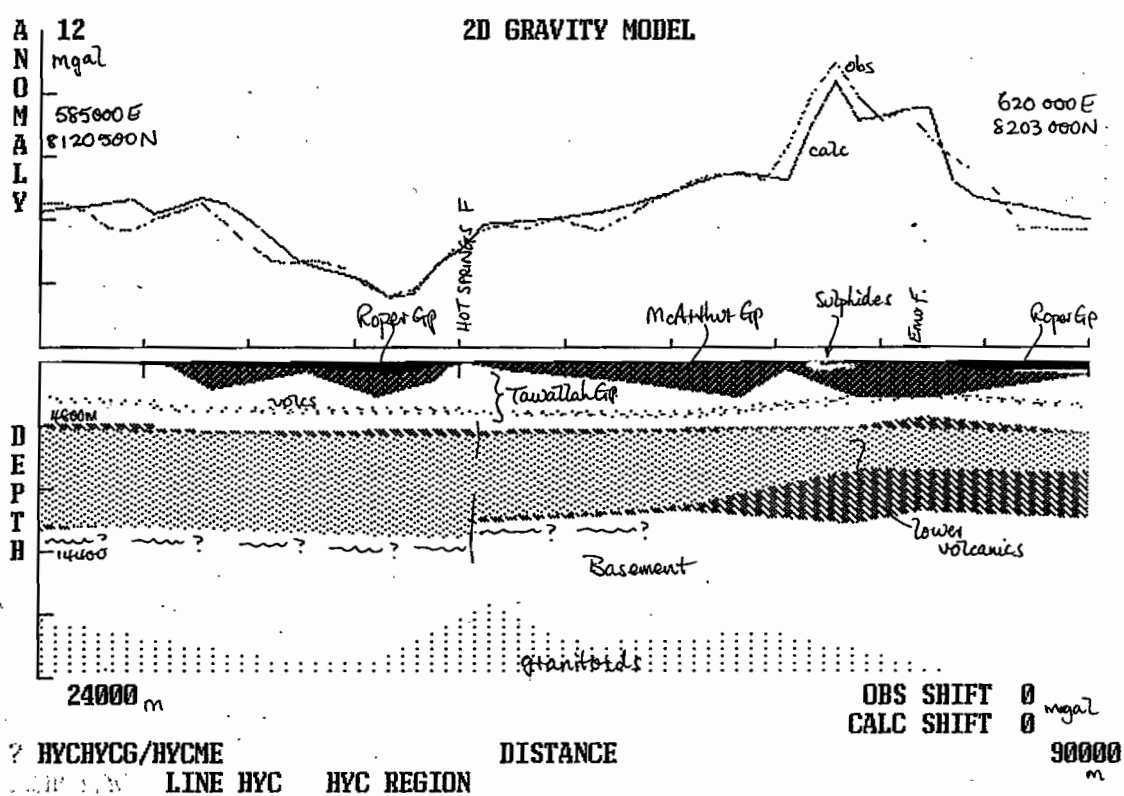
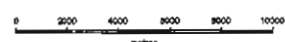


Figure 3

CODES



Cell size 100m

isochores labelled in metres

 Stratiform Pb-Zn

Geology from NTGS Bauhinia Downs 1:250K, BMR McArthur Basin 1:1M, David Selley
Geophysical interpretation by David Learman
GIS by Mark Duffett and Mike Blake
AMIRA P384A, December 1988

relative rather than absolute due to group variability and are only intended to suggest patterns of thickness change only.

The new modelled sections exemplified by Figures 2 and 3 which sample the HYC area orthogonally stress the contribution of sulphides within the dolomites of the immediate vicinity of the mine area. This effect is very localised with a radius of only a few kilometres and unambiguously defines the mineralised area - but only when seen in the context of the much more regional coverage. Much of the gravity data in the mineralised area as acquired by MIM for local exploration and assessment could not be used to provide this perspective when used in isolation since the station detail is too great and the area covered is too small for a dispersed, sedimentary ore body system.

The models, in terms of their contribution to any refinement of high level basin concepts, remain somewhat ambiguous in some areas. For example, some responses which may be associated with Abner or Roper Group cover may obscure the contribution from the McArthur Group. It may be possible to make a simple fit by ignoring the lower sequence when, if one were to assume a continuous underlying sequence, the model would require a much thicker cover or cover structure. This interplay cannot be resolved fully without a higher station density (perhaps 1 or 2 per 2 km) or the use of another supporting method in critical areas. Where the interplay involves non magnetic rocks electrical or seismic methods must be used.

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Tectono-sedimentary setting of the northern Australian sediment-hosted Zn-Pb-Ag deposits

Stuart Bull

Centre for Ore Deposit Research

The major aim of field-based studies for the P384A Basin Analysis Module was to determine the tectono-sedimentary controls on sites that host base metal mineralisation. This involved mapping and integrated structural and sedimentological analysis of known mineralised stratigraphic levels in key areas in the southern McArthur and western Mount Isa Basins. The mineralised level studied in each basin has provided a valuable contrast in deposit setting.

In the southern McArthur Basin the host rocks to the HYC deposit, the Barney Creek Formation carbonaceous, pyritic, dolomitic siltstones, were clearly deposited in fault-bounded sub-basins generated during a period of active tectonism. In this context, the specific aims of this aspect of the study were to understand the nature and controls on the basin forming and mineralising event. The research strategy involved comparing structural and

sedimentological data from around the level of known mineralisation at different sites within the regional fault network. In order to achieve this, it was necessary to move beyond the drillcore based style of analysis that underpinned all previous studies of the Barney Creek Formation and associated units.

In the western Mount Isa Basin, the Lady Loretta deposit is hosted in peri-tidal carbonates deposited during the tectonically quiescent "sag" phase sedimentation of the middle McNamara Group. In the apparent absence of a sub-basin at Lady Loretta, the aims of this aspect of the project were to determine, if possible, what does control the location of the mineralisation. The research strategy was to examine the basal McNamara Group clastics, on the premise that they would record the active tectonism that formed the template for subsequent mineralised "sag" phase sedimentation.

The Barney Creek Depositional Cycle (BCDC)

Peter Winefield, Stuart Bull and David Selley

Centre for Ore Deposit Research

Sedimentological work undertaken in the initial AMIRA P384 project concentrated on thick intersections of 'typical' Barney Creek Formation, which is dominated by sub-wave base dolomitic siltstone and shale. Detailed facies analysis of these sediments clearly indicated that an agitated shoreline facies co-existed with these 'deeper water' deposits and it was suggested that this might be represented by areas mapped as Reward Dolomite (Bull, 1995). Mapping of several key field locations and detailed study of numerous drill-cores and measured sections, based on the recognition of the Coxco Dolomite Member as a distinctive transgressive marker unit (see also Winefield, 1997), has demonstrated that there are actually several time-equivalent facies associations that represent deposition of sediment on a slope and platform margin contemporaneously with 'deeper water' lithofacies generally mapped as Barney Creek Formation. These only partly correspond to map units which comprise the published stratigraphy for this part of the McArthur Group, and as a result, the pre-existing stratigraphic scheme is largely inadequate for our work. Therefore, facies associations documented as part of a PhD study of the sedimentology of the middle McArthur Group can be considered as members within a genetically related, tectonically generated depositional package termed the Barney Creek Depositional Cycle (BCDC). This succession overlies a distinctive shallowing of lithofacies within the lowermost Teena Dolomite which is recognisable throughout the central Batten Fault Zone. This shallowing is interpreted to represent a sequence boundary which may or may not correlate with a karst surface recognised at the top of the Emmerugga Dolomite by Southgate et al. (1997). The BCDC includes units mapped as Teena Dolomite,

Coxco Dolomite Member, Barney Creek Formation, Reward Dolomite, and at least the Caranbirini Member of the Lynott Formation. Winefield (in prep.) has recognised seven genetically-related facies associations which comprise 27 individual lithofacies which are summarised in Tables 1 and 2. Also included is a schematic representation of the various BCDC facies associations (Fig. 1).

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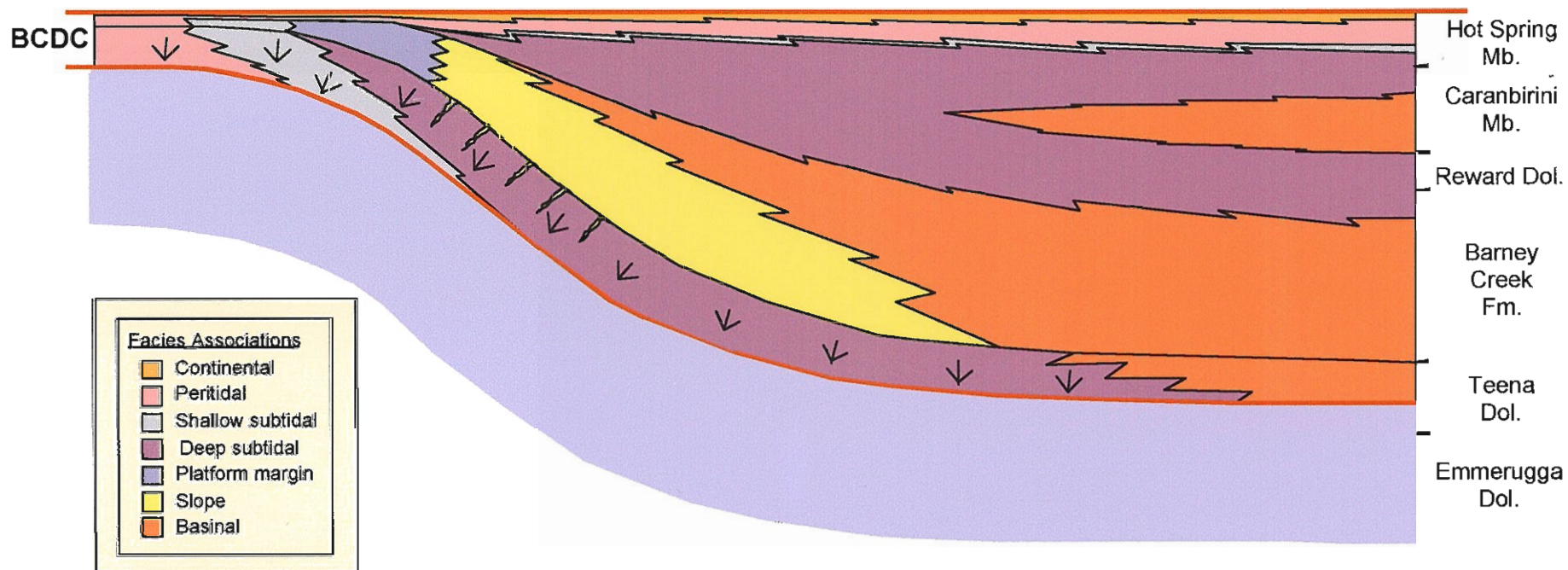


Figure 1. - Schematic representation of the facies associations documented as part of the Barney Creek Depositional Cycle (BCDC). The pre-existing stratigraphic is shown alongside as a guide, however facies associations should be considered as members of a genetically related, tectonically generated sedimentary package (ie. the BCDC). Drafted not to scale.

Table 1 - Summary of lithofacies & their characteristics

LITHOFACIES	CONSTITUENTS	BEDDING	SEDIMENTARY FEATURES
pebble-like conglomerate [1]	poorly sorted, polymict conglomerate	unstratified, no grading, disorganised internally	rounded cobbles & pebbles of various lithologies; slightly erosive bottom contact
cauliflower chert dololutite [2]	laminated dololutite; silicified cauliflower chert (after anhydrite)	finely planar laminated to thinly bedded; disrupted around cauliflower cherts	rare mudcracks; associated with quartz arenite & undulatory domal microbialite
undulatory domal microbialite	highly irregular, chert infilled 'fenestrae' & contorted dolomiticrite	highly contorted, flat laminated through columnar layered to pseudocolumnar morphology	possible evaporitic overprint & desiccation features; associated with ripple laminated quartz arenite & microdigitate microbialite
Coxco needles + peritidal microbialite	'crinkly' laminated dololutite; undulatory domal microbialite; Coxco needle layers	'crinkly' & highly irregular planar laminated dololutite	associated with undulatory domal microbialite; possible tepee-like structures
dolarenite & dololutite with halite hopper casts [5]	medium-grained dolarenite; sucrosic chert; halite hoppers; intraclast breccia	fine planar- & ripple-lamination; individual beds are lenticular in shape	halite hoppers are best developed along bedding surfaces; associated with linked/unlinked domal microbialite
quartz arenite [6]	medium- to coarse grained quartz arenite interbedded with dololutite	ripple-lamination; some imbrication of dololutite intraclasts; minor grading	associated with undulatory domal microbialite, flat pebble conglomerate & cauliflower chert dololutite
microdigitate microbialite [7]	Tufa-like, spar-rich laminae comprising microdigitate forms; clotted micrite	finely bedded; laminae are regular, 0.5 to 2mm thick; excellent lateral continuity; good vertical inheritance	associated with thick bedded dolarenite, undulatory domal microbialite & quartz arenite
flat pebble conglomerate [8]	rounded, pebble-sized clasts of massive dololutite; rippled dololutite; linked domal microbialite	imbricated clasts; commonly orientated in a swirled pattern in plan; form lenticular bodies	interbedded with symmetrical rippled dololutite; commonly associated with columnar conical microbialite
oid grainstone [9]	well sorted, coarse-grained ooid grainstone; common ooids & superficial ooids	mostly tabular with rare lenticular units; poor lateral continuity of individual beds	closely packed; cross-bedding; associated with linked domal microbialite & finely laminated dololutite
graded grain dololudite [10]	medium- to coarse grained, tabular to subspherical, coated clasts of clotted micrite; medium grained oncoids with superficial coatings; matrix of fine peloids, oncoids & ooids; well-developed isopachous fibrous dolomite cement	tabular to lenticular units	grading; cross-bedding; preferred orientation; associated with columnar conical microbialite, flat pebble conglomerate & rippled dololutite; locally within the Gorge Prospect cross-cut by numerous syn-sedimentary fractures
oid grainstone [11]	rounded peloids of massive dololutite & microbially laminated dolostone; sparry cement	some imbrication; tabular units	interbedded with ripple-laminated dololutite; associated with flat pebble conglomerate & linked domal microbialite
unlinked & linked domal microbialite [12]	linked and unlinked hemispherical stromatolites, with thin, smooth microbial laminae	excellent lateral continuity; commonly grade into each other	commonly associated with peloid grainstone & dolarenite

umose structured microbialite Coxco needle fan dololutite 3]	plumose, 'tree-like' microbialite; Coxco needle dololutite; wavy- to planar-laminated dololutite	laterally continuous, tabular beds; consists of cycles of between 1.5-2m in thickness	intricate association between Coxco needle fans & plumose microbialite; overlying wavy- to planar-laminated onlaps against & drapes over microbialite forms
anar laminated Coxco needle dololutite [14]	abundant radiating, upward divergent fans of acicular needles; planar laminated to massive dololutite	tabular unit; laterally continuous	some scouring; common onlap and draping of Coxco needle fans by sediment laminae; commonly associated with finely laminated dolomitic siltstone & plumose microbialite
olumnar conical microbialite 5]	high relief columnar conical microbialite consisting of finely laminated dolospar-micrite couplets	thick, tabular units up to 10m thick	mostly upright columns; some inclined (up to 30°) columns; commonly associated with ripple- laminated dololutite, peloid & ooid grainstones
'ormy'-textured dolostone [16]	highly irregular, disrupted dolospar grading into finely laminated to massive dololutite	thick, tabular units	graded; highly disrupted, chaotic dolospar beds; commonly associated with flat pebble conglomerate
arbonaceous flake dololutite 7]	graded dololutite beds with abundant carbonaceous 'flakes'	thick bedded sequences	graded; wavy, streaky textured carbonaceous flakes of microbial material
'avy microbialite [18]	laterally-linked hemispherical stromatolite consisting of fine microbial laminae	smooth, regular laminae; superb lateral continuity; excellent vertical inheritance	associated with columnar conical microbialite
lochthonous blocks / mega- eccia [19]	lenticular blocks of exotic platform material	internally blocks have been subject to deformation prior to complete lithification	slightly- to very-erosive basal contact; upper surface is undulatory with ponding of overlying sediment
ast-supported dolorudite & dolarenite [20]	coarse dolorudite & dolarenite; sub- angular to rounded clasts of variable lithologies	inverse grading at base of bed with a normal graded top; clast- supported; thick (10-40cm), tabular beds	commonly associated with soft- sediment deformed dolomitic siltstone
ick bedded dolorudite & dolarenite [21]	coarse dolorudite & dolarenite with numerous outsized clasts of exotic material; dolomitic siltstone	thick (up to 4m) massive beds; sharp lower & upper contacts; convolutedly laminated folded dolomitic siltstone	soft-sediment deformation; exotic clasts of platform material; amalgamation of beds
ligomictic breccia [22]	matrix-supported, oligomictic breccia; large tabular-shaped clasts	sharp, erosive lower contact; gradational upper contact	associated with enigmatic 'winged' dolostone clast; associated with coarse dolarenite beds
iffaceous dolomitic siltstone 3]	tuffaceous, dolomitic siltstone; nodular & stylolaminated dolostone	fine planar lamination; some grading of beds; scouring; microfracturing; disruption	abundant dissolution seams & bedding parallel stylolites; syn- sedimentary deformation
inly bedded fine dolomitic ndstone & siltstone [24]	very fine dolomitic sandstone & dolomitic siltstone	normal grading; small scours & flame structures; soft-sediment folds	-
assive carbonaceous shale pyrite) [25]	carbonaceous shale	massive to very finely laminated	-
odular argillaceous dolostone	nodular light grey dolostone &	well-developed stylolamination &	abundant dissolution seams

Table 2. - Summary of facies associations

FACIES ASSOCIATION	LITHOFACIES	GEOMETRY	INTERPRETATION
1. Continental	sheet-like conglomerate (Lithofacies 1)	locally extensive	subaerial environment eroding exhumed lower McArthur Group stratigraphy
2. Peritidal	cauliflower chert dololomite; undulatory domal microbialite; Coxco needles; dolarenite & dololomite with halite casts; quartz arenite; microdigitate microbialite (Lithofacies 2, 3, 4, 5, 7)	tabular to lenticular with poor lateral continuity; Lithofacies commonly arranged into cycles (up to 10m thick) which include: Lithofacies 6, 3, 7	peritidal flat complex with lithofacies forming a mosaic which represents concurrent supratidal and intertidal depositional environments
3. Shallow subtidal	flat pebble conglomerate; ooid grainstone; coated grain dololomite; peloid grainstone; linked & unlinked microbialite (Lithofacies 8, 9, 10, 11, 12)	individual lithofacies are laterally discontinuous but interfinger with other genetically related lithofacies	agitated, shallow marine ramp setting; commonly affected by storm-related processes
4. Deep subtidal	plumose structured microbialite; planar laminated dololomite; Coxco needles; columnar conical microbialite; wormy-textured dolostone; carbonaceous flake dololomite (Lithofacies 13, 14, 15, 16, 17)	tabular; laterally extensive	sub-fair-weather base, outer marine ramp setting; occasionally affected by storm-related processes
5. Platform-margin	wavy microbialite (Lithofacies 18)	tabular; localised development	structurally controlled elevated margin
6. Slope	allochthonous blocks/mega-breccia; clast-supported dololomite & dolarenite; thick bedded dololomite & dolarenite; oligomictic breccia (Lithofacies 19, 20, 21, 22)	tabular, lenticular & wedge shaped units; localised development on structurally controlled slopes	carbonate slope apron of mega-breccia, slope-related breccia, modified grain flows & high-density turbidite deposits
7. Basinal	tuffaceous dolomitic siltstone; thinly bedded, fine dolomitic sandstone & siltstone; massive carbonaceous ($\pm$ pyrite) shale; nodular argillaceous dolostone	localised development within structurally controlled sub-basins	deep, reducing environment dominated by thin distal turbidites & hemipelagic sedimentation

Geology of the BCDC in the Myrtle Basin area, southern McArthur Basin, Northern Territory

Stuart Bull and Robert Scott

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Introduction

The Barney Creek Formation and adjacent units clearly represent a period of active basin formation during accumulation of the McArthur Group. When these deposits are examined in detail adjacent to major structures, the existing layer cake stratigraphic scheme becomes inadequate. As a result, a new stratigraphic scheme for the interval above the Coxco Dolomite marker horizon has been proposed (Winefield, this report). This encompasses the Barney Creek Formation, Reward Dolomite and Lynott Formation and is termed the Barney Creek Depositional Cycle (BCDC).

Documentation of the distribution of BCDC elements along the sinuous Tawallah and Hot Springs Faults, particularly Basinal versus Shallow Subtidal/Peritidal Facies, indicated an apparently systematic structural control on sedimentation, and hence basin formation. In summary, it was proposed that Basinal Facies deposits (~Barney Creek Formation and Caranbirini Member) occur in accommodation space generated adjacent to NNW-trending fault segments by extension and growth faulting on parallel structures (Winefield et al., 1997; Fig. 1a). In contrast, areas of BCDC exposure adjacent to N-NNE-trending fault segments record sustained shallow water conditions, indicating no accommodation space was generated. It was proposed that this was consistent with transtension and transpression respectively, under a regional stress field involving NNW-SSE compression/ENE-WSW extension during accumulation of the BCDC (Fig. 1a). However, there are two marked inconsistencies between this interpretation and the current models for formation of this mineralised package.

- (1) Both the regional stress field and the controlling structures are incompatible with models currently proposed for the McArthur Group in general (Etheridge and Wall, 1994), and the Barney Creek Formation in particular (Neudert and McGeough, 1996). These invoke regional N-S extension that generated E-W-trending syn-sedimentary growth faults that extended to the west from an area just north of HYC (Fig. 1b).
- (2) In addition to being sites of low accommodation space during the BCDC, areas adjacent to N-NNE-trending fault segments (eg. Top Crossing; Winefield et al., 1997) are also sites of transpressional folding about N-NNE-trending axes. These folds are similar in geometry and scale to those documented through the same stratigraphy in an E-W cross section through HYC, which are interpreted to be the result of syn-Barney Creek Formation deformation (Hinman, 1995). However, in the Top Crossing example, this folding clearly affects stratigraphy considerably younger than the BCF, including the upper McArthur Group stratigraphy and the overlying Nathan Group. At this locality at least, this deformation may well therefore have occurred during the Isan Orogeny.

A factor that clearly contributes to the inconsistencies outlined above relates to the areas where the structural setting of the BCF and adjacent stratigraphy have been studied in detail. These are all adjacent to major N-NNW-trending structures (eg. the Emu and Tawallah Faults), and generally have complex structural histories due to major wrench faulting and associated folding during the Isan Orogeny. The Myrtle Basin is an area of

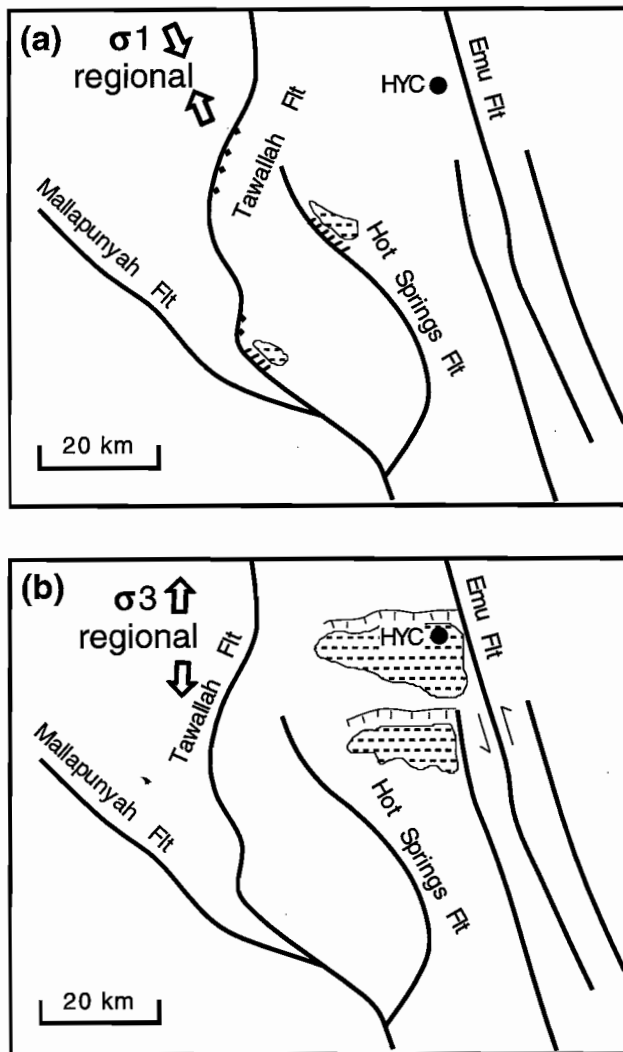


Figure 1. (a) Schematic representation of the distribution of Basinal Facies deposits along the sinuous Tawallah Fault, note the implied regional stress field. (b) Schematic representation of the structural configuration and implied regional stress field proposed by Etheridge and Wall (1994) and Neudert and McGeough (1996).

outcropping BCDC situated 18 km SSW of HYC and 10 km west of the Emu Fault Zone (Fig. 2). It has been the focus of sporadic base metal exploration since 1967. The area was chosen to clarify the structural controls on the BCDC because:

- (1) The BCDC, including the normally recessive Basinal Facies, crops out relatively well providing the opportunity to map an apparent depocentre.
- (2) The area is far enough away from the major NNW-trending structures (?transfers, eg. the Emu, Hot Springs and Tawallah Faults) to have escaped major Isan wrench faulting that could mask the original basin geometry, as may be the case at HYC.

- (3) A prominent E-W-trending fault separates the BCDC package from older McArthur Group stratigraphy (the Tooganinie Formation; Jackson et al., 1984) This fault could potentially represent a syn-BCDC structure in either proposed regional stress field; in the case of N-S extension (Neudert and McGeough, 1996) it could represent a normal (growth) fault; in the case of NNW-SSE compression (Winefield et al., 1997) it could represent a reverse (thrust) fault.
- (4) East-west-trending synclines are also developed in the BCDC in this area. These structures could represent syn-depositional drag folds developed in response to either normal or reverse movement on the adjacent E-W-trending faults, or younger structures unrelated to basin formation.

Geology of the BCDC in the Myrtle Basin

BCDC sedimentology

The BCDC deposits developed above the Coxco Dolomite in the Myrtle Basin area record two cycles of transgression/regression. The former are represented by sub-wave base Basinal Facies deposits comprising locally carbonaceous and pyritic dolomitic siltstones (~ Barney Creek Formation and the Caranbirini Member), and the latter by a diverse range of dolomitic units representing BCDC Slope, Deep Subtidal, Shallow Subtidal and Peritidal Facies (~the Reward Dolomite and Hot Springs Member).

Megabreccia deposits

Two types of megabreccia are also present in the Myrtle Basin area;

Talus breccia is restricted to the western end of the SW Myrtle Basin (Fig. 3). It consists of rockfall dolomite clasts up to > 7 m in length dispersed within Basinal Facies dolomitic siltstones. The clasts are derived from the immediately underlying stratigraphy (Coxco and Emmerugga Dolomites). The high relief source appears to have been in the area of intersection of E-W-trending and NNW-trending faults immediately to the SW, suggesting significant syn-sedimentary growth on these structures.

Massive, clast supported, heterolithic dolomitic megabreccia is present throughout the Myrtle Basin

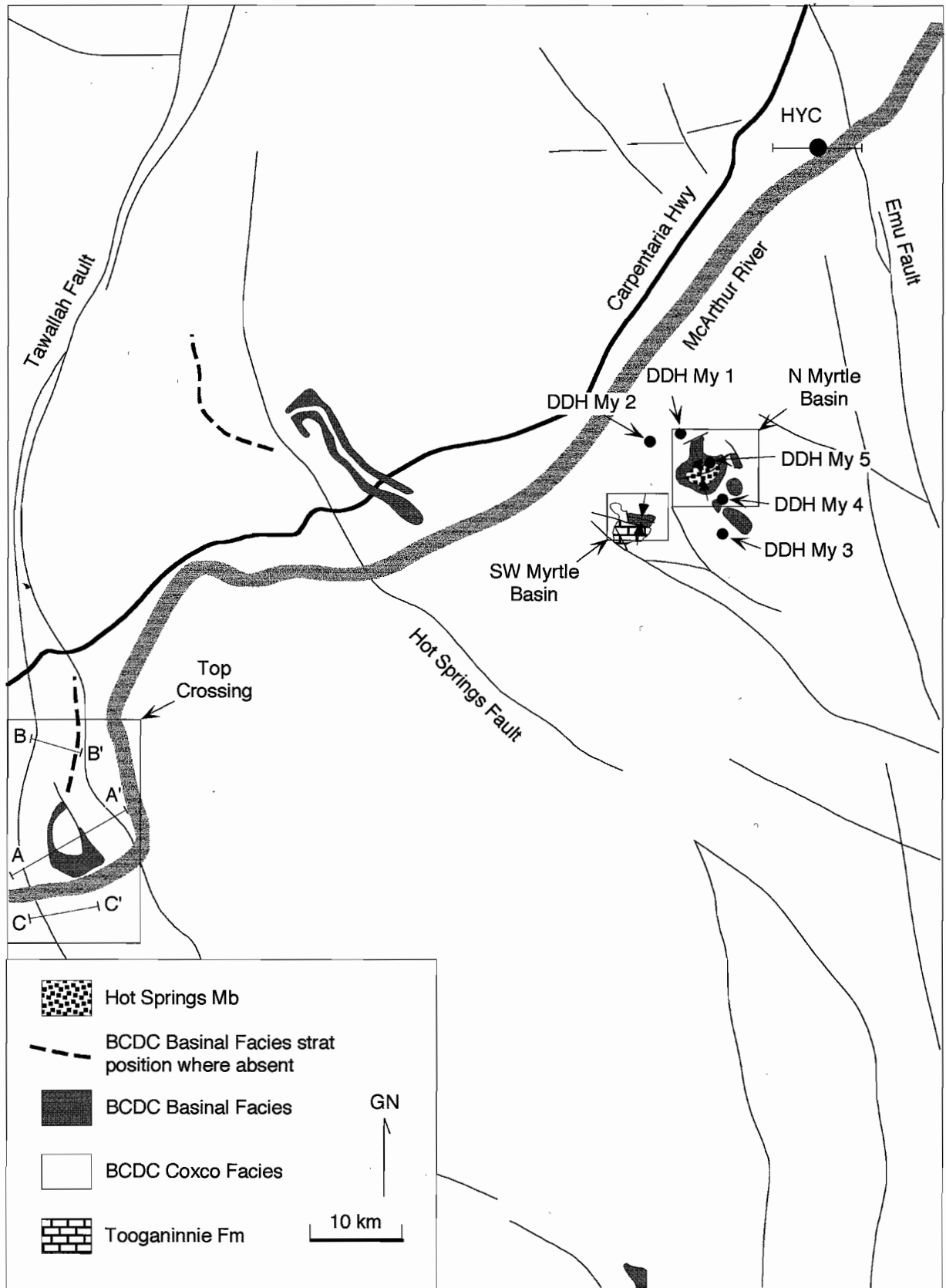


Figure 2. Locality diagram; geology modified after Pietsch et al., 1991 and Hinman, 1995.

area. It occurs as roughly bedding-parallel sheets (Fig. 3) developed by disaggregation of the complex facies package (~Reward Dolomite) overlying the basal Basinal Facies deposits. However brecciation also affects the underlying Basinal and Deep Subtidal Facies deposits, and the lowermost of the overlying Basinal and Shallow Subtidal/Peritidal Facies intervals. These spectacular breccia deposits are interpreted to represent the sudden release of overpressured pore fluids developed in the complex BCDC facies package (~Reward Dolomite), particularly the Slope Facies sandstones, below the upper Basinal Facies interval which acted as an aquaclude/seal during burial. They are regionally significant because they indicate that the formation of heterolithic breccias can occur by effectively in-situ disaggregation of BCDC units, and do not require the exhumation of kilometres of stratigraphy as has been inferred to explain similar deposits at HYC.

Basin history

In overview, the Basinal Facies intervals clearly represent active subsidence and sub-basin formation (Fig. 3). Initial, and ultimately maximum subsidence, appears to have produced aerially restricted Basinal Facies "sumps". These were localised where E-W-trending normal growth faults intersected NNW-trending faults that also had syn-sedimentary growth, and were ultimately sites of intense deformation/inversion during the Isan Orogeny. Subsequent more regional subsidence appears to have been controlled principally by the E-W-trending growth structure. The overall geometry of the resultant Basinal Facies deposits, in combination with slope indicators from near the base, suggest that sedimentation occurred within E-W-trending hanging wall synclines. These structures were subsequently tightened during the Isan Orogeny to produce the meso-scale synclinal folds present in the area today (Fig. 3).

Regional stress field

This Myrtle Basin study has produced the first detailed map of a BCDC depocentre away from the major ~N-S-trending (?transfer) faults. In terms of the implications for the regional stress field, at first pass, the apparent control of widespread Basinal Facies sedimentation by an ~E-W-trending growth fault in

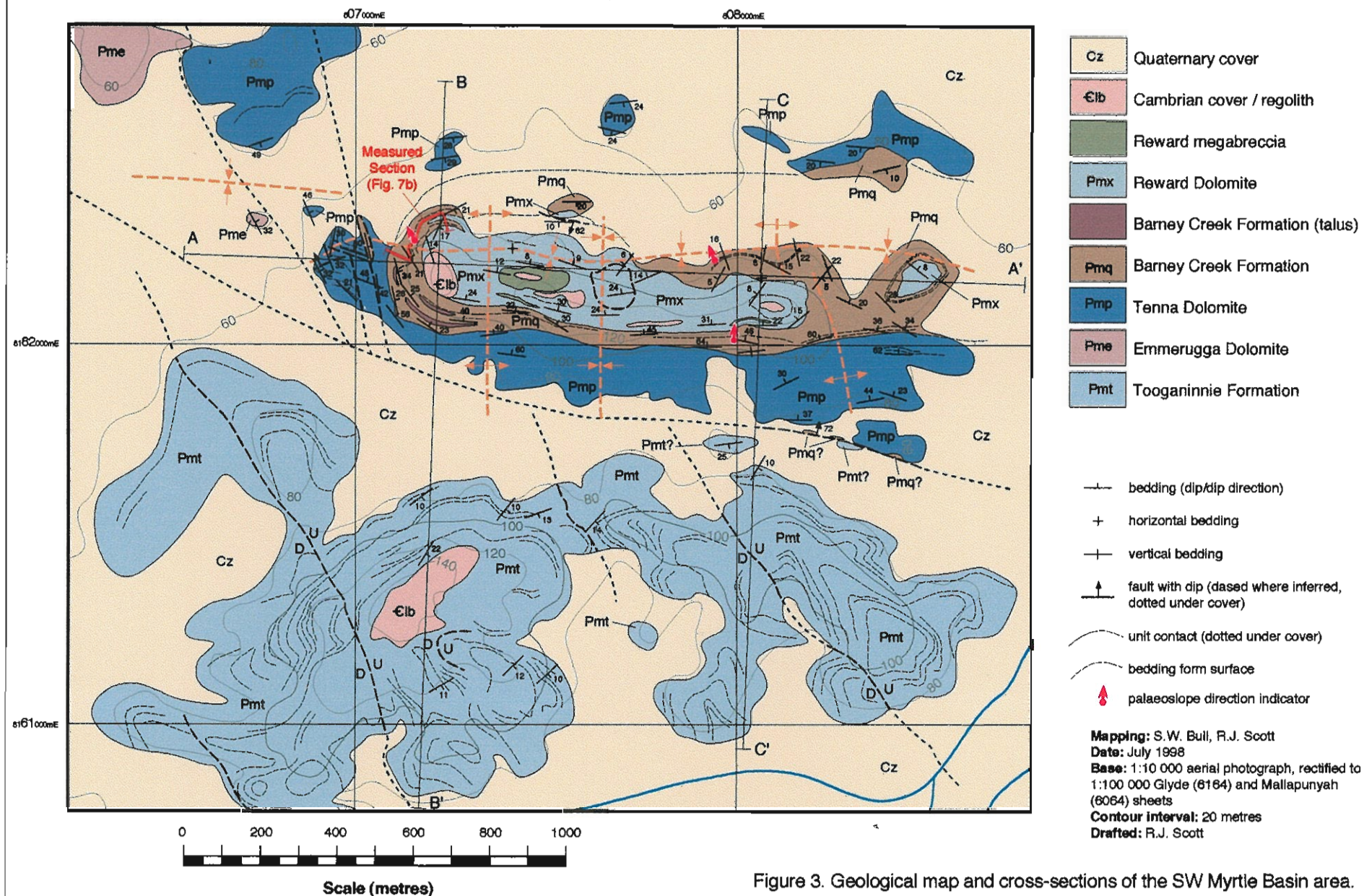
the SW Myrtle area (Fig. 3) accords well with N-S extension models (Etheridge and Wall, 1994; Neudert and McGeough, 1996; Fig. 4a). However, because there is also growth on the associated NNW-trending splays, it is not possible to exclude the NNW-SSE compression model (Winefield et al., 1997; Fig. 1a), without proving that the syn-sedimentary displacement on the main E-W-trending structure did not involve a significant wrench component. This has not been possible due to poor outcrop in the fault zone, and the fact that the Tooganinie (?footwall) block immediately to the south is remarkably unaffected by minor structures. As a result, the BCDC depocentre in the SW Myrtle Basin could also be explained as a pull apart/releasing step over between NNW-trending strike-slip faults developed during regional NNW-SSE compression (Fig. 4b).

Conclusions

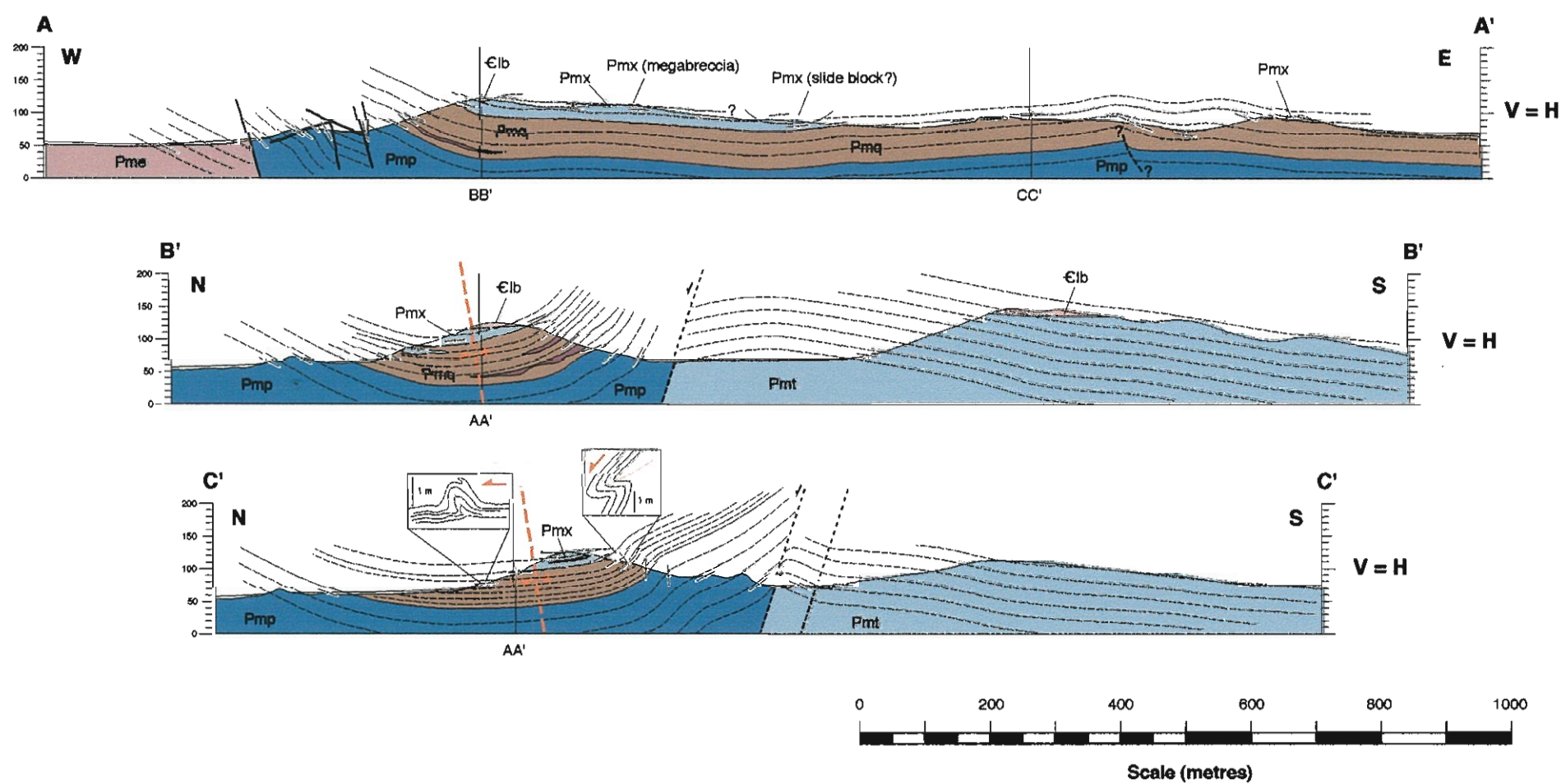
The Myrtle Basin is unique in that it is an area with locally continuous exposure where the BCDC is affected by E-W-trending folds and faults. Previous work had suggested that syn-BCDC structures that controlled basin formation should be of this orientation, associated with either broadly N-S extension (Etheridge and Wall, 1994; Neudert and McGeough, 1996; Fig. 2b) or broadly N-S compression (Winefield et al., 1997; Fig. 2a). In addition, the Myrtle Basin is situated some distance from the major N-NNW-trending structures (eg. the Emu and Tawallah Faults), where the original basin geometries have been masked by major wrenching and associated transpressional folding during the Isan Orogeny, and possibly also at upper Barney Creek Formation time (Hinman, 1995). Integrated structural and sedimentological mapping and analysis of two sub-areas within the Myrtle Basin indicate the following:

- (1) Initial subsidence and basin formation was controlled by normal displacement on an E-W-trending growth fault. This is the first example of a mapped syn-BCDC growth fault with an orientation consistent with a regional stress field comprising ~N-S extension as proposed by previous workers (Etheridge and Wall, 1994; Neudert and McGeough, 1996).

Geology of the SW Myrtle Basin, N.T.



SW Myrtle Basin: cross-sections



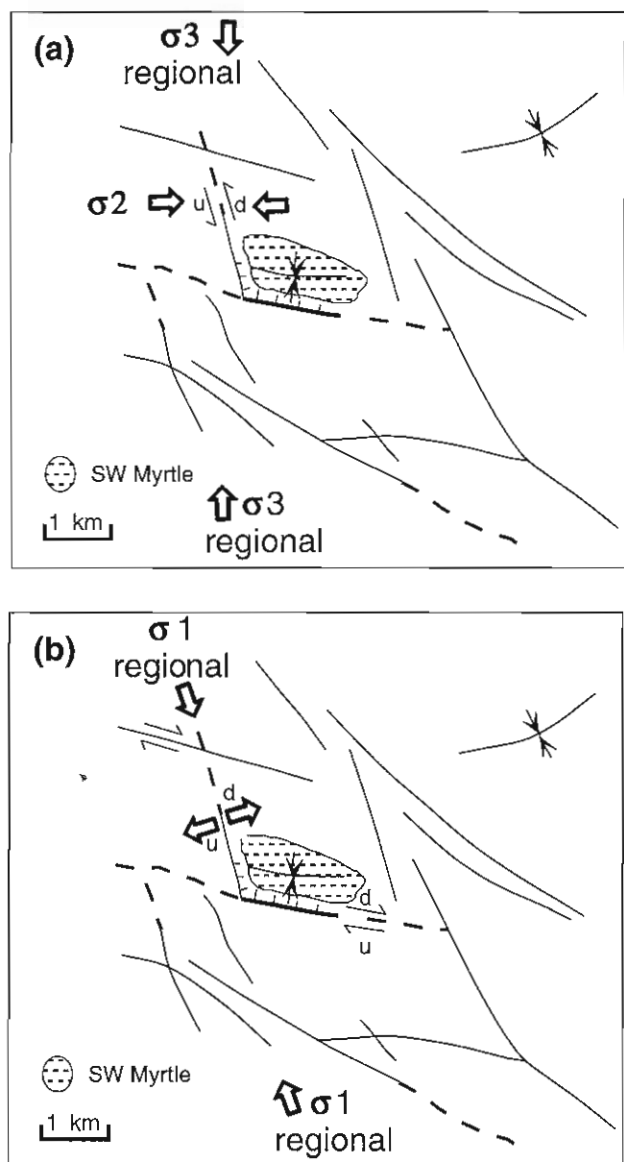


Figure 4. Schematic representation of the BCDC depocentre in the SW Myrtle Basin as: (a) A hanging wall syncline associated with a half graben developed adjacent to a N-dipping normal growth fault under conditions of ~N-S regional extension. (b) A pull apart/releasing stepover, associated with strike-slip faulting on NNW-trending faults under conditions of regional NNW-SSE compression.

- (2) The earliest, and ultimately greatest normal displacement, occurred in the area where the E-W-trending growth fault intersected NNW-trending cross faults. This resulted in the generation of Basinal Facies "sumps" that were subsequently the sites of tight folding and basin inversion during the Isan Orogeny.
- (3) Later in the basin history, the same fault intersection was the source of talus blocks of underlying stratigraphy up to 7 m long indicating it was the site of maximum relief (~growth). Although the N-NNW-trending faults have been interpreted as transfers during McArthur Group deposition (Etheridge and Wall, 1994), they were clearly therefore also the sites of subsidiary syn-sedimentary growth in the Myrtle Basin area at least.
- (3) Subsequent more widespread Basinal Facies deposition was controlled mainly by the major E-W-trending growth fault. Slump folds at the base of this succession indicates the rapid development of a N-facing slope, now the southern limb of the open E-W-trending synclinal structure within which it occurs. This structure is interpreted to represent a syn-BCDC hanging wall syncline, subsequently tightened during the Isan Orogeny.
- (4) Overlying the basal Basinal Facies package (~Barney Creek Formation) is a complex BCDC facies assemblage mapped as Reward Dolomite. It includes tabular bedded dolostone and dolomitic sandstone deposits (Deep Subtidal and Slope Facies), and plate breccias, microbially laminated and evaporitic dolomite units (Shallow Subtidal and Peritidal Facies). Taken overall, this facies association represents a regression to above-wave base to intertidal conditions. A second cycle of flooding/transgression and subsequent regression generated the upper BCDC deposits consisting of an upper interval of sub-wave base Basinal Facies (~Caranbirini Member) overlain by another phase of Marginal/Platform sedimentation (~Hot Springs Member). The latter is considered to represent the infilling of the last of the tectonically formed accommodation space generated during the BCDC.
- (5) The geometry of the BCDC depocentre in the SW Myrtle area is consistent with either of the regional stress fields proposed (NNW-SSE compression or ~N-S extension), depending on

the syn-sedimentary displacement on the main ~E-W-trending growth fault. This was unable to be determined in this study.

- (6) The BCDC stratigraphy in the Myrtle Basin area is host to considerable volumes of carbonate megabreccia. Similar units have previously been reported from the type section of the Caranbirini Member to the south of the Myrtle Basin (Jackson et al., 1987), however no analysis of these spectacular deposits was undertaken. Our study indicates that megabreccias occur over a considerably greater area, and affect a larger stratigraphic interval than was previously recognised.
- (7) The main level of brecciation begins above the basal Basinal Facies package (~Barney Creek Formation) in the lithologically diverse overlying package mapped as Reward Dolomite. However, upward penetrating "dykes" of breccia locally subdivide the upper Basinal Facies package (~Caranbirini Member) into mega-clasts 10's of metres long, and the overlying Shallow Subtidal/Peritidal Facies (~Hot Springs Member) are also locally brecciated.
- (8) The carbonate megabreccias are interpreted to represent the sudden release of overpressured pore fluids in the Platform/Marginal and especially the porous Slope Facies deposits. The overpressure is thought to have developed because the overlying upper Basinal Facies siltstones (~Caranbirini Member), acted as an aquaclude during burial of the water-saturated sediment pile. As such, the megabreccias are clearly intraformational, with the clasts sourced from in-situ disaggregation and local transport of the various BCDC facies in which they occur.
- (9) Breccias similar to those from the Myrtle Basin occur in the Barney Creek Formation at HYC. Current models invoke intense syn-sedimentary deformation, accompanied by > 2 km of incision/uplift to explain the wide variety of clast lithologies present in the breccias. Current exposure in the area of the HYC deposit is around the level of the upper Barney Creek Formation,

and the upper BCDC units, if they were ever present, are not preserved. However, if the situation during BCDC-time was similar to that documented from the Myrtle Basin, these lithologically variable upper BCDC units would have provided an alternative source for the breccia clasts, making the dramatic syn-sedimentary tectonism currently proposed unnecessary.

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Geology of the Gorge Prospect area, southern McArthur Basin

Peter Winefield, David Selley & Stuart Bull

Centre for Ore Deposit Research

Abstract

The study of the Gorge Prospect area has provided several important insights into the tectonic-sedimentary setting of the middle McArthur Group. Detailed facies analysis has documented six genetically-related facies association (continental, peritidal, shallow subtidal, deep subtidal, platform margin, and slope) in the area and recognised three distinct phases of sedimentation within the middle McArthur Group: (i) pre-Coxco Dolomite Member — records an overall transgression of lithofacies and increase in accommodation space; (ii) Coxco Dolomite Member to lower Barney Creek Formation — marks the onset of tectonically-induced basin subsidence with deposition of the Coxco Dolomite Member as a distinctive transgressive unit. Prior to or during initial stages of Barney Creek Formation deposition, a dominantly N-dipping slope was developed with a smaller E-dipping lateral ramp linking discrete segments of the slope. The development of, and ongoing deposition on, the slope is recorded by a variety of coarse clastic slope facies sediments and several gravitationally induced syn-sedimentary mesoscopic structures; (iii) upper Barney Creek Formation to Reward Dolomite — comprises a shallowing and coarsening upward cycle of deposition as accommodation space in the basin is filled. The end of middle McArthur Group deposition is marked by the deposition of an sheet-like conglomerate which provides clear evidence that at least in the Gorge Prospect, lower McArthur Group stratigraphic levels were exhumed and eroded.

Two models for basin development in the Gorge Prospect area are proposed. The model currently favoured invokes the generation of a ENE–WSW

trending depocentre in response to flexural subsidence associated with D₁ NNW directed thrusting. This model is supported by thrust repetition of the underlying pre-Barney Creek Formation sequence and an overall shallowing and coarsening upward cycle of sedimentation, culminating in localised uplift and erosion of lower McArthur Group sediments. However, a half-graben setting associated with a steeply dipping growth fault to the north of the Gorge Prospect could also produce a similar facies architecture, and although there is no direct evidence in support of this model, it can not be discounted at this time.

Introduction

The Gorge Prospect encompasses an area of approximately 25 km², adjacent to the Kilgour River (Fig.1). Fault splays of both the Tawallah and Hot Spring Fault systems bound the area. The Tawallah Fault splay is orientated NW-SE before swinging more N-S to intersect with the NNE-SSW orientated splay off the Hot Spring Fault system, south of the Gorge Prospect area. Within the Gorge Prospect area, the middle McArthur Group (Emmerugga Dolomite to Reward Dolomite) is well exposed, dipping ~N between 20° to 40°. In the centre of the Gorge Prospect area, there is a distinctive swing in strike from a WNE–ENE to more N–S with bedding sub-vertical before returning to an ~E–W orientation. Thrust repetition of the pre-Barney Creek Formation dolostone sequence is a common feature in the southern Gorge Prospect area.

Stratigraphy

The Emmerugga and lower Teena Dolomite consists of various forms of cyclic microbial dolostone, carbonate grainstones, and quartz sandstone. The Coxco Dolomite Member of the Teena Dolomite is characterised by abundant radiating acicular crystal fans, colloquially known as 'Coxco needles'. The Coxco Dolomite Member is overlain by interbedded dolomitic siltstone and coarse clastic carbonate units of the Barney Creek Formation, which is exposed mostly north of the Kilgour River in a WNW-ESE trend. The Barney Creek Formation is overlain by the Reward Dolomite, which in the Gorge Prospect area consists of interbedded quartz arenite, dolomitic sandstones and microbial dolostone. An extensive, poorly sorted, sheet-like conglomerate caps the sequence and marks the end of middle McArthur Group deposition in this area.

Facies Associations

Detailed facies analysis of measured sections and drill core from throughout the central Batten Fault Zone has recognised seven genetically-related facies associations within the middle McArthur Group sequence, which comprise 27 individual lithofacies (see Winefield, in prep.). Components of six of these facies associations are evident within the Gorge Prospect and are briefly discussed below.

Peritidal Facies Association

This facies association consists of a mosaic of peritidal lithofacies which represent a concurrent supratidal and intertidal depositional setting. In the Gorge Prospect, these depositional environments are represented by the development of: undulatory domal microbialite, interbedded dolarenite and dololutite with halite casts, ripple-laminated quartz arenite; and microdigitate microbialite. Particularly within the Emmerugga Dolomite, peritidal lithofacies cap shallowing upward cycles in association with subtidal lithofacies.

Shallow Subtidal Facies Association

Various lithofacies including flat pebble conglomerate, ooid grainstone, coated grain dolorudite, and

linked and unlinked domal microbialite are included within this facies association. These deposits are interpreted to represent an agitated shallow subtidal ramp setting which is commonly affected by storm-related processes.

Deep Subtidal Facies Association

Large, well-developed columnar conical microbialite (commonly termed Conophyton-like stromatolite) beds up to 1.5 m in height within the Gorge Prospect are inferred to be deep subtidal deposits. Genetically related lithofacies included: planar-laminated dololutite with abundant Coxco needles; plumose-structured microbialite; and planar-laminated, thin to thick bedded dolostone. These lithofacies commonly have a tabular geometry and are laterally extensive over 100s of metres. They are interpreted to have been deposited in a sub-fairweather base, outer marine ramp setting which is occasionally influenced by storms. In the Gorge Prospect, deep subtidal lithofacies generally form the basal transgressive or flooding portion of shallowing upward cycles.

Platform Margin Facies Association

Platform margin rocks consist of small bioherms (up to 5 m) of wavy, laterally linked hemispherical microbialite. Wavy microbialite displays excellent lateral continuity depending on outcrop conditions and is commonly associated with deep subtidal, columnar conical microbialite and intermittent ooid grainstones. For reasons described later, this lithofacies is interpreted to represent deposition on a structurally elevated platform margin.

Slope Facies Association

This facies association comprises abundant coarse dolorudite and dolarenite, oligomictic breccia, and large allochthonous or megabreccia blocks of stromatolitic, platform material. Geopetal evidence within the underlying sequence suggests relatively steep slope angles of ~20° to 35°. There is abundant evidence of syn-sedimentary deformation associated with deposition of sediment on an unstable slope and slope facies sediments represent a spectrum of gravitationally induced depositional processes.

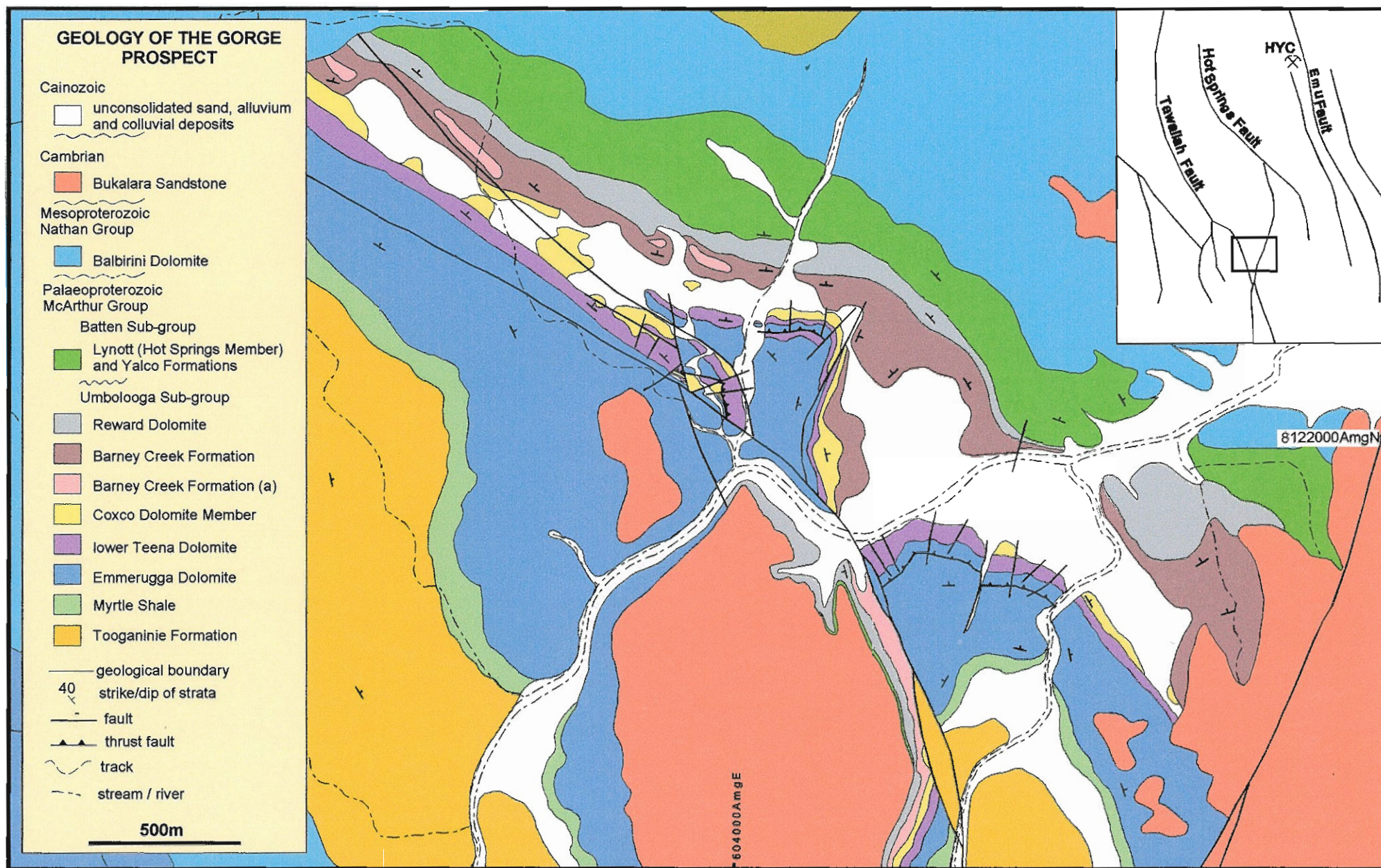


Figure 1. - Geology of the Gorge Prospect area, southern McArthur Basin.

Continental Facies Association

Within the Gorge Prospect, the Reward Dolomite is overlain by a distinctive, poorly sorted sheet-like conglomerate. It is possible to trace this thin (3–5 m thick) conglomerate unit throughout the Gorge Prospect and demonstrate that the lower contact is erosive with relief up to 2 m. The poor sorting and lack of internal stratification within the unit implies deposition as a chaotic, debris flow. A wide variety of clast types are recognised within the unit including clasts containing various forms of microbialite, carbonate grainstone, sandstone, and importantly silicified Coxco needles.

Facies Architecture

The facies architecture of middle McArthur Group sediments within the Gorge Prospect records the development and demise of a slope and platform margin during the deposition of the Barney Creek Formation and Reward Dolomite (Fig. 2). It is possible to divide the deposition of the middle McArthur Group and its facies architecture into 3 distinct phases of sedimentation: (i) pre-Coxco Dolomite Member; (ii) Coxco Dolomite Member to lower Barney Creek Formation; and (iii) upper Barney Creek Formation to Reward Dolomite.

(i) pre-Coxco Dolomite Member

The deposition of the Emmerugga Dolomite and lower Teena Dolomite occurred on a broad gently-dipping carbonate ramp with an overall deepening or transgressive trend as evidenced in measured section KP97/1 (Fig. 3). The contact between the Emmerugga Dolomite and underlying red, evaporitic dolomitic siltstone of the Myrtle Shale is gradational. The overlying Emmerugga Dolomite is characterised by a series of shallowing upward cycles. These cycles thicken up-section and imply a gradual increase in accommodation space. The lowermost Teena Dolomite is marked by an abrupt and distinctive shallowing of lithofacies recognisable throughout the central Batten Fault Zone. This shallowing is interpreted to represent a basinward shift in lithofacies and as such is interpreted to represent a sequence boundary.

(ii) Coxco Dolomite Member to lower Barney Creek Formation

Above the aforementioned sequence boundary, there is a distinct transgression of lithofacies as the carbonate platform or ramp was inundated. This is manifest initially by the deposition of a transgressive unit (i.e. Coxco Dolomite Member) which comprises abundant fan-like carbonate cements thought to have precipitated originally as aragonite. The development of these cements is believed to be in response to the upwelling of anoxic, HCO_3^{2-} -rich deep water during the initial stages of the flooding event. This transgressive unit is overlain by interbedded dolomitic siltstone and coarse clastic dolorudite and dolarenite of the Barney Creek Formation, interpreted to have been deposited in an active slope environment. The contact between the 'transgressive' Coxco Dolomite Member and Barney Creek Formation is commonly brecciated and contains numerous sediment and cement infilled fissures termed 'neptunian dykes'. Geopetal evidence from laminated internal sediment within neptunian dykes and related cavities indicates that 'tilting' of the pre-Barney Creek Formation sequence occurred prior to deposition of the overlying Barney Creek Formation. Large exotic blocks of stromatolitic, platform-derived material are recognised at several stratigraphic levels within slope facies sediments of the Barney Creek Formation. These allochthonous blocks or megabreccia are interpreted to be the result of the collapse of an adjacent platform margin.

Structural information gathered from the analysis of gravitationally-induced mesoscopic structures (e.g. intrafolial folds within the Barney Creek Formation; geopetal structures in the Coxco Dolomite Member) indicates a dominantly NW- to N-dipping palaeoslope during deposition of the Barney Creek Formation (Fig. 4). However, local complications occur at a number of stratigraphic levels and geographic positions. One such complication is in the area to the north of the Kilgour River where bedding in the pre-Barney Creek Formation swings abruptly into a N–S orientation. In this area, the palaeoslope dipped to the east during sedimentation. This change in palaeoslope away from the dominant northward dipping trend, coupled with an anomalous thickening of coarse-grained lithofacies,

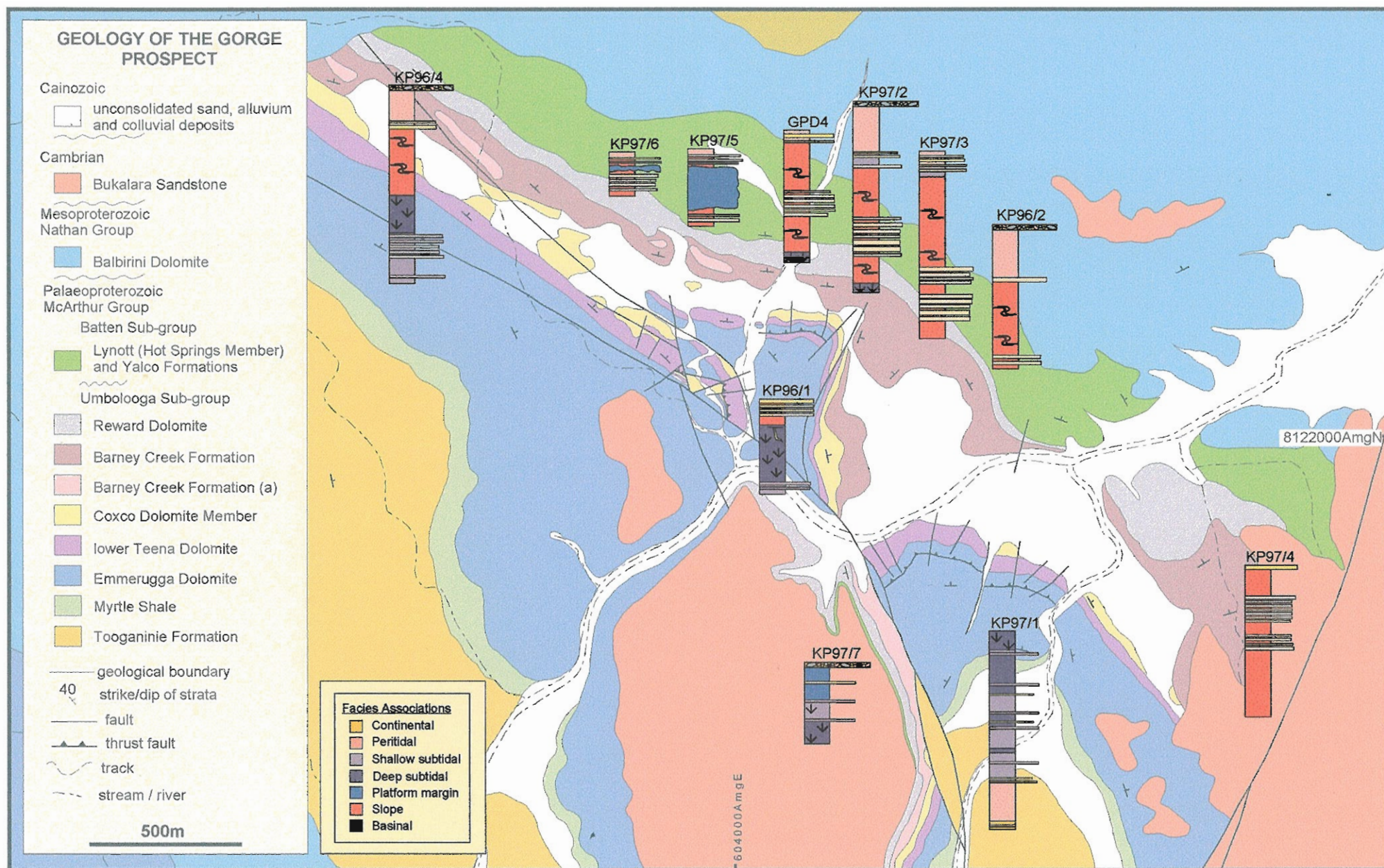


Figure 2. - Summary logs of measured sections from throughout the Gorge Prospect area.

is interpreted to define the position of a narrow NNW–SSE to N–S trending depocentre. The palaeoslope in this area is interpreted to have been an inclined ($\sim 30^\circ$) E-dipping ramp which linked discrete segments of a larger $\sim$ E–W trending basin margin.

(iii) upper Barney Creek Formation to Reward Dolomite

This phase of sedimentation is marked by a shallowing upward transition from slope facies sediments to the widespread deposition of peritidal lithofacies (Fig. 5). This shallowing upward phase of sedimentation is terminated by the deposition of an extensive, sheet-like conglomerate. The presence of clasts containing Coxco needles is clear evidence that this unit records the emergence and erosion, at least to the Teena Dolomite stratigraphic level, of lower McArthur Group stratigraphy. Although angular clasts of a similar provenance have been recognised in other parts of the southern McArthur Basin, it is only in the Gorge Prospect that these clasts are sufficiently texturally mature to unequivocally demonstrate that lower McArthur Group stratigraphy was uplifted, and the eroded clasts reworked and abraded in a very shallow marine or subaerial environment.

Discussion and possible models for basin development

During the deposition of the Barney Creek Formation, slope and platform margin facies sedimentation was both contemporaneous and proximal to each other. Two lines of evidence support this. Firstly, the upper and lower surfaces of both facies associations are linked by two chronostratigraphic marker units. The lowermost unit consists of the transgressive, Coxco needle bearing carbonates of the Coxco Dolomite Member. The upper unit is the thin but laterally extensive sheet-like conglomerate unit mentioned above. The second line of evidence is the recognition of laterally extensive and voluminous allochthonous blocks or megabreccia comprised of platform margin lithofacies hosted within slope facies sediments. Internal deformation features within individual

blocks indicate that exotic platform margin debris was redeposited to deeper basin positions prior to complete lithification.

Geopetal structures indicate that the palaeoslope angles during the deposition of the Barney Creek Formation varied between 20° to 35° . Schlager and Camber (1986) noted that carbonate sediments can record steeper slopes than siliciclastic sediments. Several reasons suggested for this observation include: carbonate content increases the shear strength of fine-grained sediments (Kenter and Schlager, 1989); the difference in lithification between siliciclastics and carbonates (Schlager, 1989); there is a relationship between sediment fabric and slope angle on carbonate platform flanks, i.e. coarse, grain-supported sediment fabrics are commonly associated with carbonate slopes up to 35° – 40° (Kenter, 1990). Therefore, the observation of coarse clastic units associated with slopes of between 20° to 35° is consistent with the work of Kenter (1990), while the early cementation and dolomitisation of the underlying pre-Barney Creek Formation dolostone sequence probably facilitated the development of such slope angles.

Two possible models for basin development could explain the distinctive facies architecture of middle McArthur Group sediments within the Gorge Prospect. The first model involves the generation of a roughly ENE–WSW trending major depocentre in response to flexural subsidence during D_1 NNW directed thrusting (see also Winefield et al., 1997). Evidence in support of a compressional model includes thrust-repetition within the pre-Barney Creek Formation succession and the development of a shallowing and coarsening upward cycle of sedimentation, characterised by cannibalisation of older strata and culminating in the emergence and erosion of lower McArthur Group stratigraphy. A second alternative model which invokes the development of a half-graben setting (with a possible growth fault under cover to the north of the Gorge Prospect) during regional N–S extension could also produce a similar facies architecture. However, no obvious steeply dipping growth faults or other direct evidence in support of this model can be identified and therefore the former model is currently favoured.

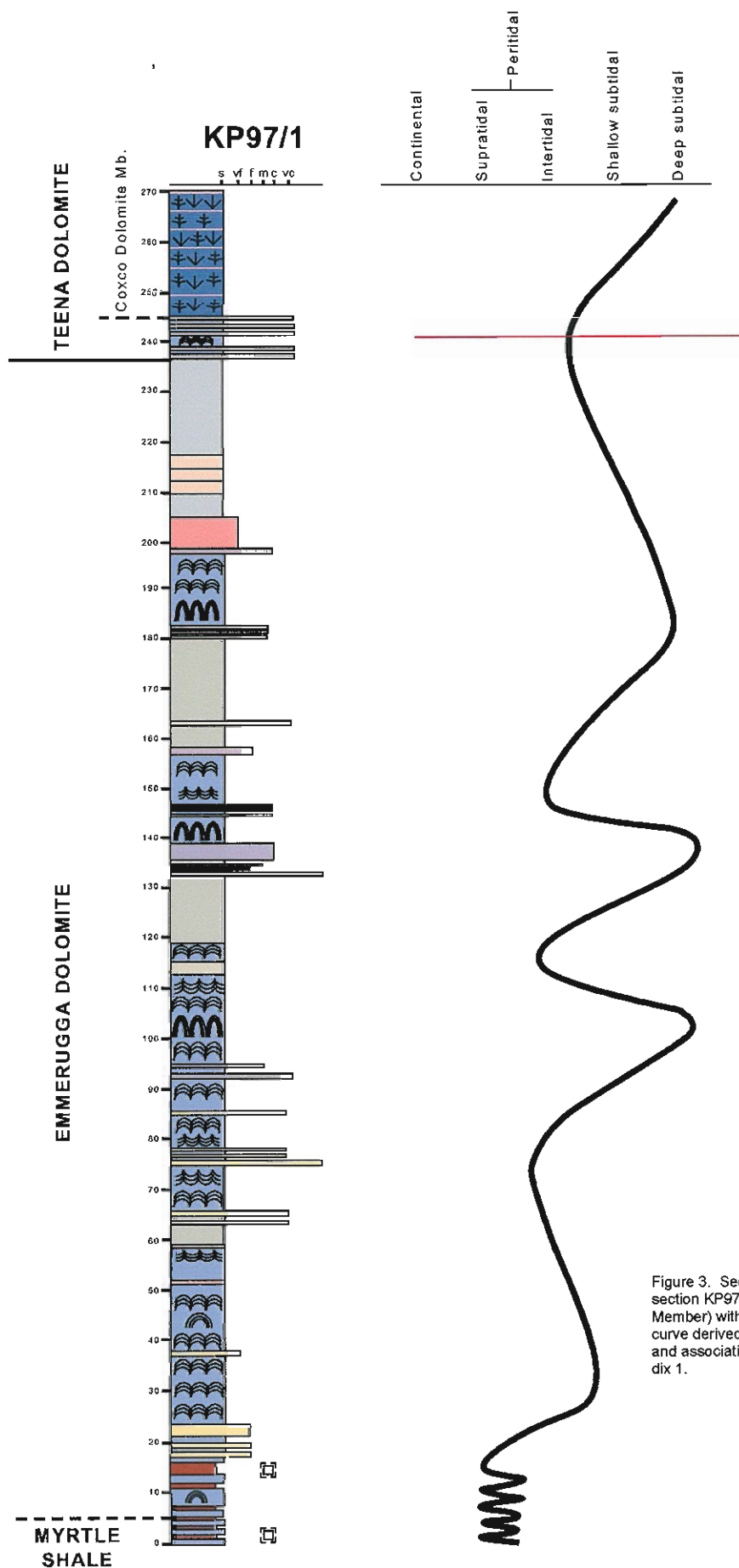


Figure 3. Sedimentary facies log of measured section KP97/1 (Myrtle Shale to Coxco Dolomite Member) with a schematic relative water depth curve derived from analysis of lithofacies types and associations. Legend is included as Appendix 1.

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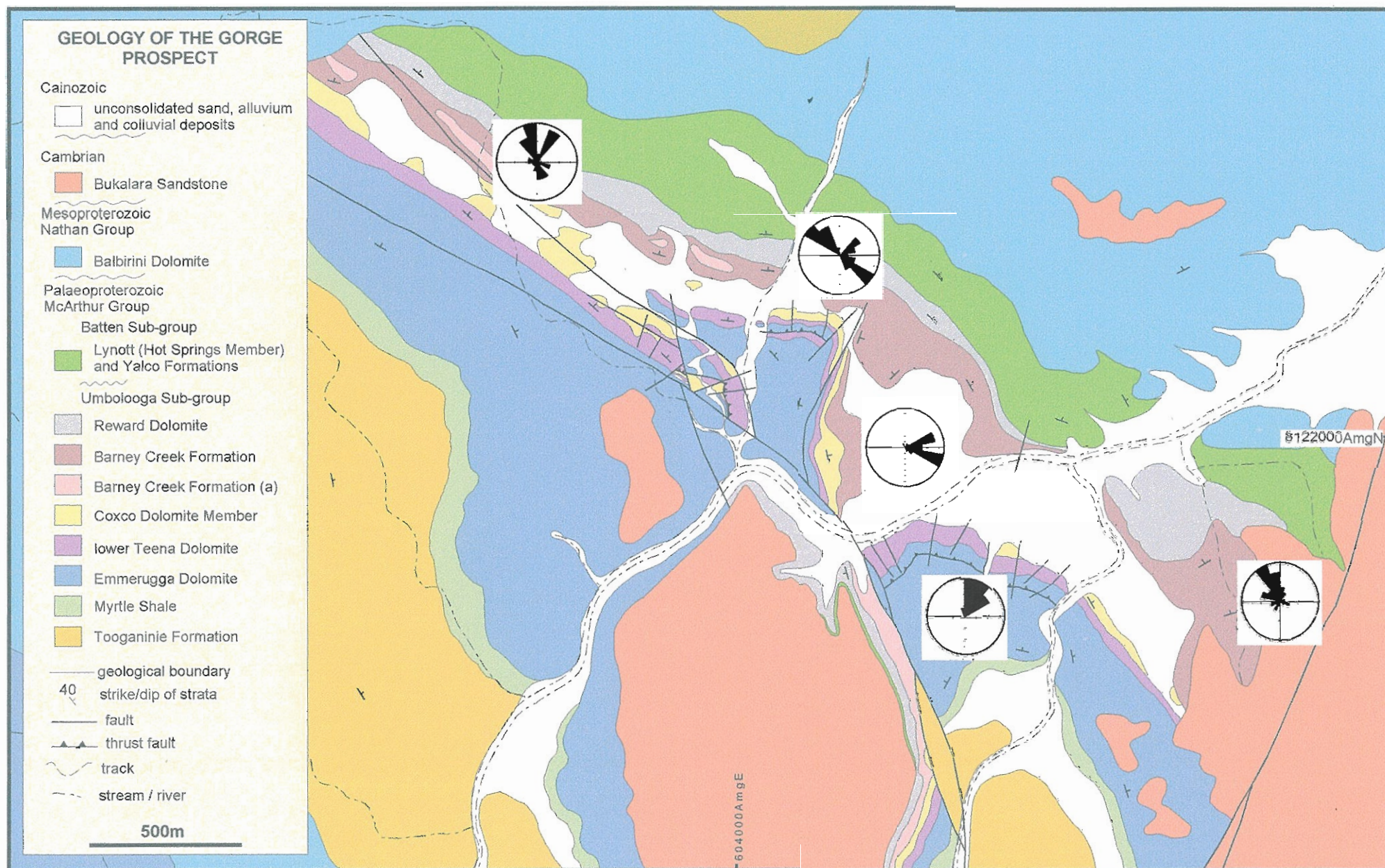


Figure 4. Palaeoslope indicators for certain areas within the Gorge Prospect area generated from analysis of various mesoscopic structures associated with slope development (e.g. intrafolial folds in the Barney Creek Formation; geopetal structures in the C Member).

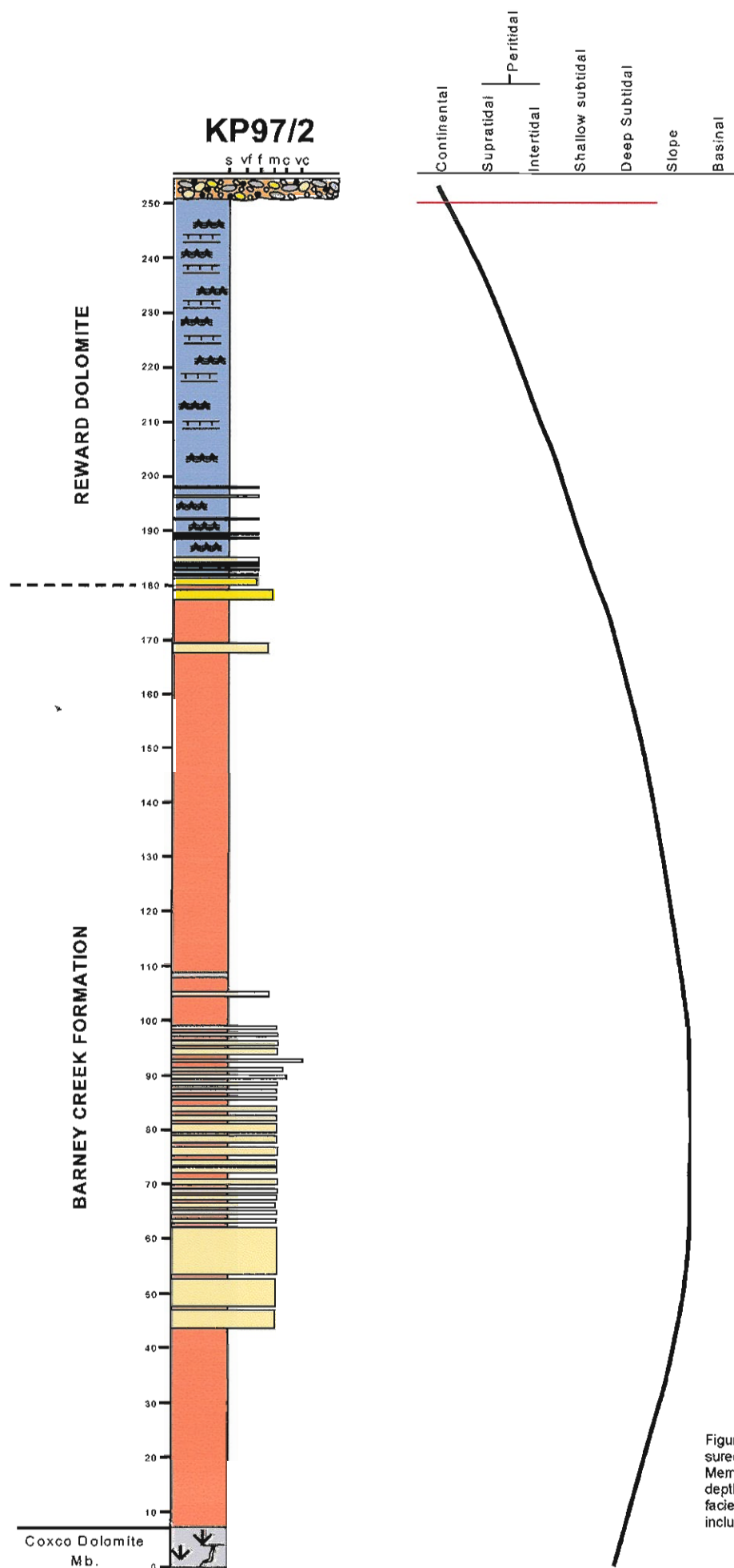


Figure 5. Sedimentary facies log of measured section KP97/2 (Coxco Dolomite Member) with a schematic relative water depth curve derived from analysis of lithofacies types and associations. Legend is included as Appendix 1.

	Intraclast breccia		Planar laminated dololomite		Microdigitate microbialite
	Polymict breccia		Graded 'wormy' textured dololomite		Undulatory domal microbialite
	Conglomerate		Sideritic horizon		Unlinked domal microbialite
	Dolorudite		Stromatolitic dolostone		Linked domal microbialite
	Dolarenite		Red siltstone with halite casts		Wavy microbialite
	Dolomitic sandstone		Coxco - planar laminated dololomite		Plumose-structured microbialite
	Dolomitic siltstone & shale		Coxco - stromatolitic dolostone		Columnar conical microbialite
	Carbonaceous shale/siltstone		Ooid/peloid grainstone		

	Radiating, acicular crystal fans - 'Coxco' needles		Cauliflower chert - evaporite pseudomorph (anhydrite)
	Fibrous cement & sediment infilled 'neptunian' dykes		Coalesced cherty nodules
	Carbonaceous black 'flecks'		Halite pseudomorph - 'hopper'
	Stylolite		Gypsum pseudomorph
	Stylo-lamination		Chert nodule - 'Reward spheroid'
	Teepee-like structure		Irregular/nodular texture
	Normal grading		Green 'tuffaceous' clay bed
	Flame structures		K- feldspar altered beds - 'pinkites'
	Intrafolial folds		Pyrite
	Imbrication		Vuggy porosity
	Cross-lamination		Sphalerite
	Wormy texture		Chalcopyrite
	Synaeresis crack		Pyrobitumen
	Desiccation crack		Galena
			Silicification

Appendix 1. Legend for sedimentary facies logs included as Figures 3 & 5.

Geology and geochemistry of the Berjaya Pb-Zn prospect, McArthur River region, N.T.

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Centre for Ore Deposit Research

Introduction

An integrated study of the sedimentology, carbonate diagenesis, mineralisation styles and geochemistry of the Berjaya Pb-Zn prospect has been undertaken to improve our understanding of the timing of brine migration and chemical composition of mineralising solutions in the McArthur Group. The Berjaya prospect is hosted in the Coxco Dolomite Member 17 km to the west of HYC (Fig. 1a). Stratiform pyrite laminae is associated with fine grained sphalerite and minor galena, with one intersection in BJ1 averaging 0.87% Zn and 0.07% Pb over 11m, including 1.8% Zn over one metre (Pietsch et al., 1991a). Another one-metre drill intersection contained 4.6% Zn and 0.46% Pb (Pietsch et al., 1991b). Sphalerite, galena and chalcopyrite also occur in late-stage discordant dolomite veins, and are intergrown with coarse, porosity-occluding saddle dolomite cement.

Sedimentology

Sedimentological analysis of selected drill cores from the Berjaya area (Fig. 1b) indicates that the stratigraphy is constrained by the presence of "coxco needles" characteristic of the Coxco Member of the Teena Dolomite in the base of the drill core intersections; and the presence of reactive pyrite characteristic of the Caranbirini Member of the Lynott Formation in the top. Correlation of these formation boundaries confirm that the intervening package, representing Barney Creek Formation/Reward Dolomite time, thins to the north from > 500 m to < 30 m over a distance of only 2.7 km. Although more detailed lithostratigraphic correlations within

this package are difficult due to lateral facies changes, the most likely mechanism for the thinning of section appears to be onlap of the lower part of the Barney Creek Formation (W-Fold and lower HYC Pyritic Shale Members) to the northwest. This configuration is consistent with tectonostratigraphic models for HYC Deposit time that invoke accumulation of the host sediments in half graben depocentres. Areas where the Barney Creek Formation/Reward Dolomite section is thin/condensed have distinctive sedimentary features that include carbonaceous units with wavy/crinkly lamination, and plastically deformed carbonaceous intracasts in graded dolomite beds. These features indicate accumulation of carbonaceous material as in-situ microbial mat in areas of low sediment input above storm wave base. In the half graben model these areas would represent deposition above the uplifted footwall block.

Diagenesis and carbonate chemistry

An understanding of the petrography and geochemistry of carbonate cements associated with Pb-Zn mineralisation can provide important constraints on the timing of mineralisation, fluid flow paths for mineralising brines and possible localisation mechanisms for sulphide precipitation. At the Berjaya Prospect, most of the 'late-stage' mineralisation is hosted within dolomite-infilled fractures which cross-cut the Coxco Dolomite Member. This unit consists of massive to thinly bedded, light grey dolomicrite with several beds of upwardly diverging, acicular dolomite crystal fans or 'Coxco needles'. These are interpreted by Winefield (in press) to have originally precipitated directly onto the seafloor as a type of

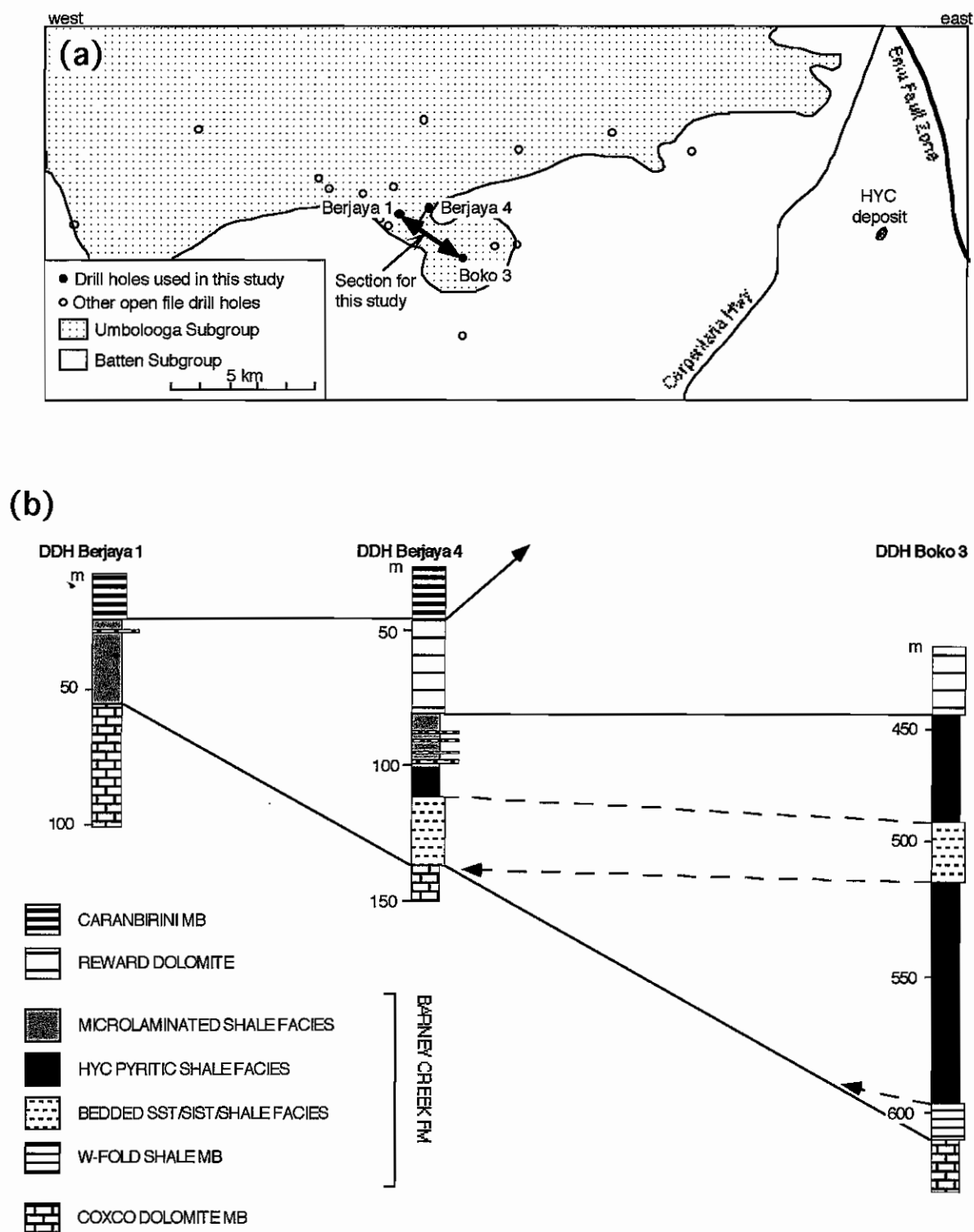


Figure 1. (a) Location of Berjaya prospect (17 km west of HYC); (b) NW facies section through Berjaya prospect.

submarine cement. The degree of preservation of fan-like cements implies very early dolomitisation of the original precursor mineral, thought to have been aragonite.

Dolomite-infilled fractures have regular, jig-saw fit textures. Internal sediment infills most fractures and comprises dark coloured (carbonaceous?) dolomicrite and finely brecciated host rock fragments. Three types of infilling dolomite cement have been identified using plain-light and cathodoluminescence (CL) petrography: fibrous dolomite (FD); clear, equant dolomite (CED); and coarse, 'saddle' dolomite (CSD). FD cement isopachously rims fracture walls and consists of linked, elongate fibres with a length to width ratio of 6 to 1. Internally, the cement displays a radial-axial texture, commonly associated with fibrous marine cements (James and Choquette, 1990). Under CL, FD cement is dull to slightly luminescent with intricate internal banding sometimes evident. CED cement overlies FD and commonly displays a distinctive dull to bright CL zoning pattern. It consists of bladed, prismatic crystals of clear, inclusion-poor dolospar cement. Late-stage sphalerite and chalcopyrite is commonly associated with the development of inclusion-rich, CSD. Pyrobitumen is also observed within CSD cement inclusions and also as a pore fill overlying earlier CED cement. Under CL, this generation of cement is non-luminescent.

Microprobe analyses of the host rock and each of the cements indicates that the average Fe and Mn contents for CSD (Fe, 29750 ppm; Mn, 3010 ppm) and CED (Fe, 16350 ppm; Mn, 2500 ppm) are significantly higher than the average values for FD cement (Fe, 2465 ppm; Mn, 935 ppm), dolomicrite (Fe, 6053 ppm; Mn, 735 ppm) and Coxco needle dolospar (Fe, 3620 ppm; Mn, 675 ppm). Fe and Mn analyses for CED are highly variable, especially for Fe. Microprobe traverses across this cement demonstrate a marked fluctuation in Fe content in the area of bright CL luminescent banding, while the Mn content remains relatively constant. This implies that Fe variation rather than the Mn content is the dominant factor in the CL signature of these cements.

Microsampling using a dental drill to sample the various cements and host rock sediment was also undertaken for carbon and oxygen stable isotope analysis. The results show a clear distinction between

average values for host rock dolomicrite ($\delta^{13}\text{C} = -0.73$ PDB; $\delta^{18}\text{O} = -8.63$ PDB), internal sediment ($\delta^{13}\text{C} = -0.98$ PDB; $\delta^{18}\text{O} = -8.53$ PDB), FD ($\delta^{13}\text{C} = -1.08$ PDB; $\delta^{18}\text{O} = -9.08$ PDB) and average values for CED ($\delta^{13}\text{C} = -2.82$ PDB; $\delta^{18}\text{O} = -10.48$ PDB) and CSD ($\delta^{13}\text{C} = -1.79$ PDB; $\delta^{18}\text{O} = -11.83$ PDB).

The petrography, CL signature and geochemistry of FD are all consistent with a marine origin for this cement, most likely associated with the deposition of internal sediment within these fractures. Conversely, the characteristics of the CED and CSD cements are typical of late stage burial cements. Thus, the diagenetic sequence for the Coxco Dolomite Member within the Berjaya Prospect is: (I) seafloor precipitation of fan-like cements (Coxco needles) and deposition of finely crystalline micrite. Early dolomitisation and lithification of sediment; (II) fracturing of the cemented sequence and infill of fractures by internal sediment and FD cement; (III) precipitation of CED cement over earlier FD cement during burial; and (IV) precipitation of CSD cement associated with sulphides and pyrobitumen.

Fluid Inclusions

A total of 91 fluid inclusions have been analysed from Berjaya. The host minerals were coarse saddle dolomite and associated sphalerite grains. Fluid inclusions in excess of 100 μm have been noted in the CSD, which are ideal for microthermometric analyses. Fluid inclusion petrography has identified the following range of fluid inclusion types:

- Type 1A: 2-phase liquid-rich inclusions with a small vapour bubble;
- Type 1B: 3-phase liquid-rich inclusions with a small vapour bubble and unknown daughter mineral;
- Type 1C: 3-phase liquid-rich inclusions with a small vapour bubble and solid hydrocarbon phase;
- Type 2A: 2-phase vapour-rich inclusions;
- Type 2B: 3-phase vapour-rich inclusions with an unknown daughter mineral;
- Type 2C: 3-phase vapour-rich inclusions that also contain a solid hydrocarbon phase;
- Type 3: Saturated fluid inclusions that contain 3 or more phases, including a small vapour bubble and halite crystal (rare);

- Type 4A: 2-phase liquid hydrocarbon inclusions with a small vapour bubble
- Type 4B: 1-phase liquid hydrocarbon inclusion

Overall, these are indicative of the presence of at least two fluid types (brine and liquid hydrocarbons), and possibly also indicate that phase separation or gas migration occurred during deposition of the CSD.

Microthermometric analyses recorded homogenisation temperatures between 56° and 172°C, with most between 90° and 120°C. Eutectic melting temperatures were between -83° and -23°C, with most between -72° and -45°C. These data are consistent with the presence of dissolved CH_4 , CO_2 and/or high concentrations of CaCl_2 in the brines. Final melting temperatures of ice were between -0.2° and -42°, with most in the range -10° to -35°C, consistent with saline brines that contain abundant dissolved salts in addition to NaCl (eg., MgCl_2 , KCl, CaCl_2). In summary, saline brines and liquid hydrocarbons have been involved in the transport and precipitation of CSD and discordant base metal sulfides at Berjaya. The presence of vapour-rich fluid inclusions in the CSD is either a consequence of boiling, or of the presence of sour gas. To resolve this, Laser Raman analyses are required to determine the composition of the vapour phase.

Sulfur isotopes

Sulfur isotopes of pyrite and sphalerite range from -3.8‰ to +29.2‰ (pyrite) and -2.8‰ to +14.1‰ (sphalerite). One galena grain was analysed and found to have a $\delta^{34}\text{S}$ value of +10.6‰. Pyrite laminae were found to have highly variable internal isotopic compositions, with values measured from one pyrite lamination varying between -3.8‰ and +24.6‰. These values are within the range of data reported for pyritic laminae from HYC (Eldridge et al., 1991), and could relate to biogenic reduction of sulfate in variably open to closed systems. The limited number of analyses of sulfur isotope data from the base metal sulfides prevents any definite conclusions being drawn about them.

Lead isotopes

Seven drilled mineral separate samples (two galenas and five pyrites) were analysed by high-resolution ICPMS (Townsend et al., 1998) at the Central Science Laboratory, University of Tasmania. The results from these samples and two samples of HYC sphalerite/galena mixtures (used as an internal check on the analyses) are presented on Table 1 and in Figure 2. Within the precision of the technique, one of the Berjaya galena samples contains Pb that is indistinguishable from Pb from HYC, the other galena and two of the pyrites also plot very close to the HYC, but may contain slightly more radiogenic Pb. The other three pyrite samples have Pb that is distinctly more radiogenic than samples from HYC. Because 'HYC-like' Pb is present in the Berjaya galena, Pb isotopes alone cannot be used to down-grade the prospectivity of the area. However, the converse is not necessarily true. If the same well mixed, low U, source area was tapped at both Berjaya and HYC, then Pb of similar isotopic would be present in both styles of mineralisation..

Lithogeochemical and C/O isotopic signatures at the Berjaya prospect

Nine samples from DDH BJ1 spanning a fifty metre interval and twelve samples from BJ4 spanning about 120 m were analysed for major and trace elements (Table 2) with a view to testing the lithogeochemical indices developed for HYC and Lady Loretta deposits (Large and McGoldrick, 1998 and Large et al., P384A Final Report Volume 1) at Berjaya prospect. Recalculating the analyses (Large and McGoldrick, 1998) indicates that little or no Fe carbonate is present in the Berjaya samples. The data in Figure 3, together with calculated 'Ankerite Ratios' (moles Fe+Mn : moles of Mg in carbonate), demonstrate that all samples contain dolomite as the only carbonate. Several samples are weakly anomalous in Zn (up to 500 ppm), however, all the samples have low values for SedexAI, AI3 and MnOd (Fig. 4). The combined poor response of these indices strongly downgrades the prospectivity of the Berjaya area for large stratiform Zn-Pb deposits at the stratigraphic level of the two drill holes. Thallium is known to form large primary

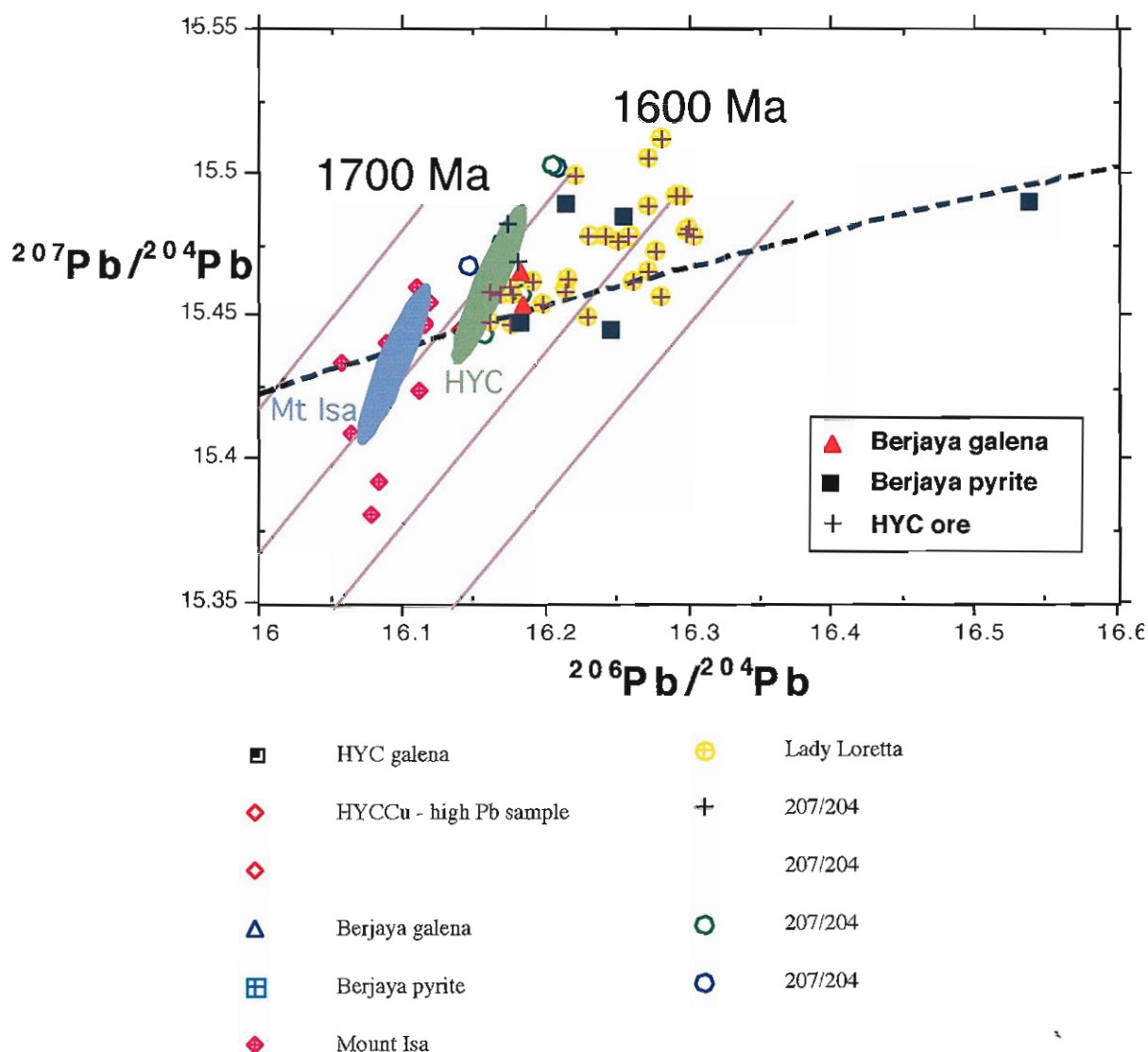


Figure 2. Lead isotope ICPMS data for eight Berjaya sulfides and two HYC samples compared to average values measured by TIMS for HYC and Mount Isa from Gulson (1985); the range shown for the TIMS data corresponds approximately to the analytical precision of the technique.

Table 1

Lead isotope ratios measured by HR-ICPMS for samples from Berjaya and HYC

		$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{206}\text{Pb}$	$^{207}\text{Pb}/^{206}\text{Pb}$
HYC A1	sphalerite/galena	16.181	15.469	35.917	2.220	0.956
HYC A2	sphalerite/galena	16.174	15.482	35.911	2.220	0.957
2 PPD20 (200.05)	galena	16.182	15.465	35.918	2.220	0.956
5 PPD20 (200.05)	galena	16.185	15.454	35.905	2.218	0.955
7 BJ4-1	pyrite	16.539	15.490	36.075	2.181	0.937
9 BJ*7	pyrite	16.183	15.448	35.852	2.216	0.955
10 BJ*2	pyrite	16.215	15.489	35.948	2.217	0.955
12 PPD (81.7)	pyrite	16.247	15.445	35.849	2.207	0.951
14 BJ1/24	pyrite	16.255	15.485	35.970	2.213	0.953

Table 2
Major and trace element analyses for samples from DDHs BJ1 and BJ4

DDH	depth (metres)	SiO2 wt%	TiO2 wt%	Al2O3 wt%	Fe2O3 wt%	FeO wt%	MgO wt%	CaO wt%	MnO wt%	Na2O wt%	K2O wt%	P2O5 wt%	Loss wt%	Total wt%	S wt%	As ppm	Ba ppm	Cu ppm	Pb ppm	Rb ppm	Sr ppm	Tl ppm	Zn ppm
BJ1	37.6	39.94	0.28	7.22	2.20	1.98	9.06	13.31	0.10	<0.05	5.44	0.12	21.80	101.45	1.06	17	247	11	23	85	33	1.7	34
BJ1	43.8	46.40	0.30	10.12	1.77	1.59	6.60	9.70	0.06	0.06	8.03	0.11	16.12	100.86	0.68	18	305	29	17	105	30	1	51
BJ1	43.9	44.14	0.36	8.88	2.30	2.07	7.56	11.09	0.07	<0.05	6.67	0.11	18.44	101.69	0.98	24	305	12	19	105	34	<1	50
BJ1	46.9	47.45	0.28	10.29	1.84	1.66	6.22	9.16	0.05	0.06	8.43	0.13	15.35	100.92	0.79	19	302	21	26	99	29	1.5	103
BJ1	52.9	14.53	0.05	1.28	1.04	0.94	17.47	25.15	0.09	<0.05	1.03	0.05	38.76	100.39	0.24	12	37	3	9	12	51	<1	18
BJ1	74.8	11.49	0.06	1.62	0.91	0.82	17.91	26.02	0.09	0.16	1.28	0.04	40.02	100.42	0.14	9	42	2	4	13	34	<1	3
BJ1	79.6	30.95	0.15	3.85	1.72	1.55	12.97	18.70	0.10	<0.05	3.10	0.11	28.44	101.64	0.99	21	149	15	66	34	30	<1	69
BJ1	90.1	8.61	0.04	1.12	0.69	0.62	18.96	27.05	0.08	<0.05	0.99	0.02	41.53	99.71	0.07	3	44	1	4	10	38	<1	8
BJ1	92.6	9.06	0.04	1.09	0.82	0.74	18.69	26.76	0.09	<0.05	0.94	0.02	41.41	99.66	0.08	7	33	1	4	9	34	<1	12
BJ4	11.8	55.26	0.18	4.85	1.65	1.48	6.61	10.96	0.11	<0.05	3.14	1.59	15.01	100.84	0.66	13	219	7	26	75	36	2.8	520
BJ4	13.0	57.27	0.21	5.29	1.46	1.31	6.72	9.24	0.11	<0.05	3.41	0.31	15.07	100.40	0.46	8	230	7	20	84	28	1.7	51
BJ4	14.0	49.82	0.19	5.22	1.70	1.53	7.99	12.07	0.14	<0.05	3.36	1.12	17.75	100.89	0.56	8	209	7	24	80	30	2.0	230
BJ4	62.3	30.31	0.07	1.65	0.65	0.58	14.48	20.51	0.07	<0.05	1.14	0.04	31.49	100.99	0.2	5	63	2	10	22	19	<1	32
BJ4	67.3	18.96	0.06	1.32	1.84	1.66	16.57	23.48	0.09	<0.05	0.91	0.13	36.17	99.51	1.12	8	65	3	8	18	17	<1	28
BJ4	76.2	24.49	0.05	1.18	0.52	0.47	16.54	22.33	0.05	<0.05	0.87	0.06	34.54	100.64	0.13	3	37	1	7	15	17	<1	145
BJ4	84.9	24.21	0.08	2.11	1.02	0.92	15.92	21.94	0.07	<0.05	1.67	0.14	33.64	101.72	0.46	17	67	5	24	24	37	<1	269
BJ4	92.8	30.53	0.07	1.70	0.70	0.63	13.99	20.08	0.06	<0.05	1.36	0.26	30.95	100.33	0.3	40	73	3	62	20	32	<1	38
BJ4	100.5	3.73	0.01	0.17	0.76	0.68	19.99	29.16	0.10	0.06	0.13	0.18	44.91	99.88	0.08	20	<4	1	19	2	51	<1	10
BJ4	106.2	33.14	0.24	6.14	2.42	2.18	10.96	15.98	0.16	<0.05	4.64	0.17	25.49	101.52	1.52	33	256	12	42	71	32	1.7	82
BJ4	125.2	36.64	0.36	7.81	2.29	2.06	9.46	14.29	0.07	<0.05	5.91	0.14	22.95	101.98	0.68	26	248	22	12	85	29	<1	30
BJ4	137.5	18.58	0.12	2.88	1.53	1.38	16.32	22.92	0.09	<0.05	2.28	0.05	35.44	100.16	0.52	46	87	9	16	27	21	<1	21

Table 3. Carbon and oxygen isotope analyses for samples from DDHs BJ1 and BJ4

DDH	depth (m)	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$
BJ1	37.6	22.4	-0.6
BJ1	43.8	22.5	-0.7
BJ1	43.9	21.9	-0.8
BJ1	46.9	20.9	-0.8
BJ1	52.9	20.4	-0.3
BJ1	74.8	21.5	-0.1
BJ1	79.6	23.3	0.1
BJ1	90.1	21.7	0.1
BJ1	92.6	20.7	-0.1
BJ4	11.8	23.1	-1.6
BJ4	13.0	23.4	-1.4
BJ4	14.0	23.0	-1.6
BJ4	62.3	22.1	-0.1
BJ4	67.3	22.2	-0.4
BJ4	76.2	18.1	-0.2
BJ4	84.9	19.9	-0.9
BJ4	92.8	20.2	-1.0
BJ4	100.5	23.4	-1.1
BJ4	106.2	22.6	-0.4
BJ4	125.2	21.7	-0.7
BJ4	137.5	20.6	-0.5

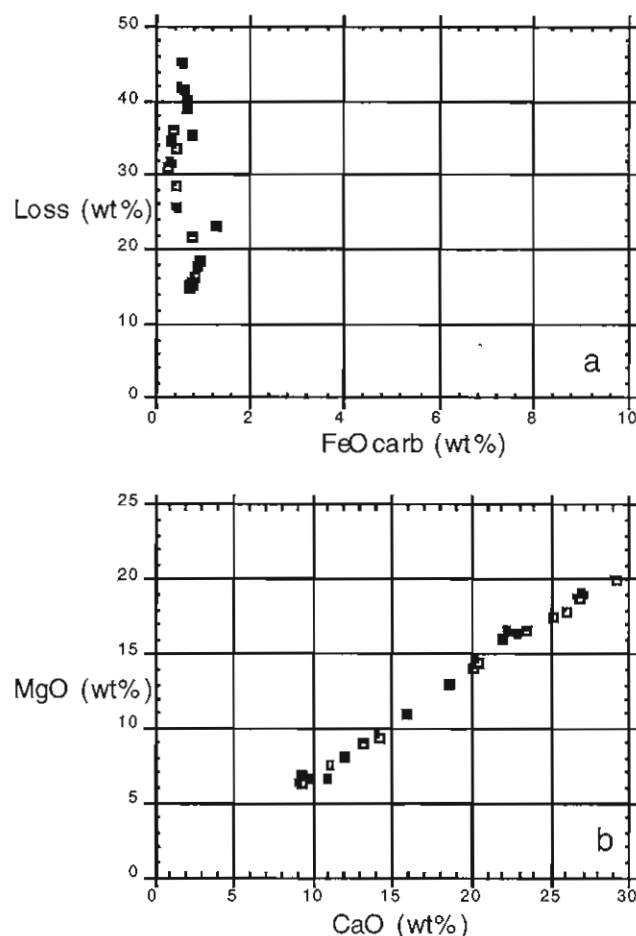


Figure 3. (c) Loss on ignition compared to calculated Fe content of carbonate for 21 Berjaya samples; the low FeOcarb and high loss:FeOcarb ratios preclude the presence of more than a trace amount of Fe-bearing carbonate (ankerite and/or siderite) in these samples; (d) MgO compared with CaO for 21 Berjaya samples; all samples plot on a 'dolomite line'.

dispersion halos around northern Australian stratiform sediment-hosted Zn-Pb deposits. All the Berjaya samples have background Tl contents (most are at, or below, detection limit – 1 ppm), consistent with their poor response for the other indices, and further downgrading the likelihood of stratiform Zn mineralisation nearby.

Whole rock carbonate C and O isotope measurements were made on the 21 samples used for the lithogeochemical investigation. The results are presented on Table 3 and in Figure 5. Figure 5 compares the Berjaya samples to fields for the Barney Creek Formation elsewhere. The Berjaya data largely overlap with the field for samples remote from known

mineralisation. The (relatively) heavy O and light C trend observed for samples in the halo to HYC (Large et al., P384A Final Report Volume 1) is not evident in the Berjaya data.

Conclusions

Although the Berjaya prospect is in a favourable stratigraphic position and contains some stratiform Pb-Zn mineralisation, the thinned target section and lack of lithogeochemical and C/O responses downgrade the prospectivity of the area for significant stratiform Pb-Zn mineralisation. The

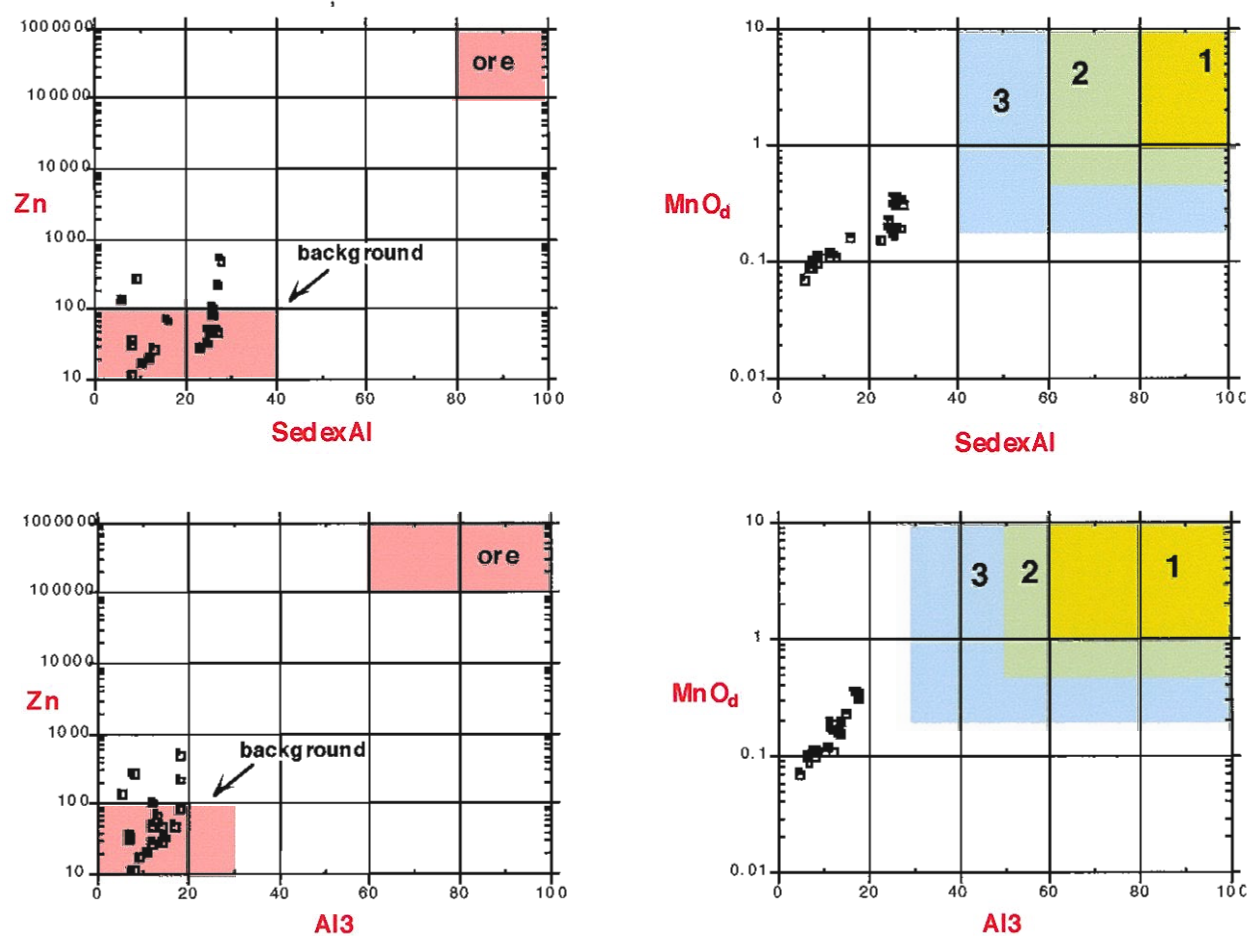


Figure 4
Zinc/SedexAl, Zn/Al₃, MnO_d/SedexAl and MnO_d/Al₃ comparisons for 21 Berjaya samples; see text for further discussion.

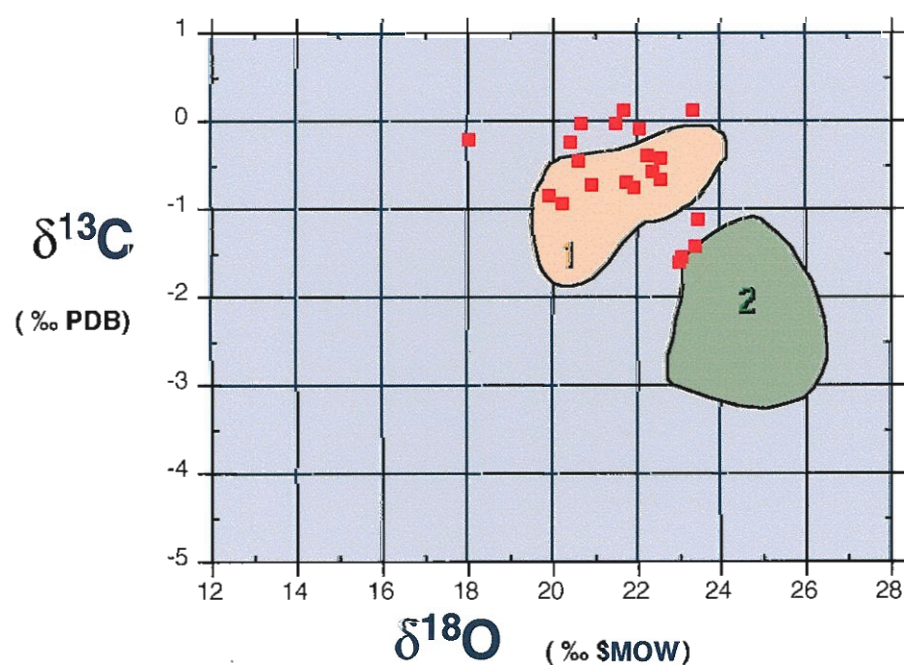


Figure 5
Carbon and O isotopic data from 21 Berjaya samples (red squares) compared to fields for samples distal to HYC (Field 1: Top Crossing area and DDH BMR#2) and samples within the isotopic halo to HYC (Field 2: samples from DDHs Homestead 6 and Barney Creek #3).

isotopic signatures are consistent with basinal sources of waterf, metals and ligands; i.e. similar to other Pb-Zn occurrences in the McArthur Group. Fluid inclusion analyses from the discordant Pb-Zn-bearing veins and cements indicate the involvement of saline connate brines and hydrocarbons in the epigenetic mineralising process (mixing?), and provide evidence for hydrocarbon migration through the sequence during diagenesis. Oxidised (sulfate-bearing) brines interacting with liquid hydrocarbons could have been the depositional mechanism for base metal sulfides in the discordant (MVT-style?) stage of mineralisation. There may be potential for more MVT-style Pb-Zn mineralisation at Berjaya, as the litho-geochemical responses of discordant Pb-Zn mineralisation remain untested.

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Sedimentology of the Torpedo Creek Quartzite in the Lady Loretta area; implications for the tectono-sedimentary setting of northern Australian Proterozoic Zn-Pb-Ag deposits

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Introduction

The Lady Loretta Deposit is a relatively small but high grade sediment-hosted base metal deposit (8.3 Mt at 18.4% Zn, 8.5% Pb and 125 g/t Ag; Hancock and Purvis, 1990). The mineralization occurs within the Mount Isa Group equivalent McNamara Group, approximately 115 km NNW of Mount Isa Mine.

Recent sedimentological work on the Lady Loretta Formation that hosts the mineralisation, concludes that the package in the mine area is indistinguishable, in terms of thickness and sedimentary facies, from the formation regionally (Dunster, 1996; Dunster and McConachie, 1998). This observation apparently invalidates prior models for the setting of the mineralisation, that have proposed a genetic link with the development of a local basinal feature, termed the "Paradise Creek Graben" (Dunnet, 1976), for which various orientations and scales have been proposed (eg. Large, D. E., 1980; Amade, 1986; Lemcke, 1986; Dunster and McConachie, 1998). Structures interpreted as growth faults active during the basin-forming event (eg. the Carlton Fault; Large, D. E., 1980) were envisaged to have been the conduits for mineralising fluids.

Given the apparent absence of growth-faulting and graben formation, the Lady Loretta Formation appears to have accumulated during a period of relative tectonic quiescence. As a result, twin problems arise with regard to the base-metal mineralisation; what controlled the deposition of the host "trap" rocks?; and what were the conduit/s for the mineralising fluid?

In order to address this important question, this study was initiated to examine the setting of the Lady Loretta mineralisation in the broader context

of its position within the lower McNamara Group stratigraphy. Previous studies have shown the potential of the basal sandstone units, for example the Masterton Sandstone at the base of the McArthur Group in the southern McArthur Basin, to record the initial tectonic regime of the basin phase in which they occur (Bull and Rogers, 1996). Specifically, facies and palaeocurrent patterns within these clastic units have proved critical in determining which faults were active during sedimentation, because these sedimentary features are preserved, even where the original structural and stratigraphic framework has been extensively modified by subsequent tectonic events. As a result, the basal unit of the McNamara Group, the Torpedo Creek Quartzite which outcrops to the north and east of the Lady Loretta deposit, was targeted for sedimentological examination.

Sedimentology

Surprise Creek Formation (SCF)

The SCF, the oldest unit exposed in the Lady Loretta area, comprises medium- to thin-bedded and cross-bedded, grey to pale pink coloured sandstone. Palaeocurrent data from the Redie Creek area shows a well defined bimodal bipolar pattern (Fig. 1) strongly suggestive of tidally influenced (ie. shallow marine) sedimentation.

Torpedo Creek Quartzite (TCQ)

The SCF is overlain, with mild angular unconformity, by the basal unit of the McNamara Group, the TCQ. This is a sequence of up to 420 m of coarse-grained clastics that forms the main focus of this study. It is conformably overlain by the succeeding units of the

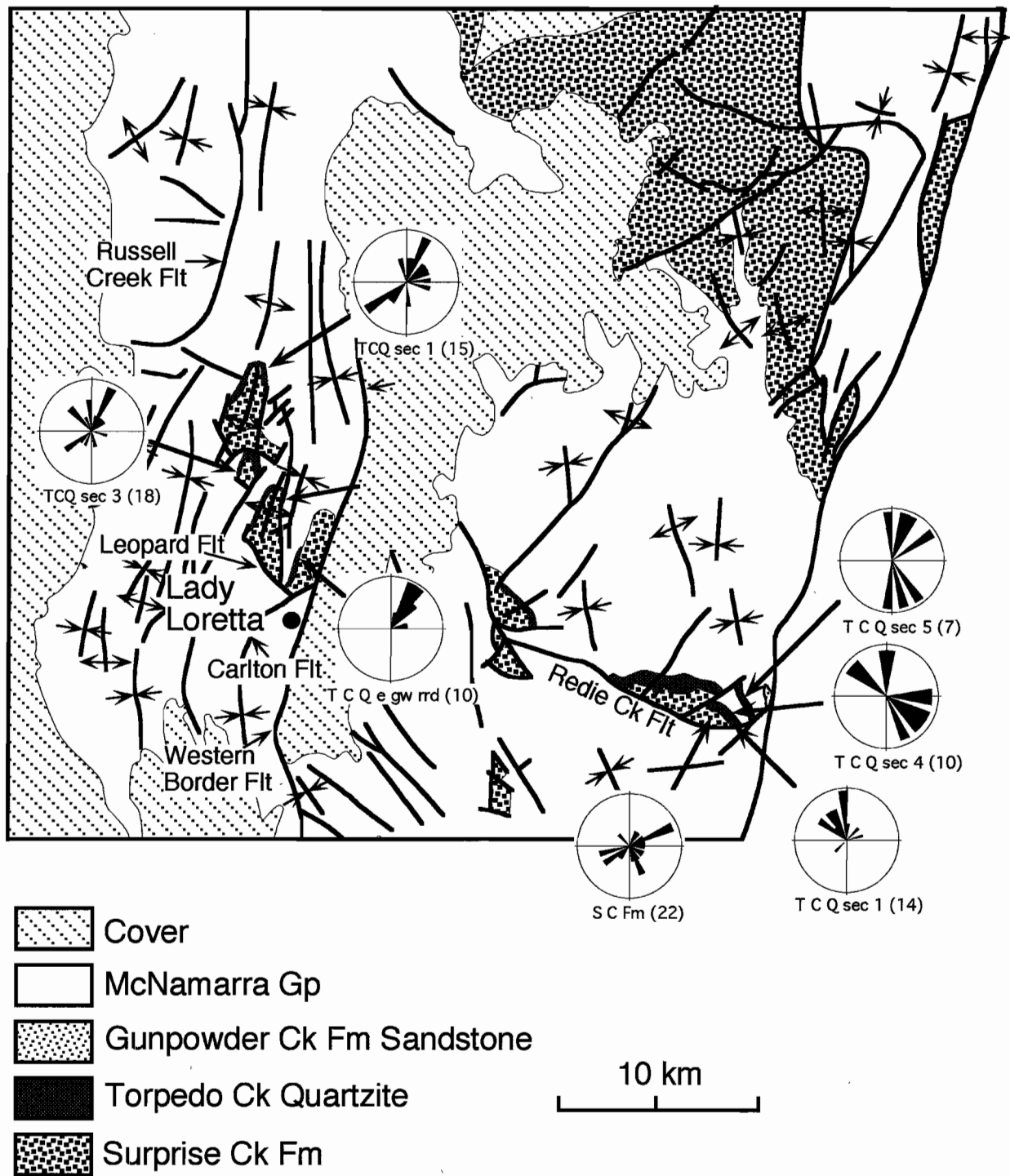


Figure 1. Outcrop geology and palaeocurrent data from the Surprise Creek Formation and Torpedo Creek Quartzite in the Lady Loretta and Redie Creek areas.

lower McNamara Group; the part clastic part carbonate Gunpowder Creek Formation; and the platform carbonates of the Paradise Creek, Esperanza and Lady Loretta Formations.

TCQ outcrops in two discrete areas were examined for the purpose of this study. In the immediate Lady Loretta region, the unit crops out at four localities as a thin but laterally persistent selvedge adjacent to the northern edge of blocks of the underlying SCF. These blocks lie within a 120 km long, 10–15 km wide, N–S trending zone of Isan folding, shearing and faulting informally termed the Paradise Creek High Strain Zone. As a result, the SCF blocks form an en-echelon set of rigid NNW-trending anticlinal horsts flanked by synclines developed in the overlying McNamara Group (Fig. 1). The TCQ was also examined in the less deformed Redie Creek area, 20 km east of Lady Loretta (Fig. 1), where the unit also occurs as a continuous selvedge at the northern edge of a block of the older SCF. In this case however there are no tight folds, and the SCF block comprises a coherent, 5 km long, dominantly ENE-trending body bounded at its southern margin by the Redie Creek Fault, and at its eastern margin by the NNE-trending Mount Gordon Fault Zone (Fig. 1).

In general, the TCQ varies in thickness from < 10 m to several tens of metres, and can be considered in terms of three constituent facies:

- A basal pebble-boulder conglomerate facies is not always present, but in places reaches a thickness of > 10 m. Clasts are sub- to well-rounded, often tabular quartz sandstone with diameters up to > 3 m. In places they are a distinctive pale pink colour. These pebble-boulder conglomerate facies are interpreted as debris flows and/or alluvial channel deposits. They indicate that the onset of the McNamara Group depositional cycle was initiated by a relief-forming tectonic event. The lateral restriction of the conglomerate deposits indicates that they accumulated either in erosive channels or as fans sourced from uplifted blocks of older material. The distinctive pink colouration of many of the sandstone clasts is identical to that of the underlying SCF. This suggests that the current stratigraphic configuration is depositional, and that the unit comprised local “basement” at lower McNamara time.
- A well sorted clean, white, cross-bedded quartz sandstone facies forms the lower to middle part of the unit in all sections. They are interpreted to represent high-energy (ie. braided) alluvial/fluvial systems. Initially these deposits would have accumulated as lateral and distal equivalents to individual conglomeratic channels/fans. However, the occurrence of the clean, fine- to coarse-grained quartz sandstone facies though the bulk of the unit indicates that the initial relief of the uplifted SCF blocks was rapidly subdued by erosion/deposition, allowing the braided fluvial systems to become dominant. Unfolded palaeocurrent data from these units indicates a dominant N–NNE component of palaeoflow in each locality (Fig. 1).
- A thinly-bedded, poorly-sorted grey-brown quartz sandstone facies forms the upper few metres of the TCQ. This unit is interpreted to represent shallow water sedimentation that records the onset of the transgression that marks the transition to the Gunpowder Creek Formation throughout the Lawn Hill Platform region (Hutton and Wilson, 1985).

Implications for the Lady Loretta mineralisation

Sedimentary Setting

The presence of boulders of lithified SCF in the basal TCQ conglomerate facies, suggest that this uplift represents the culmination of a major burial/exhumation cycle. On a basin-wide scale this contact must, therefore, represent a significant time break between two major basin phases, and sedimentation patterns in the TCQ should reflect the basin geometry at the onset of McNamara Group sedimentation. In the Redie Creek area, where the Isan deformation is less intense, palaeoflow within the TCQ was dominantly north-directed. This is approximately normal to the WNW-trending axis of the SCF block in this region (Fig. 1), which has been implicated as a source for the clasts in the base of the TCQ. The latter was, therefore, an actively eroding ridge with a relatively steep N–NE-dipping slope at its northern margin at this time. This configuration suggests that,

in this area at least, WNW-trending growth faults controlled the onset of McNamara Group sedimentation.

In the more deformed Lady Loretta area, unfolded palaeocurrent data from the TCQ has a dominant northerly component effectively identical to that from Redie Creek. This suggests that, prior to the Isan deformation, the SCF blocks in this area formed a similar semi-continuous, WNW-trending ridge. This basement ridge, and the associated syn-sedimentary faults, would have passed immediately to the north of the site that would ultimately host the Lady Loretta mineralisation. However, current evidence suggests that the structures were in active during deposition of the host sediments.

Controlling structures

Any early McNamara structural framework must explain a semi-continuous, WNW-trending ridge of actively eroding SCF "basement", flanked by syn-sedimentary faults. This feature extended from the Redie Creek area passing just to the north of the site that would ultimately host the Lady Loretta mineralisation (Fig. 2). Further constraints are provided by; geophysical evidence that indicates the current bounding structures (eg. the Redie Creek Fault) are steeply-dipping (Duffett, 1997); and by the fact that the clastic TCQ presages a period of regional subsidence that provided the accommodation space for the accumulation of the platform carbonate-dominated lower McNamara Group.

A structural model that could explain all of these factors is a regime of roughly N-S oriented regional extension, with resultant ~E-W growth faulting and half-graben formation. In this case the SCF ridge in the Redie Creek-Lady Loretta area would represent a tilt block crest separating half-graben depocentres, and the bounding syn-sedimentary fault system a planar or listric normal growth fault. Studies of active extensional half-graben systems (eg. Lake Tanganyika; Tiercelin et al., 1992) indicate that clastic wedges analogous to the TCQ accumulate, in this case as fan-deltas, in piedmont positions on the subsiding hanging wall block immediately adjacent to the border (ie. growth) fault scarp. In this case however, the onlap relationship between the SCF and the TCQ in the Redie Creek area appears to reflect subsequent deformation, possibly Isan activity

associated with wrenching on the nearby Mount Gordon Fault Zone.

The other major fault set that exists in the Lady Loretta and Redie Creek areas are numerous N-NNE-trending structures that dominate the Paradise Creek High Strain Zone, where they have been active during Isan E-W shortening (Fig. 1). Dips on these structures are interpreted to be steep based on geophysical evidence (Duffett, 1997). These structures would fit into a model involving regional N-S extension as ~orthogonal transfers to the WNW-trending normal faults (Fig. 2). This proposal is appealing for two reasons:

- Firstly, growth and transfer fault intersections are widely recognised as important sites of hydrothermal activity in modern extensional settings (eg. Lake Tanganyika; Tiercelin et al., 1992; Coussemont et al., 1994). The occurrence of several closely spaced transfers cutting a growth fault in the Lady Loretta area could, therefore, be a factor in the formation of the mineralisation.
- Secondly, if N-NNE-trending structures were present in the area prior to the onset of the Isan Orogeny, they would have been in the right orientation to be extensively re-activated during E-W shortening. The occurrence of several closely spaced transfers in the Lady Loretta area could therefore explain the high degree of Isan deformation, both folding and faulting, that characterises the Paradise Creek High Strain Zone. A clear implication is that other areas of comparable McNamara Group structural complexity in the region may have a similar structural framework, and hence have the capacity to host base metal mineralisation.

Discussion

Implications for Cover Sequence Scheme

Blake (1987) subdivided the Mount Isa stratigraphic succession that accumulated after the ~1870 Barramundi Orogeny into three "cover sequences", interpreted as discrete rift/sag cycles separated by regional unconformities. More recently, it has been proposed that there are at least four cover sequences and that Blake's (1987) cover sequence 3 can actually

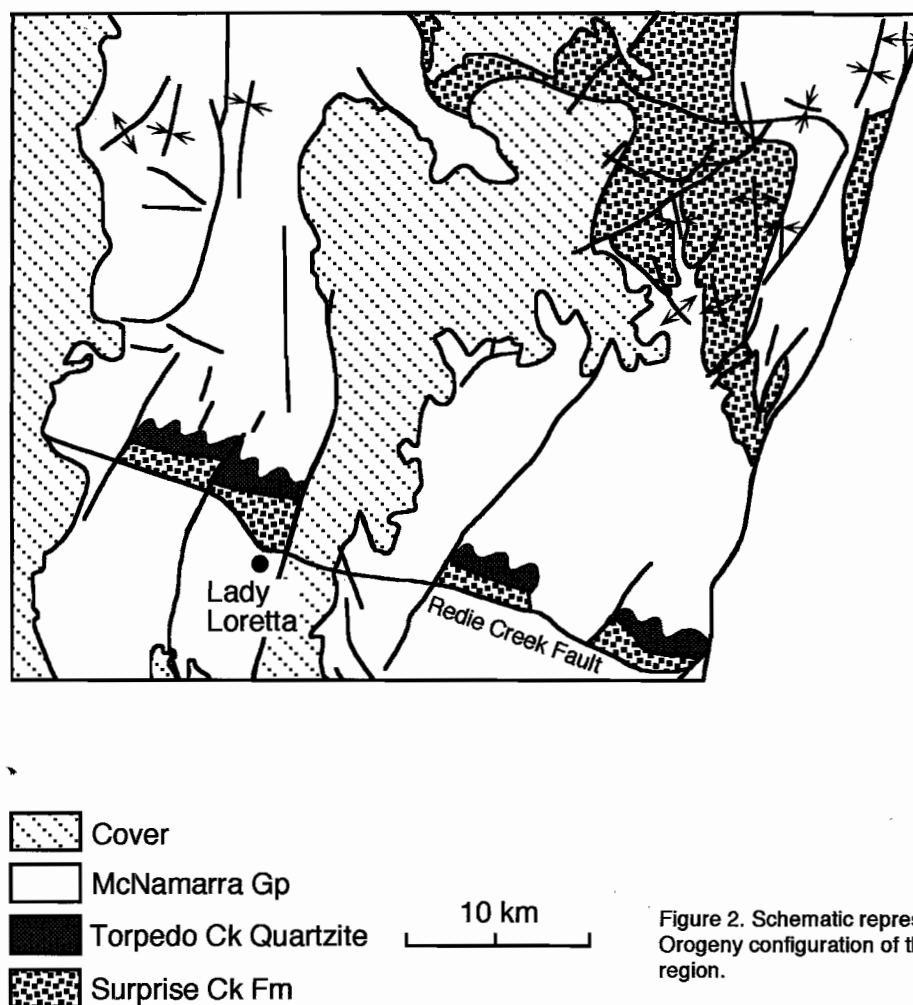


Figure 2. Schematic representation of proposed pre-Isan Orogeny configuration of the Lady Loretta-Redie Creek region.

be subdivided into cover sequences 3 and 4. (O'Dea et al., 1997). Under this scheme, the stratigraphic interval exposed in the Lady Loretta-Redie Creek area is all assigned to cover sequence 4. The SCF is interpreted as the clastic rift package that was deposited on the hanging walls of rotating tilt blocks, and the entire McNamara Group is interpreted to represent the thermal sag phase sedimentation. Sedimentological data collected in the current study suggests the need for a further revision of the cover sequence scheme. The presence of boulders of SCF sandstone in the basal conglomerate of the TCQ, clearly indicates that the units are separated by a cycle of burial, lithification and inversion. The contact therefore represents a major basin phase (ie. cover sequence) boundary, within cover sequence 4 as currently defined (O'Dea et al., 1997).

Significance of thickness

Maximum thicknesses (Blake, 1987) for the rift phase clastics identified by O'Dea et al. (1997) in the Mount Isa system are generally well in excess of 1000 m. The TCQ has a maximum recorded thickness of 420 m (Hutton and Wilson, 1985), which at face value, suggests relatively low degrees of extension and subsidence associated with this rifting event. However, there is no carbonate in the 630 m thick succession of fine-grained, clastic marine sediment that comprises the base of the overlying Gunpowder Creek Formation (Hutton and Wilson, 1985). This suggests that accommodation space was still being generated more rapidly than could be infilled by the microbial community, and that this interval may therefore also be part of the actively subsiding rift phase. Accessory evidence in support of this proposal is the provenance of the upper sandstone unit that

occurs in the Gunpowder Creek Formation at Redie Creek. It contains abundant lithic fragments and fresh microcline not present in the underlying sandstones, and may represent structural exhumation of different source rocks.

A possible explanation for the transition from subaerial/shallow marine clastic sedimentation to fine-grained shelf deposits during active rifting, is that a higher base sea level existed by this relatively late stage of the basin history, presumably due to a lower regional thermal regime. This would facilitate the existence of marine conditions during rifting, and could have led to the generation of normal growth fault bound sub-basins filled with reduced shelf sediments. Areas of maximum subsidence within this basin configuration, often discussed in terms of "third order basins", are widely considered to have the potential to host base metal mineralisation.

Implications for setting of mineralisation

In the light of the interpretation presented in this study, two important points can now be made with regard to the revised tectono-stratigraphic setting of the Lady Loretta mineralisation:

- (1) It lies close to a pre-existing WNW-trending syn-sedimentary fault system, the main phase of growth of which occurred prior to the time of the deposition of the host sedimentary package.
- (2) It occurs in an area where the growth fault appears to have been cut by several relatively closely spaced N-NE-trending (?transfer) faults.

This suggests some revision is needed to models for base-metal mineralisation that invoke essentially synchronous syn-sedimentary faulting, sub-basin formation and mineralisation (eg. HYC Fig. 3a). The implication is, that areas of growth/transfer fault intersections are potential sites for significant fluid flow even after active rifting and syn-sedimentary faulting have ceased. If this is the case, the potential for mineralisation in this structural setting is dependant on the existence of suitable "trap" lithologies (ie. reduced fine-grained sediments) accessed by fluid conduits in the thermal sag package (Fig. 3b).

In the absence of active growth faulting in this type of system, the specific nature of the conduit allowing ascension of mineralised brines is unclear.

One possibility would be systems of minor faults and/or fractures developed in the sag package sediments above the subsurface growth and/or transfer faults in response to minor movement due to weak tectonic events or sediment loading (Fig. 3b). Such conduits could be quite subtle and difficult to recognise in ancient mineralised successions. However, evidence of this type of activity could include the presence fluid escape pipes or fluidisation breccias, both of which have been described from the Lady Loretta ore zone (McGoldrick, 1993).

Implications for timing/processes of mineralisation

The setting proposed here for the Lady Loretta deposit also has implications for the timing of sediment-hosted base metal mineralisation. A syngenetic model predicts that base metal mineralisation should be located in the deepest portion of a rapidly subsiding basin. This is because in order to be effective agents of base metal mineralisation, a high-salinity (and high-density) exhalative system requires a topographic depression to allow fluid ponding and formation of a brine pool from which mineral deposition can occur. No such constraints exist for base metal mineralisation that is epigenetic in origin. In this case metal precipitation could occur wherever an ascending brine interacts with a suitable reduced "trap" lithology, and there is no requirement that this site was a depocentre when the host package was deposited.

In the case of Lady Loretta, the host pyritic siltstones were deposited in a relatively small, shallow, lagoonal depocentre (Dunster, 1996; Dunster and McConachie, 1998; Fig. 3b), situated within the thermal sag package when generation of accommodation space was slow. Due to the considerable degree of deformation that the deposit has undergone, it is not an ideal case for studies of the timing of mineralisation. However, current genetic models using the best available evidence invoke syn-genetic exhalation (McGoldrick et al., 1995). This is consistent with its location in a local depocentre, and if this interpretation is correct, then it has significant implications for the processes involved in exhalative mineralisation. For example given that there is no evidence of fluid boiling at Lady Loretta, the occurrence of this type of system in such a shallow

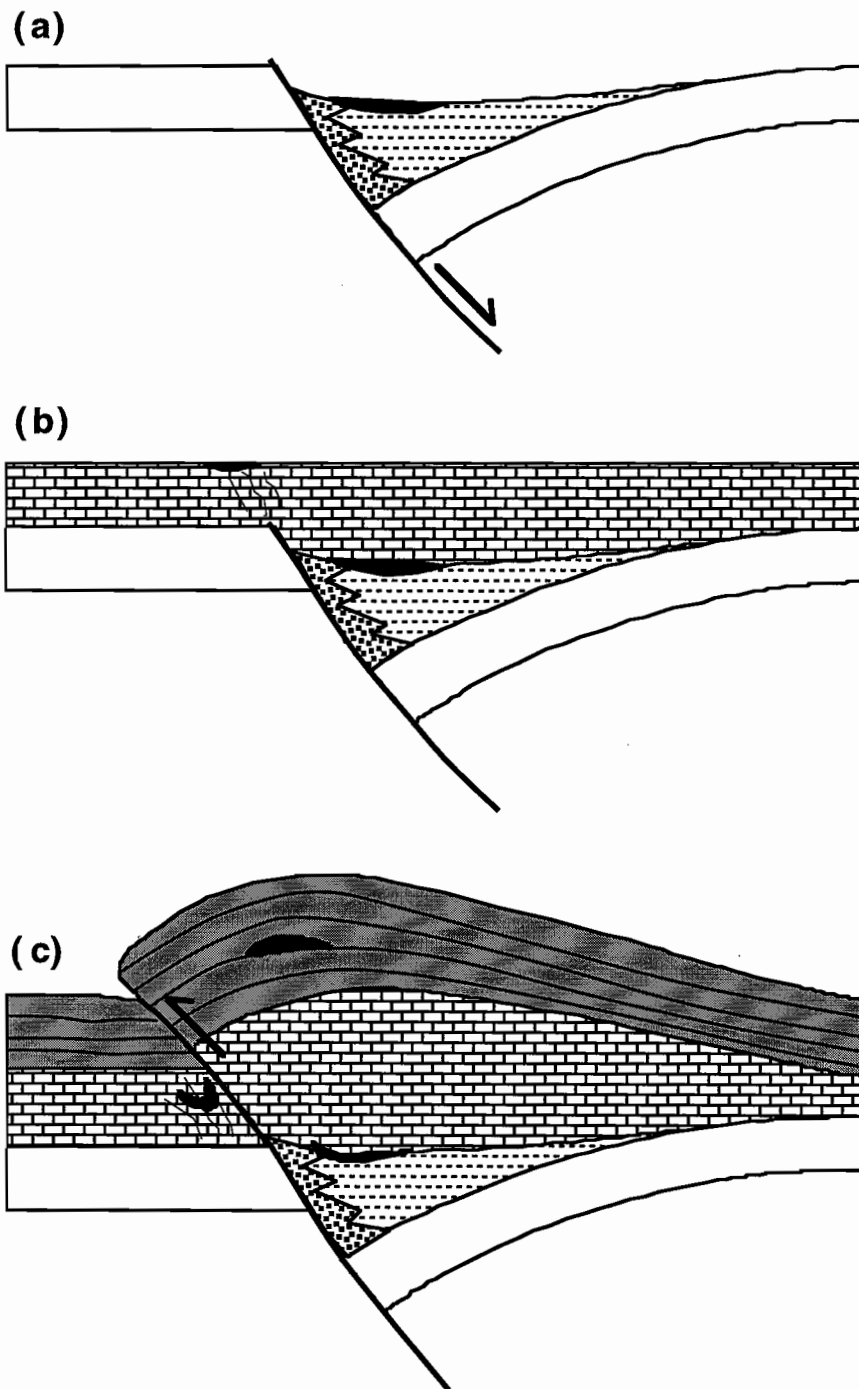


Figure 3. Schematic representation of the potential different settings/timing for base metal mineralisation (a) HYC deposit (b) Lady Loretta deposit (c) Century deposit.

water setting indicates, that in this case at least, the metal bearing brines were relatively low temperature.

Comparison between setting of Lady Loretta and Century

In some respects, the Lady Loretta tectono-stratigraphic setting resembles that of the Century deposit hosted in upper McNamara Group sediments 125 km to the northwest. It occurs immediately adjacent to a regional NW-trending structure, the Termite Range Fault (Fig. 4). This structure has had a long and complex history of syn-sedimentary activity (Andrews, 1996), and is cut by several roughly orthogonal structures in the area of the deposit (Fig. 4).

The Century deposit lies immediately to the southwest of the current expression of the proposed growth structure, the Termite Range Fault (Fig. 4). However, thickness patterns in the host rocks suggest subtle growth with a sense of downthrow to the northeast (Andrews, 1996). If the current configuration has not been too affected by subsequent tectonism, this has implications with respect to the timing of the mineralisation. It would be difficult to reconcile this position with a syn-genetic exhalative model for the mineralisation, because the topographic depression required to trap exhaled ore fluids and form a brine pool would normally occur on the downthrown (ie. northeast) side of the fault. However, it is consistent with the current model for the Century mineralisation, which advocates epigenetic mineralisation of a petroleum reservoir (Broadbent et al., 1996). In fact, the area above a subsurface growth fault is a favourable site for the development of anticlinal petroleum traps during basin inversion, and metal-bearing fluids could use the subsurface fault as a conduit.

The exploration implications of the above discussion, are that syn-sedimentary (growth) faults, especially where cut by other orthogonal structures (?transfers), are likely to be important in focussing base-metal mineralisation regardless of whether it is syngenetic or epigenetic in origin. In summary:

- (1) Where a period of syn-sedimentary faulting associated with a particular basin phase was synchronous with accumulation of suitable reduced "trap" rocks (eg. at HYC), a syn-genetic model for mineralisation is likely to be appro-

priate. In this case, a topographic depression is required to facilitate ponding of exhaled metal-bearing brines. As a result, the long envisaged third order/sub-basin style targets likely to occur on the downthrown side of growth faults remain relevant.

- (2) Given the existence of suitable reduced "trap" lithologies, the sedimentary package is also prospective above the stratigraphic level/s at which active growth faulting occurred (ie. within the thermal sag package). An epigenetic model may be more appropriate in this situation, in which case the "trap" site for base metal mineralisation need not be associated with a depocentre in the host sediments. However, fluid conduits that would facilitate this type of mineralisation are still likely to be situated near subsurface growth faults that were active earlier in the basin phase, in particular in areas where they were cut by orthogonal fault (?transfer) systems. Such areas may manifest as sites of anomalous degrees of strain during subsequent regional deformation.

Conclusions

This study illustrates the importance of understanding the rift architecture of mineralised basin settings, even where deposits occur in the tectonically quiescent sag package. Sedimentological analysis of the TCQ in the Lady Loretta area indicates that:

- (1) Although there is no evidence of syn-sedimentary faulting in the Lady Loretta Formation itself, the mineralisation hosted in the unit sits adjacent to a growth fault in the subsurface.
- (2) This structure was a northwestern continuation of the Redie Creek Fault trend, which was active during the onset of McNamara Group deposition as a growth fault.
- (3) This structure may have been cut/offset by a number of relatively closely spaced, roughly orthogonal faults (?transfers), subsequently re-activated during the Isan Orogeny to produce the present day structural complexity of the Lady Loretta area. If this was the case, other areas of equivalent structural complexity on the Lawn

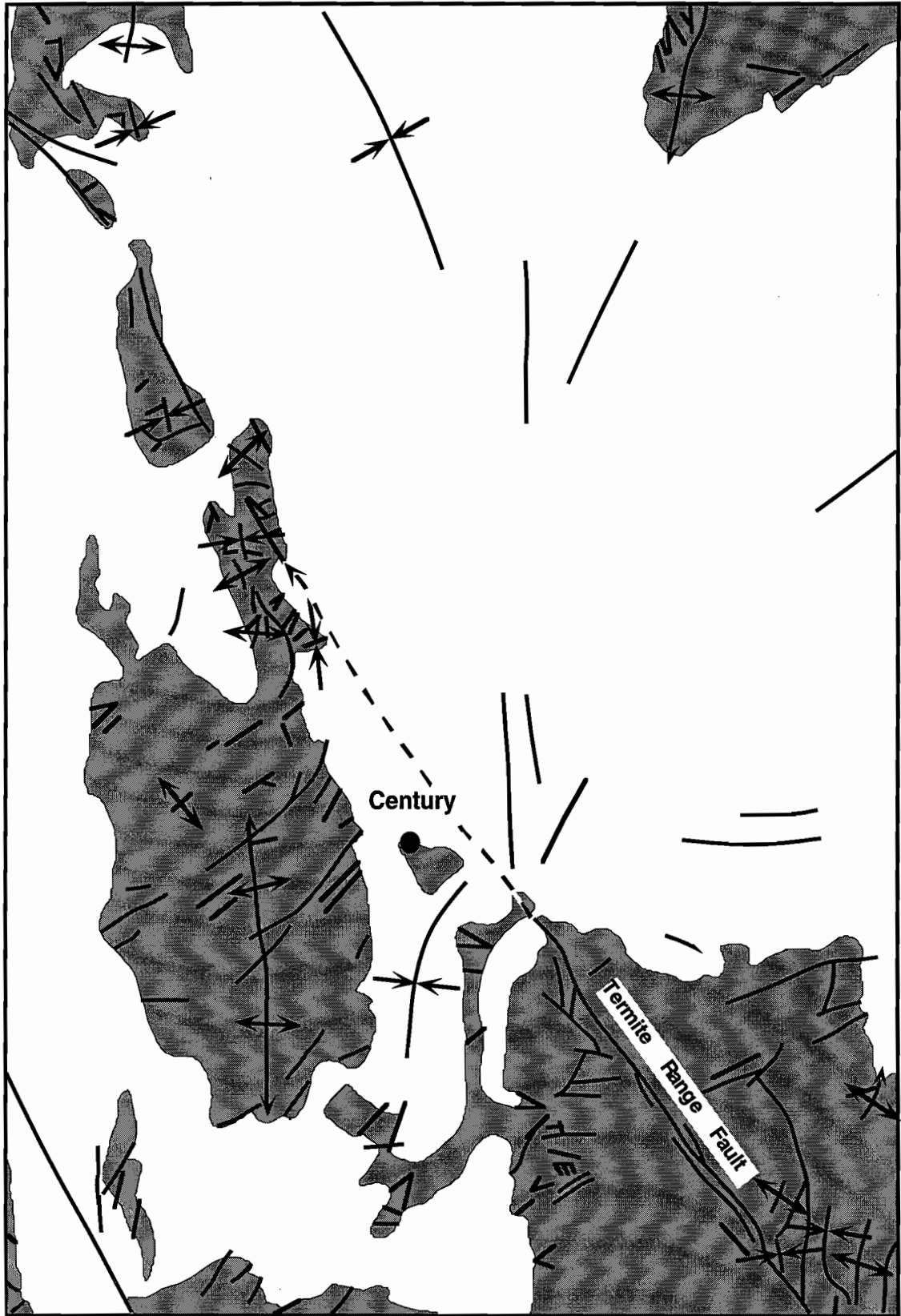


Figure 4. Location of the Century deposit adjacent to the Termite Range Fault (geology modified after Sweet and Hutton, 1982).

Hill Platform may be prospective for base metal mineralisation.

- (4) The setting of the Lady Loretta and Century Deposits indicates that, given the presence of appropriate reduced "trap" lithologies, the sedimentary packages adjacent to demonstrated syn-sedimentary (growth) faults are prospective within the overlying thermal sag package, well above the stratigraphic level/s at which the fault was active.

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Summary of lithogeochemical halos and vectors to ore for Australian Proterozoic stratiform Zn-Pb-Ag deposits

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Introduction

Our research in AMIRA P384 and P384A has shown some significant similarities in the geochemical halos associated with the major stratiform Zn-Pb-Ag deposits in northern Australia. These similarities have enabled us to develop a series of comparable halo models, which are outlined in the following pages. Most importantly the large and/or high grade deposits (e.g., HYC, Mt Isa, Century, Lady Loretta) show well developed halos with very similar lithogeochemical features, while the smaller and uneconomic deposits (e.g., Mt Novit, Walford Creek and Kamarga) show small and poorly defined halos with few anomalous samples.

Mineral chemistry vectors

The most important unifying feature of the halos associated with Australian Proterozoic SEDEX deposits is the chemical zonation of carbonate minerals within host sediments surrounding the deposits. The carbonates typically exhibit an increase in Fe and Mn and decrease in Mg approaching the ore both along strike and across strike. A complete zonal spectrum from siderite → Mg-siderite → ankerite → ferroan dolomite → dolomite passing away from the ore is exhibited by Lady Loretta and Century. Siderite is lacking in the McArthur Basin, where the zonation is ankerite → ferroan dolomite → dolomite.

Basket of exploration vectors

The following vectors have been developed for SEDEX Zn-Pb-Ag exploration in dolomitic sedimentary basins:

$$\bullet \text{ SEDEX AI} = \frac{(10\text{MnO} + \text{FeO})100}{(10\text{MnO} + \text{FeO} + \text{MgO})}$$

$$\bullet \text{ AI3} = \frac{(10\text{MnO} + \text{FeO})100}{(10\text{MnO} + \text{FeO} + \text{MgO} + \text{Al}_2\text{O}_3)}$$

$$\bullet \text{ MnO}_d = \frac{\text{MnO}_{\text{WR}} \times 30.4}{\text{CaO}_{\text{WR}}}$$

$$\bullet \text{ MnO}_s = \frac{\text{FeO}^*_{\text{WR}} \times 62.01}{\text{CaO}_{\text{WR}}}$$

- Thallium
- Oxygen and carbon isotopes of sedimentary carbonate.
- $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratio of sediments.
- $(\text{Ba}/\text{K}_2\text{O}) \times 10^4$ ratio of sediments.

Further details on the application of these vectors are briefly outlined below and discussed in the halo models that follow.

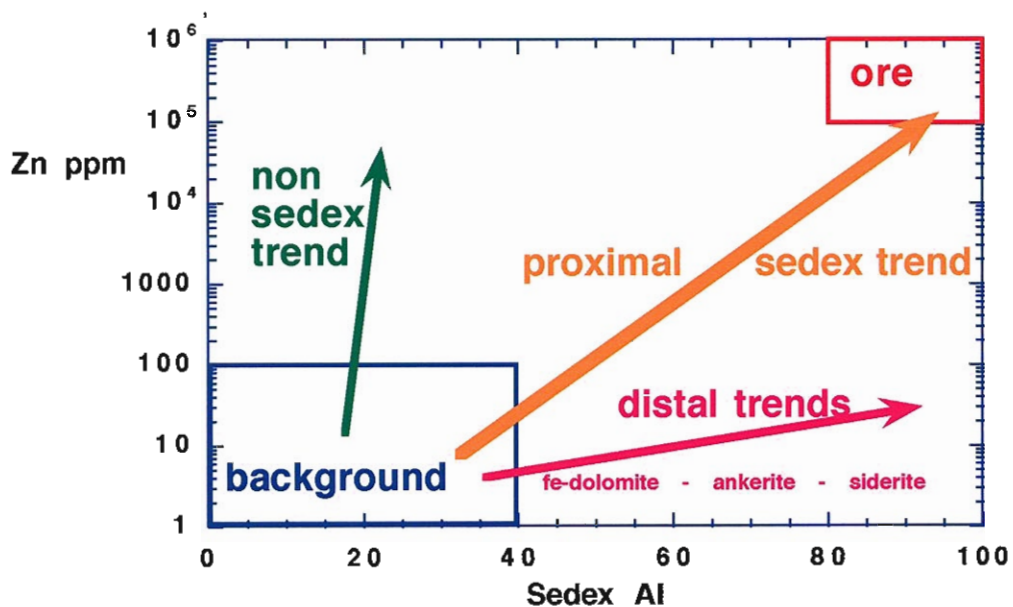


Figure 1. Relationship between zinc content and alteration index for carbonate bearing sediments in the North Australian Zinc Belt.

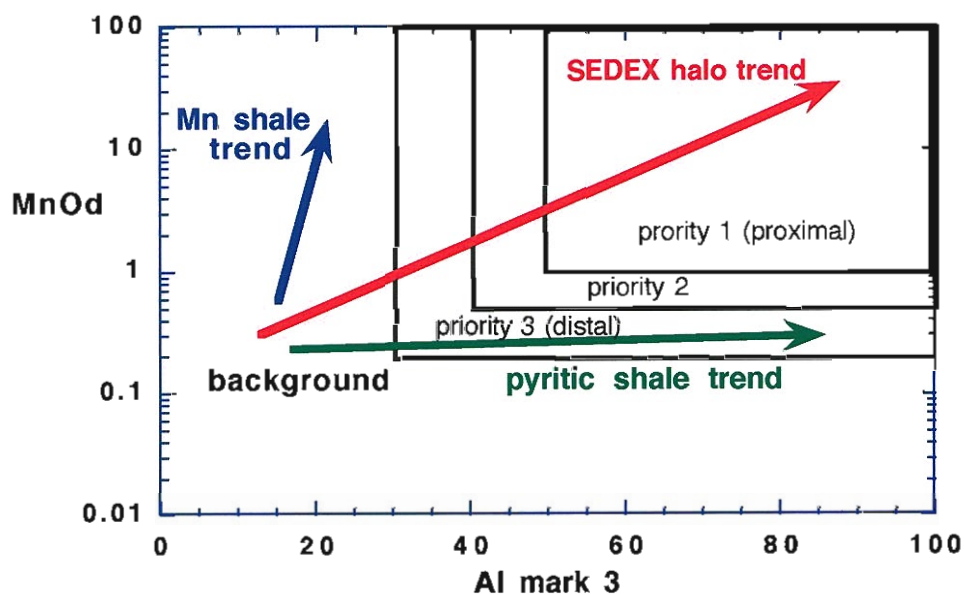


Figure 2. Priority fields to discriminate sediments within the halo of a major stratiform Zn-Pb-Ag deposit. Vertical axis is either MnO_2 or MnO_3 (Mn content of dolomite or siderite).

Alteration index trends

Our studies of the halos surrounding HYC, Lady Loretta and Mt Isa indicate a consistent positive relationship between SEDEX AI and Zn content of sediments in the immediate halo of the deposits (Fig. 1). This trend is considered to be typical of large stratiform deposits and is present in the host sediments within 1 to 2 km along strike of the deposit.

Beyond this distance the distal trends are flatter (Fig. 1) indicating elevated SEDEX AI but low Zn values (≤ 100 ppm). Deposits which form as vein systems or by replacement (e.g., Cooley Pb-Zn or Kamarga) show elevated zinc but low SEDEX AI, giving a steep pattern which is clearly distinguished from the SEDEX trend.

In evaluating these trends, comparison must be made using the AI₃ in order to eliminate the "barren shale effect" (Large, 1994).

Manganese carbonate trends

The Mn content of carbonate typically increases towards ore, as shown in the case studies at Lady Loretta, HYC and Century. However, the relationship between Fe and Mn substitution in sedimentary/diagenetic carbonate is complex and leads to overlapping envelopes of zonation that require separate evaluation. The MnO₄ vs AI₃ plot (Fig. 2) is probably the most useful method of sorting out the alteration halo patterns, and providing a priority ranking of outcrop or drill hole geochemical data. In Figure 2, samples close to ore (within several 100 m) typically plot in the Priority 1 field, samples at a medium distance (100 m to a few km) plot in Priority 2 and more distal halo samples plot in Priority 3. Prospects that are not associated with SEDEX style Zn-Pb-Ag mineralisation typically show very few samples in the Priority 1 or 2 fields (less than 10% of total population). Barren pyritic shales show a flat trend of elevated AI₃ but low MnO₄, while barren Mn-shale/carbonate sediments show a steep trend with low AI₃ values (Fig. 2).

Thallium halos

All the major Australian stratiform Zn-Pb-Ag deposits exhibit a widespread thallium halo. Thallium values of greater than 4 ppm extend well into the hanging wall sediments and along the favourable horizon. The thallium halo is commonly more extensive and less erratic than the zinc or lead halo. Thallium and zinc typically show a linear correlation within the Fe-carbonate alteration halo (Fig. 3), however, thallium extends beyond the zinc zone showing a flat trend on the Zn-Tl diagram (Fig. 3).

Oxygen and carbon isotopes

Detailed studies of isotope chemostratigraphy have shown that a distinct heavy oxygen isotope halo surrounds both the HYC and Lady Loretta deposits (see halo models following). It is likely that similar isotope halos will be found associated with the other major north Australian deposits.

The trend toward ore of increasing $\delta^{18}\text{O}$ carbonate and decreasing $\delta^{13}\text{C}$ carbonate is a unique pattern not previously reported from other carbonate-hosted styles of mineralisation (Fig. 4). The more common pattern found in MVT deposits, skarn deposits, carlin-type deposits and other carbonate replacement mineralisation (e.g., Renison Bell Tin) is for the development of oxygen isotope depletion halos (i.e., toward lower $\delta^{18}\text{O}$ values) surrounding the mineralised zone (Figs 4, 5). Also these isotope halos are commonly fairly restricted in extent and rarely of greater width than the width of the ore zone. Thus the isotope halos found at HYC and Lady Loretta are potentially very useful in exploration because they are not only very large, but have a distinctive trend toward heavy oxygen isotope values, associated with increasing Fe and Mn content of carbonate (Fig. 5).

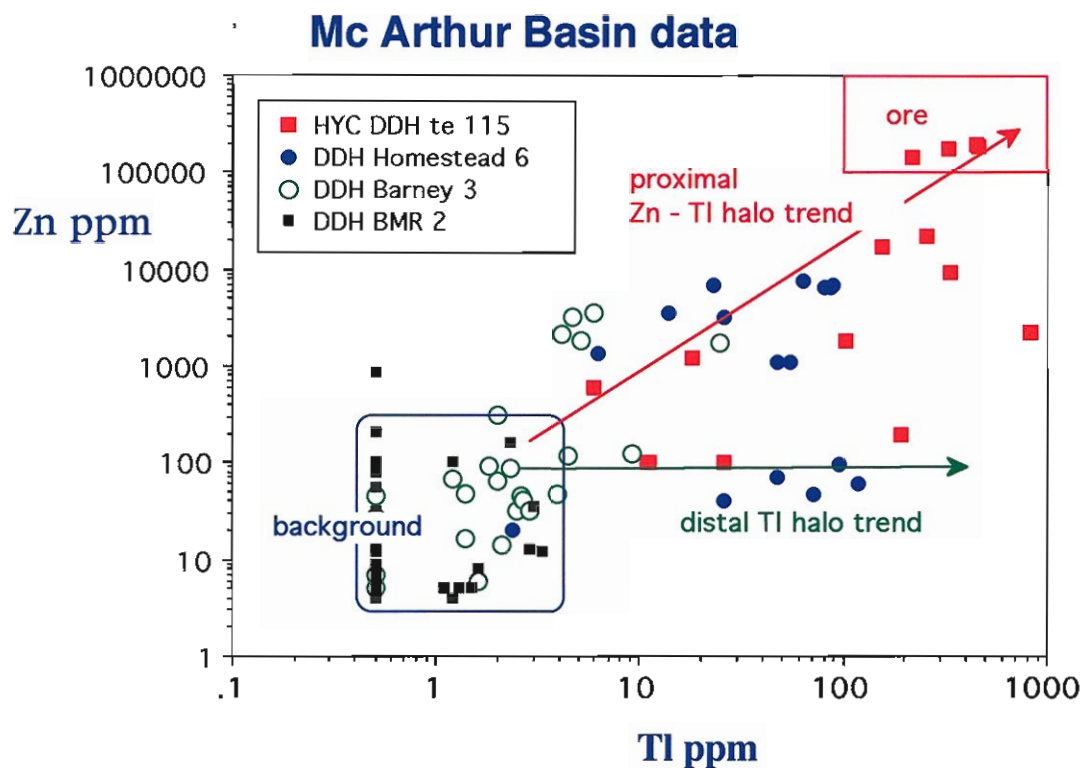


Figure 3. Relationship between Zn and Tl in sediments from the McArthur Basin surrounding HYC.

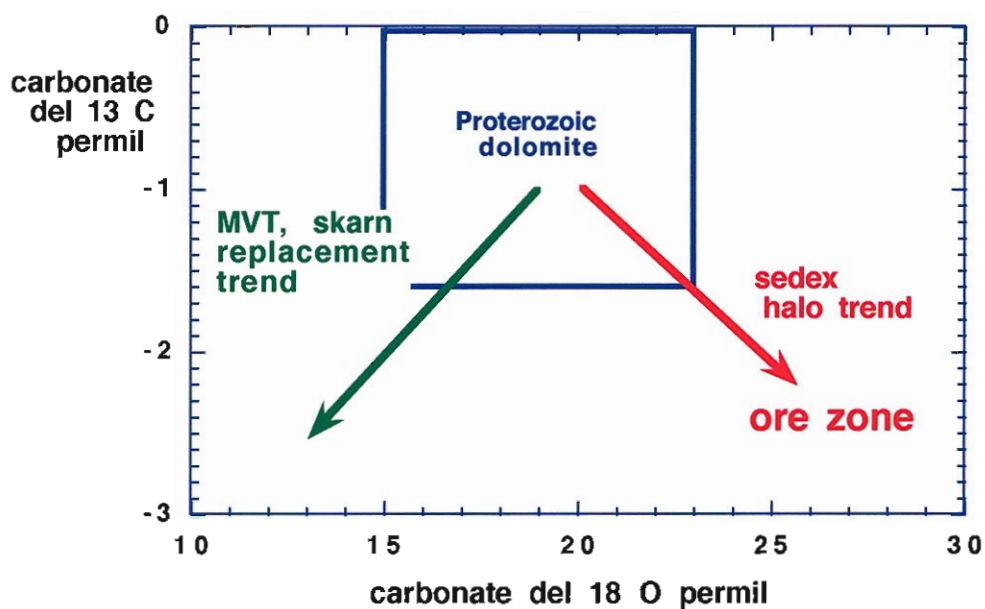


Figure 4. The carbonate isotope halo trend for HYC and Lady Loretta, compared with the more common trend for other carbonate-hosted styles of mineralisation.

Alteration halo models

A series of alteration halo models are described in the following section of this report based on our case studies in P384 and P384A. Although there are many similarities in the mineralogy and chemistry of the respective halos, there are also significant differences, especially with regard to the smaller uneconomic styles of mineralisation. The giant Canadian SEDEX deposit, Sullivan, is included here for comparison. The chemistry and mineralogy of the halo to Sullivan is very different to the Australian deposits because of the lack of significant carbonate-bearing sediments in the host rock package.

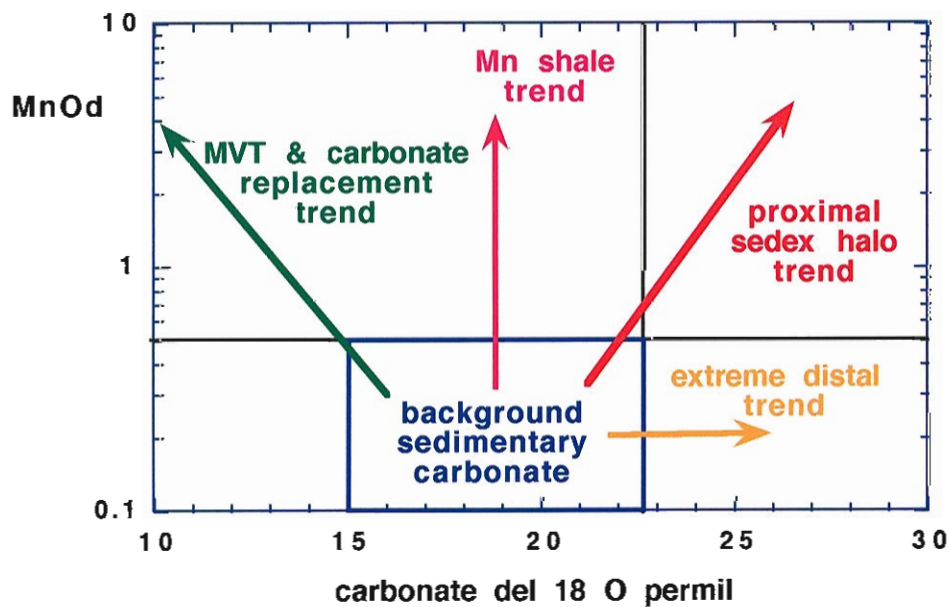


Figure 5. Diagram proposed to discriminate the halo to a carbonate-hosted SEDEX deposit, from other styles of carbonate-hosted mineralisation.

Halo model for the Lady Loretta deposit

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Summary

The Lady Loretta deposit was the first stratiform, sediment-hosted Zn-Pb deposit investigated during the course of AMIRA P384. Lithogeochemical data provided the basis for developing a series of single and multi-element and isotopic indices that can be used as vectors to mineralisation. The useful indices include: Zn, Tl, alteration indices (Sedex AI and AI3), Mn in carbonate (MnO_d), Sedex Metal Index, and C and O isotopes. The results summarised here have been discussed in several reports from AMIRA P384, and more recently in Large and McGoldrick (1998) and McGoldrick et al. (1998). New studies of sedimentology, ore textures, and S isotopes (Dunster, 1996, 1997; McGoldrick et al., 1996) were carried out in parallel to the lithogeochemical work.

Introduction

The Lady Loretta deposit was the focus of initial detailed lithogeochemical studies in AMIRA Project P384 because it provided the opportunity to work on a deposit with a substantial drill core archive and (moderately) well understood geology. New, high quality analyses of more than 150 samples for major and trace elements, together with C and O isotope measurements on a smaller number of samples were undertaken for this work. The data were used to develop a halo model for Lady Loretta that was subsequently shown to be generally applicable to other northern Australian Proterozoic deposits. This report reviews lithogeochemical work at Lady Loretta that has been presented previously in the following reports from Project P384:

- McGoldrick, 1992 report 1 Deposit Halos 1. Lady Loretta geochemical studies: preliminary results: CODES AMIRA/ARC Project P384 — Proterozoic sediment-hosted base metal deposits Report No. 1, p. 39-58.
- McGoldrick, P. J., 1993a, Deposit Halos 3. Geology of the Lady Loretta deposit: review, new developments, and implications for ore genesis: CODES AMIRA/ARC Project P384 — Proterozoic sediment-hosted base metal deposits Report No. 3, p. 1-30.
- McGoldrick, P. J., 1993b, Deposit Halos 4. Sampling and whole rock analyses for the Lady Loretta deposit: CODES AMIRA/ARC Project P384 — Proterozoic sediment-hosted base metal deposits Report No. 3, p. 31-62.
- Large, R. R., and P. J. McGoldrick, 1993, Deposit Halos 5. Primary geochemical halos related to Proterozoic sediment hosted Pb-Zn deposits and applications to exploration: CODES AMIRA/ARC Project P384 — Proterozoic sediment-hosted base metal deposits Report No. 3, p. 63-126.
- Large, R. R., and P. J. McGoldrick, 1994, Refinement of the Sedex Alteration Index and MnOD vectors: CODES AMIRA/ARC Project P384 — Proterozoic sediment-hosted base metal deposits Report No. 5, p. 1-17.
- Duhig, N., 1994, Microprobe analysis of carbonate phases at lady Loretta: CODES AMIRA/ARC Project P384 — Proterozoic sediment-hosted base metal deposits Report No. 7, p. 69-76.
- Large, R. R., P. Kitto, and P. J. McGoldrick, 1995, Variation of carbon and oxygen isotopes in the alteration halo to the Lady Loretta deposit — implications for exploration and ore genesis., AMIRA, p. 289-302.

- McGoldrick, P. J., J. Dunster, and M. Aheimer, 1995, The Lady Loretta zinc-lead-silver deposit: primary dispersion halos, sedimentology, ore textures, stable isotopes, and metal distributions — towards a genetic model, AMIRA, p. 409-446.

More recently, some of the results of this work have been published in reviewed scientific journals (McGoldrick et al., 1998; Large and McGoldrick, 1998 — see copies in Volume 3 of AMIRA P38A Final Report).

Previous work

Carr (1984) undertook a study of the primary geochemical and mineralogical dispersion about the Lady Loretta deposit, which formed the starting point for this investigation. Three principal findings from Carr's study were relevant to our research. Firstly the lead-zinc deposit is surrounded by a halo of pyrite-rich layers within the dolomite and carbonate host rocks. The proportion of pyrite-rich layers was shown to increase progressively from about 2% at

150 m stratigraphically below the ore to >90% in the top 10 m of the footwall sediments. Hanging wall rocks contain up to 20% pyrite layers for at least 100 m above the ores. Secondly, Carr (1984) recognised a distinct siderite halo surrounding the orebody, extending 50 m above and up to 75 m below the deposit. He reported that sideritic sediments gave way to dolomitic sediments beyond the halo (Fig. 1). Thirdly, he demonstrated that zinc displayed the maximum primary dispersion around the deposit, extending as a halo up to 100m into the footwall and 50 m into the hanging wall, with a lateral extent of some 1500 m along strike. Other elements (Hg, Pb, Ag, Cd, Ba) exhibited dispersion halos which were less extensive than zinc.

Deposit characteristics

The important features of the Lady Loretta Zn-Pb-Ag deposit are described and illustrated in the deposit summary and accompanying plate.

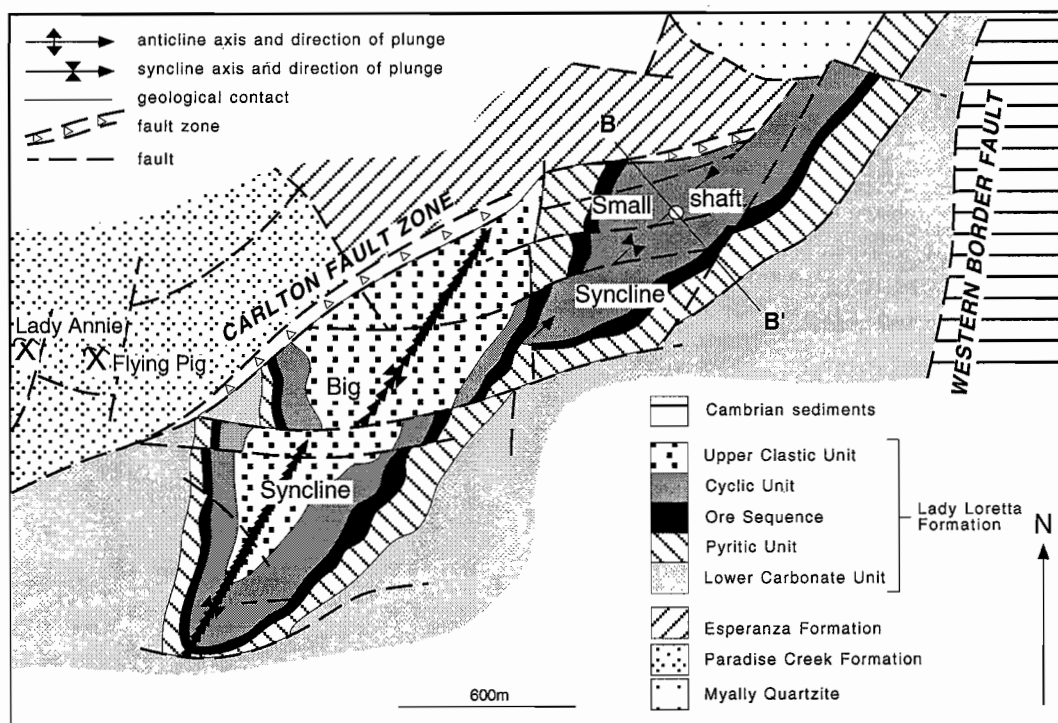


Figure 1: Geology of the Lady Loretta district (modified from Hancock and Purvis, 1990). B-B' is the section line shown in figure 2.

Host rocks

Figure 1 is a surface geological map of the Lady Loretta district and shows the distribution of the mineralised sequence in the Small Syncline, and its stratigraphic equivalent in the Big Syncline. The Lady Loretta orebody (8.3 Mt at 18.4% Zn, 8.5% Pb and 125g/t Ag) occurs in the Small Syncline, whereas no significant base metal mineralisation is known from the Big Syncline. The hangingwall and footwall host rocks to the deposit are fine grained clastic and chemical sedimentary rocks. The Lower Carbonate Unit (Fig. 2) is about 200 m thick and consists of thin bedded to laminated, variably dolomitic siltstone, claystone and carbonaceous shale, with minor dolostone and sandstone (Dunster, 1997). In the Small Syncline the unit becomes more pyritic and sideritic up section (Fig. 3). The lower carbonate unit is overlain by the Pyritic Unit which is from 25 to 80 m thick and comprises interbedded silty shale, dolomitic and sideritic siltstone, shaley fine grained sandstone, carbonaceous shale and ubiquitous bedded fine grain pyrite. In this unit the amount of pyrite increases systematically up sequence to more than 70 modal percent within a few fifts of the contact with ore (Carr, 1984). In the Small Syncline siderite is the principal carbonate mineral in the Pyritic Unit.

The hangingwall rocks in the Small Syncline are called the Cyclic Unit (Hancock and Purvis, 1990; Dunster, 1997). This unit averages about 120 m in thickness and consist of carbonaceous shales, dolomitic and sideritic siltstones, claystones, sandstones, and bedded pyrite which decreases in abundance up section (Carr, 1981; McGoldrick et al., 1996; Dunster, 1997).

Sampling strategy

More than 140 fresh rock samples were collected from a series of surface and underground drill holes. Sampling was mainly focused on the Cyclic Unit, the Pyritic Unit and the Lower Carbonate Unit in the Small Syncline. Distal stratigraphic equivalents to the mineralised sequence were obtained from drill core from surface holes in the Big Syncline. Quarter, or half core pieces, ten to twenty centimeters long, were collected every 10–15 m. Every effort was made

to collect samples with a low sulfide content (i.e., pyritic and base metal sulfide-rich layers were avoided). The sample interval included about 350 m of true stratigraphic thickness around the the orebody and the unmineralised stratigraphic equivalent of the ore sequence up to 1500 m along strike.

Lithogeochemistry

Host rock carbonates

Two groups of sediment can be distinguished on plots of whole rock CaO, FeO, MnO against CO₂ (Fig. 4). The groups correspond to samples with siderite or dolomite as the principal carbonate phase (rocks contain either dolomite or siderite but rarely both together). The relationships in Figure 4 show that the carbonates are not simply pure dolomite and siderite, but that the dolomite contains variable Fe and Mn while the siderite is enriched in Mn and Mg. Figure 4(a) gives a clear distinction between the sideritic and dolomitic sediments due to the paucity of CaO in the former. From the whole rock MnO/CO₂ relationships in Figure 4(c) it is apparent that the carbonate in the siderite halo, has a higher Mn content than the dolomite outside the halo. By extrapolation it is possible to estimate that the siderite in the sideritic sediment has a mean value of 1.6 wt% MnO compared to 0.6 wt% MnO for dolomite in the dolomitic sediments. Microprobe analyses (Duhig, 1994) have confirmed this result.

The extent of the siderite halo at Lady Loretta was established using the whole rock analyses, in particular the relationship between CaO and CO₂ (Fig. 4(a)). The siderite halo extends at least 50m into both the hangingwall and footwall of the deposit. Both our studies and those of Carr (1984) indicate that the siderite halo penetrates deeper into the footwall below the thickest concentration of Pb–Zn ore, and thins laterally towards the extremities of the ore lens.

Toward the outer boundary of the siderite halo, sideritic sediments are interbedded with dolomitic and ankeritic sediments, however on the micro scale the dolomite and siderite are mutually exclusive (Hancock and Purvis, 1990).

The whole rock and microprobe analyses indicate the presence of mixed ankerite-dolomite assemblages

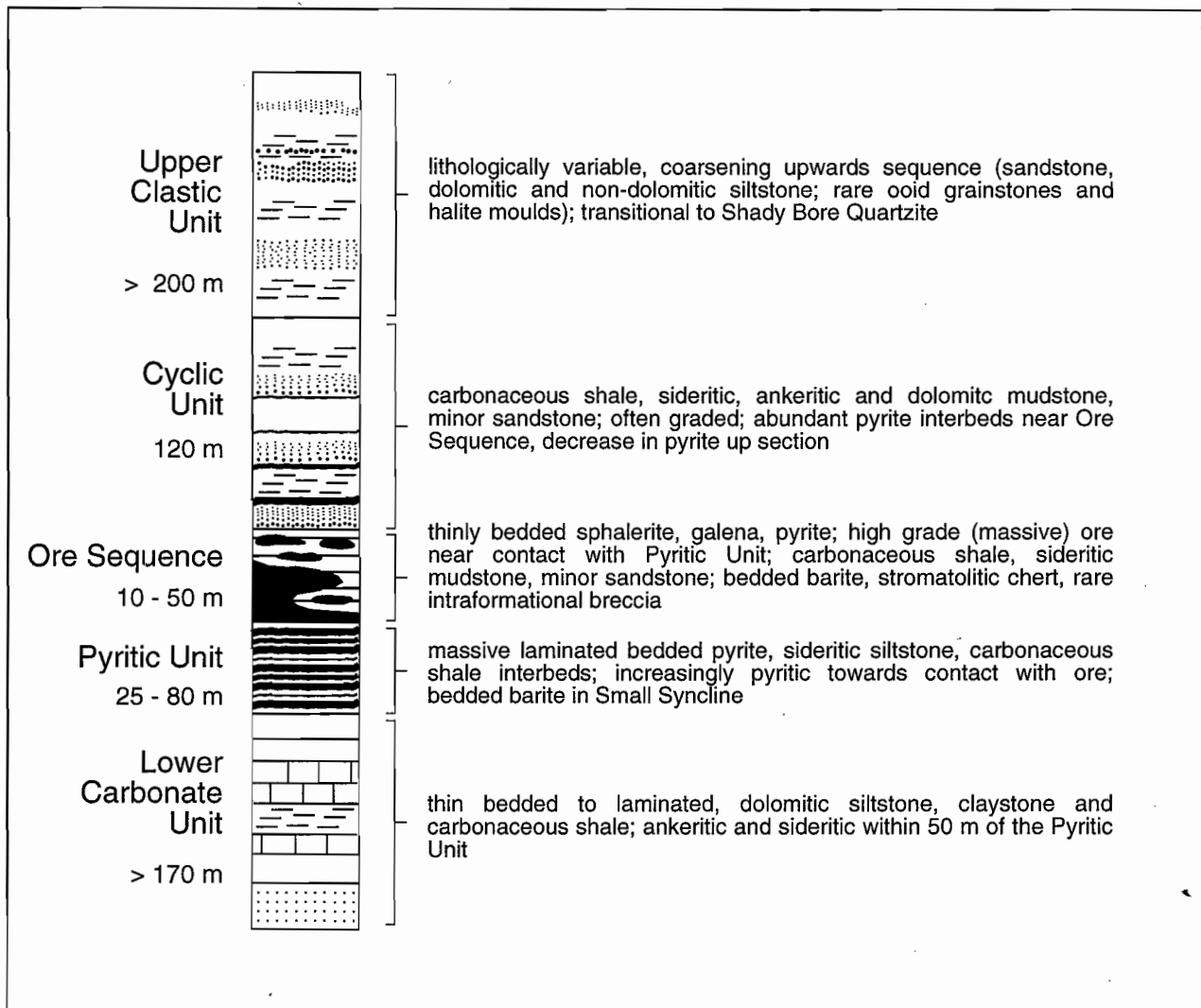


Figure 2. Schematic informal lithostratigraphic column for the Lady Loretta mine area (modified from Hancock and Purvis, 1990; Dunster, 1997).

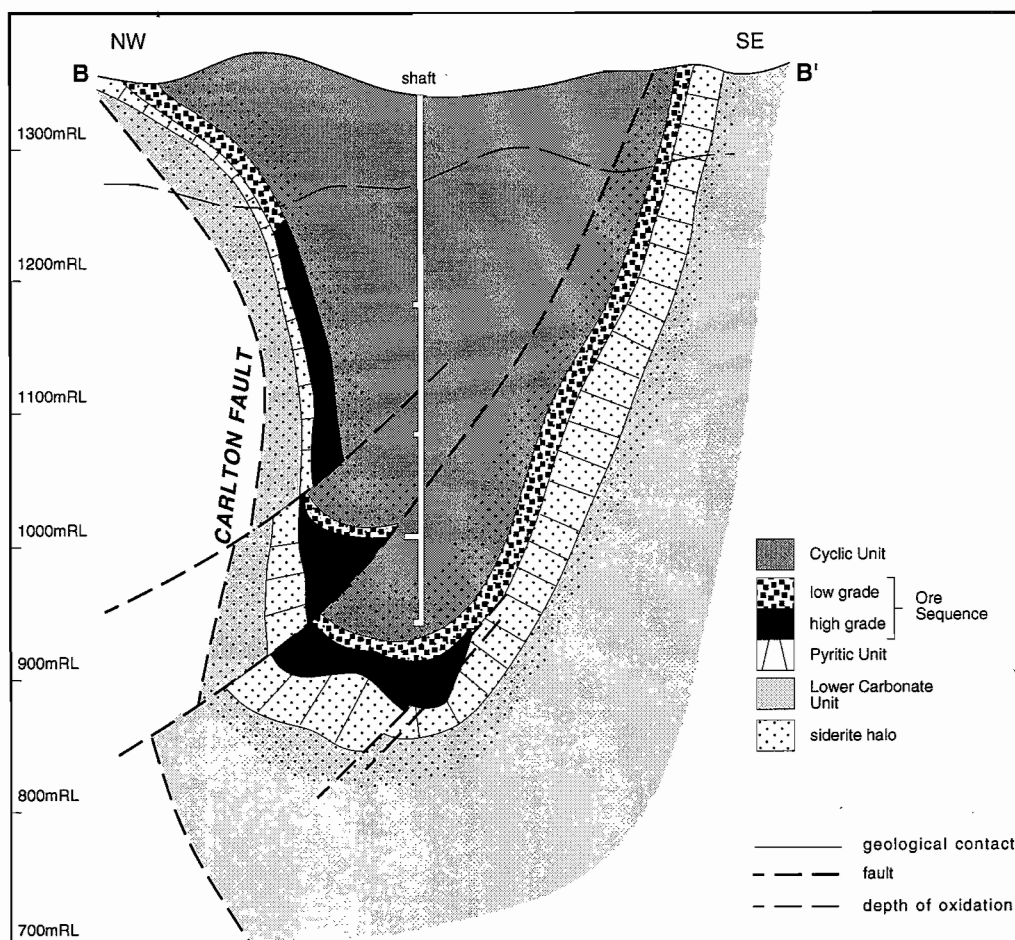


Figure 3. Typical geological cross section, Lady Loreta deposit (section 2300), modified from Hancock and Purvis (1990) and Carr (1984).

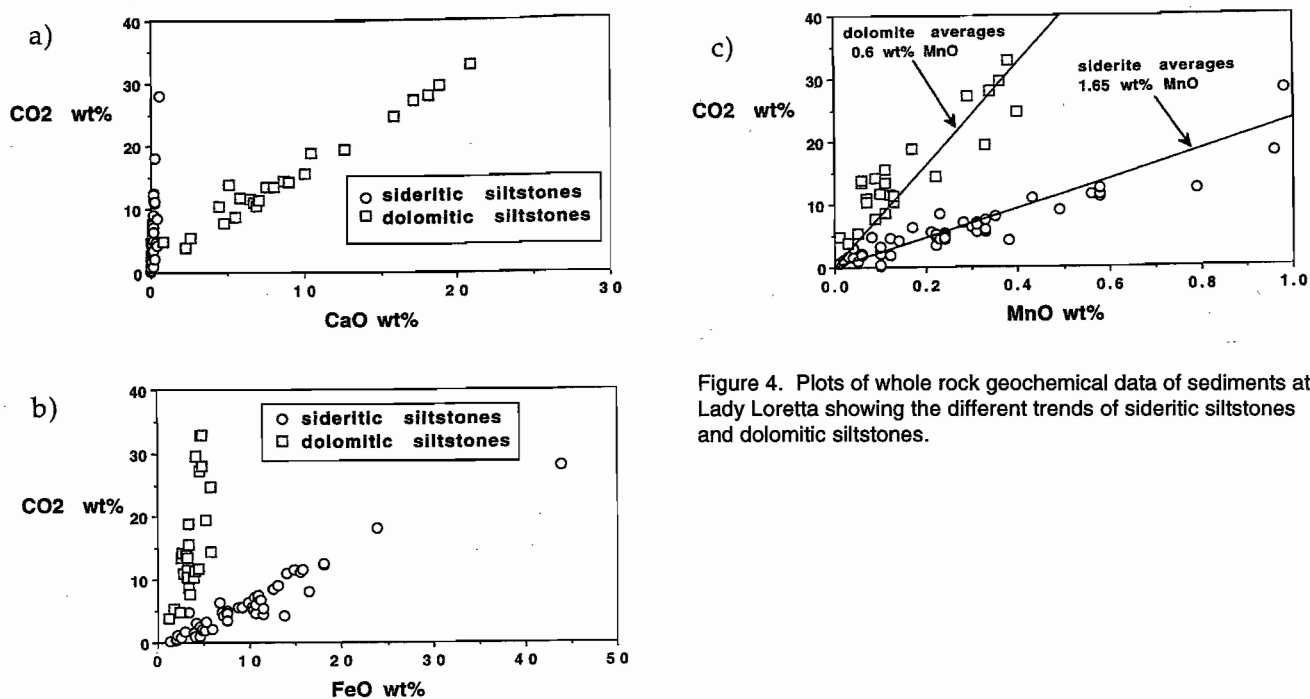


Figure 4. Plots of whole rock geochemical data of sediments at Lady Loreta showing the different trends of sideritic siltstones and dolomitic siltstones.

in the footwall sediments up to 100m beyond the siderite halo. Beyond 100 m (ferroan-)dolomite is the principal carbonate phase.

The best geochemical discriminator for sideritic siltstones versus ferroan dolomitic or ankeritic siltstones is the whole rock CaO analysis. Figure 4 (a) shows that the dolomitic siltstones contain greater than 1% CaO, while the sideritic siltstones contain less than 1% CaO. In fact, there are two orders of magnitude difference between the median sideritic siltstone (0.1% Ca) and the median dolomitic siltstone (10% CaO). Another significant factor revealed by Fig. 5 is that the dolomitic siltstones (outside the siderite halo) have much lower zinc contents (20-200 ppm Zn, median 50ppm) compared with sediments within the siderite halo (70ppm to 10% Zn, median 300ppm). In other words, the siderite halo at Lady Loretta also appears to represent a zinc halo. Based on the microprobe data from Carr (1984) and Duhig (1994) and the positive correlation between Zn and CO_2 for sediments in the siderite halo (Fig. 5b) it appears that much of the zinc, within the siderite halo (outside the ore boundaries) is due to

substitution of zinc into the siderite structure, rather than the presence of sphalerite dispersed in the sediments.

In summary, the orebody at Lady Loretta is surrounded by a zincian siderite halo, up to 50m thick, which gives way to an ankerite/ferroan dolomite halo (a further 50-100m thick) followed by low iron dolomitic sediments.

Zinc dispersion

Background Zn levels, represented by deep footwall samples, are a few tens of ppm. Zinc shows a broad primary dispersion, with anomalous levels up to 120m into the footwall and 80m into the hangingwall. Virtually all samples within the siderite halo have elevated Zn, and dolomitic siltstones up to 120 m into the footwall of the deposit can contain hundreds of ppm Zn (Fig. 6 a).

Manganese and thallium

Both Mn and Tl exhibit broad dispersion of up to 200m into the footwall sediments and greater than 60m into the hangingwall. This data (Fig. 6 b&c) indicates that Mn and Tl are dispersed well beyond the siderite halo into the footwall dolomitic sediments. Deep into the footwall (> 200m below the ore position) the sediments contain < 0.1 wt% MnO and less than 1ppm Tl. Although the Mn and Tl values are erratic throughout the footwall ankeritic and sideritic halo zones, there is a general increase in both elements towards the ore position.

Summary of element dispersion

As well as Zn, Mn and Tl several other elements vary fairly systematically across and along strike at Lady Loretta (Large and McGoldrick, 1998). Depending on the degree of across strata dispersion it is possible to group the halo indicator elements into four classes;

- Class 1: tight dispersion (less than 50m from ore): Pb, Cu, Ba, Sr
- Class 2: broad dispersion (up to 100m from ore): Zn, Fe
- Class 3: Very broad dispersion (up to 200m from ore): Mn, Tl
- Class 4: Broad depletion (up to 50m from ore): Ca, Mg, Na

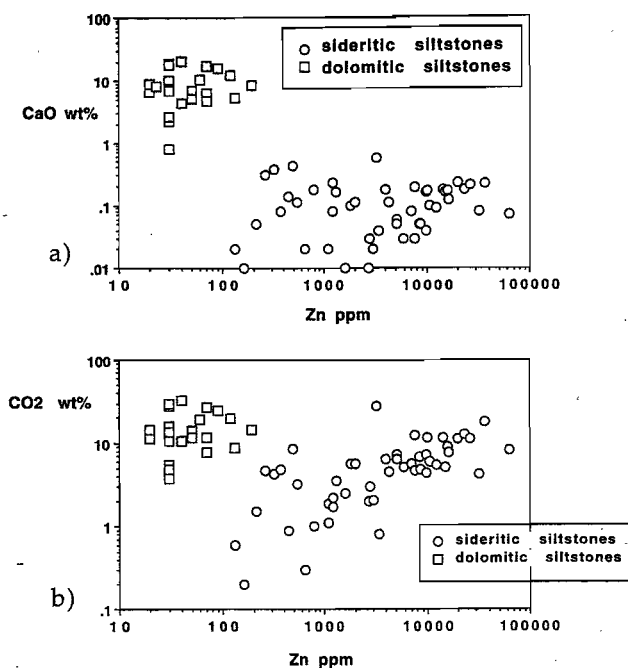


Figure 5. Separation of sideritic siltstones from dolomitic siltstones based on a) whole rock CaO-Zn relationships and b) whole rock CO_2 -Zn relationships.

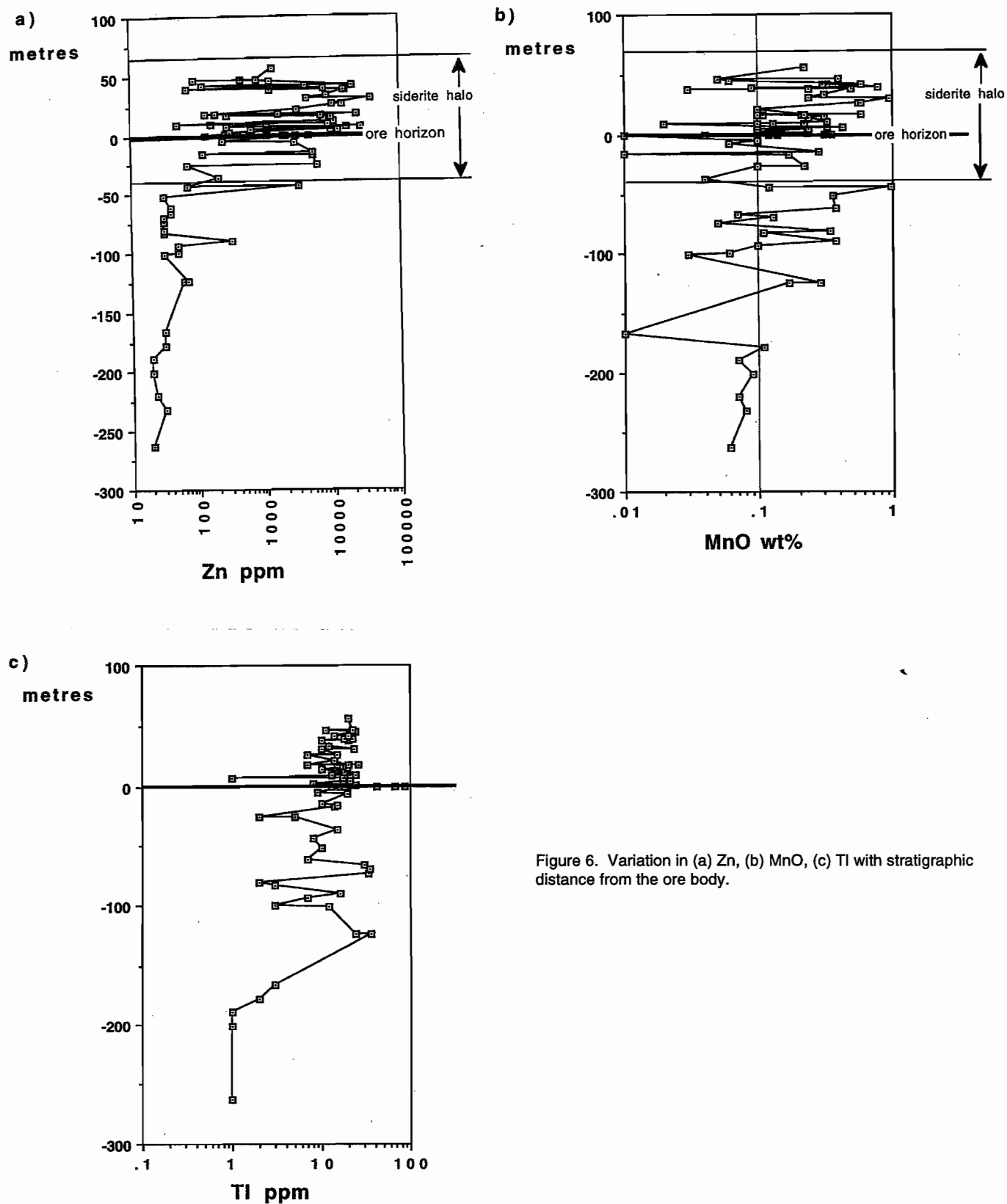


Figure 6. Variation in (a) Zn, (b) MnO, (c) TI with stratigraphic distance from the ore body.

Data from the Big Syncline indicates that the across strata dispersion summarised above, applies equally to along strata dispersion, but over a greater distance. For example, Mn and Tl dispersion extends up to 1500m from the deposit, along the favourable stratigraphy.

Multi-element vectors to ore

Sedex Metal Index (Zn+100Pb+100Tl): The most obvious index to use as a vector to ore is based on the major metal components of the orebody, zinc and lead. At Lady Loretta, Pb exhibits little dispersion outside the ore lens, and Zn shows broad dispersion both across strata and along the ore horizon. As a complement to Pb and Zn, Tl exhibits very broad dispersion and provides the ingredient to develop a regional vector. By combining these three metals

together it was possible to develop a metal index that increases toward ore throughout the full extent of the deposit halo. The metal index chosen for this purpose was:

$$\text{Sedex Metal Index} = \text{Zn} + 100 \text{ Pb} + 100 \text{ Tl}$$

with Pb, Tl and Zn measured in ppm.

This metal index increases in a regular fashion over a distance of 200m towards ore in the footwall of the Lady Loretta deposit. (Fig. 7). The pattern in the hanging wall of the deposit was not as clear due to limited sampling.

Sedex Alteration Index: The basis of an alteration index is to determine the key elements enriched during alteration and the key elements depleted during alteration and to combine them in an index that varies from 0 to 100.

Thus, Alteration Index =

$$\frac{(\text{key enriched elements}) \times 100}{(\text{enriched} + \text{depleted elements})}$$

Based on the Lady Loretta data set, MnO and FeO were selected as the key enriched elements and MgO was selected as the key depleted element. Other combinations using CaO as a depleted element and/or Ba as an enriched element were tried, but found to be less useful in terms of producing an index which gave a systematic variation from 0 to 100. The selected index is defined as;

Sedex Alteration Index =

$$\frac{(\text{FeO} + 10\text{MnO}) 100}{(\text{FeO} + 10\text{MnO} + \text{MgO})}$$

MnO is factored by 10 to bring its base value up to the magnitude of the other elements used; FeO and MgO.

Sedex AI was seen to increase fairly systematically from a background of about 40 to a maximum of 95 approaching the orebody from the footwall side (Fig. 8a). In the hangingwall sediments, the alteration index varies from 50 to 90 within 100 m of the orebody.

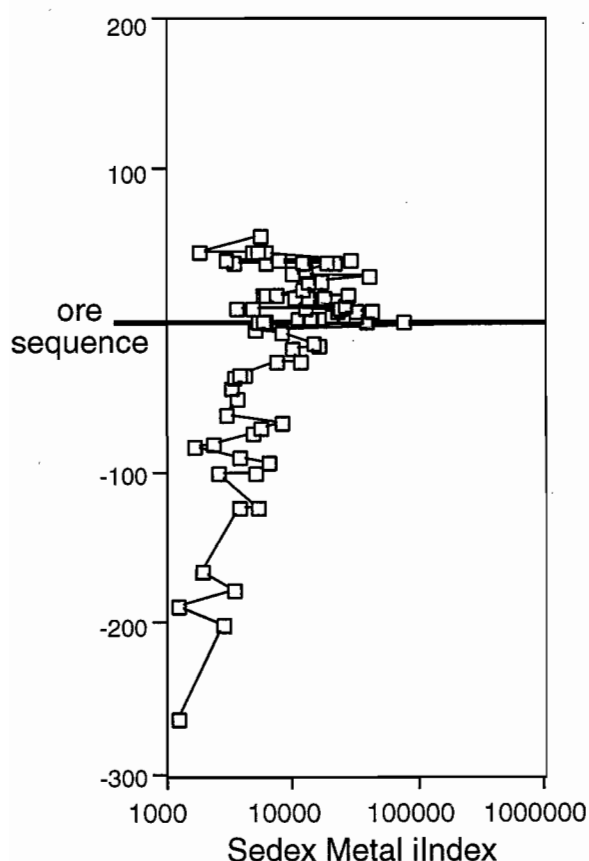


Figure 7. Variation in Sedex Metal Index with stratigraphic position showing a regular increase toward the ore position (zero meters on the y-axis represent the entire orebody thickness).

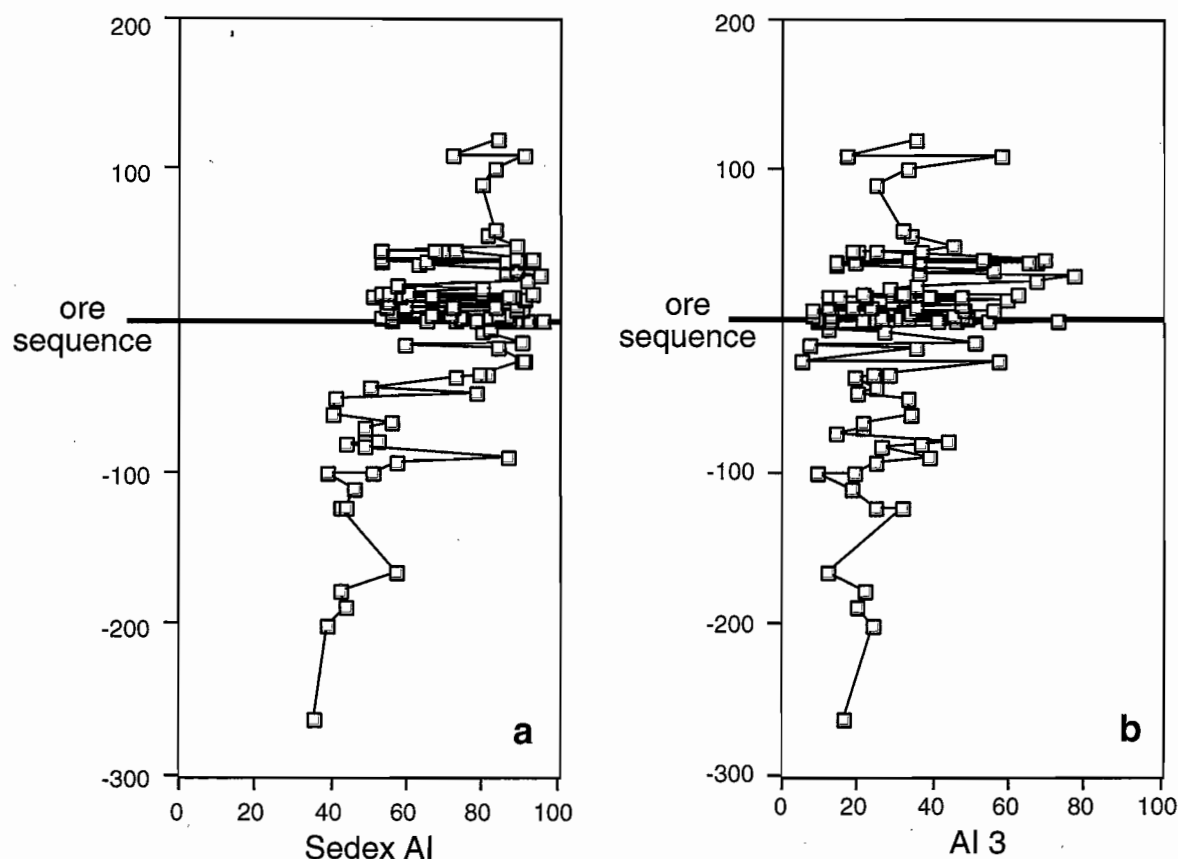


Figure 8. (a) Variation in Sedex AI with stratigraphic position showing a general increase toward the ore position; (b) Variation in AI 3 with stratigraphic position showing a general increase toward the ore position

Sedex Alteration Index Mark 3: Subsequent work at Lady Loretta and elsewhere (Large, 1994) indicated that 'shaley' rocks could have elevated Sedex AI values unrelated to the presence of Zn mineralisation. In order to compensate for this effect a modification to the original Sedex AI was proposed which incorporates Al_2O_3 into the denominator of the alteration index formula. Hence the new index (AI3) was defined as:

Sedex Alteration Index Mark 3 =

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

A similar systematic increase from background to elevated levels approaching ore is seen for AI3 for the footwall rocks at Lady Loretta, except that these absolute values for AI3 are somewhat lower than those for SedexAI. For AI3 background is less than 30, and maximum values are in the eighties.

Manganese content of carbonate: Mn was shown to substitute in carbonate minerals siderite and ferroan dolomite at Lady Loretta, and shows a somewhat erratic increase up through the footwall of the deposit. The erratic variation is largely due to variable amounts of carbonate in the siltstones and shales. Because dolomite and siderite are the only major carbonate minerals present in the samples, and because they are virtually mutually exclusive of each other, it is possible to eliminate the effect of variable sediment carbonate content by re-calculating sample MnO (to 100% carbonate) using the following relationships:

MnO content of dolomite; $\text{MnO}_d =$

$$\frac{\text{MnOwr} \times 30.41}{\text{CaOwr}} \quad \dots(1)$$

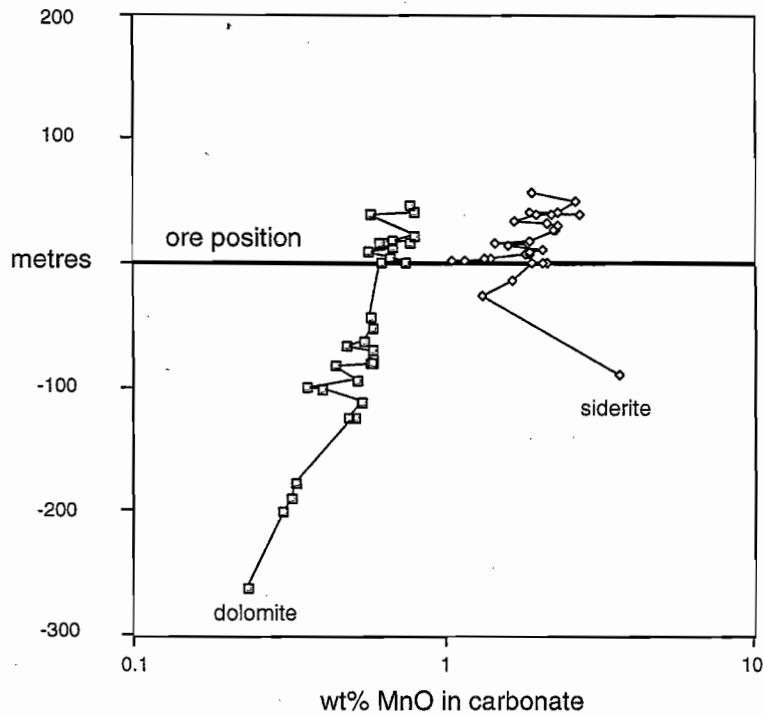


Figure 9. Variation in wt % MnO in carbonate, calculated from the whole rock data, using the equations discussed in the text. Note the systematic increase in MnO content of dolomite from deep in the footwall sediments up toward the ore position.

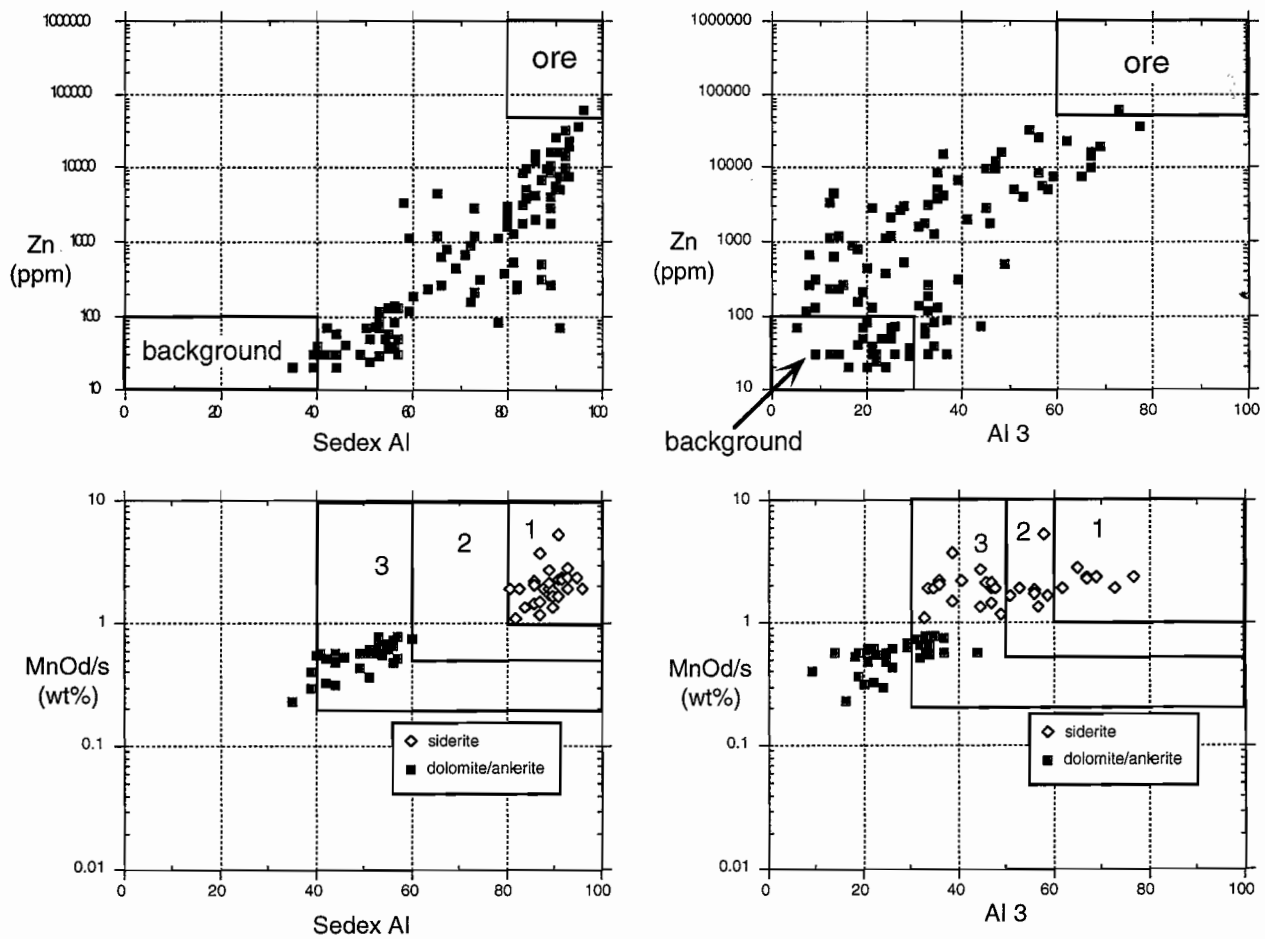


Figure 10. Cross plots of Zn, Sedex Al, Al 3 and $MnO_{d/s}$ for samples from the Small Syncline at Lady Loretta. Note: box 1 on the $MnO_{d/s}$ / alteration index plots is the most prospective part of the diagrams.

MnO content of siderite; $MnO_s =$

$$\frac{MnO_{wr} \times 62.01}{FeO^*} \dots(2)$$

where $FeO^* = (\text{whole rock } FeO) - (FeO \text{ present in pyrite})$ and MnO_{wr} and CaO_{wr} are the whole rock values.

These formulae were only used for rocks with >1 wt% CaO, as rocks with <1 wt% CaO were virtually devoid of significant dolomite.

Figure 9 shows the calculated the MnO content of carbonates from the Lady Loretta Small Syncline. MnO in ferroan dolomite and ankerite shows a very systematic increase in the footwall sediments towards ore from a background value of 0.2 wt% to a maximum of 0.6 wt% at the dolomite/siderite boundary. MnO in siderite has considerably higher values generally in the range 0.4 to 4.0 wt% MnO; however, some samples close to, or within, the ore-bearing sediments contain values of greater than 4 wt% MnO. Compared to the other two indices (Sedex Metal Index and Sedex AI), MnO_d shows the most systematic and smooth variation towards the

orebody from the footwall side over the entire sampled stratigraphic interval of 265 m.

Interrelationships between Zn, Sedex AI, AI3 and $MnO_{d/s}$: Cross-plots of log Zn against Sedex AI and AI3 (Fig. 10a) define a strong positive trend that indicates that Zn enrichment in the halo sediments is accompanied by an increase in alteration index values. This 'Lady Loretta trend' was subsequently shown to be a characteristic feature of other large northern Australian stratiform Zn deposit host successions. A comparison of log $MnO_{d/s}$ with alteration indices (Fig. 10b) show a curvilinear trend that has been used to prioritise samples into a 'prospectivity' hierarchy.

Carbon and oxygen isotopes

A subset of 29 carbonate-rich whole rock samples from Lady Loretta were analysed for C and O isotopes (Large et al., 1995; McGoldrick et al., 1998). These data indicate that the dolomitic and ankeritic footwall rocks show a trend to heavy O approaching the orebody. The siderite samples contain distinctly heavier O than the dolomite and ankerite samples (Fig. 11). Carbon is isotopically similar in the siderite

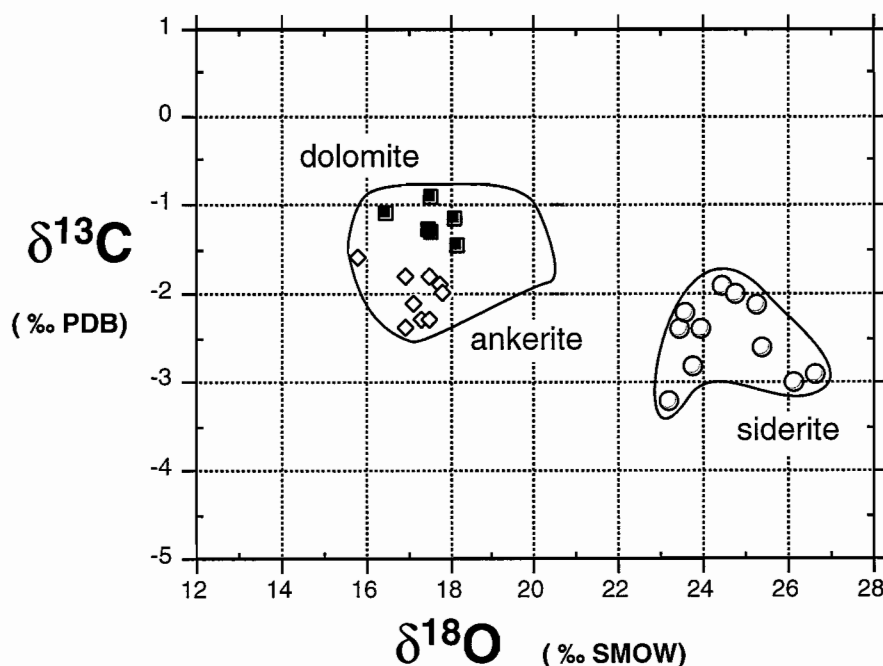


Figure 11. Cross plot of C and O isotope data for 29 samples from Lady Loretta. Note: 'ankerite' samples are distinguished from dolomite samples by having moles $(Fe+Mn)/Mg > 0.25$.

and ankerite samples, and both have lighter C than the dolomitic samples. Hence, relatively heavy O and relatively light C in carbonates may be an additional guide to stratiform Zn mineralisation.

A halo model for Lady Loretta

Figure 12 is a diagrammatic summary of the Lady Loretta halo model from AMIRA P384.

Identification of favourable sedimentary units

Parameters useful in the identification of a potential ore-bearing host unit in the Lady Loretta Formation at a distance of at least a kilometre from ore are:

- (1) Sedex AI > 40
- (2) AI3 > 30
- (3) MnO content of dolomite > 0.2 wt%
- (4) Thallium > 4ppm
- (5) Zn > 70ppm
- (6) Sedex Metal Index > 3000.

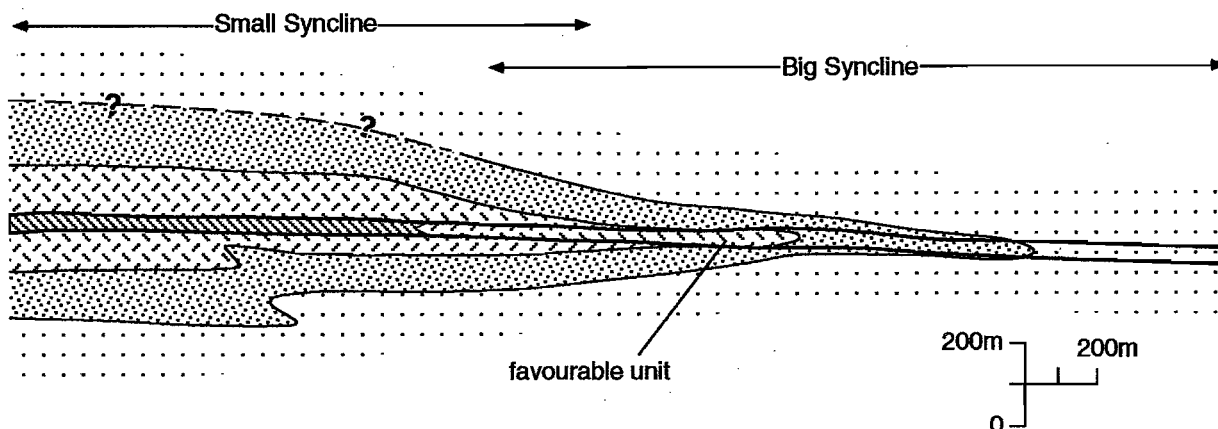
Coincidence of all six parameters was considered to indicate a high priority for stratiform Zn-Pb-Ag mineralisation within the sedimentary unit elsewhere in the basin.

Vectors to ore

Based on the Lady Loretta study, the following vectors were recommended for the discovery of Proterozoic Zn-Pb-Ag deposits in the Northern Australia dolomite-rich sedimentary basins.

- (1) Change in carbonate composition from dolomite to ankerite to siderite within the sediments. The change dolomite to ankerite occurs within 150 m across strike, while the change to siderite occurs within 50 m across strike of the orebody. Along strike variations are an order of magnitude greater in distance.
- (2) MnO content of dolomite (MnO_d) increases systematically from 0.2 wt% to 1 wt% over 300 m approaching the orebody from the footwall side.
- (3) Sedex Alteration Index, defined by

LADY LORETTA HALO MODEL



		Zn	Pb	dominant	Tl	MnO	CaO	SEDEX AI	MnO_d/s	Metal
		ppm	ppm	Carbonate	ppm	%	%		%	Index
Zn-Pb ore		>5%	>1000	siderite	>50	0.1-0.4	0-1	80-100	1-10	>8x10 ⁴
Siderite halo		100ppm to 5%	10-1000	siderite	2-50	0.01-1	0-1	60-100	1-10	2x10 ³ -3x10 ⁴
Ankerite halo		20-200ppm	<70	ankerite	2-50	0.01-0.04	1-2	38-60	0.4-0.7	2-7x10 ³
Dolomite halo		<30ppm	<20	dolomite	<2	<0.01	5-10	10-40	<0.3	<3x10 ³

Figure 12. Halo model (pre-folding) for the Lady Loretta deposit based on geochemical data from the Small Syncline and Big Syncline.

$$\text{Sedex AI} = \frac{(\text{FeO} + 10 \text{ MnO}) 100}{(\text{FeO} + 10 \text{ MnO} + \text{MgO})}$$

increases for 40 to >90 over at least 300 m approaching the ore across strike.

- (4) Sedex Alteration Index Mk3, defined by

$$\text{AI3} = \frac{(\text{FeO} + 10 \text{ MnO}) 100}{(\text{FeO} + 10 \text{ MnO} + \text{MgO} + \text{Al}_2\text{O}_3)}$$

- (5) increases for 30 to >80 over at least 300 m approaching the ore across strike.

- (6) Zinc content of sediments increases erratically from 100 ppm to 1 wt% over 100 m in the footwall and hanging wall.

- (7) Thallium content of sediments increases erratically from <4 ppm to 50 ppm over a distance of 200 m approaching the ore position across strike.

- (8) Sedex Metal Index (Zn + 100 Pb + 100 Tl) increases from 1000 to over 10,000 towards ore both across strike and along strike.

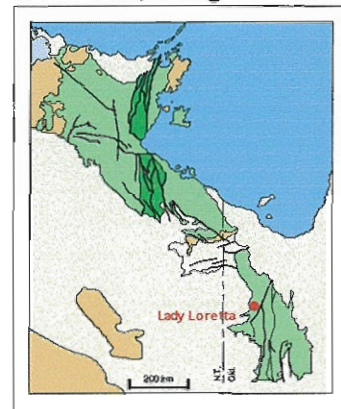
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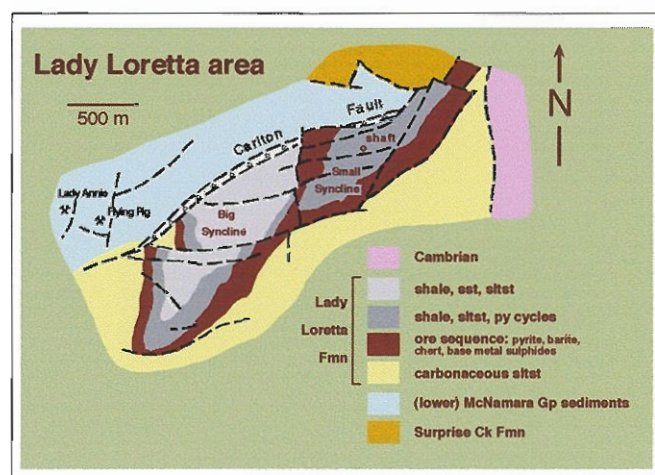
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Lady Loretta Deposit Summary

Regional Setting: The deposit occurs in late Palaeoproterozoic sediments of the Lady Loretta Formation (Dunster, 1996), part of the McNamara Group in the central Lawn Hill Platform (Blake, 1987). The lower McNamara Group rocks in the vicinity of the deposit occur in a (relatively) high strain N-S corridor. The Lady Loretta Formation is dominated by carbonates in the N, but becomes more clastic to the S.

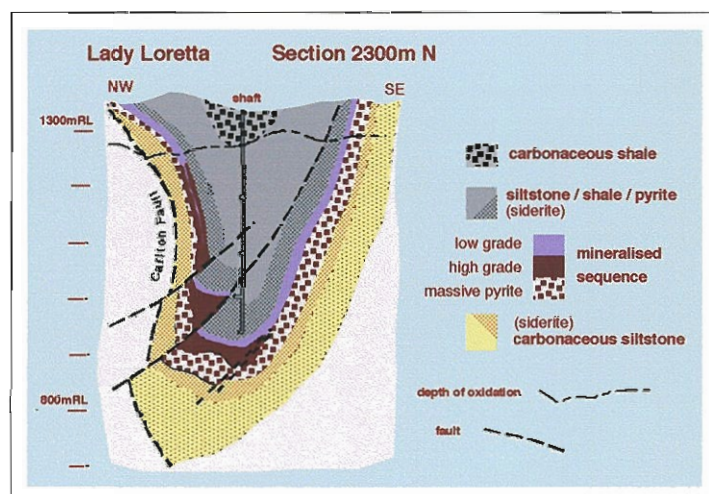


Host Rocks: The deposit occurs in the upper third of the Lady Loretta Formation and the mine sequence comprises a variety of fine grained clastic and chemical sedimentary rocks (Dunster, 1996; Large and McGoldrick, 1998) folded into a double syncline structure. Footwall rocks are thinly bedded carbonaceous shales and variably dolomitic siltstones; these become more pyritic and sideritic close to the orebody. Hangingwall rocks are carbonaceous shales, dolomitic and sideritic siltstones interbedded with laminated pyrite. The mineralised interval is 15 to 40 m thick and contains abundant pyrite, siderite, base metal sulfides, barite and stromatolitic chert. Pseudomorphs and moulds of gypsum are present in hangingwall and ore sequence rocks. Similarities between the mine sequence rocks and the Lady Loretta Formation regionally indicate deposition in a restricted water body on an emergent carbonate platform (Dunster, 1996). Zircons from tuffaceous sediments in the footwall of the deposit have an age of 1647 ± 4 ma (R.W. Page, pers. comm.)

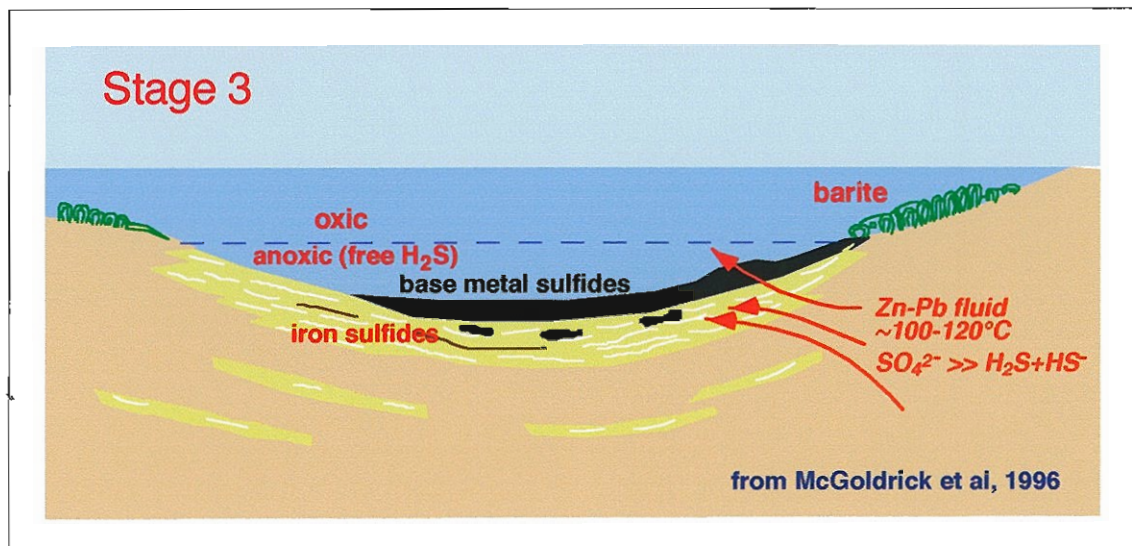


Size and Grade: Lady Loretta is a small, high grade deposit with a published resource of 8.3 Mt at 18.4 wt% Zn, 8.5 wt% Pb and 125 g/t Ag (Hancock and Purvis, 1990). A single (faulted and folded) ore lens about 400 m long and between 15 and 40 m thick occurs as a canoe-shaped body in the hinge zone of the smaller of the two synclines.

Mineralisation: Sulfide base metal ores contain sphalerite, galena, minor chalcopyrite and tetrahedrite, and quartz and siderite gangue (Hancock and Purvis 1990). Rare hematite is found in galena-rich ore and intergrown with siderite. Pyrite is ubiquitous, but often occurs as discrete, low-base sulfide beds. Massive, high grade (>30 wt% Zn+Pb) ores occur at the lower contact of the sulfide orebody. Most of the base metal sulfides are recrystallised, but fine layering parallel to sedimentary layering in the host sediments is common. Lower grade parts of the orebody contain more pyrite and sediment interbeds. A barite-chert unit is the lateral facies equivalent of sulfide ores and it contains ore-grade Zn, but low Pb. This unit is present in the upper parts of the eastern and western fold limbs in the northern part of the deposit.

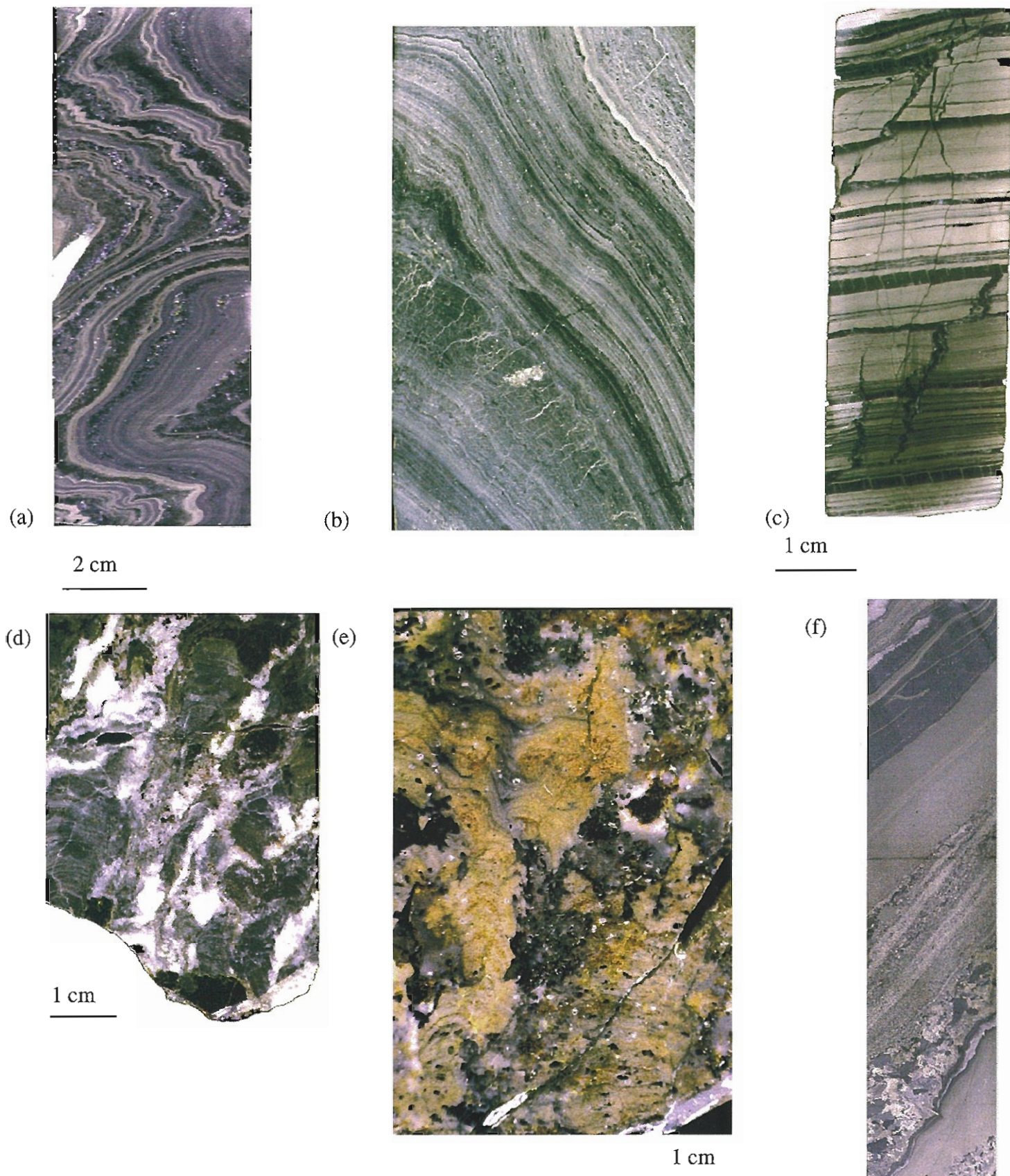


Genetic Models: Lady Loretta has been previously interpreted as a syngenetic exhalative deposit (e.g., Carr, 1981) formed in a deep marine sub-basin (e.g., D. Large, 1980). A more recent model, incorporating constraints from sedimentology, ore textures, isotopic studies and geochemistry, proposes a shallow lagoonal setting and a syn-diagenetic timing for the formation of base metal sulfides (McGoldrick et al., 1996). In this model, base metals transported by oxidised basinal brines are precipitated as sulfides when the brines encounter and react with the organic-rich, highly reduced sedimentary environment of the mine sequence sediments. Base metal sulfides form in the anoxic water column, and as infillings in primary porosity in unconsolidated microbially laminated sediments.



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All samples are polished slabs

a) Tightly folded, high-grade Zn-Pb-Ag ore; grey bands are base metal sulfide-rich, light brown bands are fine grained pyrite, dark bands are coarsely recrystallised base metal sulfides and carbonate and quartz gangue.

b) Delicately laminated high-grade Zn-Pb-Ag ore; stratigraphic top is at top right; note shrinkage (?dessication) cracks in lower middle of the specimen.

c) Massive bedded pyrite (brassy colour) with (dark) sphalerite bands and pygmatic veins; layer parallel veins replace the bases of some of the pyrite units; sphalerite veins may have been early infill of open fractures

d) Barite-sphalerite ore (barite is white, sphalerite is black and light brown); grey areas with convex-up banding (e.g. lower left) are silicified stromatolites.

e) 'Honeycomb' microbially laminated chert with microdigitate stromatolites; honeycomb moulds may be after siderite, gypsum or pyrite.

f) High grade massive Zn-Pb-Ag sulfide ore with clastic (fragmental) textures; note the very coarse bases of two lower beds and normal grading to sulfidic mud in the upper parts of the two beds.

Halo model for the Mount Isa and Hilton/George Fisher Zn-Pb-Ag deposits

Peter McGoldrick

Centre for Ore Deposit Research

Summary

Lithogeochemical data from published and unpublished sources indicates that several of the basket of indices developed for the Lady Loretta and HYC deposits can be used as vectors to the Mount Isa and Hilton/George Fisher deposits. The useful indices include: Zn, Tl, SedexAl, Al₃ and MnO₄. The results summarised here have been discussed in detail in AMIRA P384 Report 7, pp. 115–140, November 1994.

Introduction

Two giant stratiform sediment-hosted Zn-Pb-Ag mineralised systems occur in the late Palaeoproterozoic Urquhart Shale in northwest Queensland. These are the Mount Isa Zn-Pb-Ag lodes, at Mount Isa (pre-production resource of about 150 Mt at 7wt% Zn, 6wt% Pb and 150 g/t Ag - Forrestal, 1990), and the Hilton and George Fisher deposits 20 km to the north (Hilton pre-production resource was 120 Mt at 10.2 wt% Zn, 5.5 wt% Pb and 100 g/t Ag - Forrestal, 1990; George Fisher global resource is 108 Mt at 11.5 wt% Zn, 5.4 wt% Pb, 93 g/t Ag - MIM annual reports).

Public domain geochemical data provided an opportunity to test the alteration halo models developed from our work at Lady Loretta and HYC. Although these data were of variable quality and completeness, they confirm the existence of primary element dispersions for the Mount Isa Zn-Pb-Ag deposits that are similar to those at HYC and Lady Loretta.

Deposit characteristics

The important features of the Mount Isa and Hilton/George Fisher deposits are summarised on data sheet #3.

Previous work

Investigations carried out at the Bureau of Mineral Resources in the 1960s (Smith and Walker, 1970, 1971) were the first published account of primary lithogeochemical dispersions around the Mount Isa deposits. Smith and Walker used a combination of atomic absorption spectroscopy and optical emission spectroscopy to analyse for Ag, Ba, Ca, Cd, Co, Cu, Fe, Ge, La, Mg, Mn, Mo, Ni, Pb, Sc, Sr, Ti, V, Y, Zn, and Zr. Later unpublished studies (Scott and Taylor, 1979 and McGoldrick, 1986) used different analytical techniques to measure a wider range of major and trace elements. The latter study demonstrated the existence of giant primary dispersion halos of Tl related to the Zn-Pb mineralisation, and showed that formation of the 'silica dolomite' (the host to the Cu ores) destroys some, but not all, of the primary element dispersion patterns within the silica dolomite alteration envelope. The genetic implications for these observations are discussed in McGoldrick and Keays (1990).

Sampling strategy

These deposits were not the focus of any new sampling for AMIRA P384/384A. However, information from existing data sets (Smith and Walker, 1970; Scott and Taylor, 1979), and a small amount of new data from an old sample set (McGoldrick, 1986) was available to test the applicability of some of the 'basket of indices' developed as vectors to the HYC and Lady Loretta deposits. The Hilton analyses were from a single drill hole through the mineralised sequence. No geochemical data were available from the George Fisher deposit. However, recent work by MIM geologists confirms Hilton and George Fisher were part of a single group of lodes, subsequently offset by sinistral movement on NW trending strike-slip faults. Hence, they should share the same primary element dispersion patterns.

The first data set considered here comprise 104 samples from underground workings and drill-core (Fig. 1); these comprise a full suite of major and trace elements. The second data set comprises several hundred partial analyses (Smith and Walker, 1970) from a drill-hole located along strike from the upper Zn-Pb-Ag lodes (DDH G27W – Fig. 2) and from the lower third of a surface drill hole through the Hilton deposit (N21/21A – Fig. 3).

Lithogeochemistry

The earlier (Smith and Walker, 1970) data set provide a good spatial coverage for the Mount Isa deposits, but because neither Al nor Ti were analysed for, only a limited number of vector parameters can be assessed for these data. The newer data sets are more comprehensive, but samples are mostly restricted to the mine sequence, making along strike changes in primary dispersions more difficult to ascertain.

Host rock carbonates

The Urquhart Shale host to the Mount Isa and Hilton/George Fisher deposits comprises current deposited dolomitic siltstones and fine sandstones, and hemipelagic carbonaceous mudstones. Much of the

mineralised sequence is highly pyritic. 'Dolomite' is by far the most common carbonate and it has a range of compositions from ferroan dolomite to ankerite (Neudert, 1983). Calcite can be locally important, and sideritic beds and sideritic alteration are also recognised (Neudert, 1983).

The whole rock data from McGoldrick (1986) and Scott and Taylor (1979) confirm the predominance of dolomite and/or ankerite as the major carbonate. Most of the 104 samples lie on a 'dolomite' composition trend on a CaO/MgO plot (Fig. 4a). A few samples have relatively elevated CaO and, hence, may contain calcite, and a few are relatively MgO-rich and may contain chlorite and/or phlogopite. The CaO/CO₂ relationship, in samples for which CO₂ analyses are available, confirms siderite is not present in these samples. The Fe+Mn/Mg mole ratios in low-sulfide samples ranges from about 0.1 to 1, with approximately two thirds of the samples containing 'ankerite' by definition (Fe+Mn/Mg > 0.25). Clearly, Fe-rich carbonates are intimately associated with mineralised rocks at Mount Isa, but whether the ankeritic samples are more proximal to base metal sulfides than those with ferroan dolomites cannot be determined due to a lack of systematic sampling by Scott and Taylor (1979) and McGoldrick (1986).

Zinc dispersion

Zinc in the Mount Isa and Hilton/George Fisher host rocks displays the same spiky and erratic distribution that is characteristic of many northern Australian Palaeoproterozoic fine grained sediments (McGoldrick, P384A Final Report). Zinc in low sulfide rocks ranges from less than 10 ppm to more than 1000 ppm (Figs 5–9).

Alteration indices

A large proportion of the Scott and Taylor (1979) and McGoldrick (1986) samples have strongly anomalous Sedex AI and AI3 ratios, and Zn/SedexAI and Zn/AI3 diagrams (Fig. 5) display the same positive correlation from background to high Zn and high alteration index observed at Lady Loretta and HYC

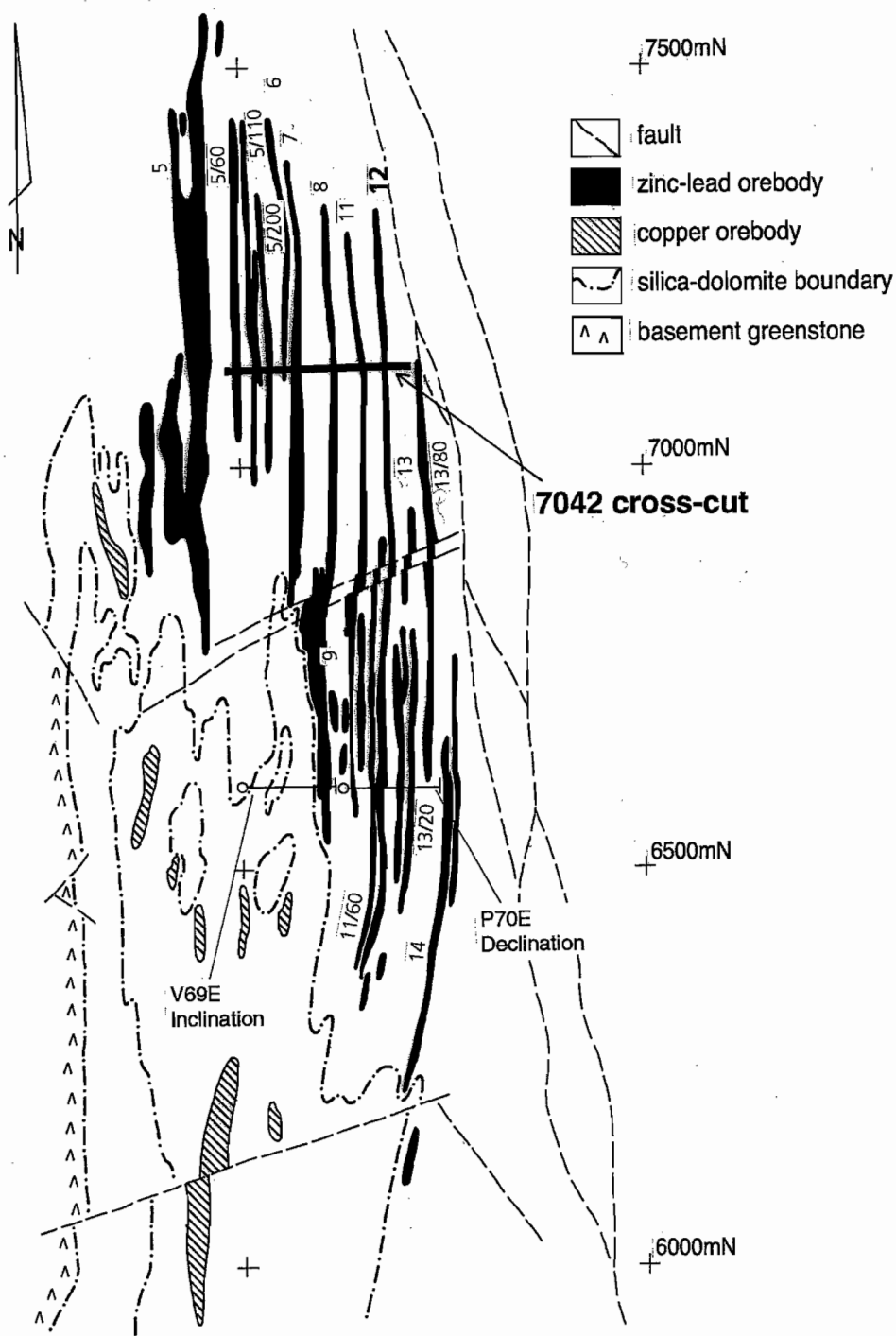


Figure 1. 1. Level plan from 15B sub-level at Mount Isa mine showing the location of drill holes P70E decline and V69E incline, 7042 cross-cut, and 12 orebody (McGoldrick, 1986; Scott and Taylor, 1979).

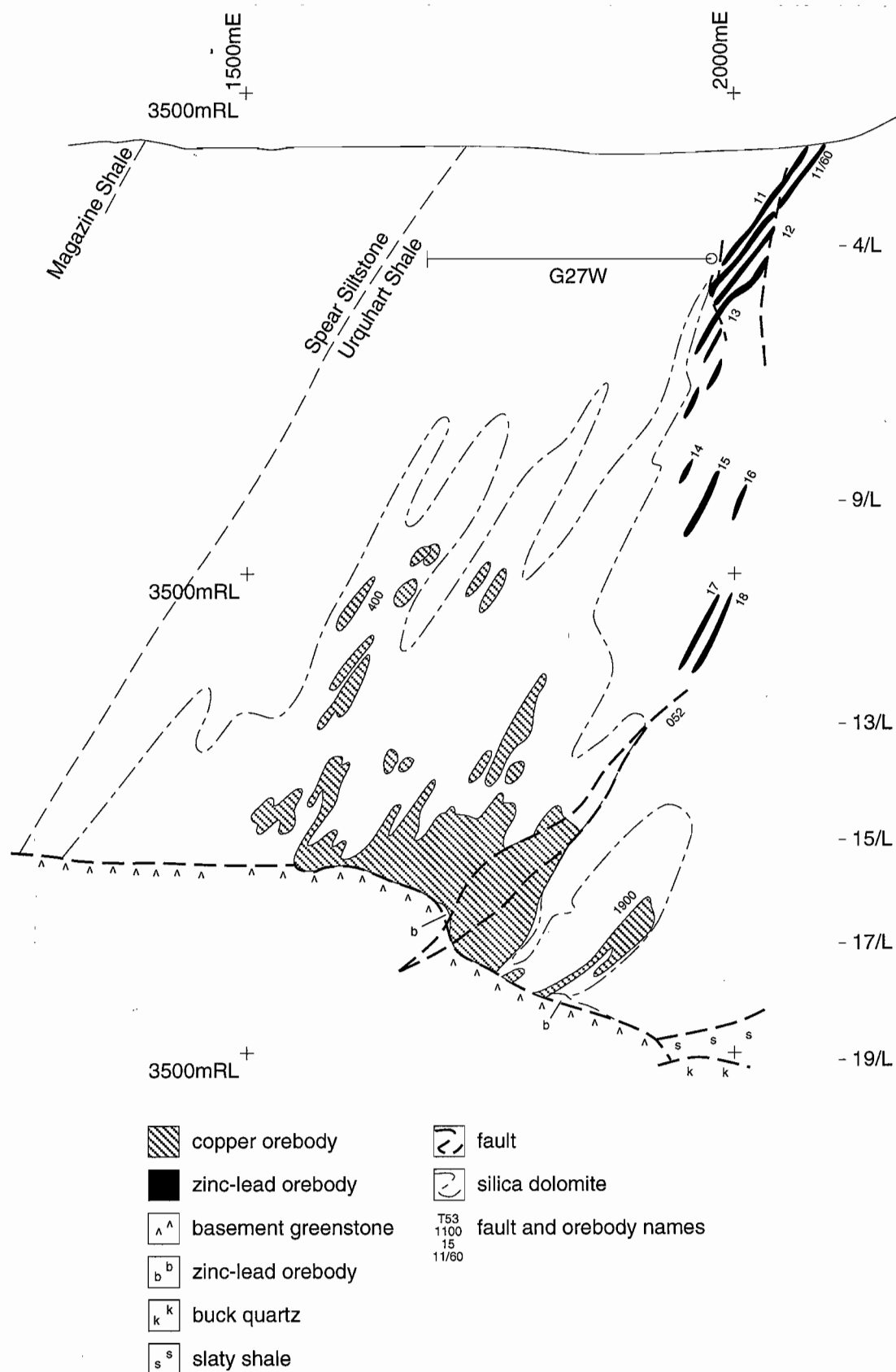


Figure 2. Cross section from Mount Isa mine at 5232 m N showing the position of DDH G27W (Smith and Walker, 1970).

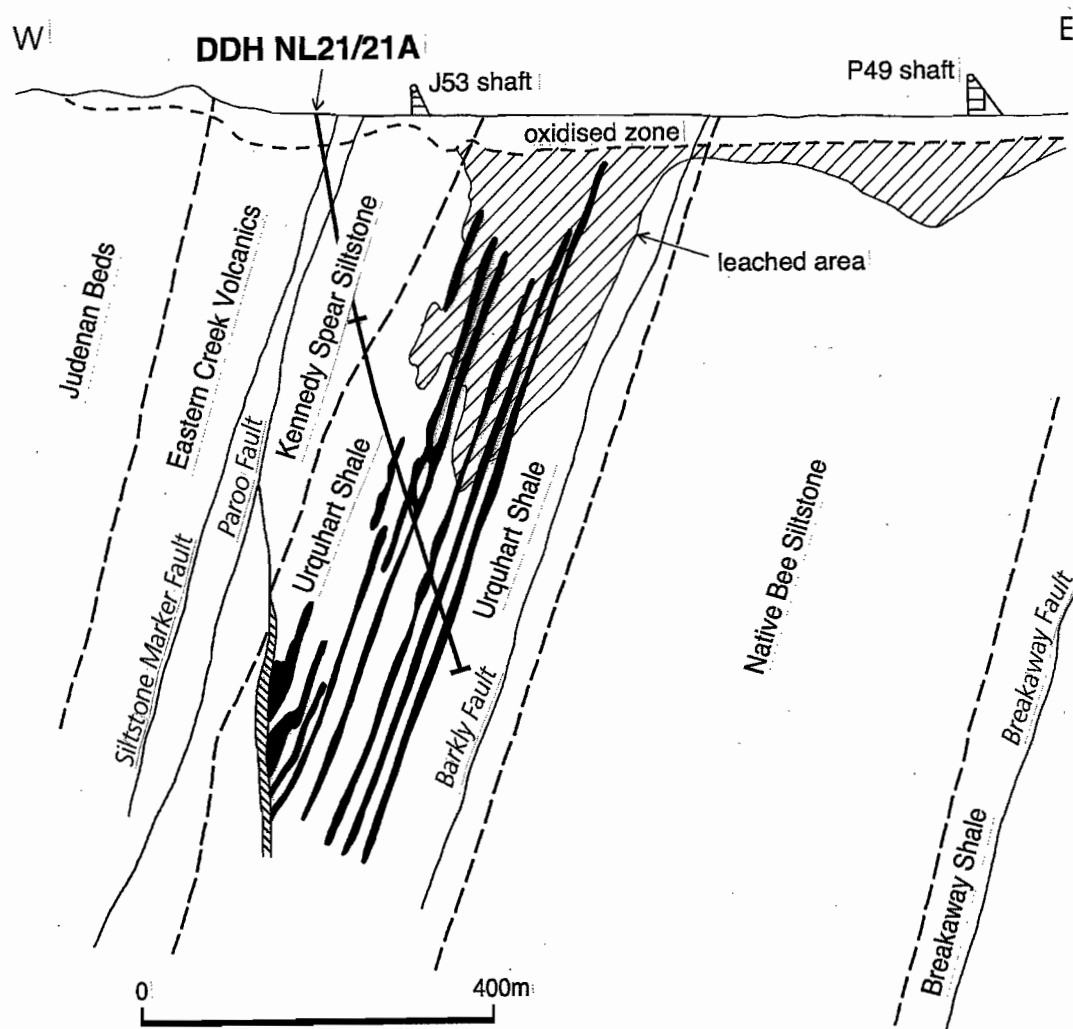


Figure 3. Cross section from Hilton mine at 5300 m N showing the position of DDH NL21/21A (Smith and Walker, 1970).

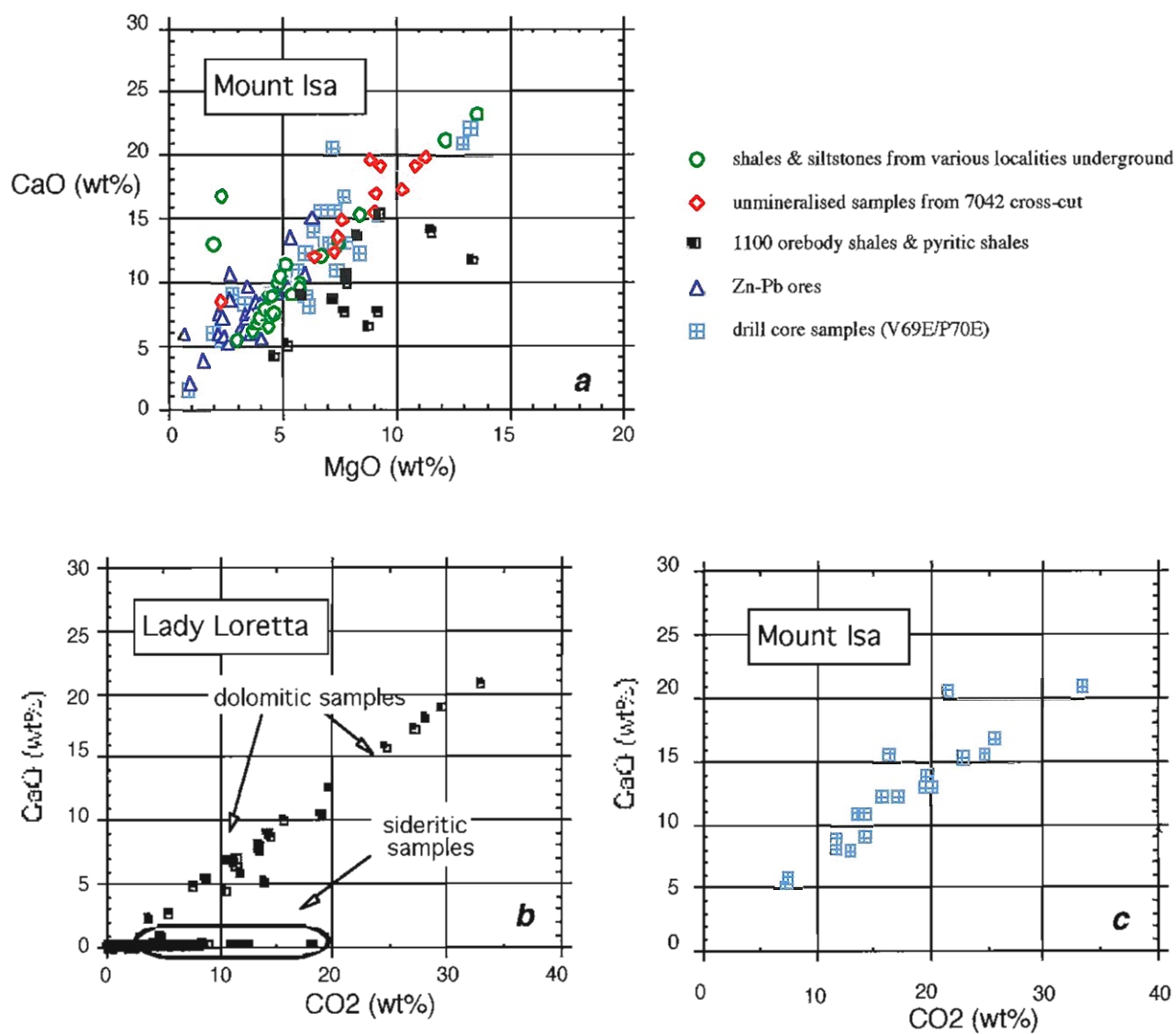


Figure 4. (a) CaO/MgO relationship for 104 samples from Mount Isa; (b) CaO/CO₂ cross-plot for 79 hanging wall and footwall sediments from the Small Syncline, Lady Loretta; (c) CaO/CO₂ relationship for 19 core samples from Mount Isa.

('Lady Loretta trend' — Large and McGoldrick, 1998). The Mn content of carbonates (MnO_d) is similarly anomalous in most of these samples (Fig. 5). More than two thirds of the samples plot in either prospectivity 1 or 2 areas of MnO_d /SedexAI and MnO_d /AI3 diagrams (Fig. 5).

The data from DDH G27W (Smith and Walker, 1970) provide an indication of the behaviour of two of these indices about a kilometre along strike from the main Zn-Pb mineralised sequence at Mount Isa (and away from the effects of silica dolomite alteration). The SedexAI and MnOd response is still very strong, although a smaller proportion of samples are anomalous (Fig. 6).

Samples from NL21/21A through the Hilton orebodies (Fig. 7) have the same strong response shown by the underground samples from Mount Isa, indicating similar primary element dispersion are present in both deposits.

Thallium

Thallium is an important minor component of the ores at Mount Isa (up to a few hundred ppm in high grade ores and highly pyritic samples). Elevated Tl (4 to 50 ppm) is also present in unmineralised mine sequence rocks. Background Tl in northern Australian late Palaeoproterozoic fine grained is around 1 to 2 ppm (McGoldrick, P384A Final Report). At Mount Isa anomalous Tl levels persist for several kilometres north along strike from the northern extremity of the main Zn-Pb mineralised sequence (McGoldrick, 1986) suggesting similar scale Tl halos at Mount Isa to those from HYC (Smith, 1973; Large et al., this volume).

No Tl data were available from Hilton/George Fisher, but it is likely that similar giant primary dispersions surround these deposits.

Carbon and oxygen isotopes

No C or O isotope measurements of Mount Isa samples was carried out for AMIRA P384/384A, however, analyses from an unpublished thesis (Waring, 1990) can be used to compare Mount Isa to other (barren and mineralised) samples from the Lawn

Hill Platform, and southern McArthur Basin. Figure 8 compares Waring's data C and O isotope measurements from several other data sets, most acquired during P384/384A. The Mount Isa samples ('distal Urquhart Shales' — Waring, 1990) define two distinct fields. Eighteen of twenty one samples have distinctly lighter O and C than any of the other case studies; three samples partly overlap data from the other areas. It is not clear if the light signatures are mineralisation process related, or a primary (diagenetic) feature of the Urquhart Shale.

Vectors to ore

Using existing data sets from Mount Isa and Hilton it has been demonstrated that most of the 'basket of indices' developed for Lady Loretta and HYC can be used as guides to the Mount Isa and Hilton/George Fisher Zn-Pb-Ag deposits. Useful vectors would include Zn, SedexAI, AI3, Mn in carbonates and Tl. Mount Isa host rocks have distinctive C and O isotopic signatures, however, insufficient data exist to test if they show the trend to heavier O and lighter C approaching ore that has been documented at HYC and Lady Loretta (Large et al., this volume; McGoldrick and Large, this volume).

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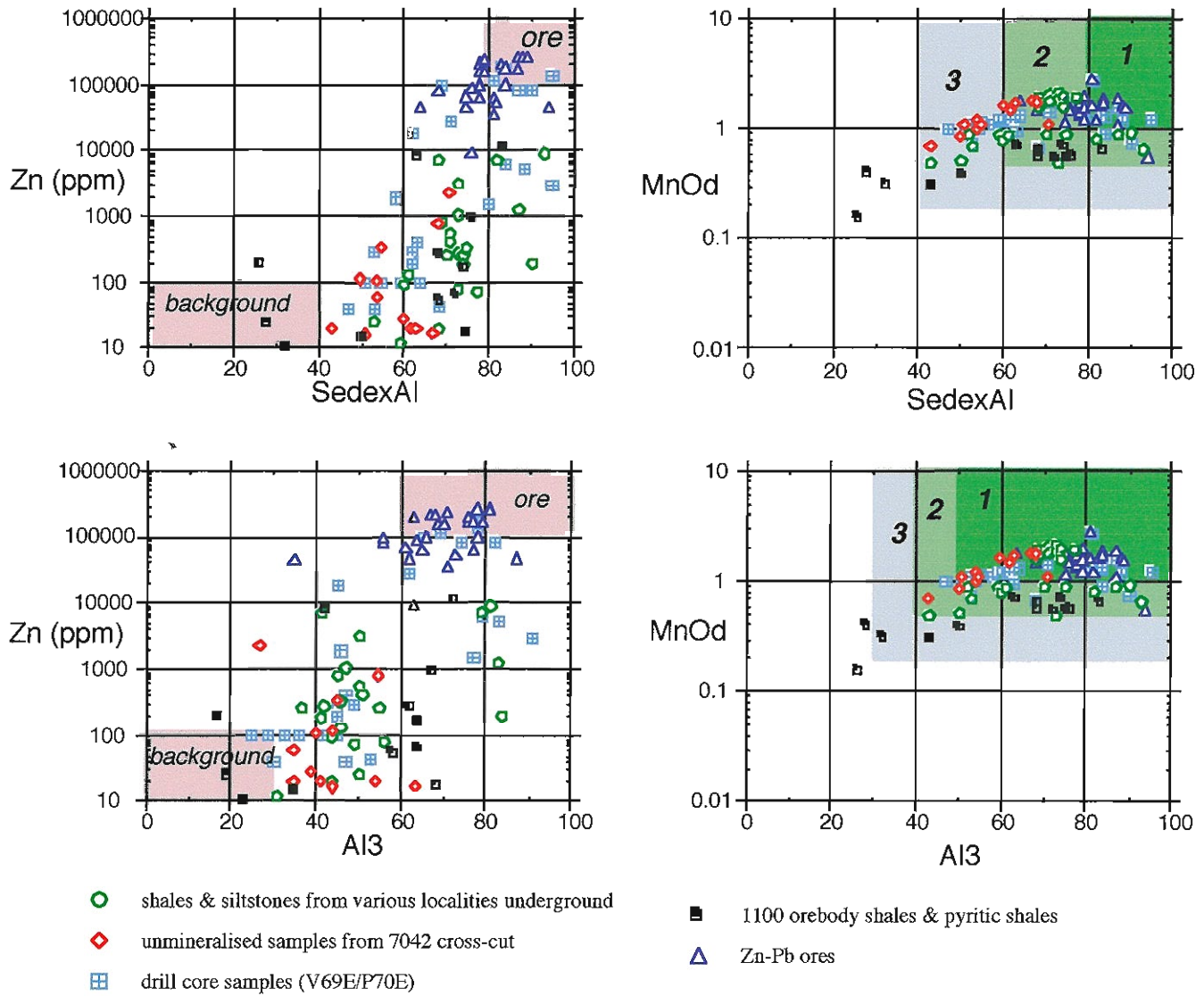


Figure 5. Zn/SedexAl/Al₃ and MnO₂/SedexAl/Al₃ cross-plots for 104 samples from Mount Isa.

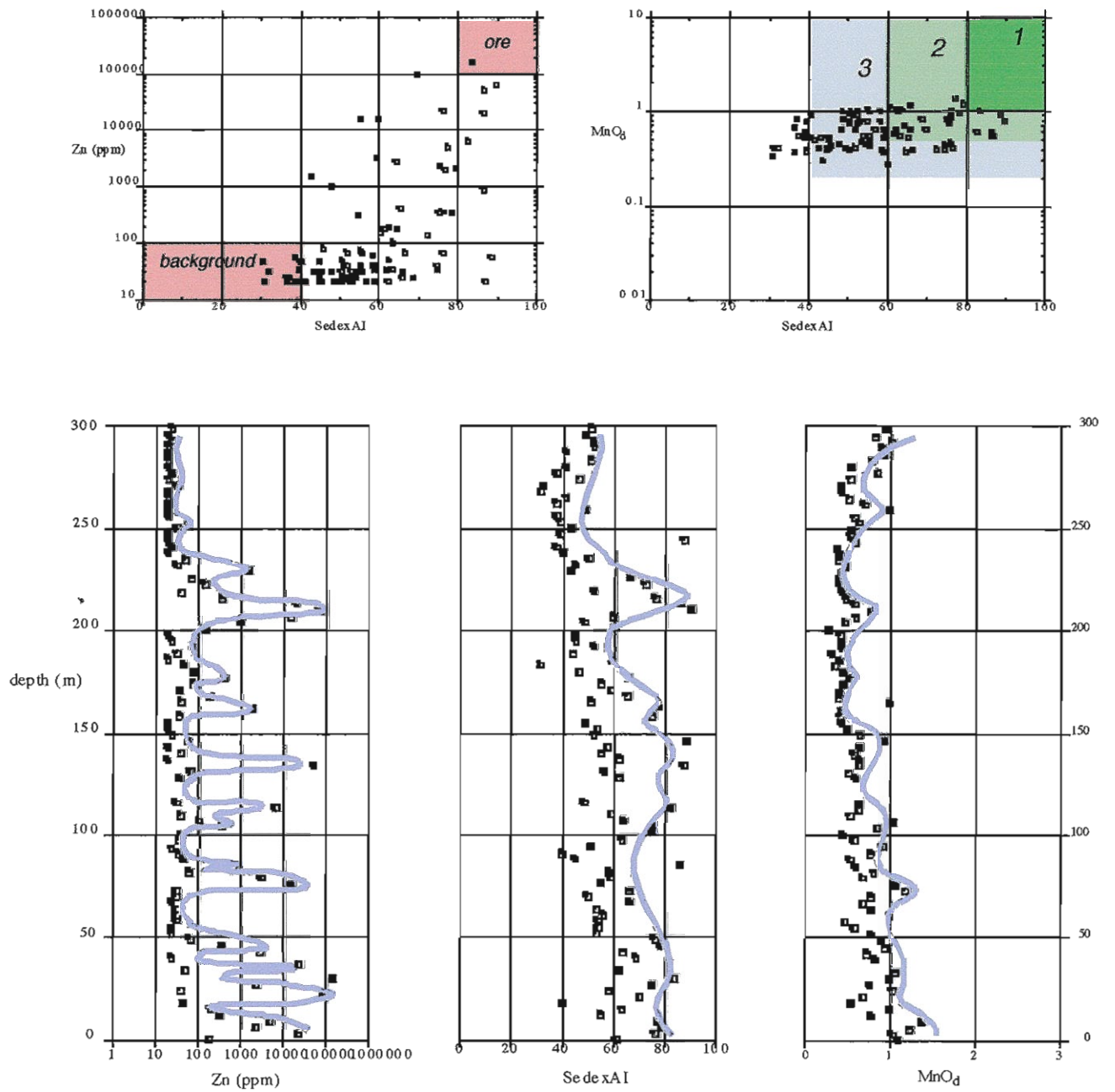


Figure 6. Zn/SedexAl, MnO_d/SedexAl and 'downhole' plots for samples from DDH G27W (lateral stratigraphic equivalent of Zn-Pb lodes approximately 1 km north along strike)

DDH G27W

- DDHs P70E, V69E and M14E, Mount Isa Mines: CSIRO Restricted Investigation Report, v. 1021R, p. 12.
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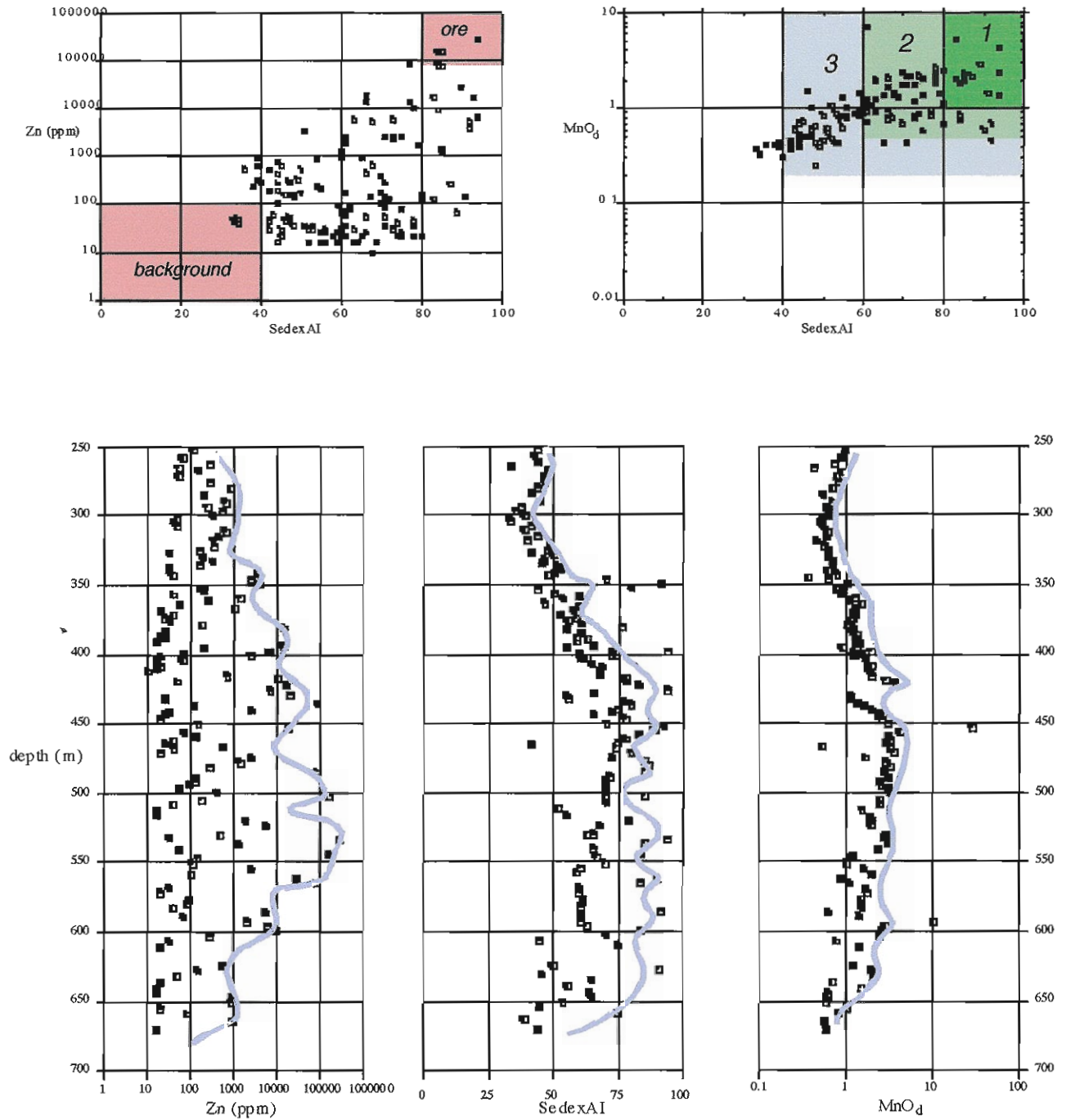


Figure 7. Zn/SedexAl, MnO₄/SedexAl and 'downhole' plots for samples from DDH NL21/21A.

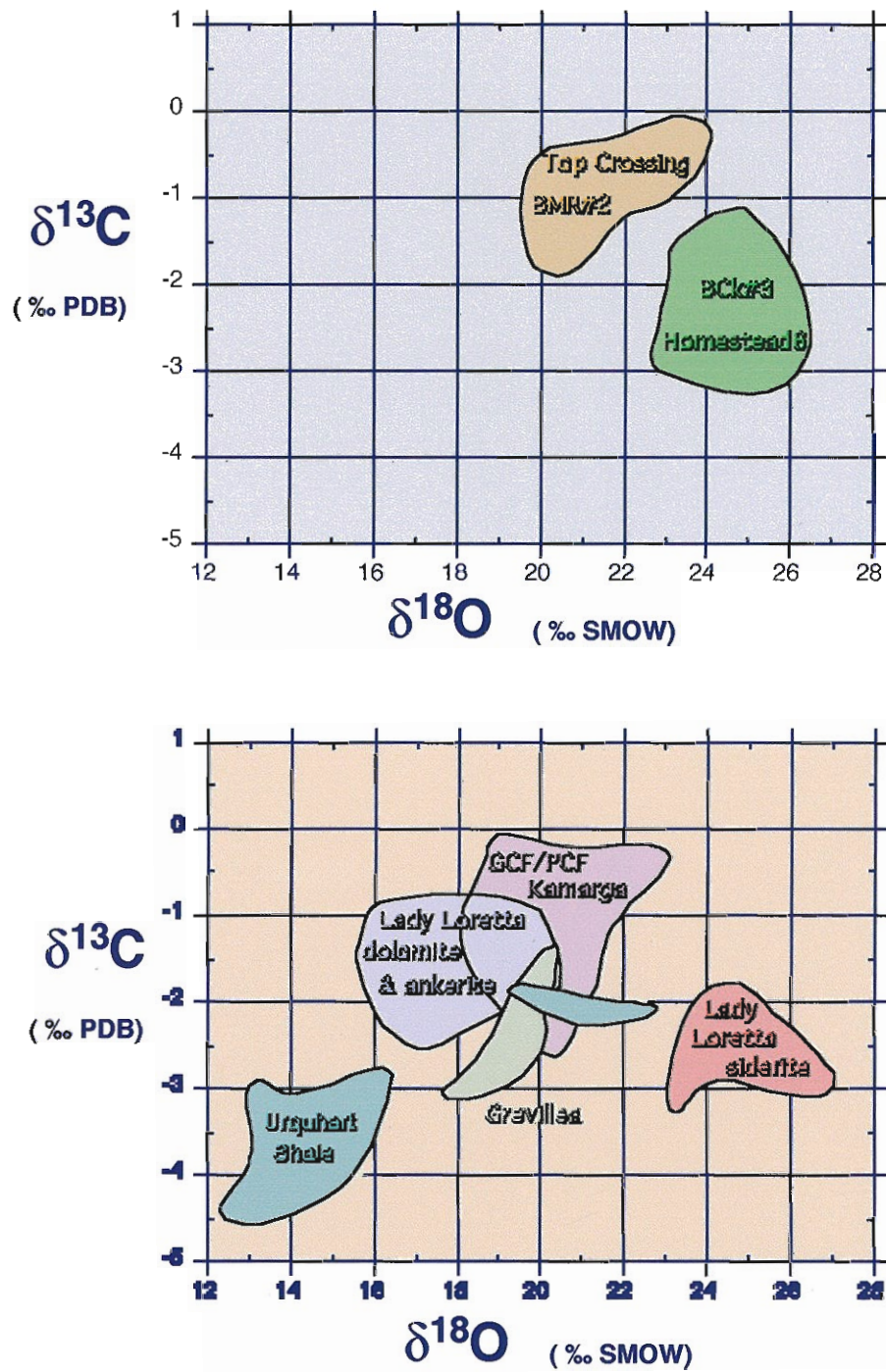


Figure 8. C and O isotope data for 'distal' Urquhart Shale (Waring, 1990) samples compared with various samples sets from the McNamara Group, north west Queensland, and for the Barney Creek Formation, southern McArthur Basin.

Mt Isa Zn, Pb, Ag Deposit Summary

Regional Setting: The deposit occurs in late Palaeoproterozoic sediments of the 'Leichardt River Fault Trough' (Blake, 1987), part of the Western Succession of the Mount Isa Inlier. To the north, in the Lawn Hill Platform' and the southern McArthur Basin, broadly similar age rocks also contain stratiform sediment-hosted Zn-Pb-Ag deposits (the Carpentaria Zinc Belt – Sweet et al., 1993; McGoldrick and Large, 1998).

Host Rocks: The immediate host rocks are pyritic and carbonaceous shale, dolomitic siltstone, and minor fine sandstone of the Urquhart Shale Member of the Mount Isa Group. Pseudomorphs of dolomite and Fe sulfide after gypsum occur in the Urquhart Shale and halite casts and strong albite alteration are present in the overlying Kennedy-Spear Siltstone. TMBs ('tuff marker beds') are microcline-rich beds used for correlation within the mine sequence. A U/Pb SHRIMP age of 1652 ± 7 has been obtained from zircons from TMB samples (Page and Sweet, 1998).

The upper Mount Isa group has been interpreted to have formed in a large perennial saline lake setting by (Van den Heuvel, 1969) and (Neudert, 1983). A recent alternative suggestion (AGSO NABRE team) is that the Mount Isa Group represents the deep water end of a carbonate ramp.

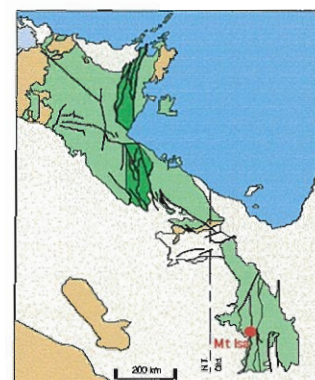
The Mount Isa Group occurs on the steeply W dipping limb of a regional anticline, and is truncated to the W by the Mount Isa Fault. This regional structure juxtaposes amphibolite grade rocks to the W against greenschist facies rocks (including the Mount Isa Group) to the E.

Size and Grade: The deposit comprises more than 30 stacked (en echelon) ore lenses in the 1000 m thickness of Urquhart Shale (most are in the upper 650 m). Pre-production reserves were about 150 Mt @ 7% Zn, 6% Pb and 150 g/t Ag; most production has been from the Black Star lodes (#s 1 to 5 orebodies) and the Racecourse lodes (5/60 to 14 orebodies; Forrestal, 1990).

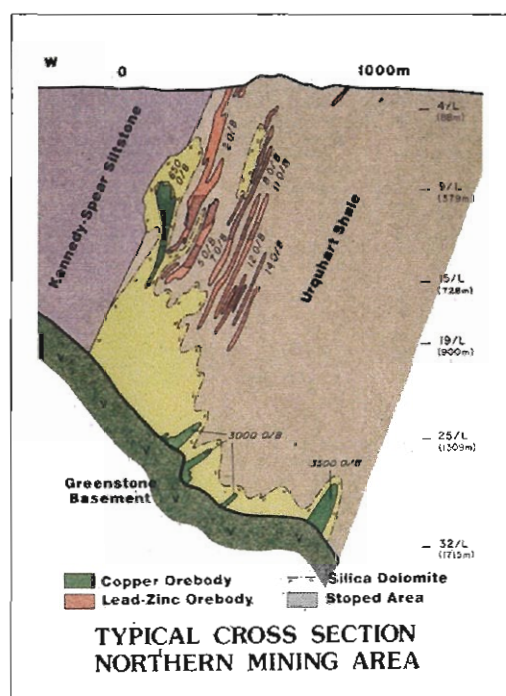
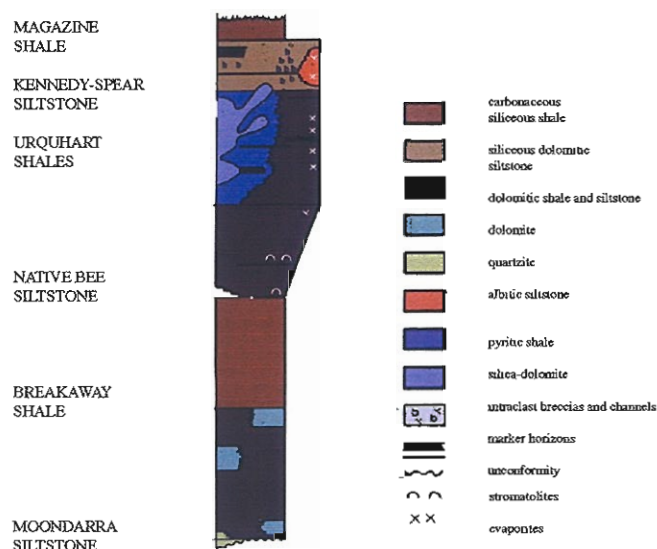
Mineralisation: Stratiform orebodies with variable amounts of pyrite, sphalerite, galena and tetrahedrite (freibergite); pyrrhotite is locally abundant, and magnetite spots occur in Z-Pb lodes close to silica dolomite. Locally ores can be intensely deformed, but some primary sulfide textures are preserved. Several examples of Mount Isa Zn-Pb-Ag ore are illustrated on Plate 3.

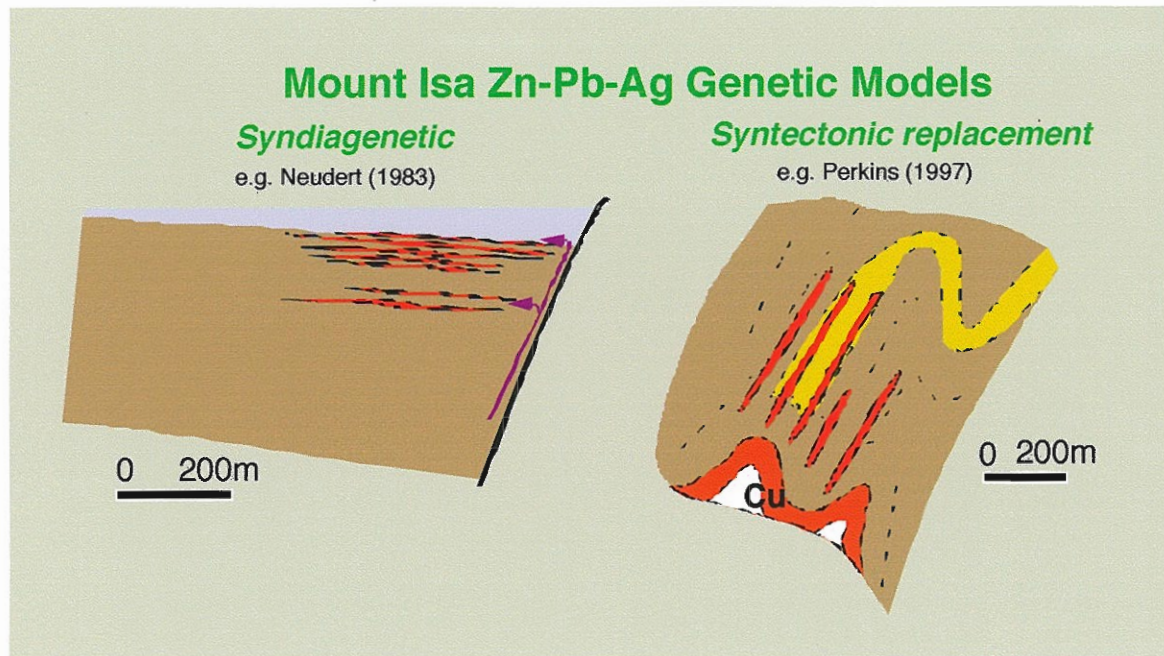
Genetic Models: In general there are two disparate types of genetic model for the Mount Isa Zn-Pb-Ag lodes. One model type invokes syn-deformational hydrothermal replacement of lithified rock by deep sourced (?metamorphic) fluids (e.g., Grondijs and Schouten, 1937; Myers et al., 1996; Perkins, 1997), the other invokes syngenetic and/or diagenetic processes and timing for ore formation (e.g., Neudert, 1983; McGoldrick and Keays, 1990). The latter models envisage Mount Isa as one of a spectrum of genetically similar giant deposits of the Carpentaria Zn Belt.

Lat 20°44'S, Long 139°29'E



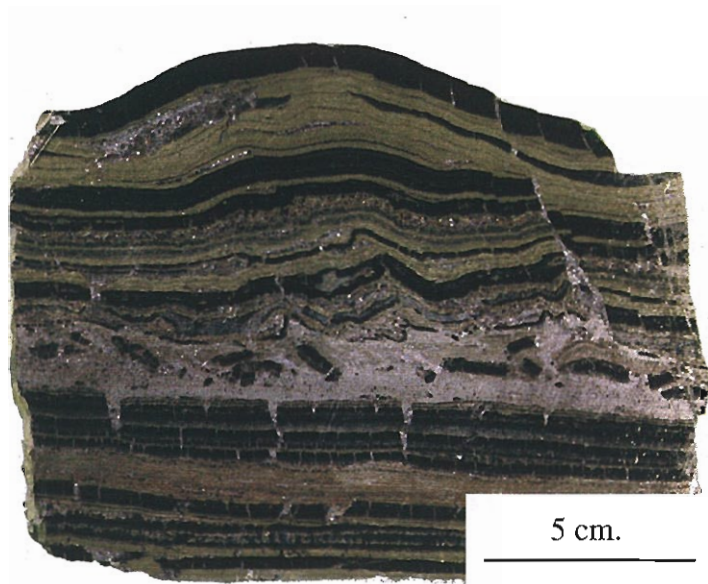
Mt Isa Group: stratigraphy and lithologies



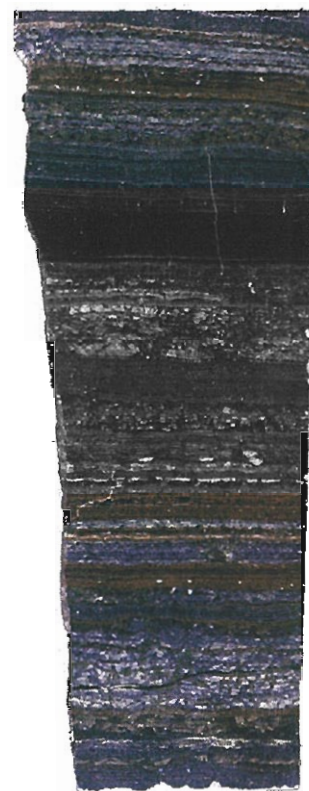


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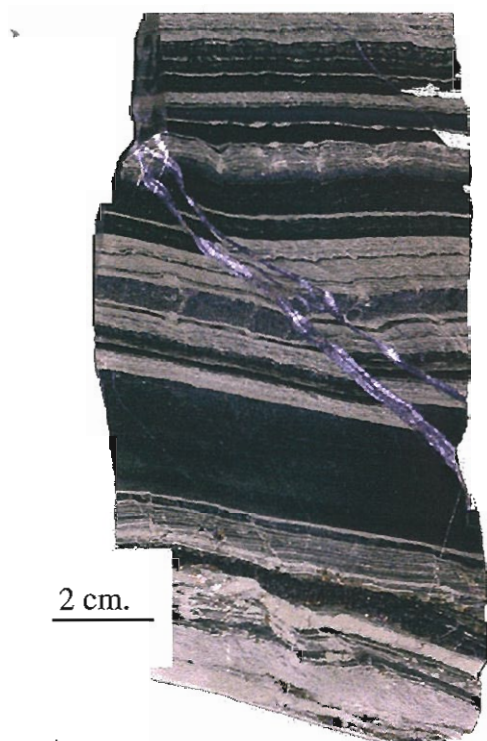
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(a)



(b)



(c)



(d)

1 cm.

All samples are polished slabs

a) High grade Zn-Pb-Ag ore; brown bands in the upper third of the specimen are delicately laminated fine grained pyrite, grey band with (black) shale fragments is galena-rich, the lower third of the sample is mainly laminated brown sphalerite.

b) High grade Zn-Pb-Ag ore; brown bands are sphalerite-rich, grey speckled bands are (bladed) pyrrhotite/phillosilicate/ carbonate beds, black band at top is carbonaceous shale.

c) Delicately laminated pyrite and black shale interbeds; fine crenulated pyrite may have originally been a microbial lamination; note the sample is Fe sulfide-rich but contains only a single (dark) sphalerite-rich band near the base of the specimen

d) Pyrrhotite-rich high grade Zn-Pb-Ag ore; note different texture of pyrrhotite in this sample compared to bladed pyrrhotite in (b)

Lithogeochemical and isotopic halo model for the HYC stratiform Zn-Pb-Ag deposits, Northern Territory

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Introduction

The HYC deposit in the McArthur Basin, Northern Australia, was selected for detailed halo studies as part of AMIRA projects P384 and P384A, because it represents a large unmetamorphosed example of the SEDEX class, and drill core was available to allow a characterisation of the nature and extent of the halo. Previous studies by Lambert and Scott (1973), and Corbett et al., (1975) provided a solid database of whole-rock chemical analyses, especially within and close to the ore deposit. As access to sampling the HYC deposit was not available to the AMIRA project team these previous studies proved invaluable.

In the first three years of P384, our research focussed on testing the lithogeochemical vectors defined from our studies at Lady Loretta (Large and McGoldrick, 1993; Large 1994) and refining these vectors to fit the particular characteristics of the McArthur Basin sediments (Large and McGoldrick, 1994; Large and Duhig, 1995). The first phase of this research, completed in P384, has been prepared for publication (Large et al., in press).

Further work in P384A was concentrated on determining the relationship between lithogeochemistry and sedimentology of the Barney Creek Formation and documenting the carbonate isotope chemostratigraphy and its relationship to the ore deposit halo (Bull and Large, 1995; Large and Bull, 1996; Large and Bull, 1998).

Most recently the halo and isotopic studies have been combined with alkali alteration studies (Davidson, 1995) and fluid modelling (Garven, 1998) to develop an innovative approach to determine the criteria to distinguish hydrothermal recharge and discharge zones in the McArthur Basin, and thus

focus exploration to high priority sites (Large et al., 1998).

Previous AMIRA P384/P384A reports on HYC halo studies

1. Large, R.R. and McGoldrick, P.J., 1993, Primary geochemical halos related to Proterozoic sediment hosted Pb-Zn-Ag deposits and applications to exploration: AMIRA P384, Report 3, October 1993, p. 63-126.
2. Large, R.R. and McGoldrick, P.J., 1994, Refinement of the SEDEX Alteration Index and MnO_d vectors: AMIRA P384, Report 5, June 1994, p. 1-16.
3. Large, R.R., 1994, Background data on AI and MnO_d from McArthur Basin sediments: AMIRA P384, Report 5, June 1994, p. 17-23.
4. Large, R.R., 1994, Case studies: application of the alteration index to selected areas in the McArthur Basin: AMIRA P384, Report 5, June 1994, p. 23-40.
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6. Bull, S. and Large, R.R., 1995, Sedimentology, geochemistry, alteration patterns and C/O isotope chemostratigraphy, DDH BMR McArthur 2, McArthur Basin, NT: AMIRA P384, Final Report, June 1995, p. 159-182.
7. Large, R.R. and Duhig, N., 1975, Ankerite halo to the HYC deposit: AMIRA P384, Final Report, June 1995, p. 273-282.
8. Duhig, N., 1995, A microprobe study of

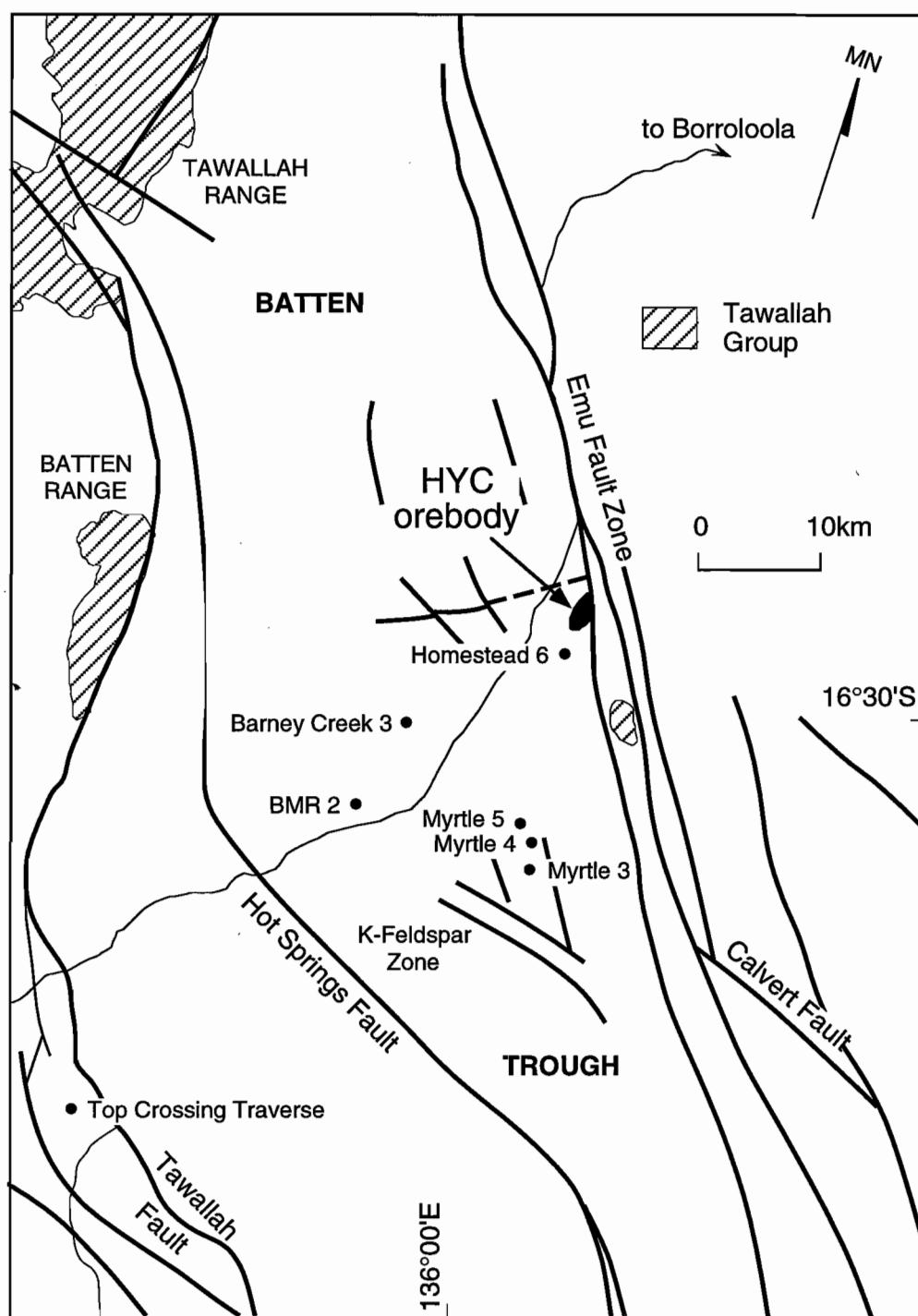


Figure 1. Batten Trough showing location of HYC deposit and the drill holes sampled in this halo study.

carbonates from DDH BMR 2, McArthur Basin, AMIRA P384, Final Report, June 1995, p. 283-288.

9. Large, R.R. and Bull, S., 1996, Lithogeochemistry and isotope chemostratigraphy of the Barney Creek Formation, McArthur Basin, AMIRA P384A, Report 2, p. 41-86.
10. Large, R.R. and Bull, S., 1998, Lithogeochemistry and isotope chemostratigraphy of the Myrtle Sub-basin, McArthur Basin, N.T. : AMIRA P384A, Final Report, November 1998.
11. Large, R.R., Bull, S. and Garven, G., 1998, Criteria to determine recharge (downflow) and discharge (upflow) zones related to stratiform Zn-Pb-Ag deposits, McArthur Basin, N.T., : AMIRA P384A, Final Report, November 1998.

Sampling strategy

Although no sampling was carried out through the host stratigraphy at the HYC mine site, data was available from previous drill hole sampling, in particular DDH Te 115, which passed through the HW, orebody and FW sequences of the Barney Creek Formation (BCF) (Corbett et al., 1975). Our sampling focussed on a series of drill holes and traverses, which intersect the host BCF, at various distances from the orebody (Fig. 1):

DDH Homestead 6 : 2 km SSW of HYC
 DDH Barney 3: 15 km SW of HYC
 DDH BMR 2: 23 km SW of HYC
 DDH Myrtle 3: 21 km S of HYC
 DDH Myrtle 4: 18 km S of HYC
 DDH Myrtle 5: 17 km S of HYC
 Top Crossing traverse : 53 km SW of HYC.

Samples taken at 5–15 m down each drill hole were analysed for a range of selected major and trace elements.

Major Elements : SiO_2 , TiO_2 , Al_2O_3 , FeO^+ , MnO ,
 MgO , CaO , Na_2O , P_2O_5 , S
 Trace Elements : Cu, Pb, Zn, Tl, Ba, Sr, Gr, Zr, V, Y,
 U, Rb, Th, As, Bi, Ni

All samples were also analysed for CO_2 and those samples with carbonate content greater than about 10 wt% were analysed for their carbonate oxygen and carbon isotopes.

Ore deposit characteristics

Form of orebody

The HYC deposit consists of eight stacked stratiform ore lenses from 2 to 10 m thick at the base of the Barney Creek Formation. The base metal sulfides occur in micro bands 100-500 microns thick parallel to the layering in the dolomitic black shale host sediments.

Size and grade

Global reserve : 237 million tonnes @ 9.2% Zn, 4.1% Pb, 41 g/t Ag
 Mining reserve : 104 million tonnes @ 14.1% Zn, 6.4% Pb, 64 g/t Ag.

Age

1640 ± 3 Ma U/Pb zircon data on minor tuff units in the Barney Creek Formation at HYC (Carr et al., 1996).

Structural setting

Located adjacent to Emu fault (forms the eastern margin of the Batten Trough). Fault intersections related to the Calvert Fault, Emu Fault and an unnamed E-W fault north of HYC may have been important fluid conduits.

Stratigraphy and host rocks

Regionally the orebody occurs in the McArthur Group, a sequence of shallow water dolomites. Locally the orebody is located at the base of the Barney Creek Formation consisting of dolomitic black shales, made up of mass flow units (turbidites) and organic-rich siltstones. The BCF is interpreted from our studies (Bull, 1998) to vary from relatively shallow to relatively deep water conditions, controlled by regional faulting and sub-basin development. HYC is developed in deep water facies adjacent to the Emu Fault.

Orebody mineralogy

- Very fine-grained sphalerite, galena, pyrite with trace chalcopyrite, mercosite, arsenopyrite;
- Two types of pyrite: Py1 - fine euhedral; Py2 - nodular, radiating and overgrows Py1
- Two types of sphalerite: mode 1 - micro laminations; mode 2 - nodular with ankerite.
- Sedimentary gangue minerals: quartz, dolomite, ankerite, illite(phengitic) and organics

Deformation/metamorphism

- Very low grade metamorphism
- Several generations of faulting; early soft sediment slip (Hinman, 1995) and several later generations of brittle faulting.

Halo model

Our research in the southern McArthur Basin has defined a complex lithogeochemical and isotopic halo surrounding the HYC deposit. The two major components of the halo are shown in Figure 3 and outlined below.

Ferroan dolomite halo

A zone of iron-rich carbonate varying from ferroan dolomite to ankerite surrounds the HYC deposit, extending at least 15-20 km SW of the deposit. At HYC the halo extends 250 m into the hangingwall BCF dolomitic shales and 50 m into the footwall (W-fold shale and Coxco Dolomite). Regionally the ferroan dolomite halo extends along the favourable pyritic black shale facies at the base of the HYC Pyritic Shale. Anomalous levels of zinc, lead, thallium and pyrite are erratically developed throughout the ferroan dolomite halo. The most Fe-rich dolomite/ankerite occurs in the ore zone and regionally along the base of the HYC Pyritic Shale.

Manganese carbonate halo

An extensive, basin wide, manganese carbonate halo is developed in the W-Fold Shale unit, footwall to the orebody and favourable horizon (Fig. 3b). At HYC the manganese carbonate (either Mn-Fe dolomite or Mn-ankerite) halo tightly encloses the deposit (Fig. 3b), with maximum values of 12 wt% MnO in dolomite, in the immediate footwall to the

ore (Fig. 4). The average MnO content of dolomite (MnO_d) decreases systematically along the W-Fold Shale unit to the west of HYC to levels of 0.5–1.5 at 23 km (DDH BMR 2) (Fig. 4). Regionally the Mn concentration in the W-Fold Shale marks the redox boundary associated with the transition from oxidised shallow water carbonates to the reduced deeper water pyritic shales, that host the ore.

Base metal dispersion in the halo

Zinc and lead are enriched to anomalous levels (commonly Zn > 1,000 ppm, Pb > 100 ppm) throughout most of the ferroan dolomite halo, but are typically present at background levels in the Mn carbonate halo (Large and Bull, 1996; Large et al., in press).

Thallium

Thallium is probably the most useful zinc-lead indicator element showing a more even (less erratic) distribution than zinc or lead, and extending beyond the ankerite halo, along the favourable horizon, (e.g., Myrtle Basin). At HYC the outer limits (HW and FW) of the Tl halo have not been defined due to its broad distribution. Through the ore zone Tl varies from 100 to 1,000 ppm (Fig. 5), decreasing to 50–100 ppm at 2 km distant, and then 5–25 ppm at 15 km (DDH Barney 3). Beyond 20 km the BCF contains Tl values of less than 4 ppm, which are considered to represent the background population (Fig. 5).

Alteration Indices

The alteration vectors, Sedex AI, and MnO_d developed for Lady Loretta (Large and McGoldrick, 1993, 1998) have been shown to apply equally well at HYC. In addition a new vector, AI3, has been developed to overcome the "shale factor" (Large, 1994).

Sedex AI

This vector was developed at Lady Loretta to account for three factors that increase toward stratiform Zn-Pb-Ag ores:

- Increase in Fe and Mn content of sedimentary carbonate;
- Increase in pyrite content of sediments;
- Increase in shale/dolomite ratio of sedimentary facies.

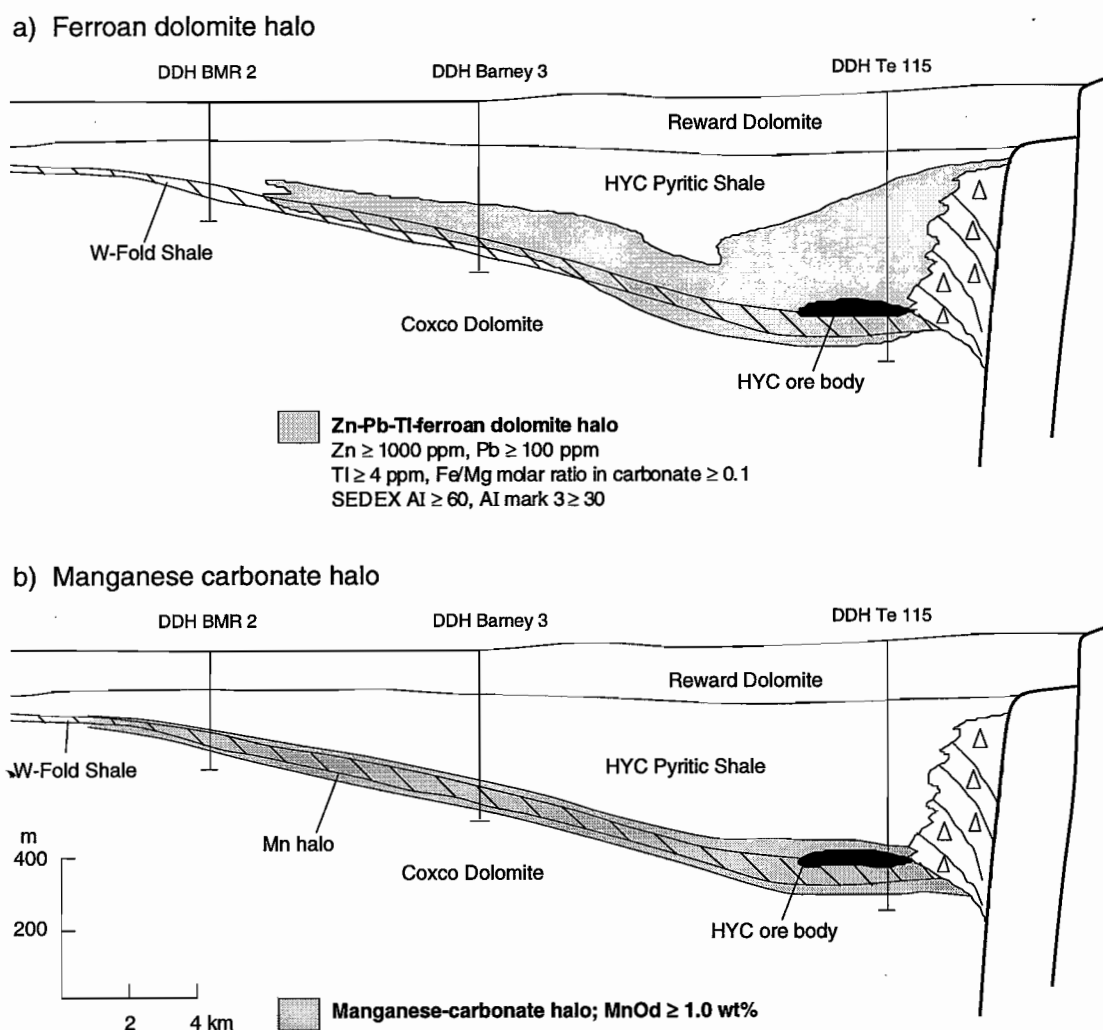


Figure 3. (a) Ferroan dolomite halo at HYC; (b) manganese carbonate halo at HYC.

Sedex AI =

$$\frac{100(FeO + 10MnO)}{(FeO + 10MnO + MgO)}$$

The data from DDH Te 115, through the ore stratigraphy at HYC, shows a trend of increasing Sedex AI with increasing zinc content (Fig. 6). Background Barney Creek Formation sediments (e.g., DDH BMR 2) have values of 0–40 Sedex AI, whereas ore zone samples increase to Sedex AI values of 80–100. Sediments in DDH Barney 3 and DDH Myrtle 5, at the outer limit of the ferroan dolomite halo, show a similar trend of increasing AI with increasing Zn. A gradual increase in Sedex AI from the top of the

drill hole to the base of the HYC Pyritic Shale in DDH Barney 3 provides an excellent vector to the ore position (Fig. 7).

AI3

This modification of the Sedex alteration index was developed to reduce the "shale factor" and avoid spurious anomalies related to changes in the shale/dolomite ratio of the sediments (Large, 1994).

AI3 =

$$\frac{100(FeO + 10MnO)}{(FeO + 10MnO + MgO + Al_2O_3)}$$

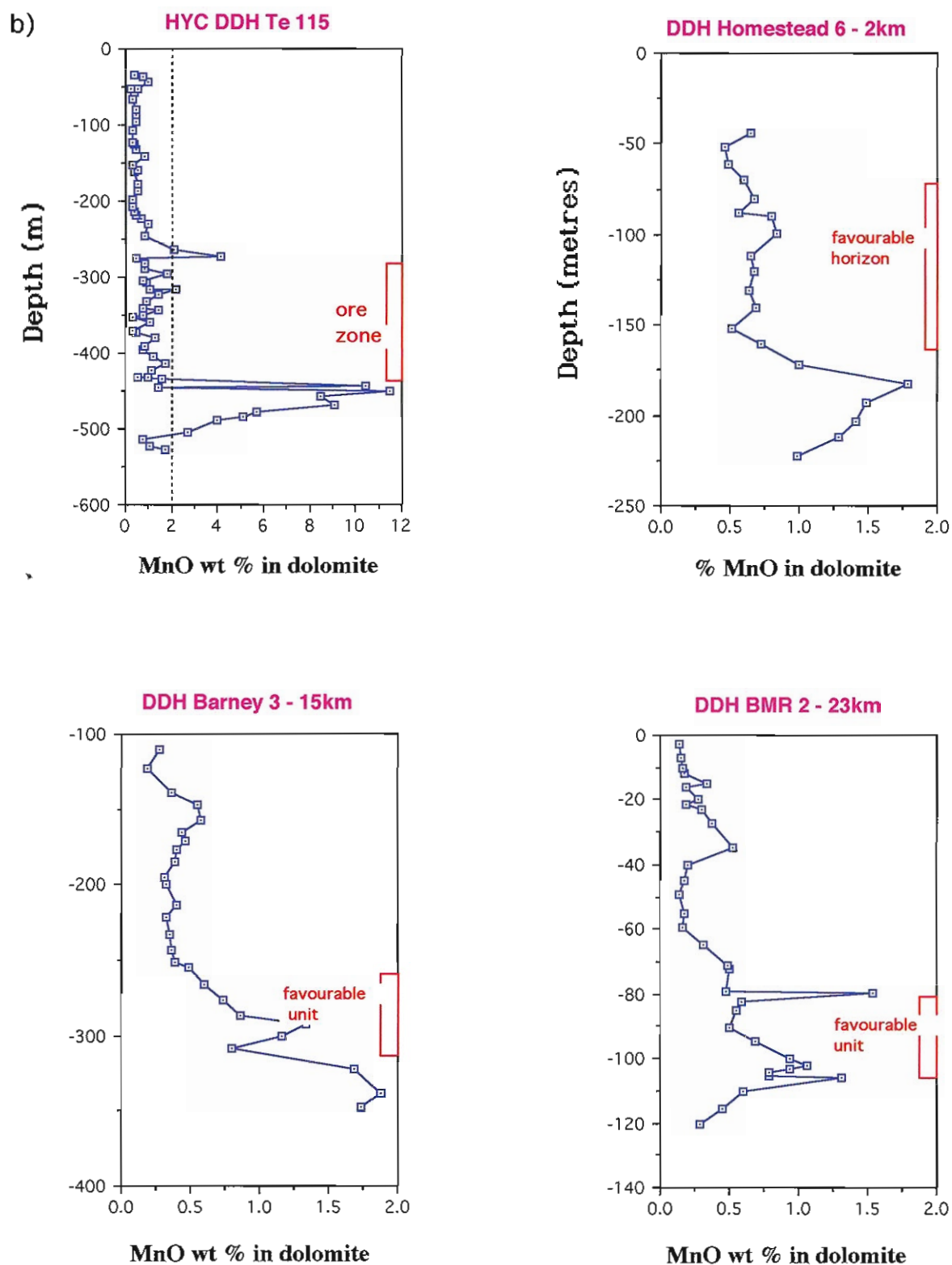


Figure 4. MnO content of dolomite in a series of drill holes passing SW from HYC. Note the maxima developed in the W-Fold Shale Unit, immediately below the potential ore horizon.

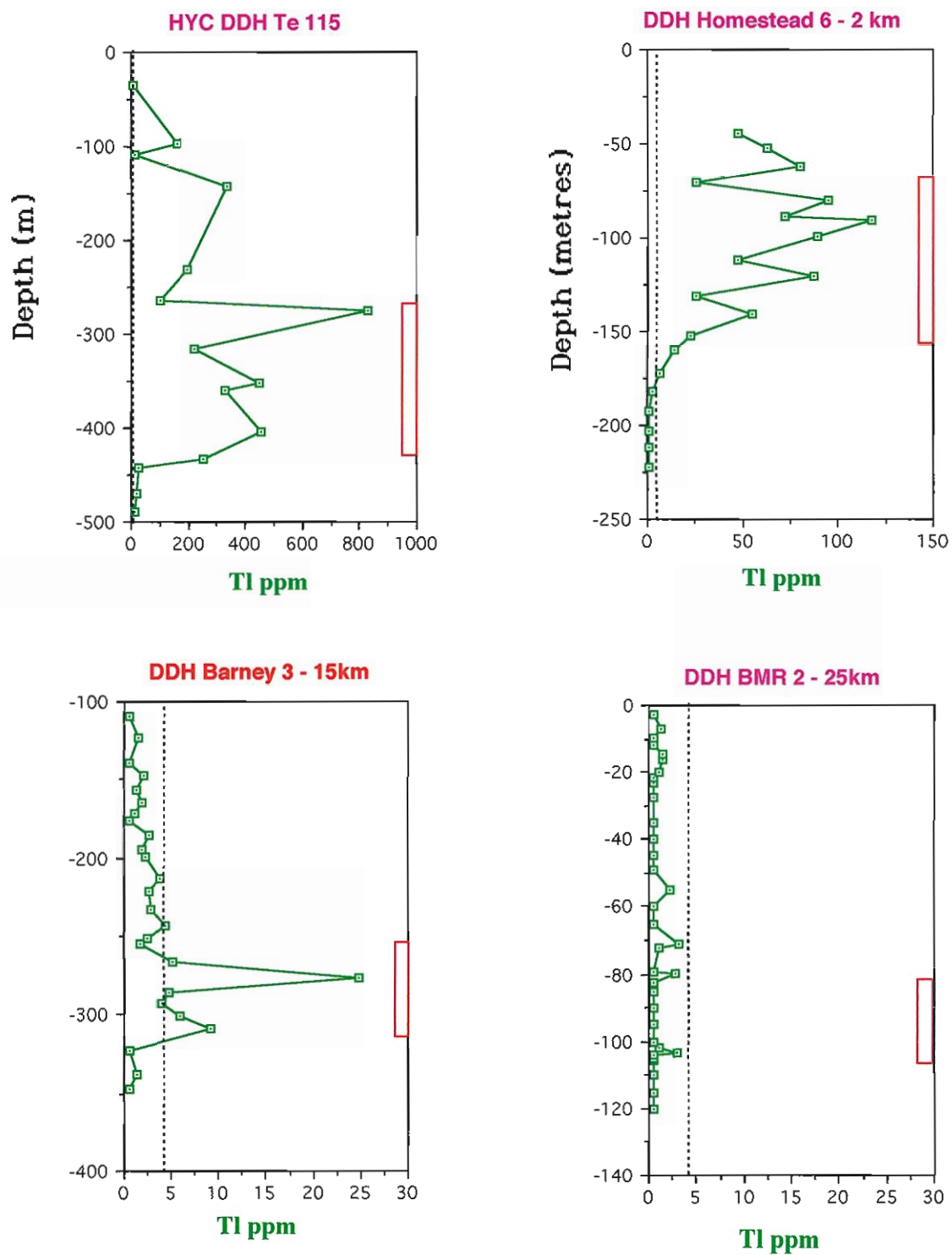


Figure 5. Tl content in a series of drill holes passing SW from HYC.

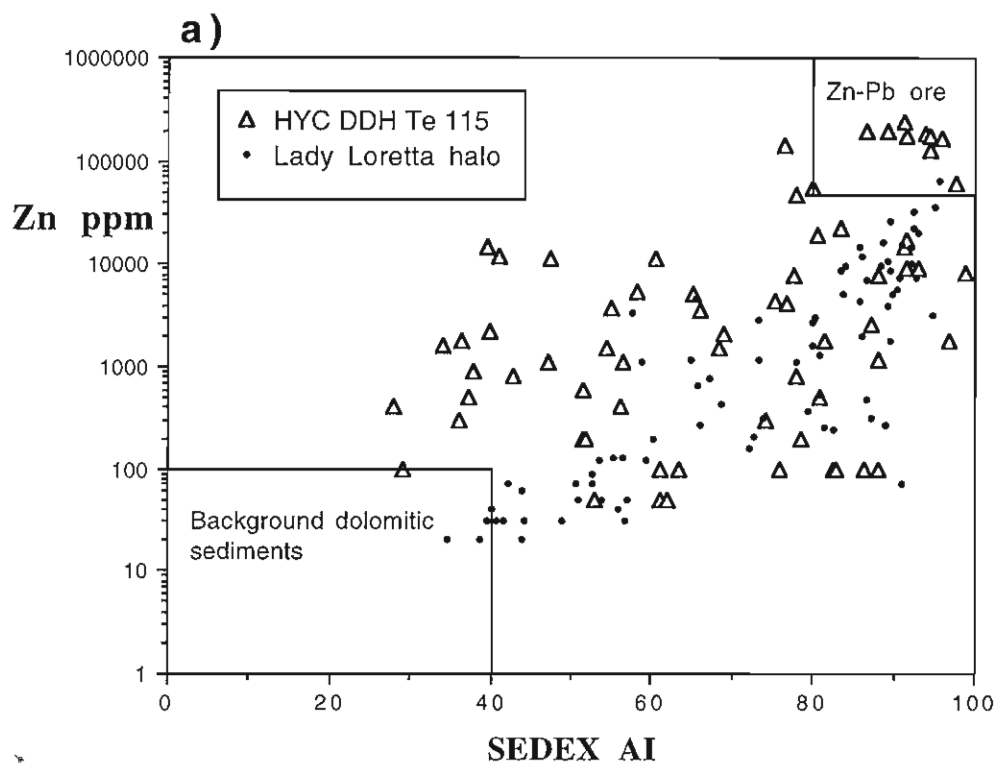


Figure 6. SEDEX AI vs Zn showing a similar pattern for HYC and Lady Loretta.

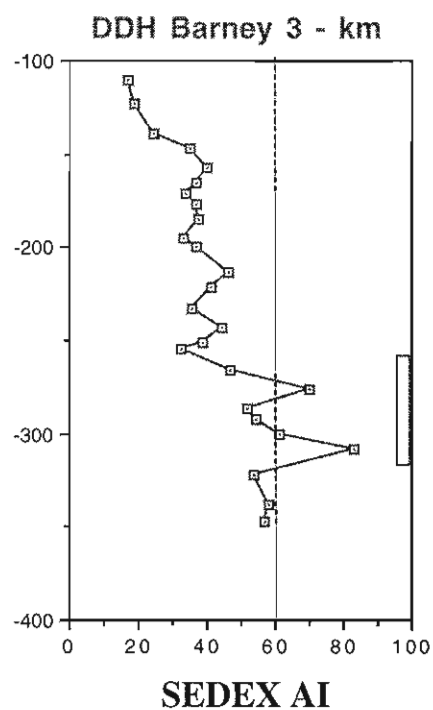


Figure 7. SEDEX AI variation downhole in DDH Barney 3, 15 km SW of HYC. Note the increase in SEDEX AI toward the ore position.

Background sediments in the McArthur Basin vary from 0 to 30 Al₃. The positive trend between zinc and Al₃ shown in Figure 8 is typical of the HYC ankerite halo and ore zone.

Manganese content of dolomite (MnO_d) :

There is a systematic increase in the Mn content of dolomite, within sediments, passing vertically up through the FW W-Fold Shale to the ore position (Fig. 4). Background dolomitic sediments have MnO_d values of less than 0.5 wt%, while maximum values in the immediate footwall to the orebody reach 12 wt%. A similar pattern of increasing MnO_d in the FW of the favourable horizon is seen in other drill holes distal from HYC (Fig. 4).

A combination plot of Al₃ and MnO_d proves to be an excellent discrimination of samples within the halo of stratiform Zn-Pb-Ag deposits (Large and McGoldrick, 1994).

As shown in Figure 9, the data plots in three priority zones related to the halo for stratiform Zn-Pb-Ag mineralisation.

Priority 1 : Inner halo of a stratiform deposit, Al₃ >50, MnO_d >1 (e.g., DDH Te 115).

Priority 2 : Intermediate halo position, Al₃ >40, MnO_d >0.5 (e.g., DDH Homestead 6).

Priority 3 : Outer halo position, Al₃ >30, MnO_d >0.2 (e.g., DDH Barney 3).

Oxygen and Carbon Isotopes of Carbonates

Our previous research on the Lady Loretta deposit in project P384 (Large et al., 1995), indicated the presence of an oxygen isotope halo coincident with the zone of siderite development surrounding the ore zone.

In this extension project (P384A) we have undertaken oxygen and carbon isotope analyses on sedimentary carbonates from a number of drill holes in the southern McArthur Basin to determine stratigraphic variation in C/O isotopes in the BCF and test for the presence of an isotopic halo surrounding the HYC deposit.

Isotope chemostratigraphy has now been completed on the following drill holes:

DDH Barney 3 :	23 samples
DDH BMR 2 :	32 samples
DDH Homestead 6 :	20 samples
Top Crossing traverses :	23 samples
DDH Myrtle 3 :	10 samples
DDH Myrtle 5 :	10 Samples

This work has outlined a major C/O isotope halo extending throughout the lower and upper BCF for a distance of at least 15 km beyond the HYC deposit (Fig. 10).

In the most remote locations (DDH BMR 2, Top Crossing) the dolomite varies from $\delta^{18}\text{O} = 20$ to 23‰ and $\delta^{13}\text{C} = 0$ to -2‰ (Fig. 11). These values are similar to normal background sedimentary carbonates in Proterozoic dolomites (Donnelly and Jackson, 1988). However, in the drill holes through the BCF closer to HYC (e.g., DDH Barney 3, and DDH Homestead 6) the dolomite exhibits heavier oxygen isotopes ($\delta^{18}\text{O} = 23$ to 26‰) and lighter carbon isotopes ($\delta^{13}\text{C} = -2$ to -3.5‰) similar to values within the HYC ore zone (Figs 11, 12). The outer edge of the oxygen isotope halo to HYC corresponds to a value of ($\delta^{18}\text{O} = 22.5$ ‰, and occurs between DDH Barney 3 and DDH BMR 2).

The oxygen isotope halo roughly coincides with the ferroan dolomite + Mn carbonate halos (compare Figs 3 and 10), however the isotope halo appears to extend further into the hangingwall BCF sediments than the Fe/Mn halos.

Large and Bull (1996) suggested that by combining data on the MnO content of dolomite (MnO_d) with oxygen isotope values of the dolomite provides a good discrimination of Mn halos related to Sedex deposits, from regional stratigraphic Mn anomalies unrelated to mineralisation (Fig. 13).

Potassium mineral distribution

Preliminary studies on the Al₂O₃/K₂O ratio of sediments in the McArthur Basin (Beeson et al., 1989; Large and Bull, 1996) have indicated a change in K-Al silicate assemblages across the Batten Trough zone. Further recent studies (Large et al., 1998) suggest the presence of an illite (or phengite) dominant zone surrounding the HYC deposit roughly corresponding to the ferroan dolomite and oxygen isotope halo. FTIR studies on the drill hole samples have shown

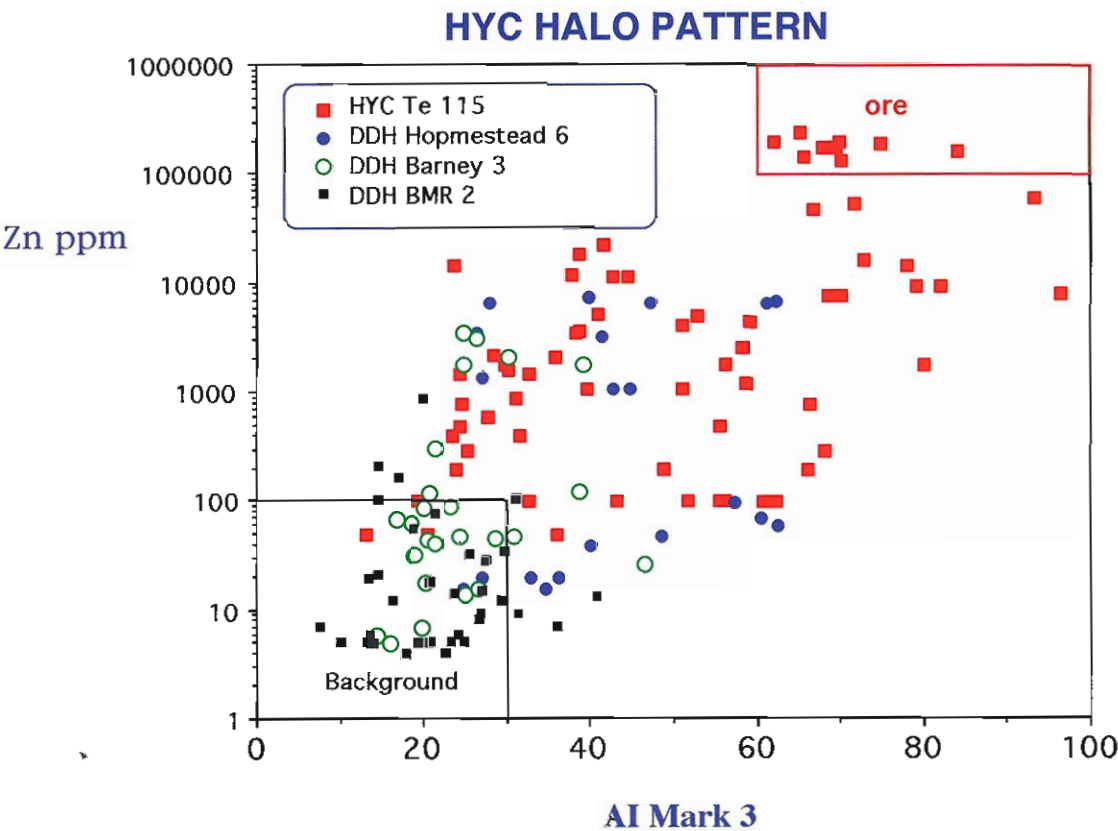


Figure 8. Correlation between AI Mark 3 and Zn for sediment hosting the HYC deposit in DDH Te 115.

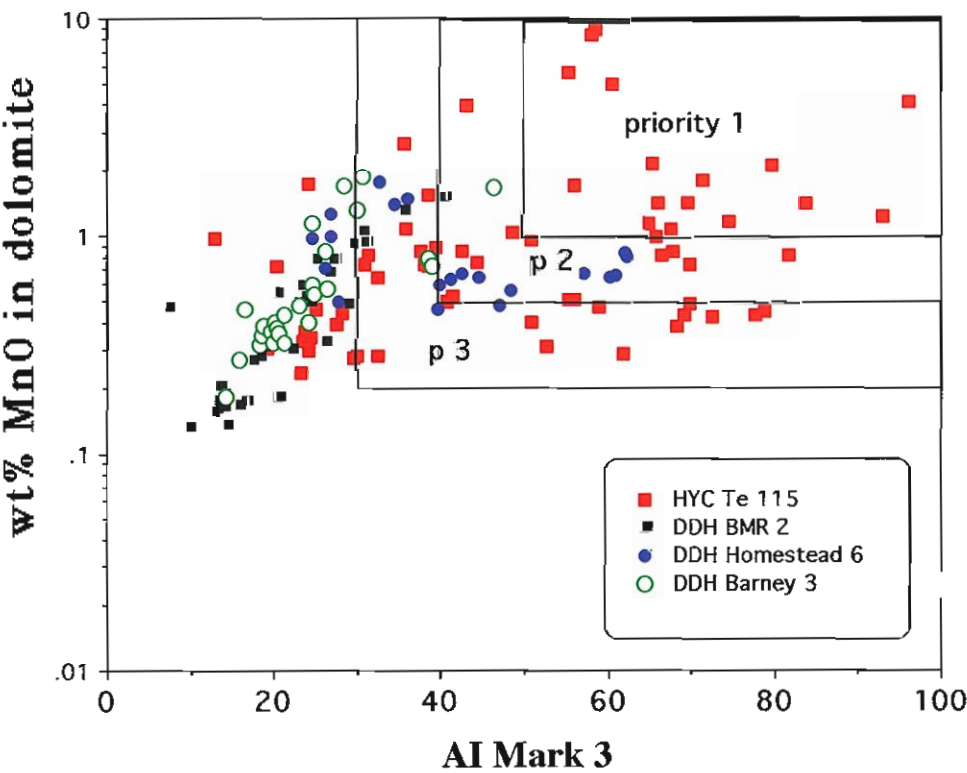


Figure 9. AI_3 vs MnO_d discrimination diagram showing the priority zones useful for mineral exploration.

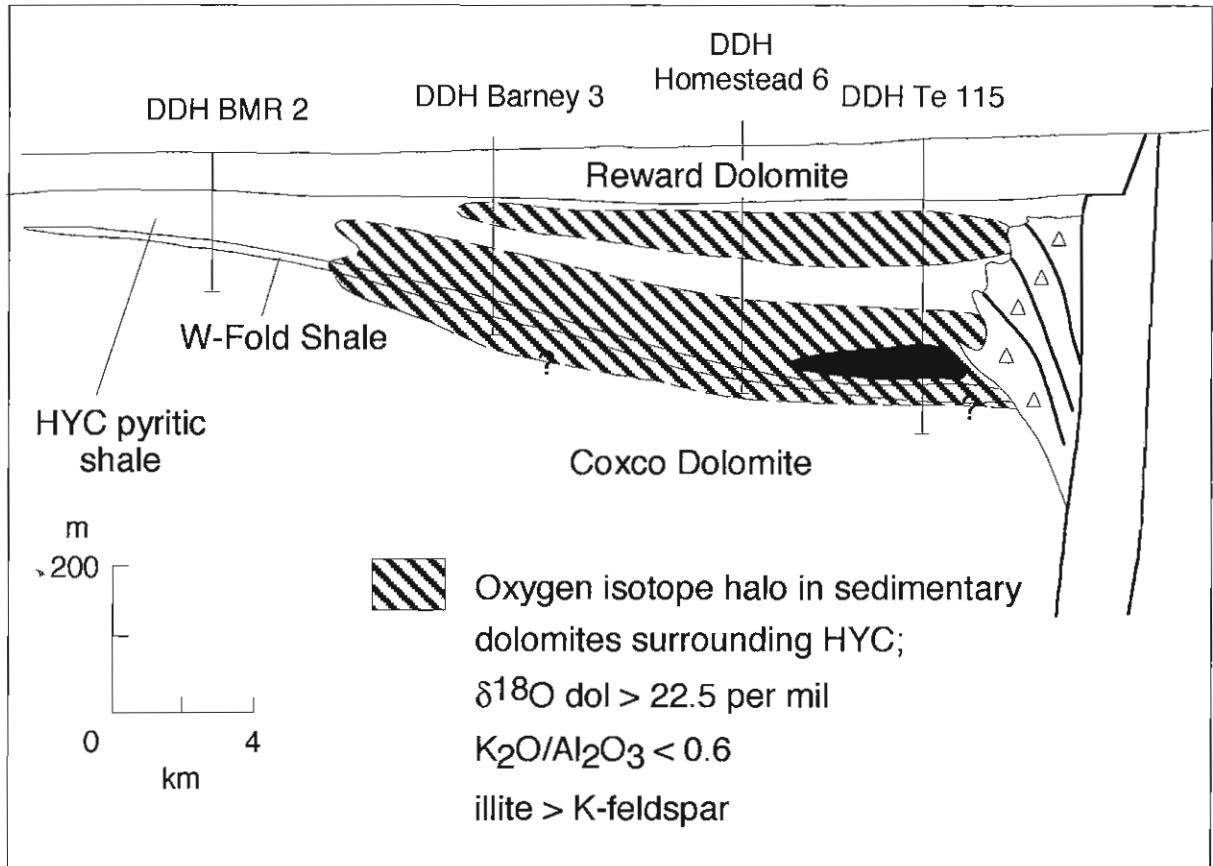


Figure 10. Oxygen isotope halo extending SW of the HYC deposit. Based on data from the ore zone, DDH Homestead 6, DDH Barney 3 and DDH BMR 2.

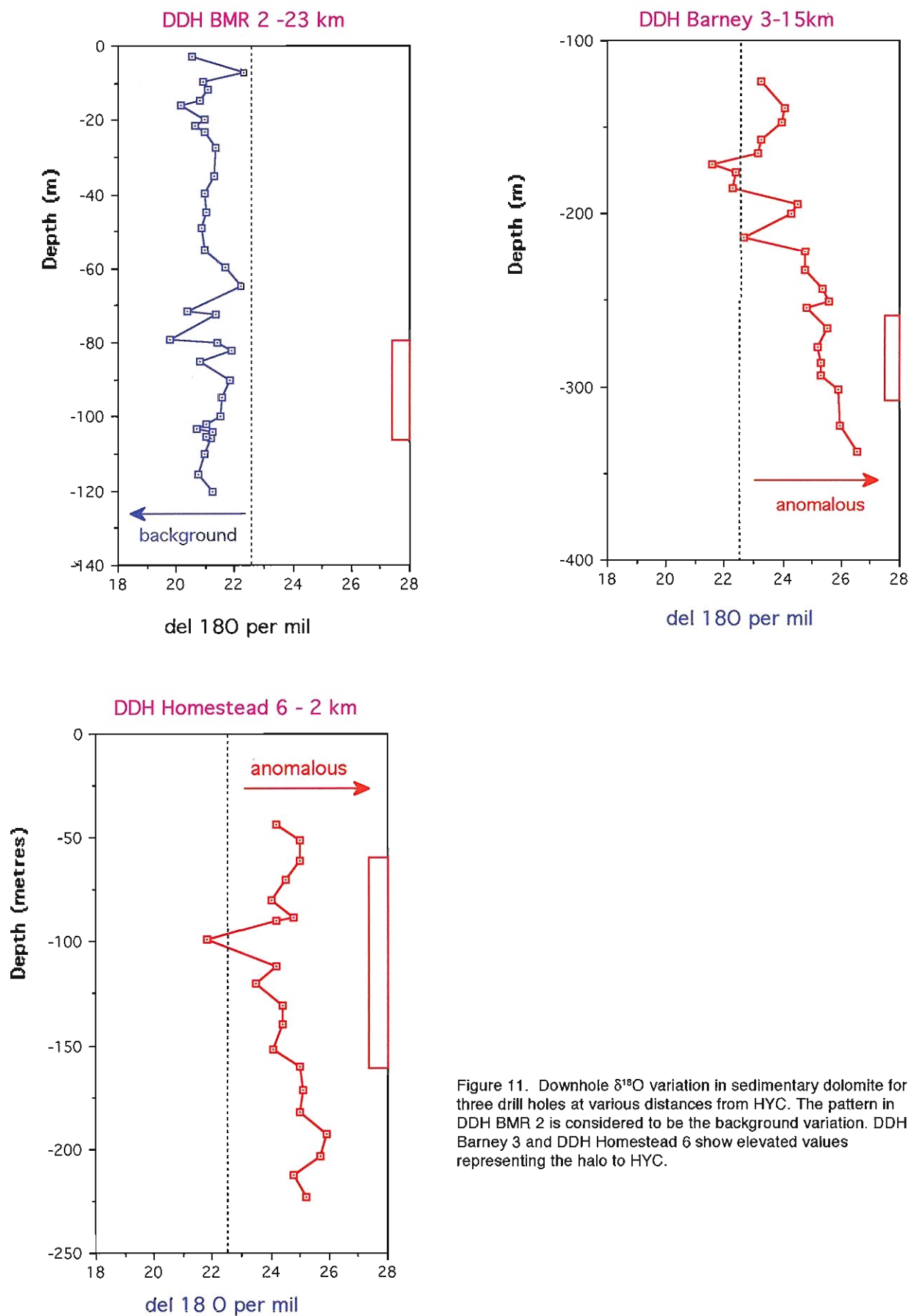


Figure 11. Downhole $\delta^{18}\text{O}$ variation in sedimentary dolomite for three drill holes at various distances from HYC. The pattern in DDH BMR 2 is considered to be the background variation. DDH Barney 3 and DDH Homestead 6 show elevated values representing the halo to HYC.

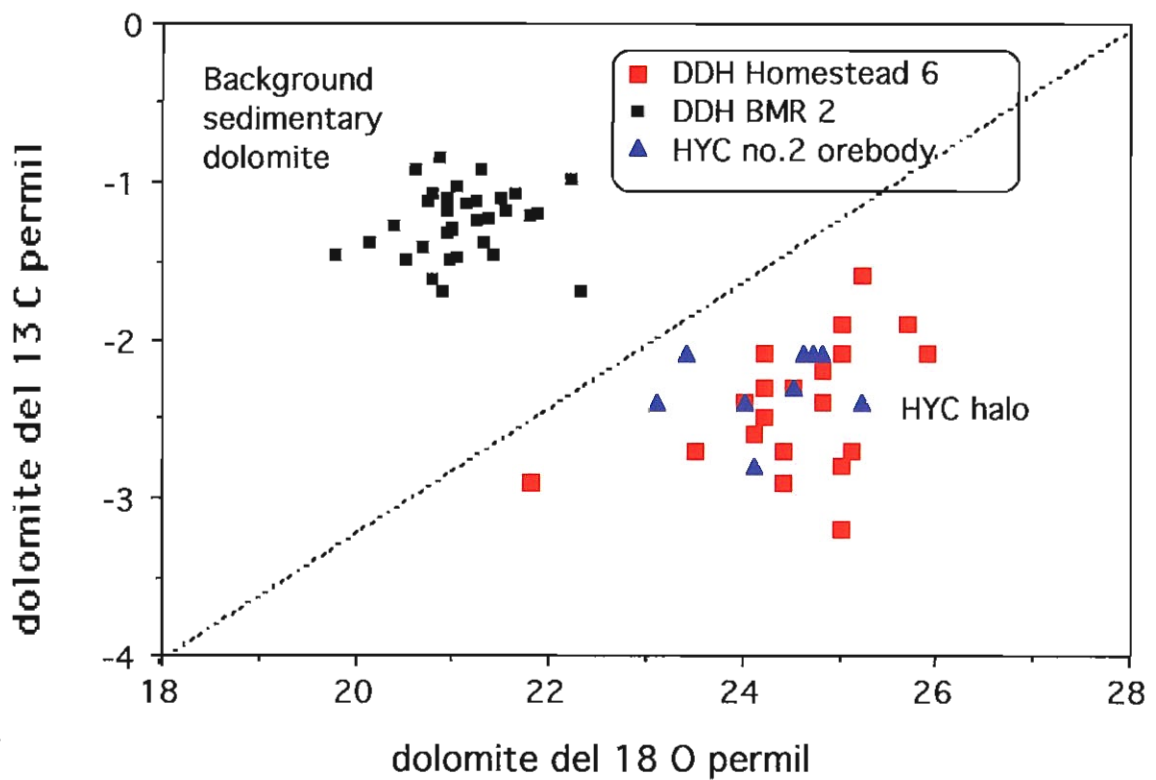


Figure 12. $\delta^{18}\text{O}$ vs $\delta^{13}\text{C}$ variation for selected sedimentary carbonates from the southern McArthur Basin, showing the two discrete fields of background dolomite (BMR 2) and halo dolomite (HYC, Homestead 6).

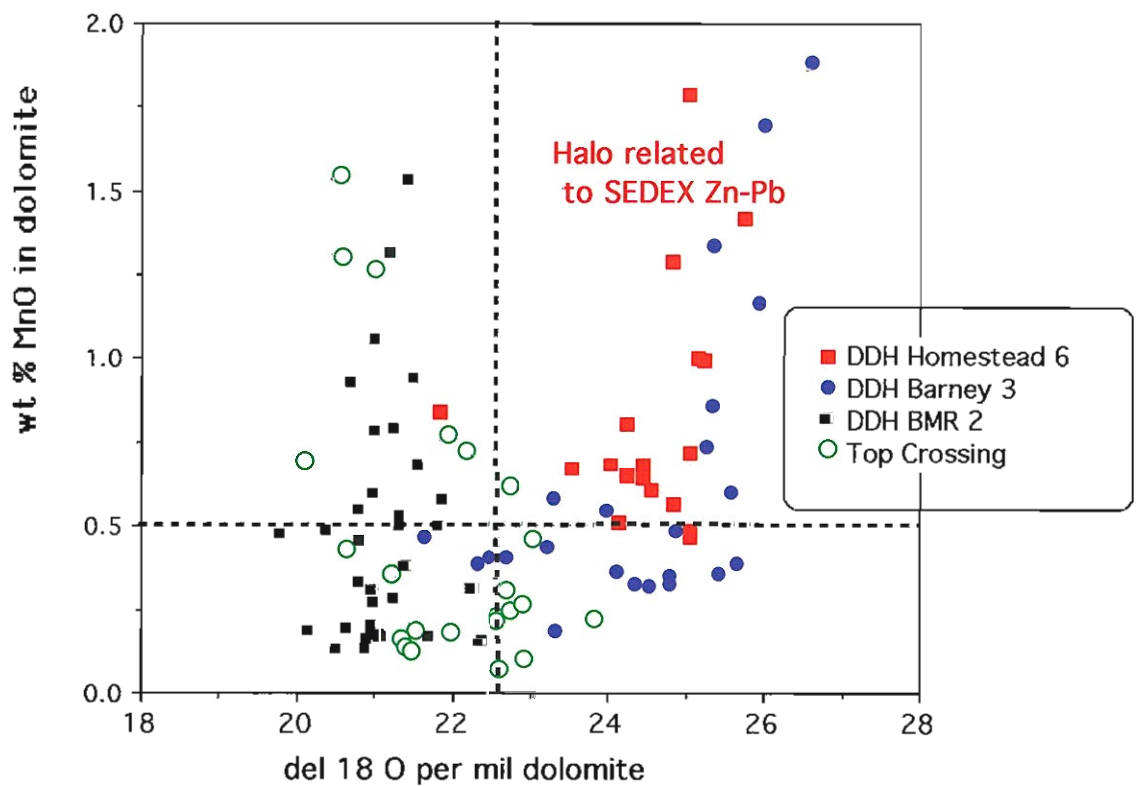


Figure 13. $\delta^{18}\text{O}$ - MnO_x discrimination diagram for samples from DDH Homestead 6, DDH BMR 2, DDH Barney 3 and Top Crossing traverse. Samples with $\text{MnO}_x > 0.5$ wt%, and $\delta^{18}\text{O} > 22.5$ ‰ fall with the HYC halo.

that the fine-grained illite within the organic-rich shales is an Fe, Mg-rich variety (phengite).

Our research indicates that within the oxygen isotope halo at HYC, phengite is the dominant K-Al mineral (i.e., phengite > K-feldspar and $K_2O/Al_2O_3 < 0.6$), while beyond the halo in DDH BMR 2 and Myrtle 3, K-feldspar is the dominant K-Al mineral (i.e., K-feldspar > phengite and $K_2O/Al_2O_3 > 0.6$).

Recharge-discharge model for the McArthur Basin

Fluid flow modelling (Garven and Bull, 1998) has demonstrated the critical role played by syn-sedimentary faults in the McArthur Basin, as either recharge (downflow) zones or discharge (upflow) zones (Large et al., 1998). Our lithogeochemical and isotopic studies have shown that discharge zones related to major SEDEX deposits such as HYC are defined by regional AI and MnO_d anomalies associated with heavy oxygen isotopes in carbonates ($\delta^{18}O > 22.5\%$) and diagenetic phengite > k-feldspar (i.e., $K_2O/Al_2O_3 < 0.6$) (Fig. 14).

Recharge zones, on the other hand, are defined by sedimentary packages with diagenetic K-feldspar > phengite (i.e., $K_2O/Al_2O_3 > 0.6$) and commonly normal sedimentary carbonate oxygen isotope values ($\delta^{18}O < 22.5\%$) (Fig. 15). Our preliminary work combining fluid flow modelling with lithogeochemistry and isotope chemostratigraphy suggests the development of a powerful tool to discriminate discharge faults from recharge faults and thus focus exploration into the priority areas for ore discovery.

Vectors to ore

This study has defined a series of lithogeochemical and isotopic exploration vectors (we call basket of indices) which enable mineral explorers to:

- Identify favourable host units for stratiform Zn-Pb-Ag within dolomite-shale sequences similar to those in the McArthur Basin.
- Place priorities on weak to moderate Zn-Pb lithogeochemical anomalies within carbonate-

bearing sediments by discriminating Sedex targets from other styles of zinc mineralisation.

- Estimate proximity to stratiform Zn-Pb mineralisation and direction to go for follow-up drilling.

The basket of indices includes the following:

1. Sedex Alteration Index:

$$\text{Sedex AI} = \frac{(10\text{MnO} + \text{FeO}) 100}{(10\text{MnO} + \text{FeO} + \text{MgO})}$$

2. Alteration Index Mark 3:

$$\text{AI3} = \frac{(10\text{MnO} + \text{FeO}) 100}{(10\text{MnO} + \text{FeO} + \text{MgO} + \text{Al}_2\text{O}_3)}$$

3. MnO content in dolomite:

$$\text{MnO}_d = \frac{\text{MnO} \times 30.4}{\text{CaO}}$$

4. Thallium: Tl ppm

5. Ankerite Ratio:

$$\frac{(\text{Fe} + \text{Mn})}{\text{Mg}} \text{ molar ratio in carbonates}$$

6. AI3 vs MnO_d plot; provides a priority rating as the percentage of samples in Priority 1, Priority 2 or Priority 3.

7. Oxygen isotopes in carbonate; ($\delta^{18}O$ carbonate).

8. Carbon isotopes in carbonates; ($\delta^{13}C$ carbonate).

9. K_2O/Al_2O_3 ratio (which determines K-feldspar, illite proportions).

10. Barium content of K-silicates; $(\text{Ba}/K_2O) \times 10^4$.

Table 1 provides the range of values for each vector at varying distances from the HYC deposit.

Table 1

Vector	Orebody	Close Proximity ~ 2 km	Distal from ore 5 - 25 km	Very remote > 25 km
1 Zn ppm	>100,000	1000-10,000	10-3000	<20
2 Pb ppm	>10,000	50-1000	20-1000	<30
3 Sedex AI	50-100	50-90	40-75	20-50
4 AI3	60-95	50-90	20-50	20-40
5 MnO _d wt%	2-12	1.0-2.0	1.0-2.0	0.5-1.5
6 Thallium ppm	200-900	20-120	4-25	1-2
7 Ankerite Ratio	0.2-10	0.2-1.0	0.1-1.0	<0.2
8 Al ₃ v MnO _D	>25% Priority 1	>40% Priority 2	4%-25% Priority 2	0%-15% Priority3
9 $\delta^{18}\text{O}\text{‰}$	23-26	22-26	20-26	20-23
10 $\delta^{13}\text{C}\text{‰}$	-2 to -3.5	-2 to -3.5	-1 to -3.5	0 to -2
11 K ₂ O/Al ₂ O ₃	0.3-0.5	0.45 - 0.55	0.4 - 0.6	0.7 - 0.9
12 (Ba/K ₂ O)*10 ⁴	~ 110	~ 60	30-90	No data

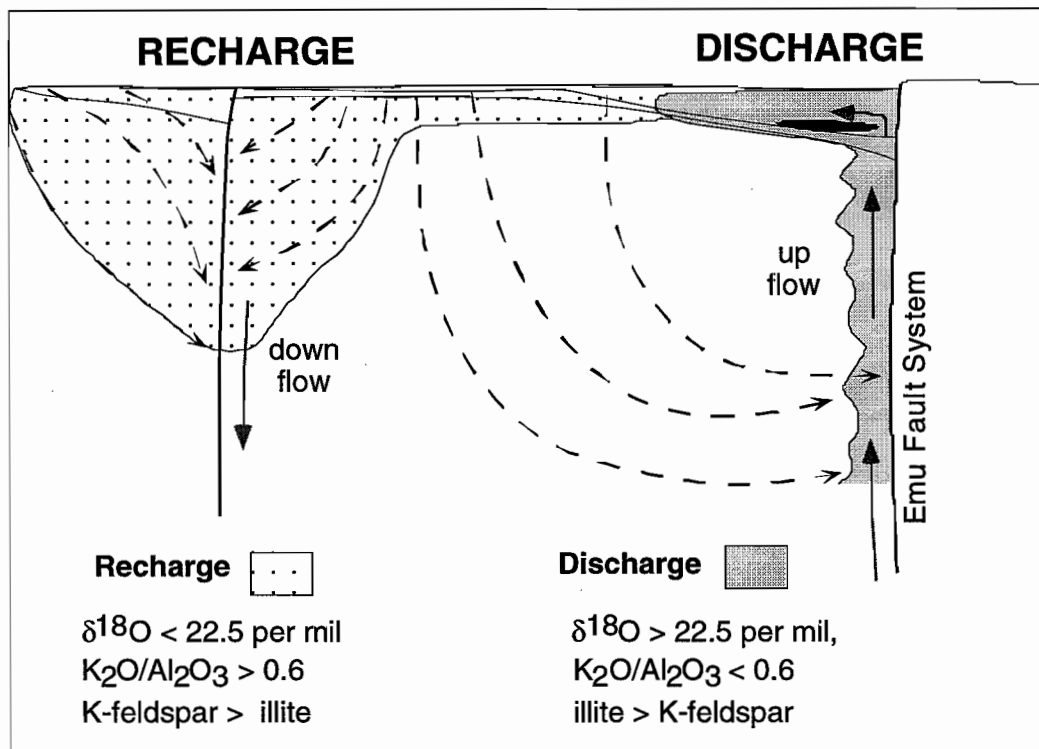


Figure 14. Recharge-discharge model for the southern McArthur Basin (Large et al., 1998).

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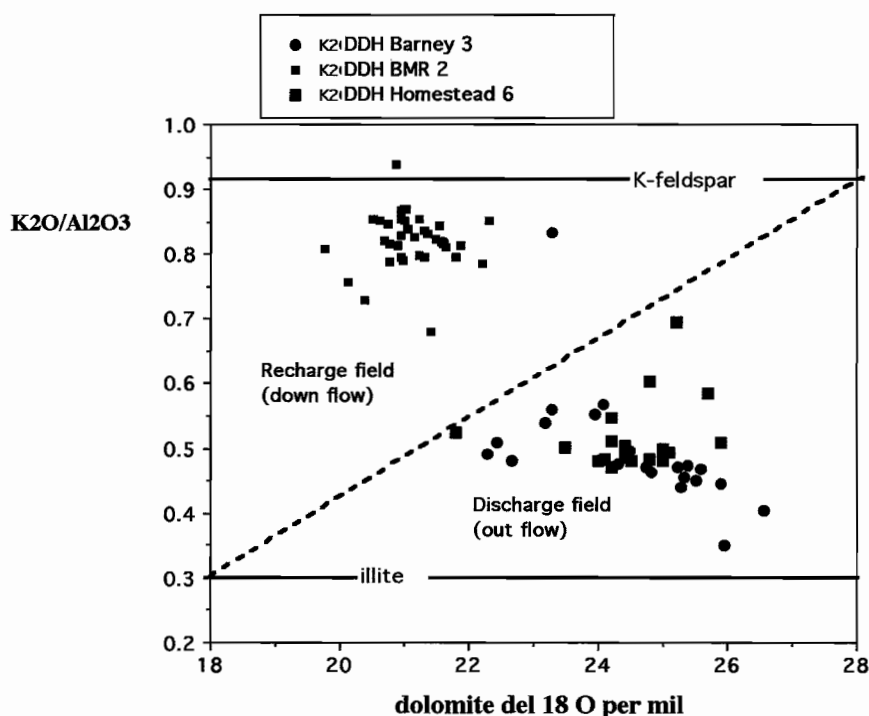
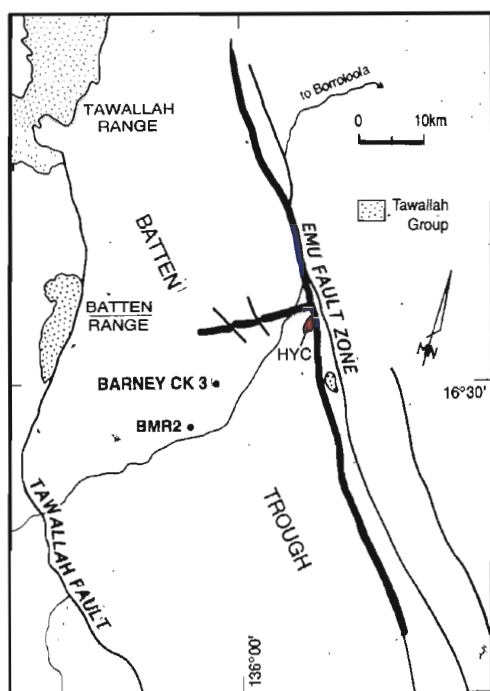
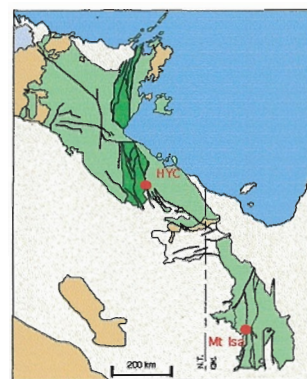


Figure 15. Recharge-discharge lithogeochemical - isotope discrimination diagram (Large et al., 1998).

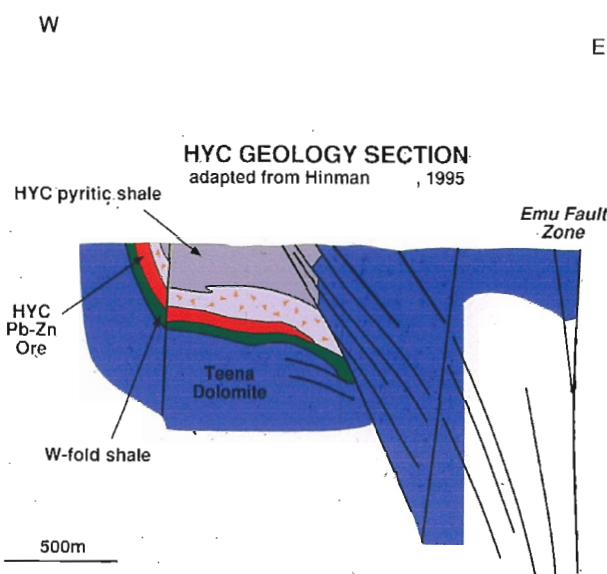
HYC Deposit Summary

Regional Setting: The HYC deposit occurs in unmetamorphosed Palaeoproterozoic sediments (upper Umbolooga Subgroup of McArthur Group) of the Batten Trough, southern McArthur Basin (Plumb et al., 1990). The deposit lies just W of the NNW trending Emu Fault Zone which form the eastern margin of the Batten Trough. Thicker McArthur group sequences are present in the Batten Trough, and cryptic E-W structures have been an important control on sediment deposition. The upper Umbolooga Subgroup is dominated by dolomitic carbonates.

Lat 16°26'S, Long 136°06'E



Location of HYC deposit



Host Rocks: The HYC deposit is hosted in a fine grained clastic carbonaceous and pyritic unit of the Umbolooga Subgroup; the Barney Creek Formation. Page and Sweet (1998) recently published a revised, robust, age of 1639 ± 2 Ma from zircons in minor tuff units in the mineralised sequence from HYC. The Barney Creek Formation reaches its maximum thickness (about 800 metres) near HYC. Previous workers (Lambert, 1976; Logan, 1979) supported both shallow and deep water settings for deposition of the Barney Creek Formation. Recent work (Bull, 1998; Bull and Scott, 1998; Winefield, et al., 1998) supports a quiet, sub-wave base origin for the siltstone host rocks, which are localised by regional faulting and sub-basin development, and grade laterally to complex slope and peri-tidal facies at the basin margins. The HYC deposit is hosted in a sub-basin adjacent to the Emu Fault. The orebody has an average thickness of about 55 metres and covers an area of 2 square kilometres. It occurs in the lower third of the highly pyritic basal 200 metres of the Barney Creek Formation (HYC Pyritic Shale Member). The mineralised interval contains seven stacked ore lenses separated by barren sediments. The lowermost (2 and 3/4) lenses are the focus of current mining operations (Logan et al., 1993). Coarse mass flow units, and finer turbidite deposits sourced from underlying carbonate units form a significant proportion of the mineralised sequence.

The mine sequence rocks are flat lying and lack penetrative deformation textures. Some (?late) brittle normal faults have disrupted ore lens continuity. Hinman (1995) recorded a variety of soft-sediment deformation features in the ores that indicate pre-consolidation tilting of the orebody.

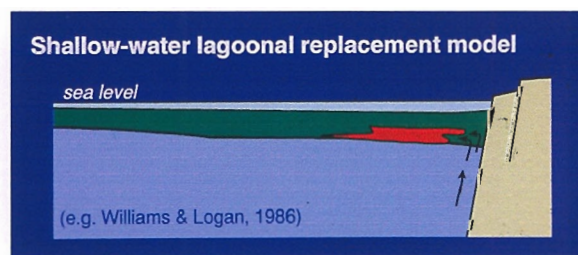
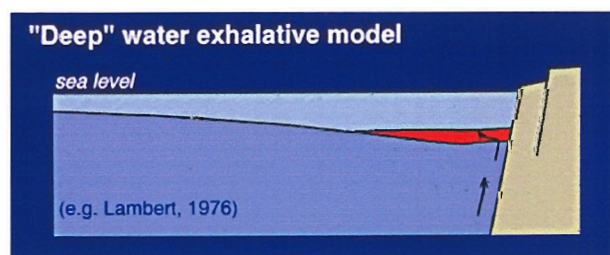
Size and Grade: The discovery history of HYC is described by Logan et al. (1990), and early mining feasibility planning was based on an open pit resource of 237 million tonnes @ 9.2 wt% Zn, 4.1 wt% Pb, and 41 g/t Ag. The current underground mining operation is based on a resource of 104 million tonnes @ 14.1% Zn, 6.4% Pb, 64 g/t Ag (Logan et al., 1993).

Mineralisation: In detail, HYC ores comprise delicately laminated, half to one millimetre, beds of very fine-grained, intergrown, sphalerite and galena ('Mode 1 sphalerite' – Large et al., 1998). These beds may be pure base metal sulfide, or may contain fine grained disseminated pyrite and coarser nodular pyrite. A second, much less common sphalerite forms coarse intergrowths with ankeritic carbonate in bands up to five millimetres thick ('Mode 2 sphalerite' – Large et al., 1998). Sulfide beds are interlaminated with clean silty turbidite beds and fine grained organic-rich beds (Large et al., 1998). Other minor sulfides include marcasite, chalcopyrite and arsenopyrite.

Two prominent types of pyrite are recognised (Williams, 1978a); Py1 which occurs as fine euhedral single grains and grain aggregates (framboids), and Py2, which is coarser and duller than Py1 and occurs as nodules and radiating overgrowths and intergrowths with Py1.

Gross metal zoning in the deposit is Cu to Pb to Zn to Fe from N to S in the lower parts of the deposit, and from E to W in the upper parts (Logan, 1979).

Genetic Models: Early genetic models for HYC invoked submarine syngenetic-exhalative processes to explain the mineralisation (e.g., Croxford (1968); Lambert (1976)). Subsequently, Williams (1978) used textural and geochemical evidence to argue for infiltration of ore fluids and precipitation of base metal sulfides within the unconsolidated Barney Creek Formation sediments after formation of diagenetic Fe sulfides (Py1 and Py2). Further refinements of this model incorporated sedimentological arguments for a shallow lacustrine setting for the Barney Creek Formation (Logan, 1979), and detailed S isotope studies (Eldridge et al., 1993). Recently, new ore textural studies and recognition that the Barney Creek Formation at HYC was deposited in the deepest part of the basin (100s metres water depth), has seen a return to a syngenetic-exhalative model for HYC (Large et al., 1998).



Schematic Models for HYC formation

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(a)

1 cm.



(b)

true scale



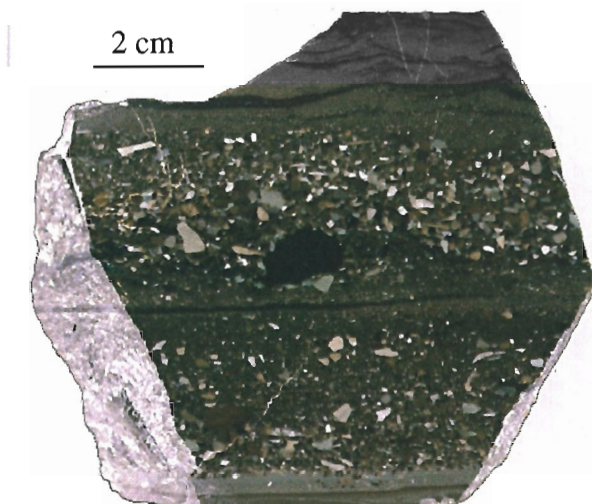
(c)

2 cm



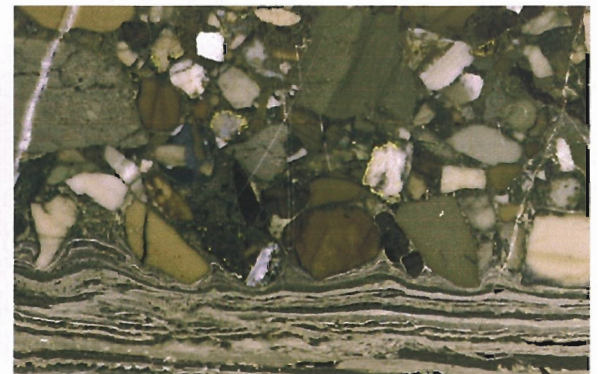
(d)

1 cm



(e)

2 cm



(f)

1 cm

(a) High grade laminated sphalerite-galena (light grey) with patches of pyrite (cream) and soft sedimentary structures.

(b) Laminated sphalerite-galena (grey), carbonaceous silt (black), and pyrite nodules (white).

(c) Laminated Zn-Pb ore with bands of nodular dolomite.

(d) Laminated sphalerite-galena (grey), graded siltstone turbidites (brown), and pyrite patches (cream).

(e) Mass flow sedimentary breccia units typical of the inter-ore breccias.

(f) The base of a graded sedimentary breccia unit sitting on laminated Zn-Pb sulphides and siltstone. Note the loading and compaction textures along the basal contact of the breccia.

Halo model for the Mount Novit Zn-Pb-Ag deposit

Peter McGoldrick

Centre for Ore Deposit Research

Summary

The Mount Novit deposit is a large, uneconomic, stratiform Zn resource in amphibolite grade Mount Isa Group sediments about 18 km S of Mount Isa (Russell, 1978). New geochemical analyses from three drill holes that straddle the mineralised interval indicate a weak response from the 'basket of indices' developed for Lady Loretta and HYC. The weak response is probably commensurate with the size and grade of the Mount Novit deposit and serves to downgrade the likely existence of undiscovered high grade parts to the system. However, the results indicate primary geochemical dispersions are not disturbed by metamorphism. Furthermore, because Mount Novit has the same types of primary element dispersion as the other northern Australian stratiform deposits then it probably shares a similar origin, and is not a metamorphogenic deposit. The results summarised here have been discussed in detail in AMIRA P384A Report 2, pp. 135–156, October 1996.

Introduction

Samples from a laterally extensive, weakly mineralised, stratiform pyrite sequence from amphibolite grade rocks at Mount Novit to the south of Mount Isa (Fig. 1) provide an opportunity to test some of the indices developed as lithogeochemical vectors to the large stratiform sediment-hosted Zn deposits of northern Australia. This investigation had two principal aims. The first was to determine the effect of deformation metamorphism on the indices known from deposits in low metamorphic

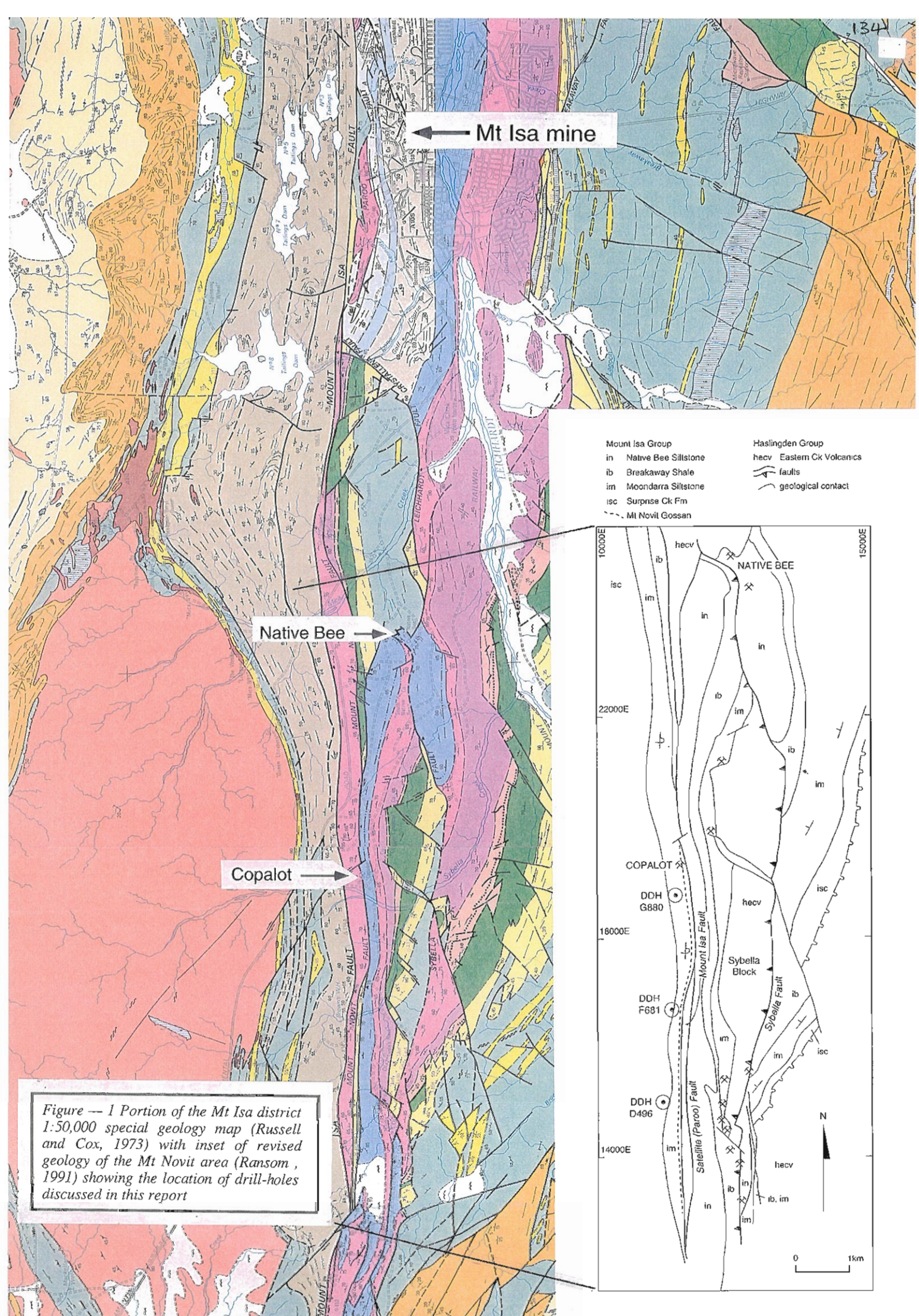
grade rocks. The second was to test the indices in the vicinity of a large, but low grade, Zn resource.

Deposit characteristics

The important features of the Mount Novit deposit are summarised on Mt Novit deposit data sheet and accompanying plate.

Host rocks

The Mount Novit host succession comprises metamorphosed dolomitic (sometimes carbonaceous) siltstones and mudstones. These rocks have been correlated with the upper part of the Moondarra Siltstone (MIM Ltd unpublished data). The sequence occupies the steeply west dipping overturned limb of a faulted synform, and is fault bounded on all sides. It has been metamorphosed to upper greenschist and lower amphibolite grades. A variety of textures, reflecting a complex history of ductile and brittle behaviour during deformation and metamorphism (Ransom, 1991), are present in the host sedimentary rocks. Depositional sedimentary layering is well preserved in some intersections, while phyllitic and schistose rock types are present in others. Post-cleavage brecciation and flooding by calcite is also common, producing what are locally termed 'birdswing' textures. Metamorphic minerals include chlorite, biotite, tremolite, phlogopite and calcite, and possibly other carbonates (Ransom, 1991).



Sampling strategy

Samples straddling the Mount Novit mineralisation were obtained from three drill holes each about two kilometres apart. Grab samples were collected every 10 to 15 m in the hangingwall and footwall of the sulfide lens. Ten samples of low metamorphic grade Moondarra Siltstone from a drill hole to the north of Mount Isa were also analysed.

In all, 71 samples were analysed for major and selected trace elements by XRF at the University of Tasmania.

Lithogeochemistry

Host rock carbonates

Unlike low metamorphic grade sedimentary rocks, it is not possible to estimate the Fe carbonate content of amphibolite grade metasediments because several Fe-bearing mineral phases may be present. However, plots of CaO against MgO (Fig. 2) indicate that dolomite is the important carbonate phase in many of the Mount Novit samples. Samples lying off the 'dolomite trend' may contain other carbonates (?calcite, ?siderite), but were excluded from the MnO_d calculations (see below).

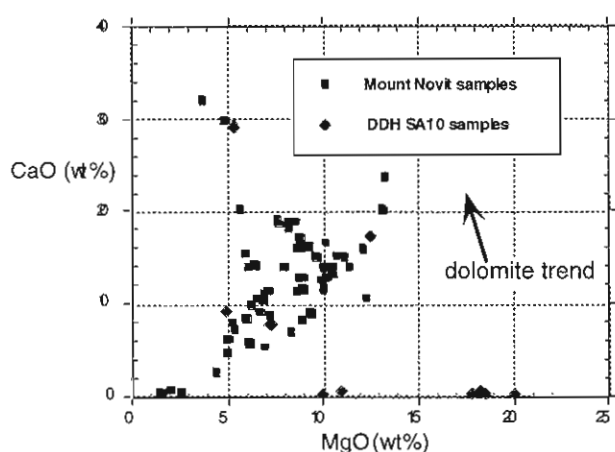


Figure 2. CaO/MgO relationships for 71 samples from drill holes through the Moondarra Siltstone at Mount Novit, and north of Mount Isa.

Zinc dispersion

All but four of the Mount Novit samples contain less than two percent sulfur, and as is observed at Mount Isa the Zn distribution is spiky and erratic. Zinc ranges from less than 10 ppm more than 1000 ppm, with the northernmost hole having weakly anomalous Zn (up to several hundred ppm) at least 200 m into the hanging wall of the sulfide zone (Fig. 3).

Alteration indices

Figure 4 displays Zn, SedexAI, AI3 and MnO_d interrelationships for the Mt Novit and SA10 samples. None of the SA10 samples have anomalous Zn or AI3 values, and only three SA10 samples have enough dolomite for meaningful MnO_d calculations, and none are anomalous. About a dozen of the Mt Novit samples have anomalous AI3, but generally low Zn causes the Zn/AI plots to be discouraging. The AI/MnO_d relationship is more encouraging, with one sample from F681 plotting in the 'Prospectivity 2' box of the AI3/MnO_d plot, and 10 samples lying in the 'Prospectivity 3' box (Large and McGoldrick, 1998). Downhole plots of AI3 (Fig. 5a) indicate that the anomalous samples are present for some distance in the footwall of the sulfide zone, but not more than a few metres into the hangingwall. MnO_d has a similar pattern to AI (Fig. 5b)

Thallium

The Tl response at Mount Novit displays a similar pattern to AI and MnO_d, with a few anomalous samples, mostly concentrated close to the mineralised interval (Fig. 5c). Although enriched over the 1–2 ppm background values in the unmineralised Moondarra Siltstone samples, the absolute levels of Tl are much lower (5–15 ppm) than those observed in unmineralised mine sequence rocks from the Mount Isa Zn-Pb-Ag deposits (McGoldrick, 1994, 1998a), which contain 15 to 50 ppm Tl.

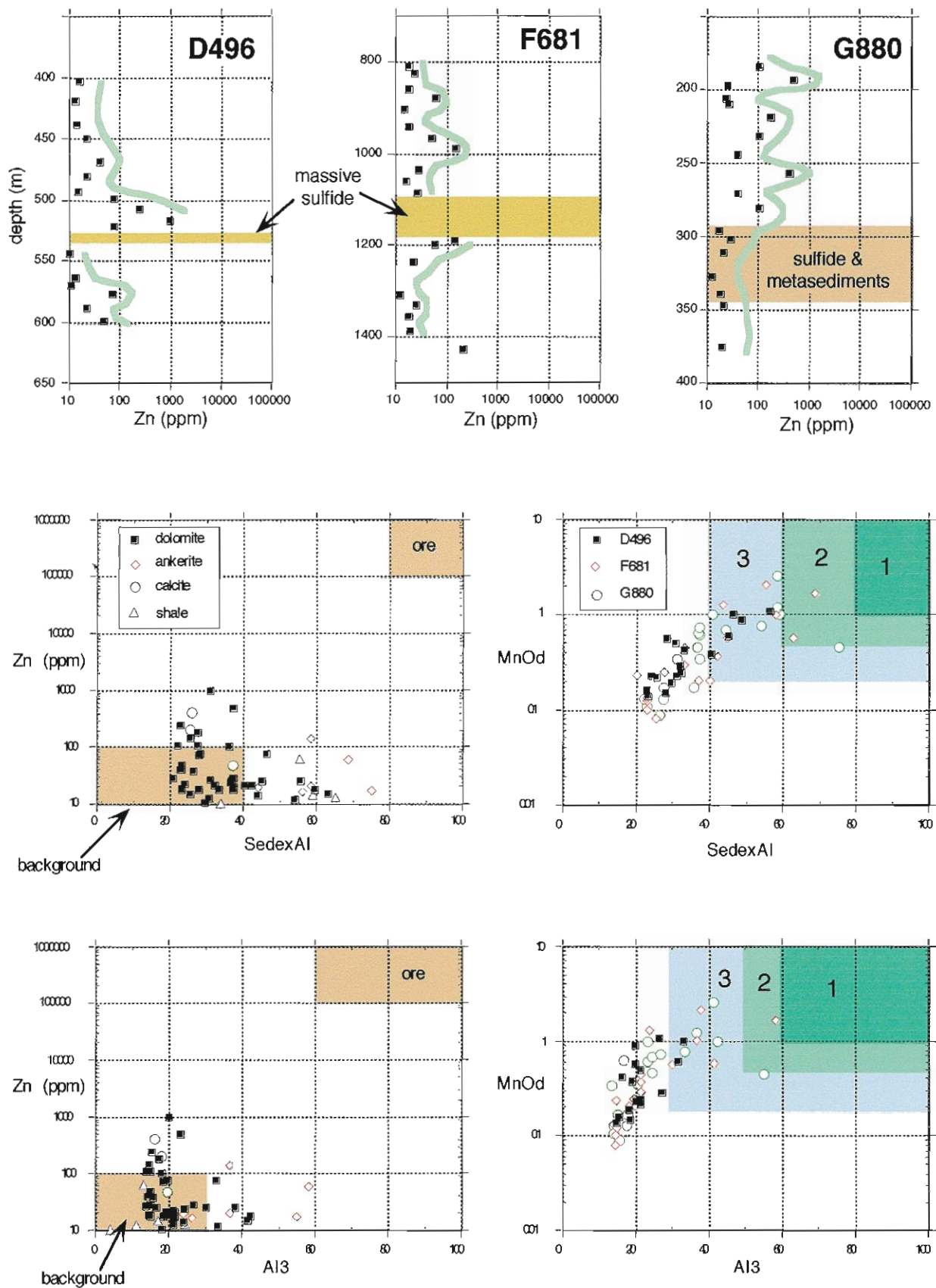


Figure 3. Zinc distribution in DDH D496, F681 and G880; see Fig. 1 for location of the drill hole collars.

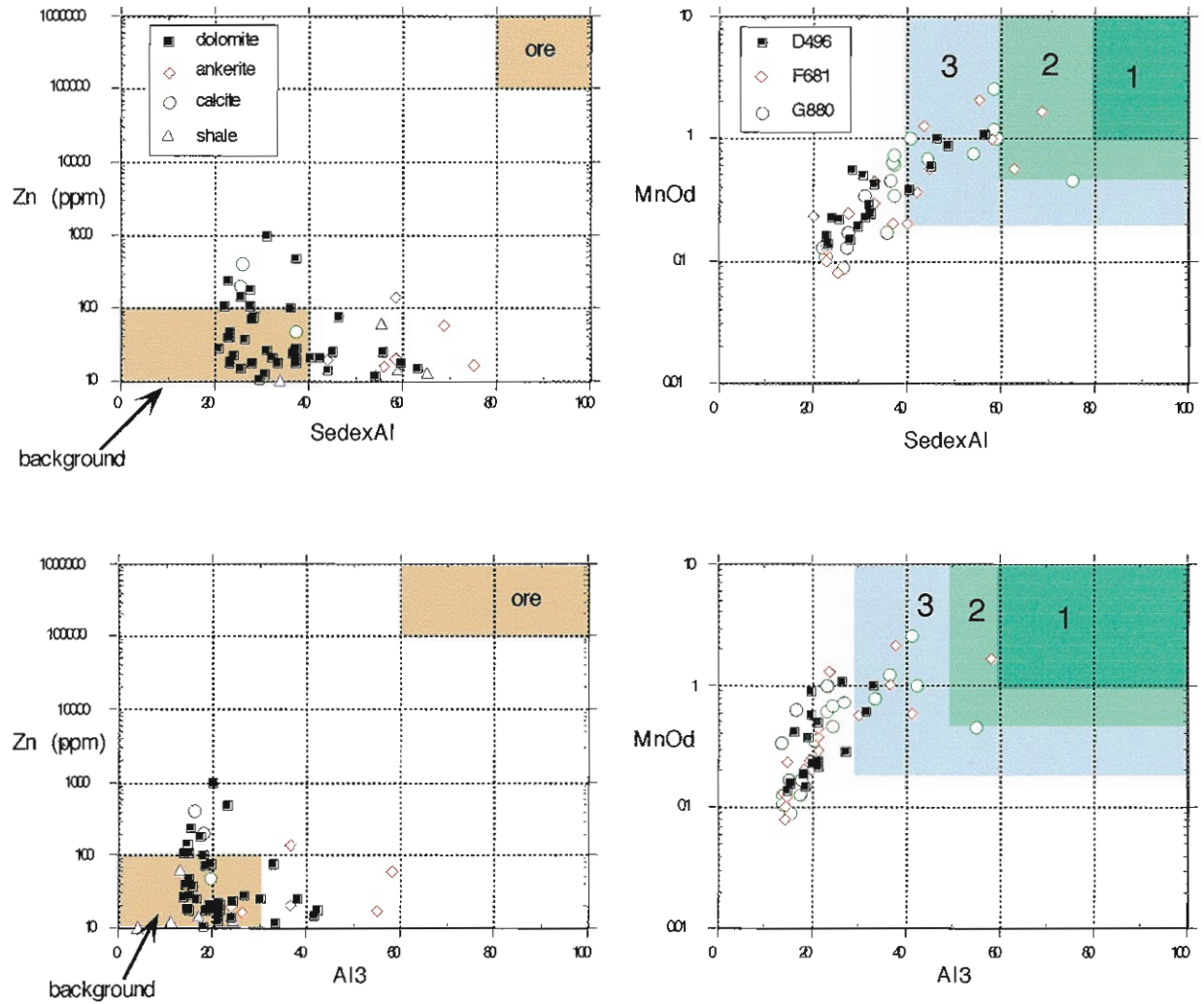


Figure 4. Zn/SedexAl/Al₃ and MnO₃/SedexAl/Al₃ cross-plots for samples from Mount Novit; low carbonate samples have been excluded from the MnO₃ plots.

Vectors to ore

New lithogeochemical data from this study has shown that the host rocks to the Mount Novit low grade Zn deposit have a weak response in terms of SedexAl, Al₃, MnO₄ and Tl. The data indicate that the parameters useful for vectoring deposits hosted in low metamorphic grade sedimentary can be used in higher grade rocks.

The response at Mount Novit is probably a little stronger than that for the (subeconomic) base metal mineralised pyrite lenses at Walford Creek (McGoldrick, 1998b).

Although the possibility exists that amphibolite grade metamorphism has dampened a strong lithogeochemical response from an (as yet) undiscovered large Zn resource at Mount Novit, it is more likely that weak *primary* dispersions have persisted during metamorphism and deformation, and that no large Zn deposit exists in the area.

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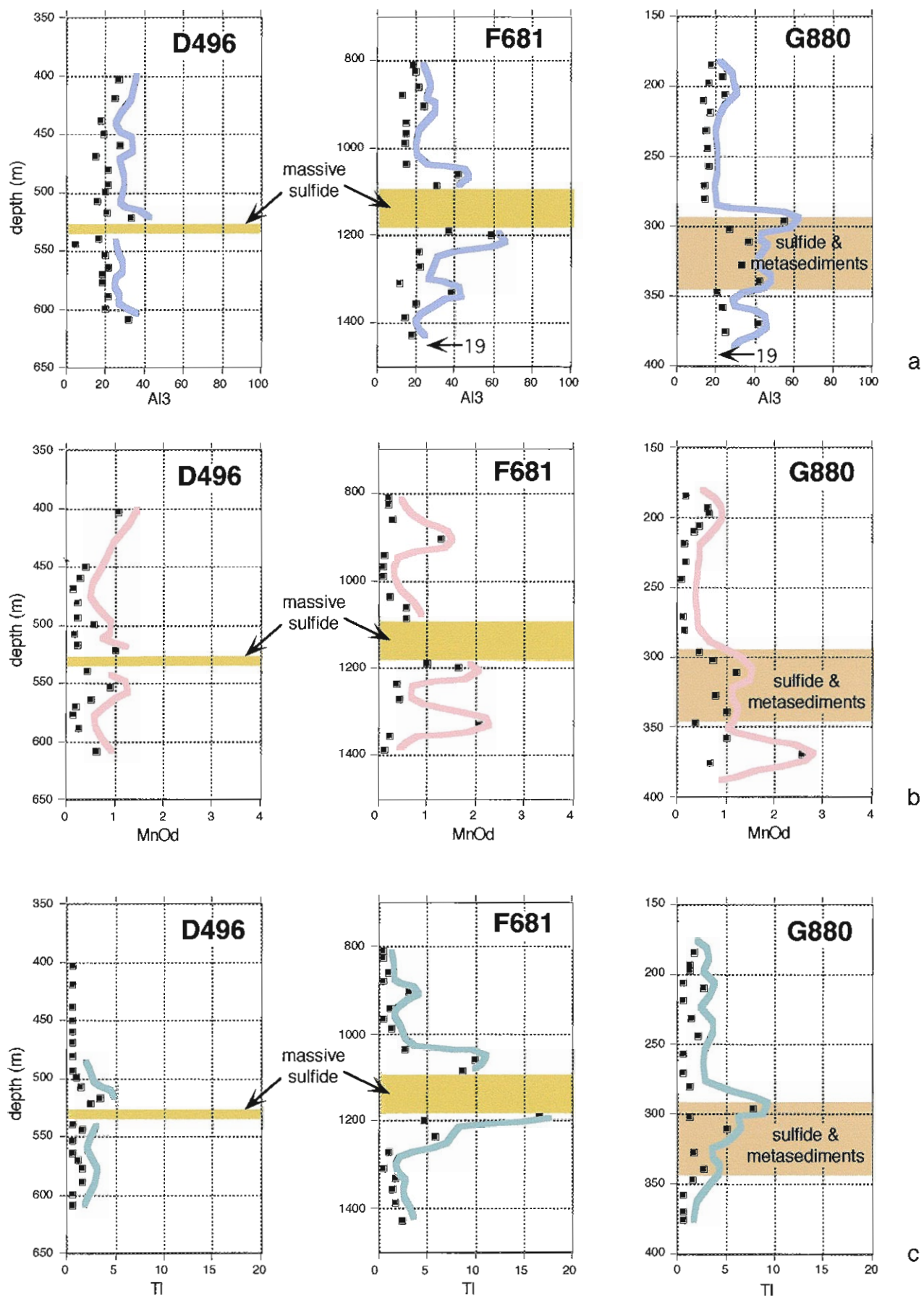
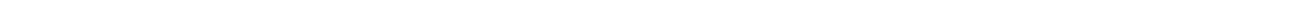


Figure 5. (a) Al₃ distribution in DDH D496, F681 and G880; (b) MnO₂ distribution in DDH D496, F681 and G880; (c) TI distribution in DDH D496, F681 and G880

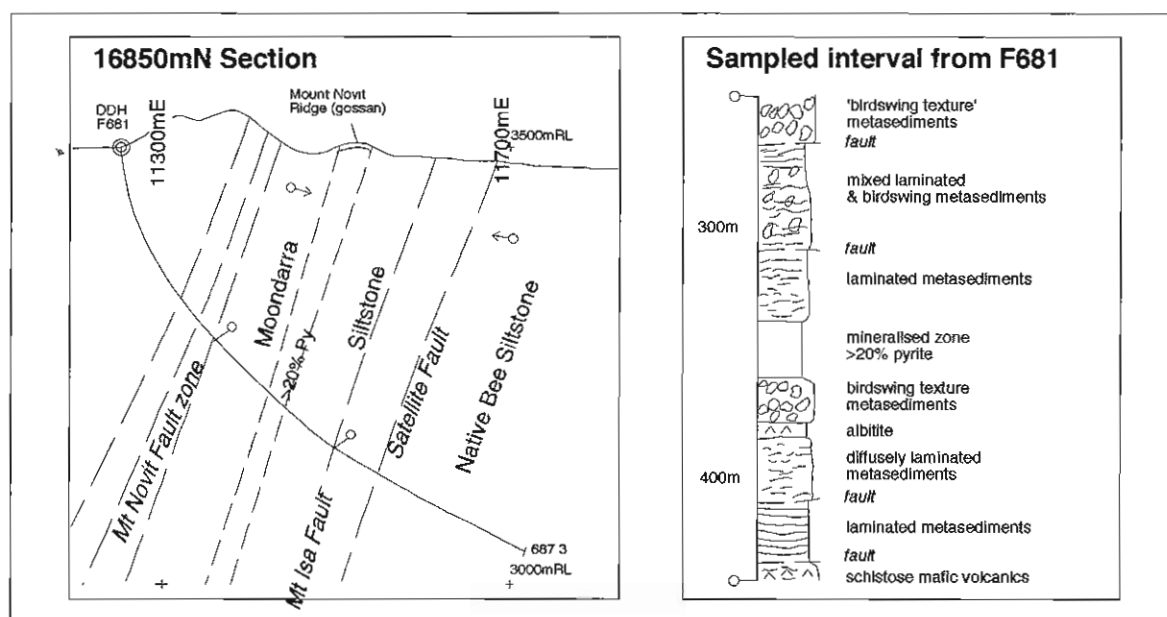
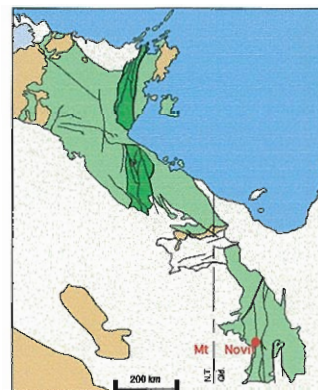


Mount Novit Deposit Summary

Regional Setting: The deposit occurs in late Palaeoproterozoic sediments of the 'Leichardt River Fault Trough' (Blake, 1987), part of the Western Succession of the Mount Isa Inlier. To the north, in the Lawn Hill Platform' and the southern McArthur Basin, broadly similar age rocks also contain stratiform sediment-hosted Zn-Pb-Ag deposits (the Carpentaria Zinc Belt – Sweet et al., 1993; McGoldrick and Large, 1998).

Host Rocks: The immediate host rocks are a fault-bounded, steep W dipping, overturned slice of transitional upper greenschist to lower amphibolite metasediments close to the Mount Isa Fault. Lithologies include pyritic and carbonaceous (dolomitic) shales and siltstone. Primary sedimentary textures are variably preserved with schistose, brecciated and recrystallised rock types commonplace. Metamorphic minerals include chlorite, biotite, tremolite, phlogopite and calcite (Ransom, 1991). The host rocks are correlated with the Moondarra Siltstone of the lower Mount Isa Group (MIM Ltd unpublished data).

Lat 20°54'S, Long 139°28'E



Size and Grade: There is no published resource for the Mount Novit mineralisation, but the mineralised pyrite lens and/or pyritic stratigraphy, and/or gossanous outcrop up to 20 m thick is recognisable along about 5 km of strike extent. Several drill intersections of better than 10 wt% combined Zn and Pb are known from this interval.

Mineralisation: Stratiform and/or stratabound coarse (massive) pyrite with variable amounts of sphalerite, galena, pyrrhotite and porphyroblastic magnetite. Coarse siderite is present in some parts of the massive pyrite. Examples of Mount Novit mineralisation and massive pyrite are illustrated in Plate 4.

Genetic Models: There is no published genetic model for the Mount Novit mineralisation, but similar models to those proposed for Mount Isa should be considered. If the deposit is syndiagenetic, it represents the earliest manifestation of sedimentary Zn mineralising processes in the Mount Isa Western Succession.

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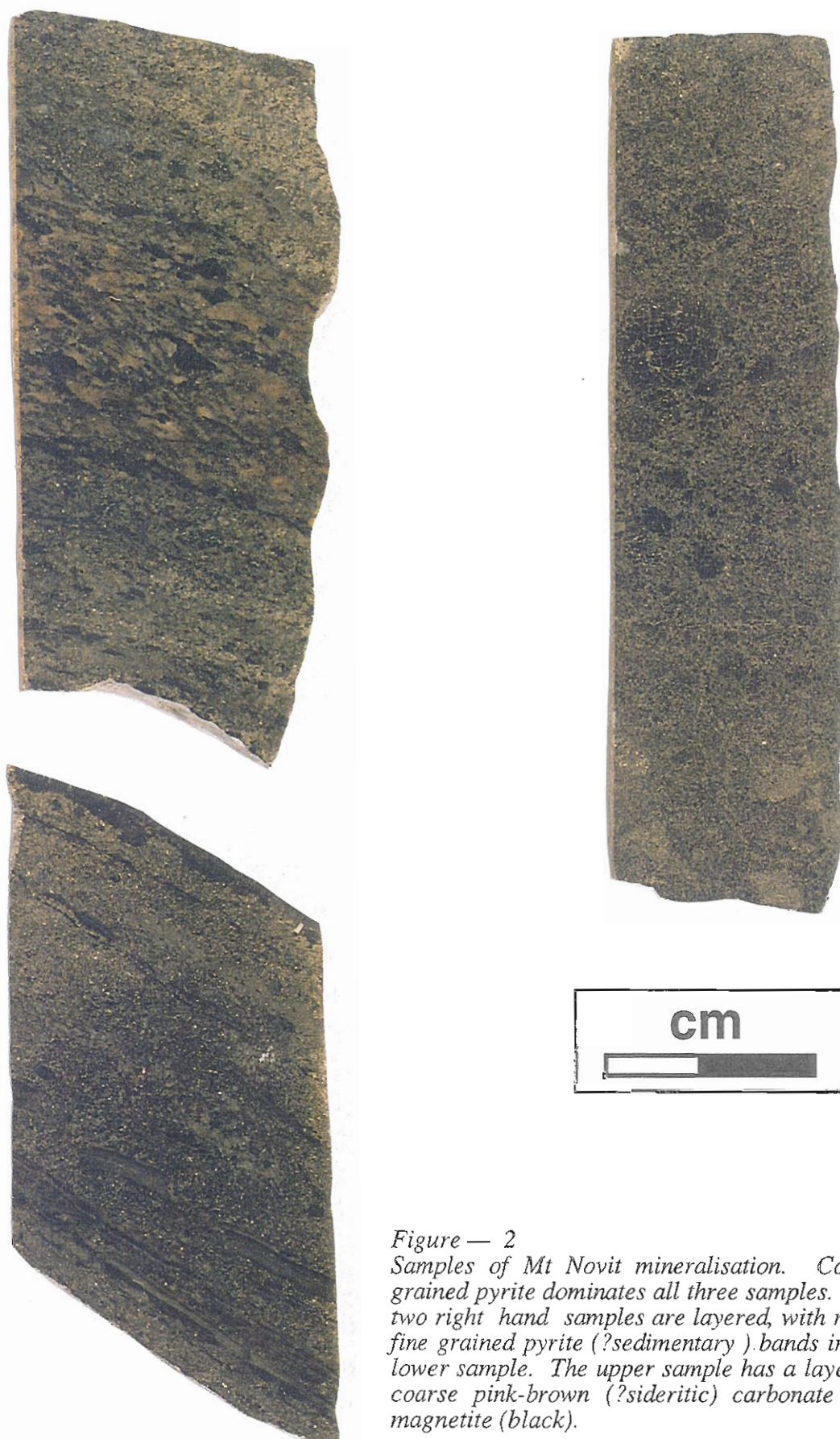


Figure — 2
Samples of Mt Novit mineralisation. Coarse grained pyrite dominates all three samples. The two right hand samples are layered, with relict fine grained pyrite (?sedimentary) bands in the lower sample. The upper sample has a layer of coarse pink-brown (?sideritic) carbonate and magnetite (black).

Halo model for Century Zn-Pb-Ag deposit, Queensland

Ross R. Large

Centre for Ore Deposit Research

Introduction

No sampling has been carried out by the CODES P384A project team on the Century Deposit, however a set of lithogeochemical data from a series of six drill holes was made available from the AGSO Rockchem database. This data set allowed us to test the presence of a lithogeochemical halo and make comparisons to our other halo studies at Lady Loretta and HYC (Large, 1998).

This lithogeochemical study of Century host rocks was particularly critical to our P384A halo research, as it was the first time we were able to test the alteration indices and exploration vectors on a set of siliclastic host rocks to a major stratiform Zn-Pb-Ag deposit. Our previous research had concentrated on carbonate-rich host successions.

Host rocks

The Century ore lenses occur with unit Pmh4 of the Lawn Hill Formation, which comprises carbonate-poor shales, siltstones and sandstones interpreted to be deposited in a shelf environment above storm wave base (Broadbent et al., in press; Andrews, in press).

Previous research on the Century halo

Broadbent et al. (in press) states "there is a broad envelope of weak siderite development surrounding the deposit, extending for up to 100 m vertically above the mineralisation and 20 to 30 m below it." (Fig. 2). Broadbent et al. (in press) also provide

microprobe analyses on the siderite, which indicates an increase in Mn content from values of around 0.6 to 1.5 wt% MnO in the lower Footwall to 1.3 to 5.9 wt% in the upper Footwall to 7 to 14 wt% MnO in the ore zones (Large, 1998; Table 2).

Ore deposit characteristics

The important features of the Century deposit are summarised on the Century deposit data sheet.

Sampling strategy

The AGSO data set from around Century comprises 165 sediment samples collected from six drill holes, the locations of which are shown in Figure 1. The samples were collected by CRA geologists to provide a representative set of lithogeochemical data for the major units of the Lawn Hill Formation: Pmh1, Pmh2/3, Pmh 4 and Pmh6. The samples were analysed at the AGSO laboratories for a range of major and trace elements. However neither CO₂ nor Tl were analysed; two critical elements for SEDEX lithogeochemical studies.

Halo model

Utilising the whole rock geochemistry it was possible to divide the data set into dolomitic sediments, sideritic sediments and shales (Large, 1998). The graphic representation of the division of the data set is shown in Figure 3. Sideritic-bearing sediments comprise 42% of the data set, and are not just

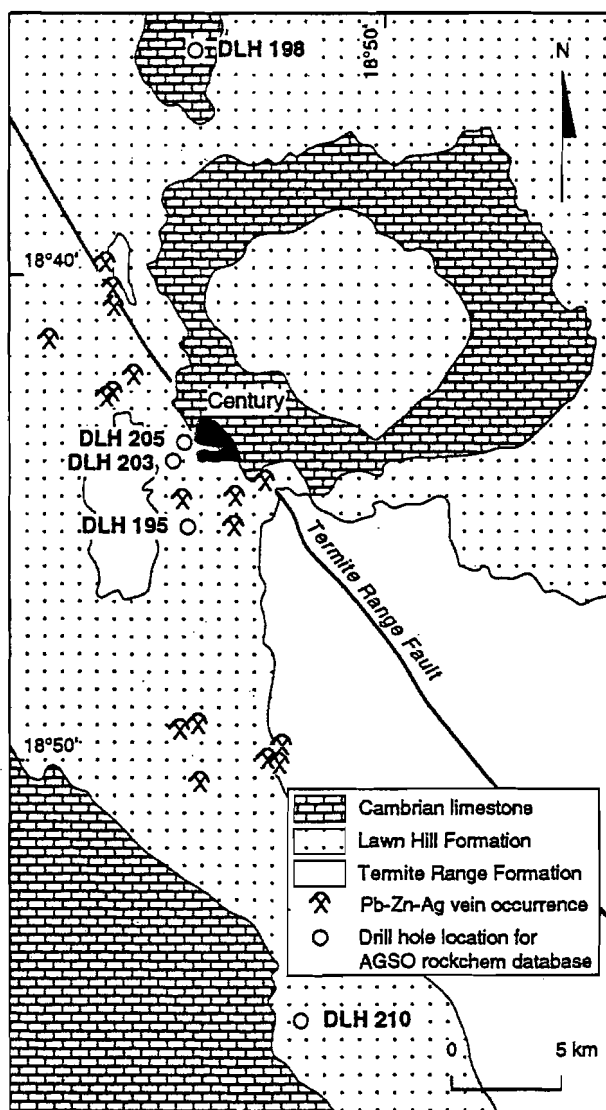


Figure 1. Location of drill holes in Century area sampled for the Rockchem database.

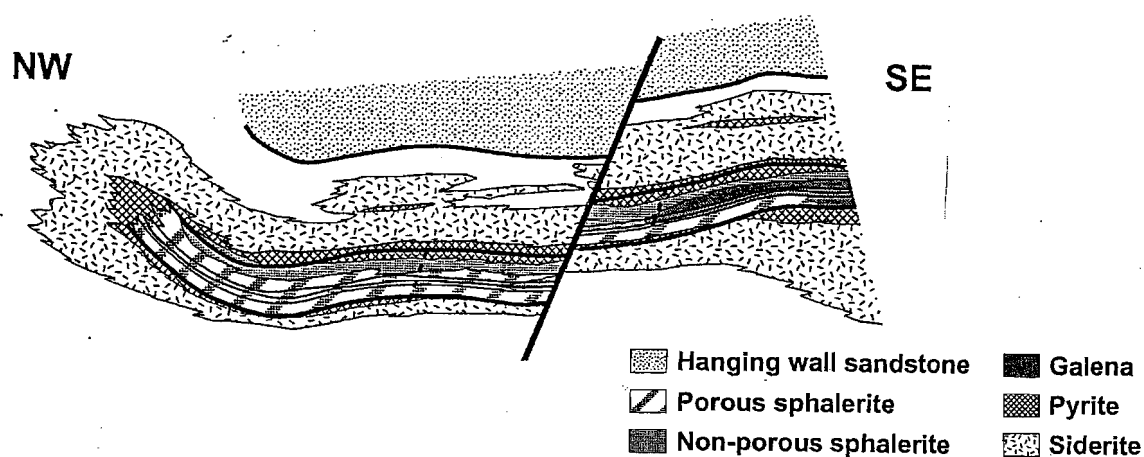


Figure 2. Siderite halo at Century defined by Broadbent et al., (in press).

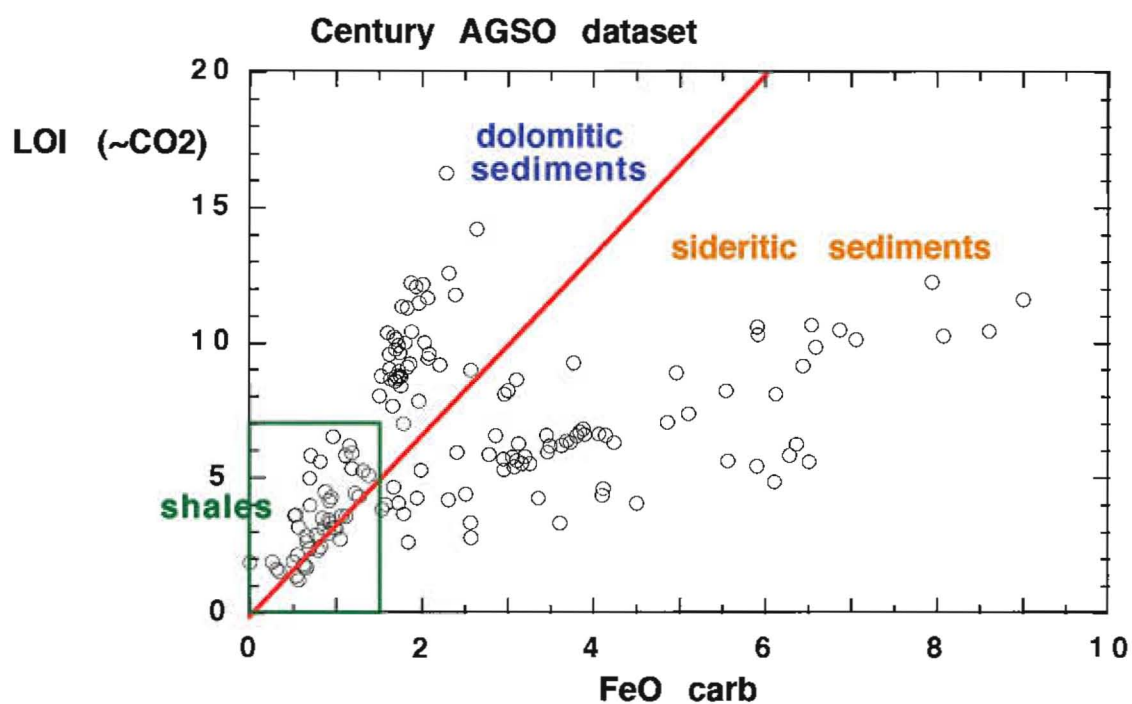


Figure 3. Graphical division of the AGSO Rockchem data set into sideritic sediments, dolomitic sediments and shales.

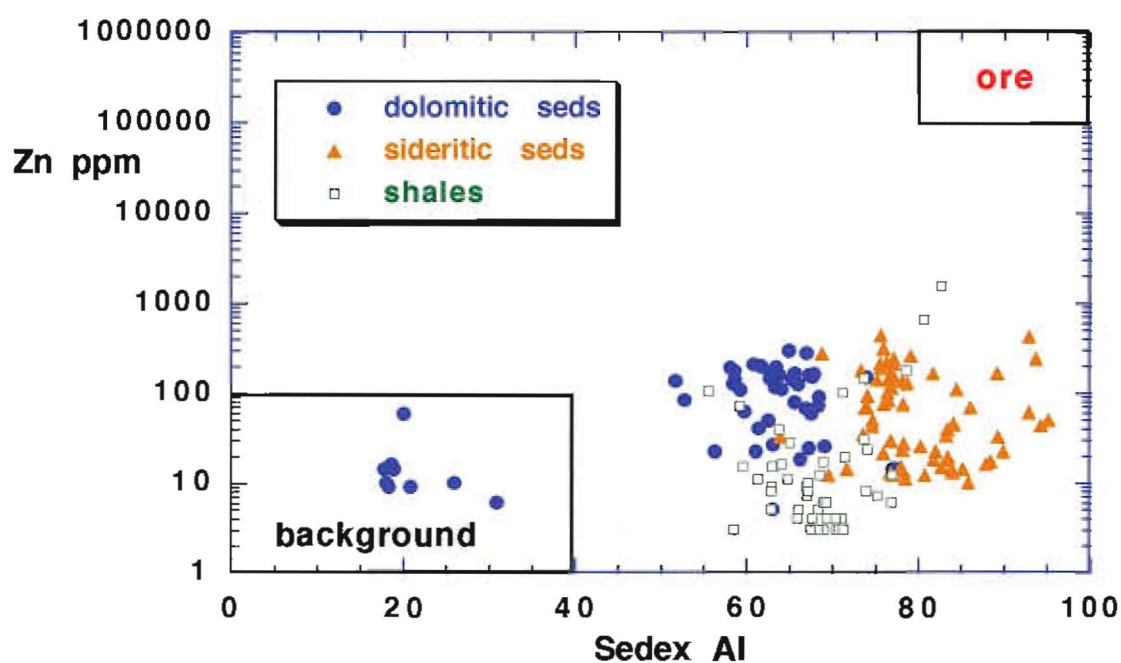


Figure 4. SEDEX Al vx Zn for the Century data set.

restricted to the host sediments in Pmh4. They have also been defined in Pmh1, Pmh2/3 and Pmh6.

Siderite halo

Due to the fact that the host stratigraphy at Century is fault bounded, it is not possible, on the available data, to determine the full extent of the siderite halo recognised by Broadbent et al. (Fig. 1). However on the basis of the AGSO data set it is evident that siderite is distributed throughout the stratigraphy surrounding Century at levels of 5 to 50 wt% (Large, 1998).

Ankerite distribution

Insufficient data is available to determine whether an ankerite halo is present at Century, surrounding the siderite halo, as previously defined for Lady Loretta (Large and McGoldrick, 1998). However the FeO_{carb} content of the dolomitic sediments varies from 2–4 wt% suggesting the possibility of a widespread ankerite or ferroan dolomite halo (Fig. 3).

Znc Dispersion

Both the zinc and pyrite content of sediments surrounding Century is relatively low, with most samples containing less than 100 ppm Zn and less than 2 wt% pyrite. Elevated levels of zinc occur in Pmh 4 (100–1000 ppm) in DDH LH 198 and LH 205.

Alteration Indices

SEDEX AI : In Figure 4 the sideritic and ferroan-dolomitic sediments clearly show elevated SEDEX AI values from 50 to 95; typical of the halo to a major sedex deposit. However compared to Lady Loretta and HYC, the iron-rich carbonate sediment of Century have distinctly lower zinc contents. This may be due to the fact that the laterally equivalent Pmh4 sediments have not been sampled, or alternatively, that Century does not or never did, exhibit a broad zinc dispersion halo.

AI Mark 3 : About 50% of the sideritic sediments show highly anomalous character in Figure 5, typical of proximity to a major stratiform zinc deposit.

Manganese Content of Carbonate : (MnO_s and MnO_d) : Calculation of the MnO content of carbonate, using the procedure developed by Large and McGoldrick (1993), indicates the siderites in the Century area are highly anomalous in Mn. MnO_s

values of 2–5 wt% were found in samples from Pmh1, 2–8 wt% in Pmh2/3, 1–3 wt% in lower Pmh4 and 5–18 wt% in Pmh6. This compares with values of 7–14 wt% reported by Broadbent et al., (in press) for the Century ore zone.

The upwardly increasing values of MnO_s found in DDH LH 203 and DDH LH 210 (Fig. 7) are very similar to the footwall patterns present at Lady Loretta and HYC, and suggest the possibility of stratiform Zn-Pb-Ag mineralisation hosted toward the top of Pmh2/3 and Pmh6.

On the priority discrimination diagram in Figure 6, 8% of the data falls into the high priority 1 field, and a further 16.5% in priorities 2 and 3. This is a very similar trend to that shown by the Lady Loretta siderite halo (Large, 1998a, Fig. 12).

Vectors to ore

Our study, using the AGSO Rockchem data set, has shown that the SEDEX AI, AI Mark 3 and MnO_s , MnO_d vectors developed for carbonate-rich sequences work equally well for exploration in siliciclastic sequences such as the Lawn Hill Formation at Century (Large, 1998).

This research has also shown that Pmh 4 is not the only favourable stratigraphy in the Lawn Hill Platform. The alteration index and Mn vectors indicate that potential also exists at three other stratigraphic levels (Fig. 8):

- The base of Pmh 1;
- The top of Pmh 2/3;
- The upper part of Pmh 6.

No isotopic studies have been carried out on the Century samples to test for a carbonate isotope halo, similar to those defined at HYC and Lady Loretta.

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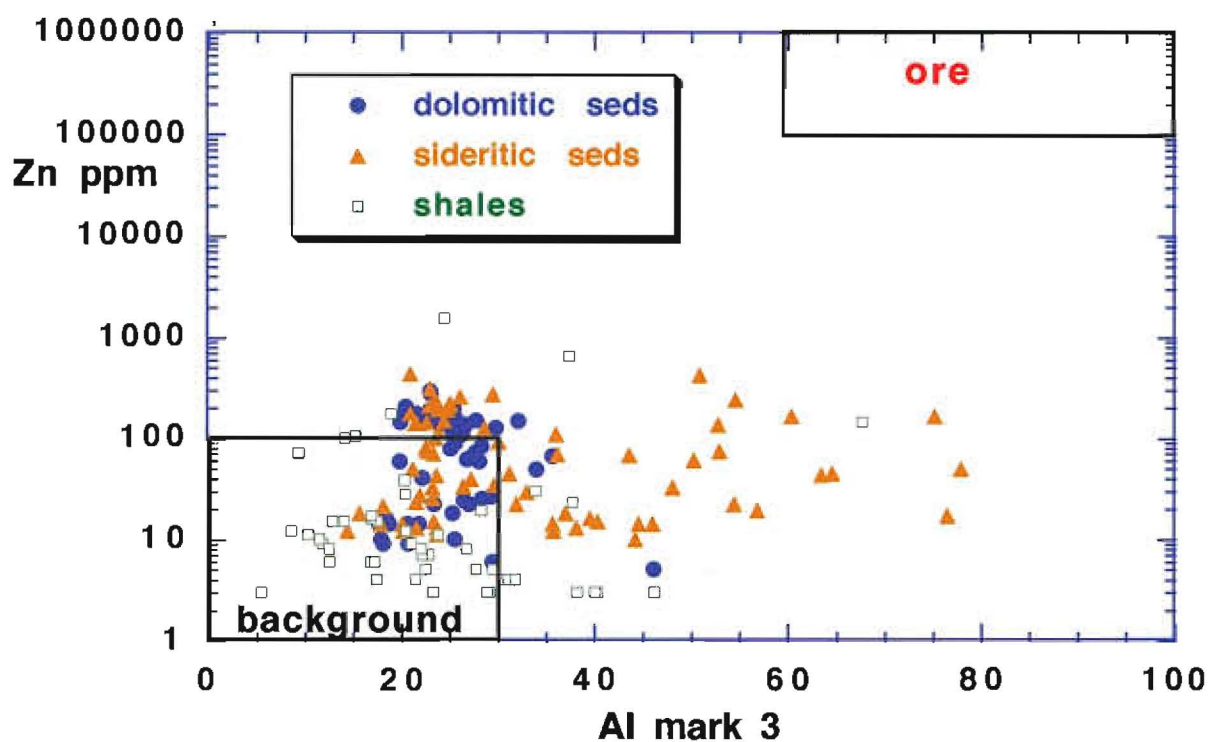


Figure 5. Al MARK 3 vs Zn for the Century data set.

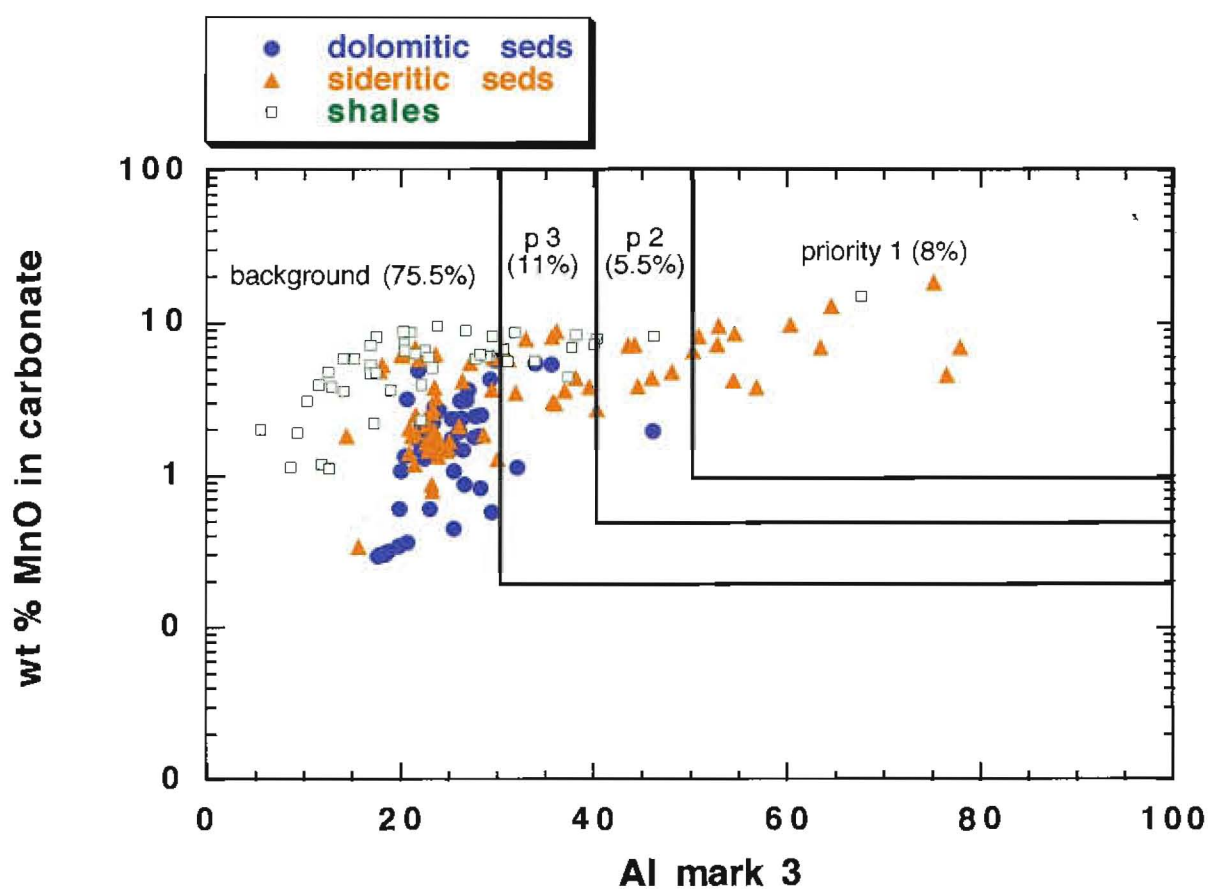


Figure 6. Priority discrimination plot for the Century data.

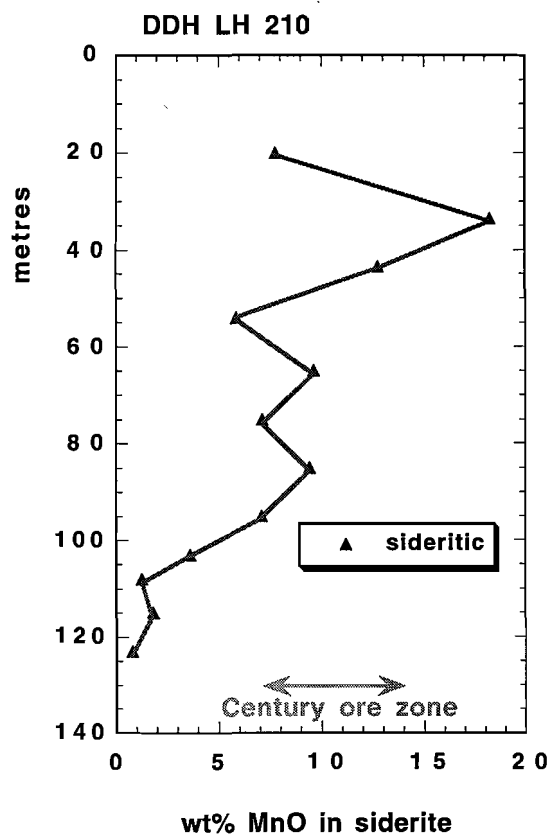


Figure 7. Downhole plot of MnO content of carbonate in DDH LH 210, 20 km southwest of Century. Note that MnO_s levels are similar to those in the ore zone at Century.

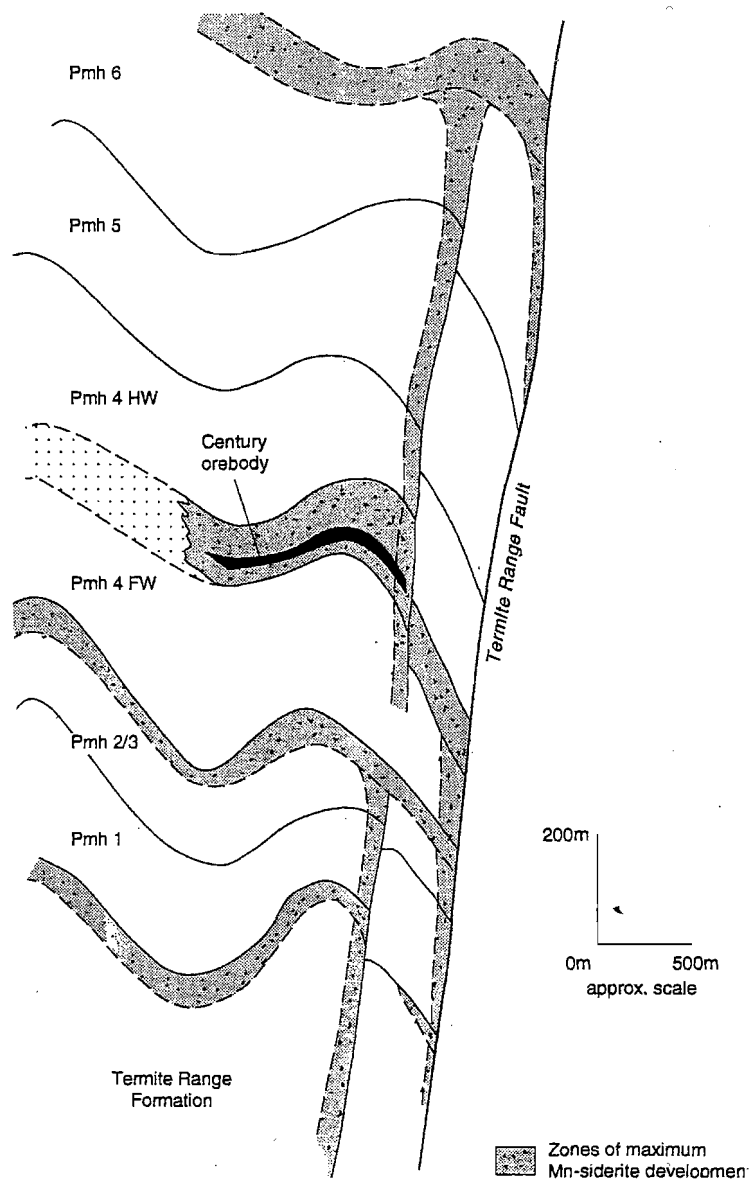


Figure 8. Regional halo model developed for the Lawn Hill Formation, Century area. (Large, 1998)

Large, R.R., 1998, Lithogeochemical study of a select group of sediments from the Century area, Lawn Hill Platform : CODES AMIRA/ARC Project P384A, Report no. 6, August 1998, p 1-21.

Large, R.R. and McGoldrick, P.J., 1998, Lithogeochemical halo and geochemical vectors to stratiform sediment-hosted Zn-Pb-Ag deposit. Part 1 : Lady Loretta deposit, Queensland: Journal of Exploration Geochemistry.

Century Deposit Summary

Regional Setting: The Century deposit occurs in gently folded late Palaeoproterozoic sediments of the upper McNamara Group (Blake, 1987). The upper McNamara Group is a more siliclastic dominated package than the lower McNamara Group (Sweet and Hutton, 1982), and exists only in the northern half of Lawn Hill Platform. Century occurs in the Lawn Hill Formation, the youngest preserved unit of the McNamara Group that comprises about 2000 metres of unmetamorphosed shale, siltstone, tuff (illite beds), tuffaceous siltstone, sandstone and dolomite (Sweet and Hutton, 1982).

Lat 18°45'S, Long 138°37'E



Host Rocks: The upper part of Unit 4 of the Lawn Hill Formation is the immediate host to the Century orebody (Waltho et al., 1993; Waltho and Andrews, 1993). At the deposit, this unit comprises about 300 metres (cf 100 metres elsewhere) of upwards coarsening interbedded siltstone and shale, interpreted to have been deposited in a deep marine setting (Broadbent et al., 1998). The 40 metre thick mineralised sequence is subdivided into four distinct units and these in turn into several subunits. Sulfide mineralisation is almost entirely confined to black shale units.

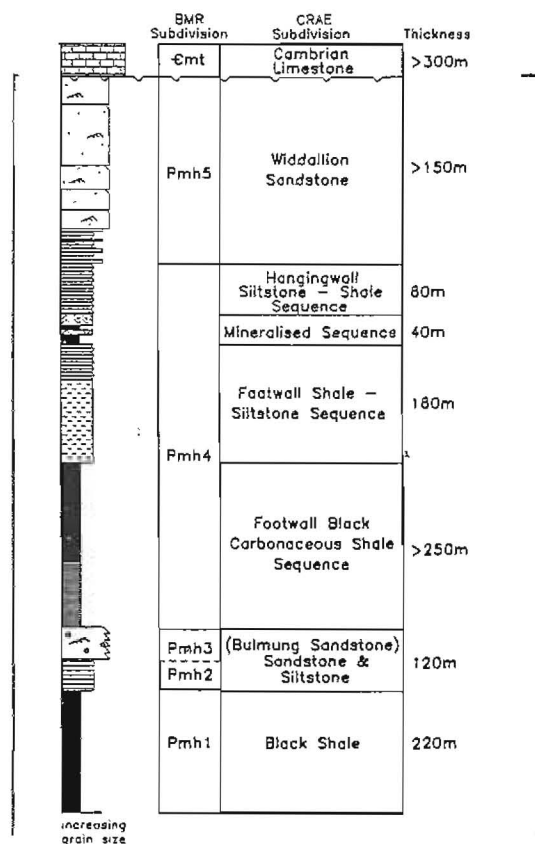
The orebody has been gently folded and dips vary between five and twenty five degrees. It is bounded either by faults or an unconformity surface with overlying Cambrian sediments.

Page and Sweet (1998) reported an age of 1595 ± 6 Ma for zircons from tuffs in the Century ore sequence.

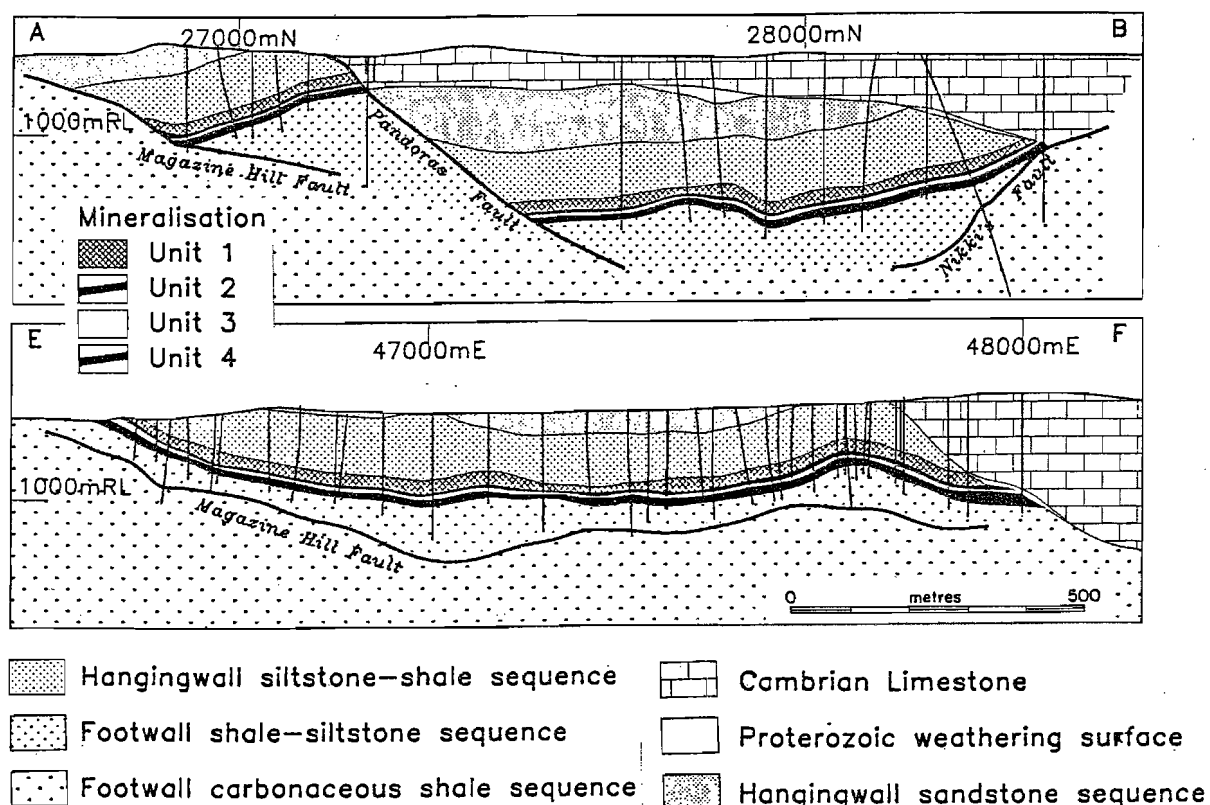
Size and Grade: The Century deposit has an indicated resource of 118 Mt at 10.2 wt% Zn, 1.5 wt% Pb and 36 g/t Ag.

Mineralisation: Waltho and Andrews (1993) describe a simple sulfide assemblage of sphalerite, pyrite, galena $\pm$ chalcopyrite with associated organic carbon, (Mn+Mg) siderite, and authigenic silica. Metallic grey coloured lamellae (1 to several millimetres thick) contain two main types of sphalerite; 'non-porous' – single grains and cryptocrystalline aggregates to 50 microns; and 'porous' – polycrystalline aggregates of 0.3 micron sphalerite grains and pyrobitumen inclusions to 2 microns. Pyrite (less than ten percent

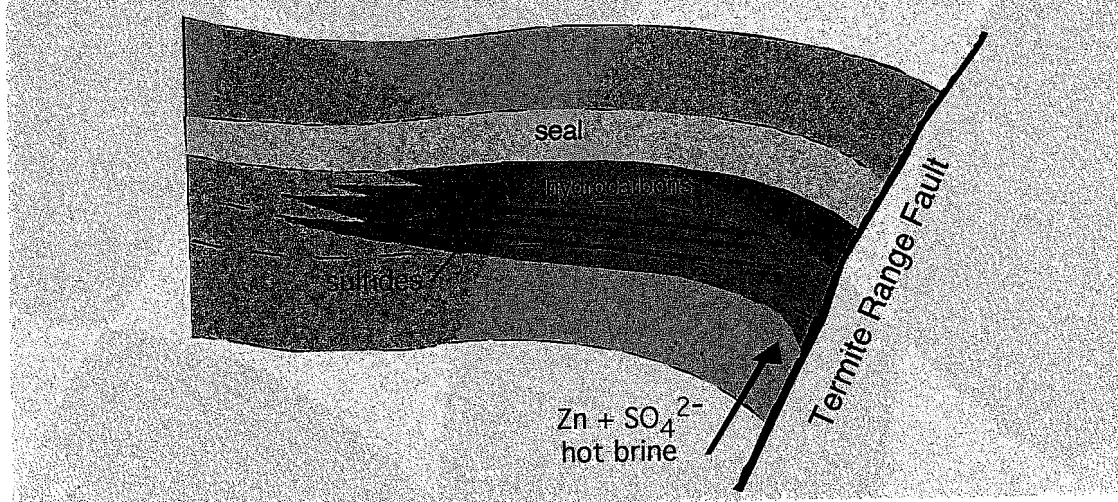
of total sulfides in ore) occurs as euhedral 2 to 10 microns crystals; it is proportionately more abundant in an envelope to the orebody. The lower part of the orebody is grossly zoned from NE to SW, with highest Zn grades proximal to the Termite Range Fault. Zn zoning is more complex in the upper part of the deposit (Waltho et al., 1993). The deposit is also vertically zoned, with most of the Pb and Ag resource occurring in the upper half (Waltho et al., 1993).



Genetic Models: A novel genetic model has recently been proposed for the Century deposit (Broadbent et al., 1998). They suggest mineralisation formed during early stages of basin inversion ('late diagenesis') when tectonically driven basin fluids migrated into an overpressured/undercompacted shale sequence. These hot, Zn- and sulfate-bearing fluids migrated out of the Termite range Fault and promoted gas and liquid hydrocarbon generation from host sequence shales. The hydrocarbons, in turn, were utilised in thermochemical sulfate reduction processes leading to base metal sulfide precipitation. Gas mediated sulfate reduction produced 'non-porous' sphalerite, whereas oil mediated sulfate reduction produced the porous, pyrobitumen-rich, sphalerite.

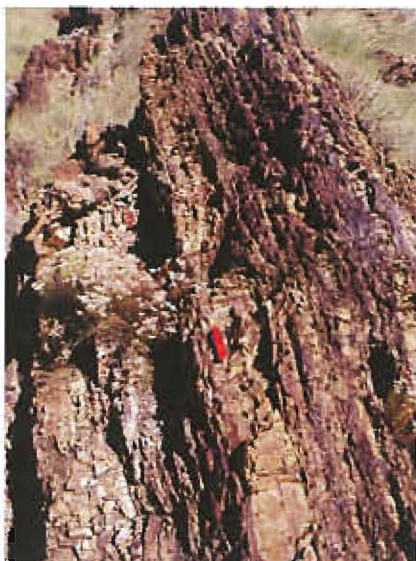


Late diagenetic — early basin inversion model for Century (after Broadbent et al., 1998)



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(a)



(b)



(c)



(d)

- (a) Outcropping Century mineralisation ("Eastern Floater Block").
 (b) Century pit looking towards Silver King in hills on skyline. Ore zone is weathering white below known hanging wall siltstones.
 (c) Typical Century high-grade Zn mineralisation.
 (d) Close up of Century high-grade Zn mineralisation.

Halo model for the Grevillea prospect

Peter McGoldrick

Centre for Ore Deposit Studies

Introduction

The Grevillea prospect is the most recent significant sediment-hosted base metal mineralisation discovery in the Carpentaria Zinc Belt. This report reviews a reconnaissance lithogeochemical study of the deposit reported in AMIRA P384A Final Report v. 2 (McGoldrick, 1998).

Deposit characteristics

The Grevillea mineralisation has many similarities to the Lady Loretta deposit and important features of the prospect and some ore types are described in the Grevillea Deposit Summary.

Host rocks

Figure 1 is a surface geological map of the area around Grevillea. The host sequence comprises about 100 m of highly pyritic carbonaceous shales and siltstones. Pyritic stratigraphy is present under shallow cover for at least a kilometre to the N of a gossan developed on pyrite and base metal sulfides. Faulting has removed the mineralised sequence to the S of the gossan.

Sampling strategy

Twenty three samples of core and thirty two percussion pulps were analysed for major elements and selected trace elements. As in all previous case

studies, sulfide-rich samples were avoided where possible. The drill hole locations are shown in Figure 1. Precise correlation between the percussion holes and the mineralised part of RVD17 was not possible, but the interval sampled from the percussion holes was broad enough to include the stratigraphic equivalent of the base metal mineralisation.

Lithogeochemistry

Host rock carbonates

On CaO/MgO crossplots the samples fall into two groups (Fig. 2). Most lie on a 'dolomite' (or ankerite) trend. Five low CaO, but high MgO samples from RVD17 are sideritic. Recalculating the whole rock analyses, assuming all Fe is pyrite and carbonate, indicates that most of the 'dolomite' samples are ankeritic (moles Fe+Mn:Mg > 0.25). sediments.

The sideritic samples correspond to the mineralised interval in RVD17. All samples from RVC34, 250 m N along strike from the gossan, and two thirds of samples from RVC30 and 31, 450 m N of the gossan, are ankeritic.

Zinc dispersion

All but one of the samples analysed from Grevillea had less than 100 ppm (Fig. 3), hence, there is no indication of enrichment in the host sediments nor does Zn form primary dispersion halo in the drill holes to the N. This is in marked contrast to Lady Loretta where Zn forms a broad primary dispersion, and zincian siderite is present in mine sequence rocks (Carr, 1981)

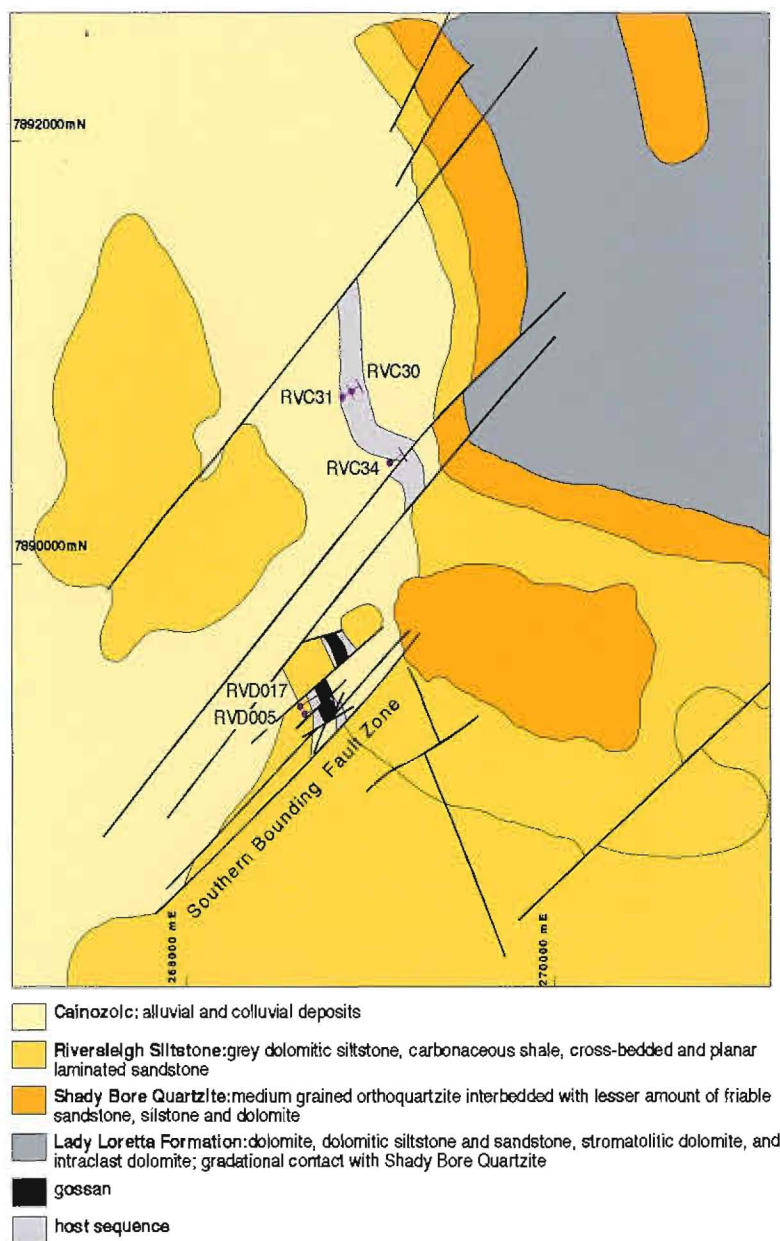


Figure 1. Geology of the area around the Grevillea gossan (AMG co-ordinates; geology from Sweet and Hutton, 1982 and Coolgardie Gold unpubl. Data).

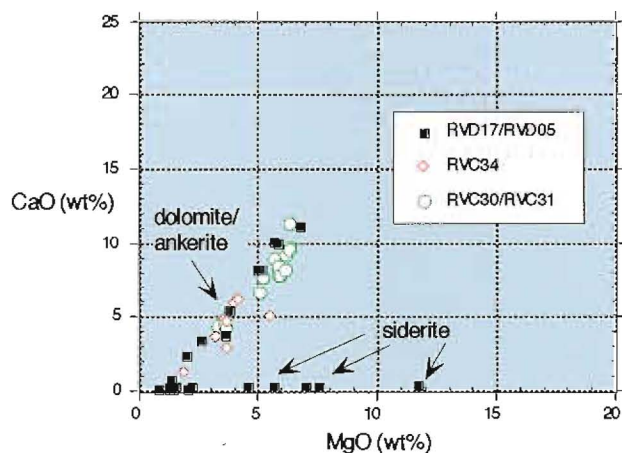


Figure 2. CaO and MgO relationship for 55 samples from Grevillea.

Manganese

Mn forms a broad primary dispersion at Grevillea. Most of samples contain anomalous Mn, and the Mn content of the carbonate (Fig. 3) ranges from about 1 wt% to 4 wt%. Sideritic samples from the mineralised interval of RVD17 are uniformly high in Mn (3 to 4 wt% MnOs).

Thallium

Down hole Tl distributions for RVD17/RVD05 and RVC330/RVC31 are presented in Figure 3. The entire sampled interval of RVD17 is strongly anomalous in Tl (6 to 60 ppm). All samples from RVC34, 250 m along strike, have more than 4 ppm Tl (up 47 ppm), and six (of sixteen) samples from RVC30/31, 450 m along strike, have more than 4 ppm. Hence, Tl has a strong primary dispersion about the Grevillea mineralisation, that persists for at least 450 m along strike.

Alteration indices

Both Sedex AI and AI3 are anomalous in the mineralised interval of RVD17, with AI3 having a more 'spiky' pattern (Fig. 3). Although absolute values are somewhat lower, anomalous values are still present in RVC30/RVC31, and define a zone in the upper two thirds of the section. On this basis this zone could be interpreted as the exact stratigraphic equivalent of the mineralised sequence in RVD17.

Sedex Metal Index

Sedex Metal Index ($\text{Zn} + 100 \text{ Pb} + 100 \text{ Tl}$) values are between 1000 and 10000 in most samples from Grevillea, similar to the range shown by host sediments to Lady Loretta (Large and McGoldrick, 1998). There is a systematic increase approaching the mineralised zone from the hangingwall in RVD17/RVD05, and high values in RVC30/RVC31 define the same interval as AI3 and Sedex AI in these holes.

Interrelationships between Zn, Sedex AI, AI3 and $\text{MnO}_{\text{d/s}}$

The Grevillea samples lie below the 'Lady Loretta trend' (Large and McGoldrick, 1998) on cross-plots of log Zn against Sedex AI and AI3 (Figs 4 and 5), reflecting the overall low-Zn character of the host rocks. On plots of log $\text{MnO}_{\text{d/s}}$ against the two alteration indices most samples lie in the prospective parts of the diagram (Figs 4 and 5); all the siderite samples lie in the 'prospectivity 1' box.

Carbon and oxygen isotopes

Eleven carbonate-rich whole rock samples from Grevillea were analysed for C and O isotopes. These data are insufficient to define spatial trends, but do suggest important similarities and differences between Grevillea and Lady Loretta (McGoldrick et al., 1998) with respect to O and C isotopes. In terms of O there is no overlap between the Grevillea data and the Lady Loretta data; the heavy O observed in Lady Loretta siderite is not evident at Grevillea. There is, however, an indication that, as at Lady Loretta, C in dolomites at Grevillea is lighter than C in ankerites and siderites.

Vectors to ore

The data reported here indicate that many of the vectors developed for the Lady Loretta deposit may be applicable to the Grevillea prospect.

These include:

- (1) Change in carbonate composition from dolomite to ankerite to siderite within the sediments. Ankerite is still present several hundred metres along strike from known mineralisation.
- (2) Systematic increase in MnO content of carbonate (MnO_d and MnO_s) toward mineralisation. More detailed sampling is required to confirm spatial changes in these parameters at Grevillea. The available data indicate that highest carbonate

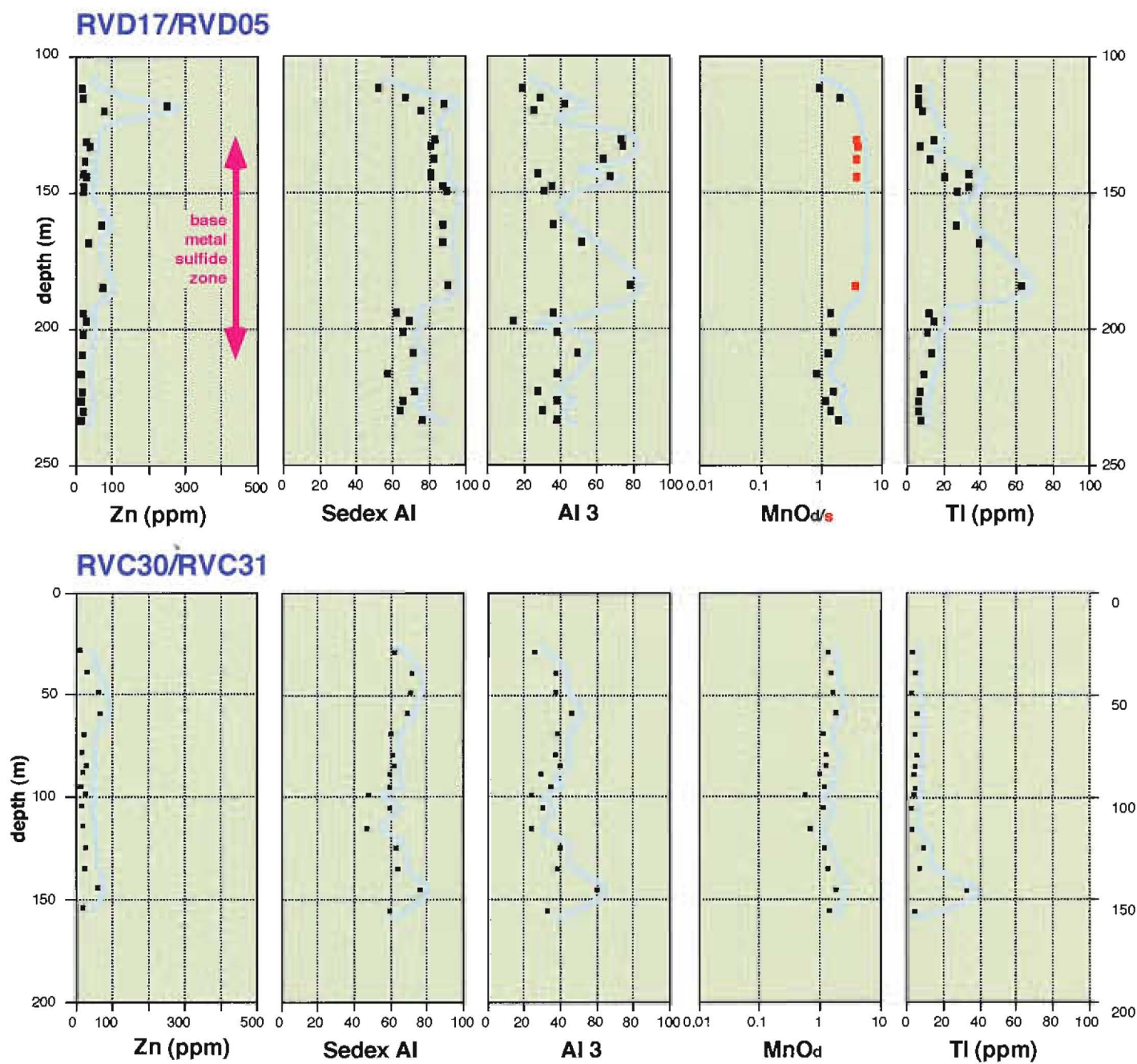


Figure 3. Downhole variation in Zn, Sedex Al, Al₃, MnO_{d/s} and TI in proximal (RVD17/RVD05) and distal (RVC30/RVC31) samples from Grevillea.

RVD17 & RVD5 (proximal) samples

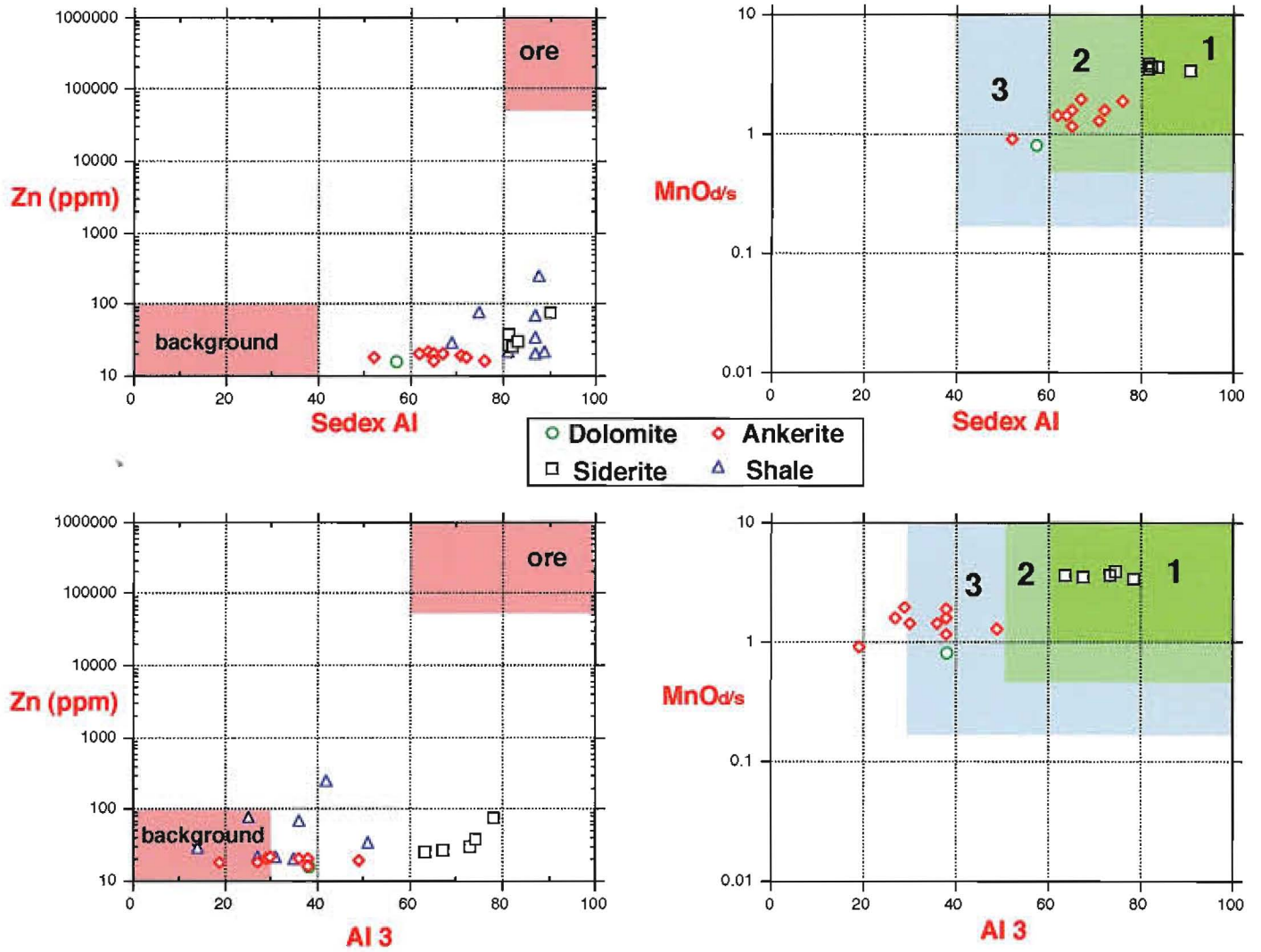


Figure 4. Zinc, alteration indices and MnO_{d/s} interrelationships for proximal samples from Grevillea (shales have not been used for MnO_{d/s} calculations).

MnO occurs in the mineralised part of RVD17, and lower, but still anomalous, levels are present in the most distal samples.

- (3) The alteration indices (Sedex AI and AI3) are weakly anomalous 450 m along strike in the stratigraphic equivalent of the mineralised sequence, and show an increase toward mineralisation.
- (4) Thallium is quite anomalous 450 m along strike in the stratigraphic equivalent of the mineralised sequence, and increases toward mineralisation.
- (5) Sedex Metal Index ($\text{Zn} + 100 \text{ Pb} + 100 \text{ Tl}$) increases from around 1000 to over 10,000 towards ore both across strike and along strike.

Zinc by itself does not appear to be a useful vector to the Grevillea mineralisation. Further work is required to see if the trend to isotopically heavy O in carbonate approaching ore, observed at Lady Loretta (McGoldrick and Large, 1998) and HYC (Large et al., 1998), is apparent at Grevillea.

Size of the halos at Grevillea

The strong positive response from Grevillea for most of the 'basket of indices' developed for northern Australian Proterozoic stratiform deposits is a good indication that substantial (Lady Loretta size or better) base metal sulfide is or was present in the immediate vicinity of the known mineralisation. The intensity of the indices seems to drop away N along strike from the gossan, suggesting better mineralisation to the S. Unfortunately, the host sequence has been removed by faulting in this area.

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RVC30 & RVC31 (distal) samples

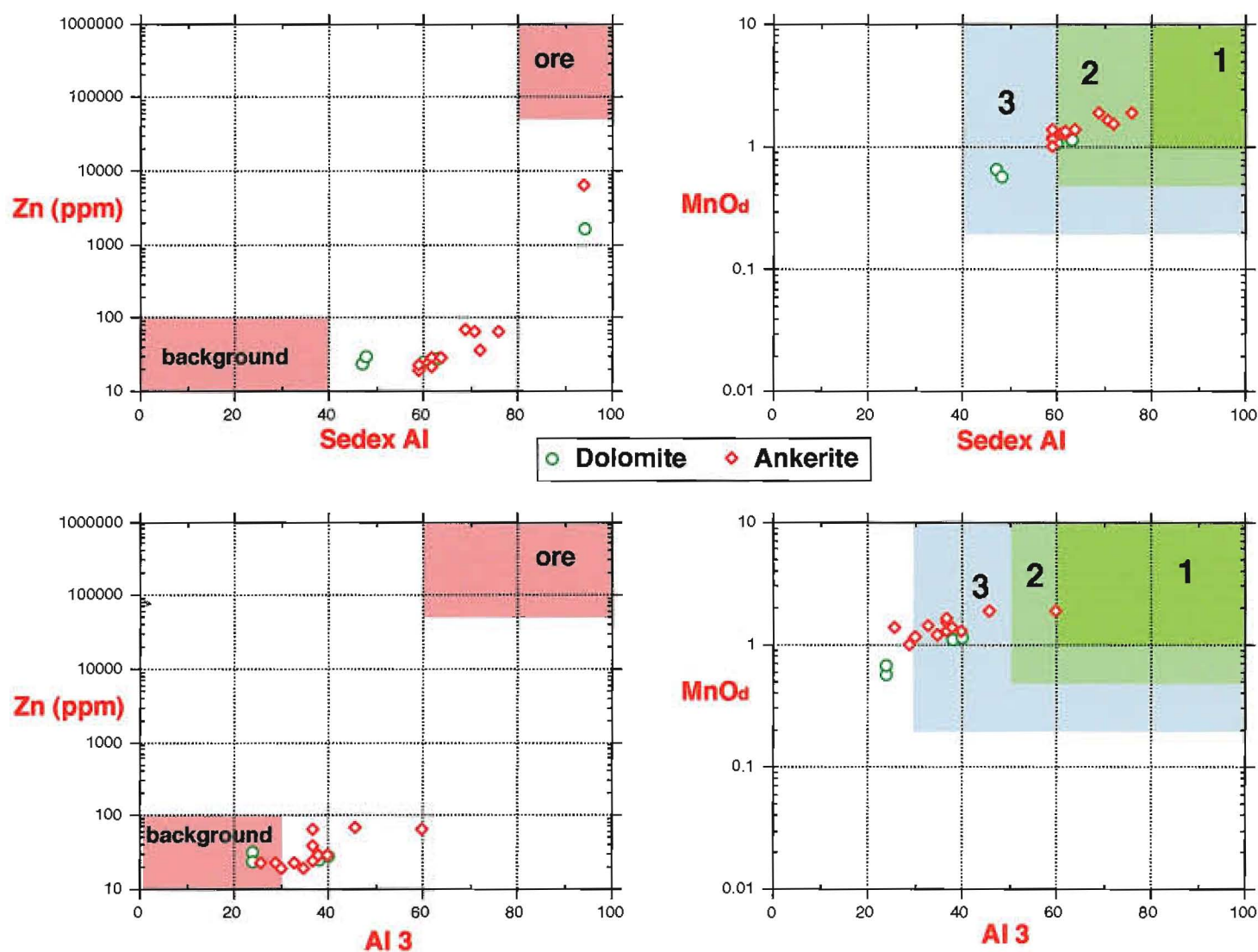


Figure 5. Zinc, alteration indices and MnO_d interrelationships for distal samples from Grevillea.

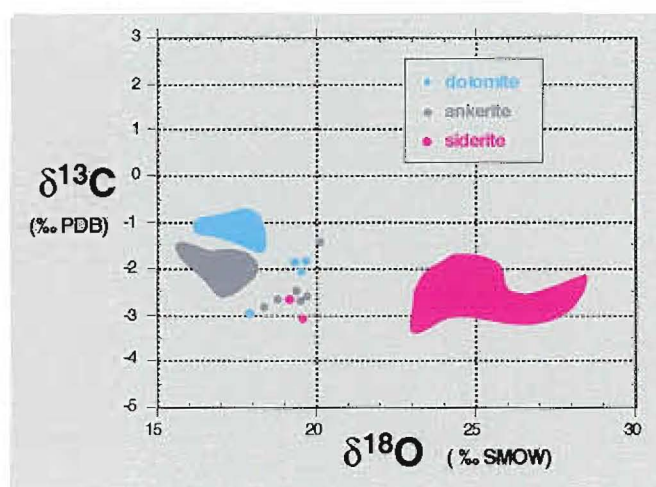


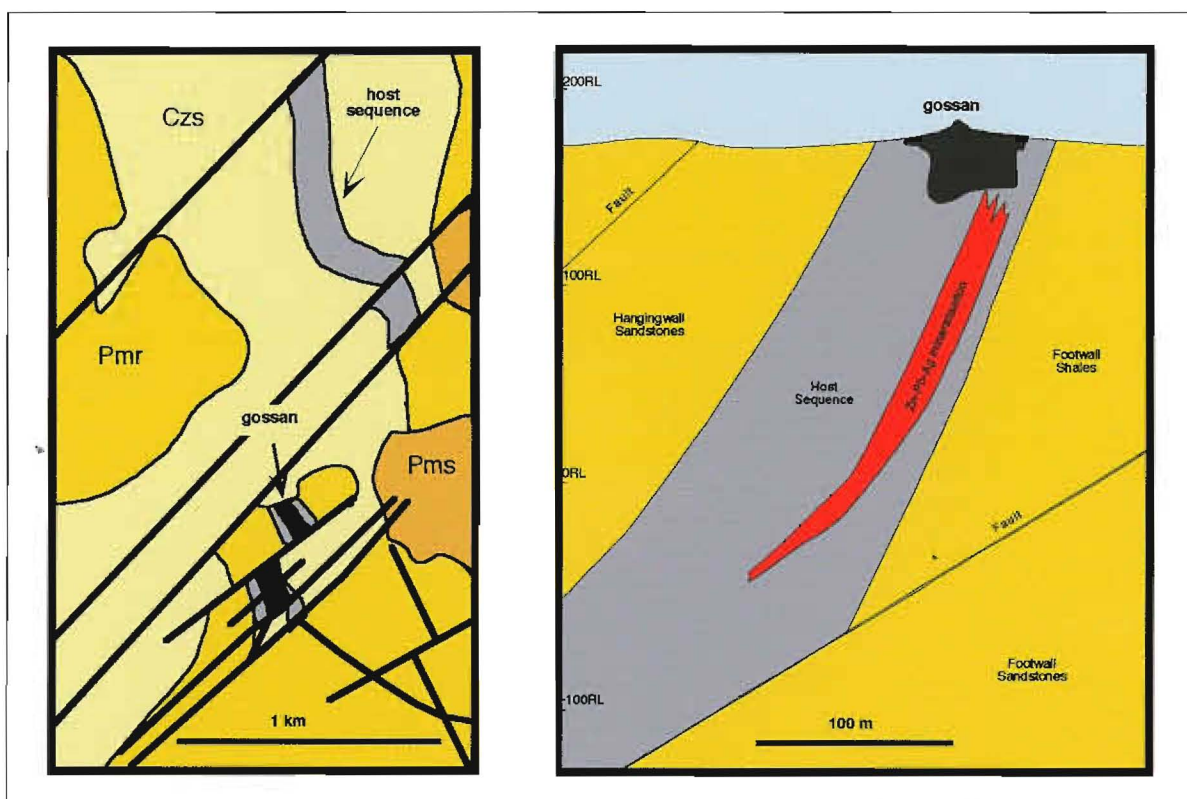
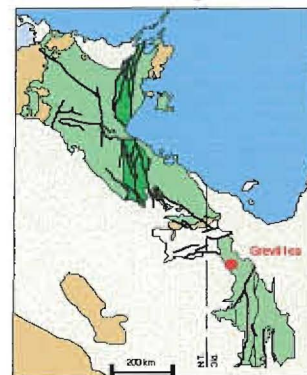
Figure 6. Cross plot of C and O isotope data for 12 samples from Grevillea; fields for 29 samples from Lady Loretta are plotted for comparison. Note: 'ankerite' samples are distinguished from dolomite samples by having moles (Fe+Mn)/Mg > 0.25.

Grevillea Deposit Summary

Regional Setting: The deposit occurs in unmetamorphosed late Palaeoproterozoic McNamara Group sediments of the central Lawn Hill Platform (Blake, 1987). It is about eight kilometres SW of the Termite Range Fault (Sweet and Hutton, 1982).

Host Rocks: Base metal mineralisation and barite occur in carbonaceous and highly pyritic shales and siltstones of the lower Riversleigh Siltstone. The 100 metre thick mineralised sequence dips at about 60° W and is overlain by (?shallow marine) sandstones. Footwall shales are transitional to the underlying Shady Bore Quartzite (?marginal marine).

Lat 19°4'S, Long 138°48'E



The age of the Riversleigh Siltstone is bracketed by zircon dates of 1636 ± 10 Ma for the overlying lower Termite Range Formation (Page and Sweet, 1998) and 1647 ± 4 from the upper Lady Loretta Formation (R.W. Page pers. comm.).

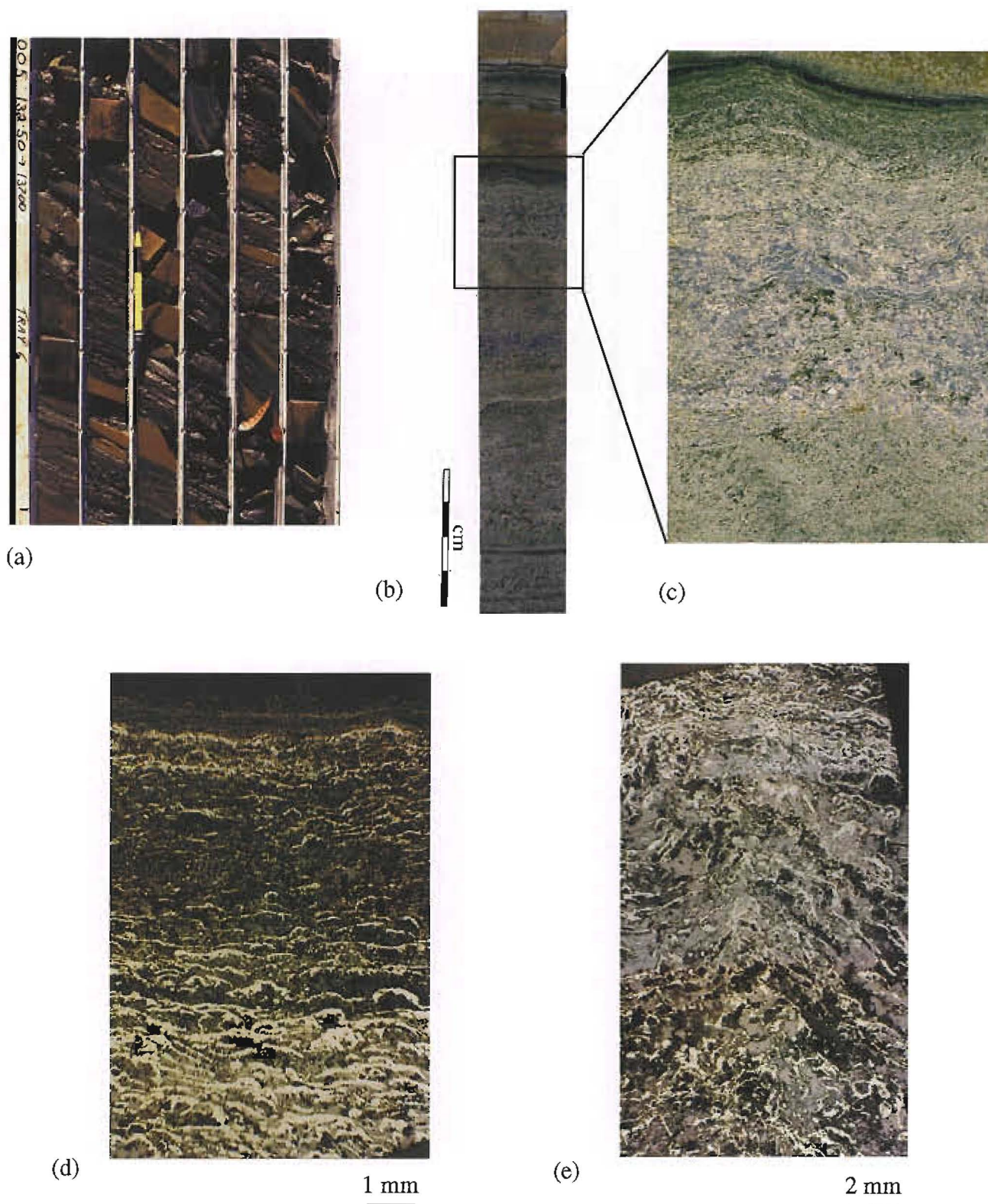
Size and Grade: There are no published estimates of the base metal resource at Grevillea. Significant base metal grades were obtained along a strike length of a 250 metres (e.g., 25 m @ 4.7% Zn, 1.0% Pb, 29 g/T Ag in RVC001, and 20 m @ 6.0% Zn, 1.5% Pb, 56 g/T Ag in RVD005) beneath a prominent gossan. Fault offset, sulfide-rich equivalent stratigraphy to the mineralisation is present over a kilometre to the north of the gossan. The sulfide zone is truncated by faulting to the S at depth.

Mineralisation: Base metal sulfides and barite occur as infillings and impregnations in delicately (?microbially) laminated, highly pyritic rocks and (less commonly) replacing oolitic beds (McGoldrick, 1998). Coarse barite may be pseudomorphous after primary gypsum or anhydrite. Interbedded siltstones are sideritic and contain obvious gypsum pseudomorphs (carbonate).

Genetic Models: Grevillea mineralisation shares many characteristics with the Lady Loretta deposit, notably the association of base metal sulfides, abundant pyrite and siderite, and (possibly) a shallow water depositional setting for the host sequence. The delicately laminated base metal sulfide-rich beds observed at Lady Loretta and used to support an exhalative origin for part of Lady Loretta (McGoldrick et al, 1996) have not been reported from Grevillea. Pyrite – base metal sulfide textures indicate base metal sulfides were precipitated prior to compaction of porous and permeable microbially laminated organic-rich sediments (McGoldrick, 1998) providing support for an early diagenetic timing for base metal sulfide precipitation.

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a) Drill core of sideritic and carbonaceous-pyritic siltstones and shales from the mineralised sequence in DDH RVD05.

b) Massive banded sulfide (pyrite-sphalerite-galena) beds and (brown) sideritic siltstones in polished half-core from DDH RVD17 (stratigraphic top is up).

c) Detail from b) showing sphalerite (+/- galena) infilling 'crinkly' textured pyrite.

d) Reflected light photomicrograph of sphalerite (+/- galena) occurring as a matrix to crinkly pyrite; note, the crinkly pyrite has a consistent convex up orientation, and is interpreted to be formed as an original microbial lamination.

e) Reflected light photomicrograph of unusual crinkly pyrite/sphalerite, interpreted as an original microstromatolite structure.

Halo model for the Walford Creek Zn-Pb-Cu-Ag prospect

Peter McGoldrick

Centre for Ore Deposit Research

Summary

Walford Creek is a low grade Zn-Pb-Cu-Ag deposit hosted in highly pyritic parts of carbonaceous shale units of the Mount Les Siltstone. Three syngenetic pyrite lenses occur in a 250 metre thick interval abutting the Fish River Fault. Base metal sulfides form impregnations and infillings in primary porosity in the pyrite lenses. Four drill holes from the Walford Creek area were sampled to investigate the behaviour of the lithogeochemical indices developed during AMIRA P384 for Lady Loretta and HYC.

Samples from two proximal holes (including one through the pyrite lenses) have a poor response in terms of alteration indices and Tl. The MnO_d data are mostly low, but sporadic high values unrelated to high Zn, Tl or alteration indices do occur. Samples from two drill holes 5 km along strike from the pyrite lenses do not have a weak lithogeochemical response attributable to the Walford Creek mineralisation.

The results summarised here have been discussed in detail in AMIRA P384 Final Report, pp 303–318, June 1995.

Introduction

The Walford Creek Zn, Pb, Cu, Ag prospect comprises three stratiform pyrite horizons containing base metal mineralisation occurring within the Mount Les Siltstone Member of the late Palaeoproterozoic Fickling Group. Western Mining Corporation drilled more than 80 holes to test the seven kilometre strike extent of the pyrite lenses for base metals. However, although some significant intersections were encountered, an economic resource could not be defined.

Hence, Walford Creek provided an opportunity to test the response from lithogeochemical vectors developed for Lady Loretta and HYC (Large and McGoldrick, 1998; Large et al, 1998) in a well drilled, uneconomic, Zn mineralised system.

Deposit characteristics

The Walford Creek prospect shares many characteristics of the large stratiform sediment-hosted Zn-Pb-Ag deposits of northern Australia. Important features of the deposit are summarised on Deposit Data Sheet #7 and examples of the sulfides are illustrated in Plate 6. A detailed description and genetic model for the mineralisation is presented in Rohrlach et al., (1998).

Host rocks

An anomalously thick (about 310 metres) interval of Mount Les Siltstone is the host to mineralised syngenetic pyrite lenses at Walford Creek. The massive pyrite lenses pass laterally into thinner black carbonaceous and pyritic shales away from the Fish River Fault. Green and grey (dolomitic) siltstones separate, underlie, and overlie the two black shale members containing the pyrite lenses (Rohrlach et al., 1998).

Sampling strategy

Thirty six samples of siltstone and shale from four diamond drill holes were analysed for major and selected trace elements by XRF at the University of Tasmania for this study. One hole (WFDD58) was drilled through the main thickness of the pyrite lenses proximal to the Fish River Fault. A second (WFDD17) was drilled through the southern fringe of the mineralisation. Two holes, WFDD84 and Amoco

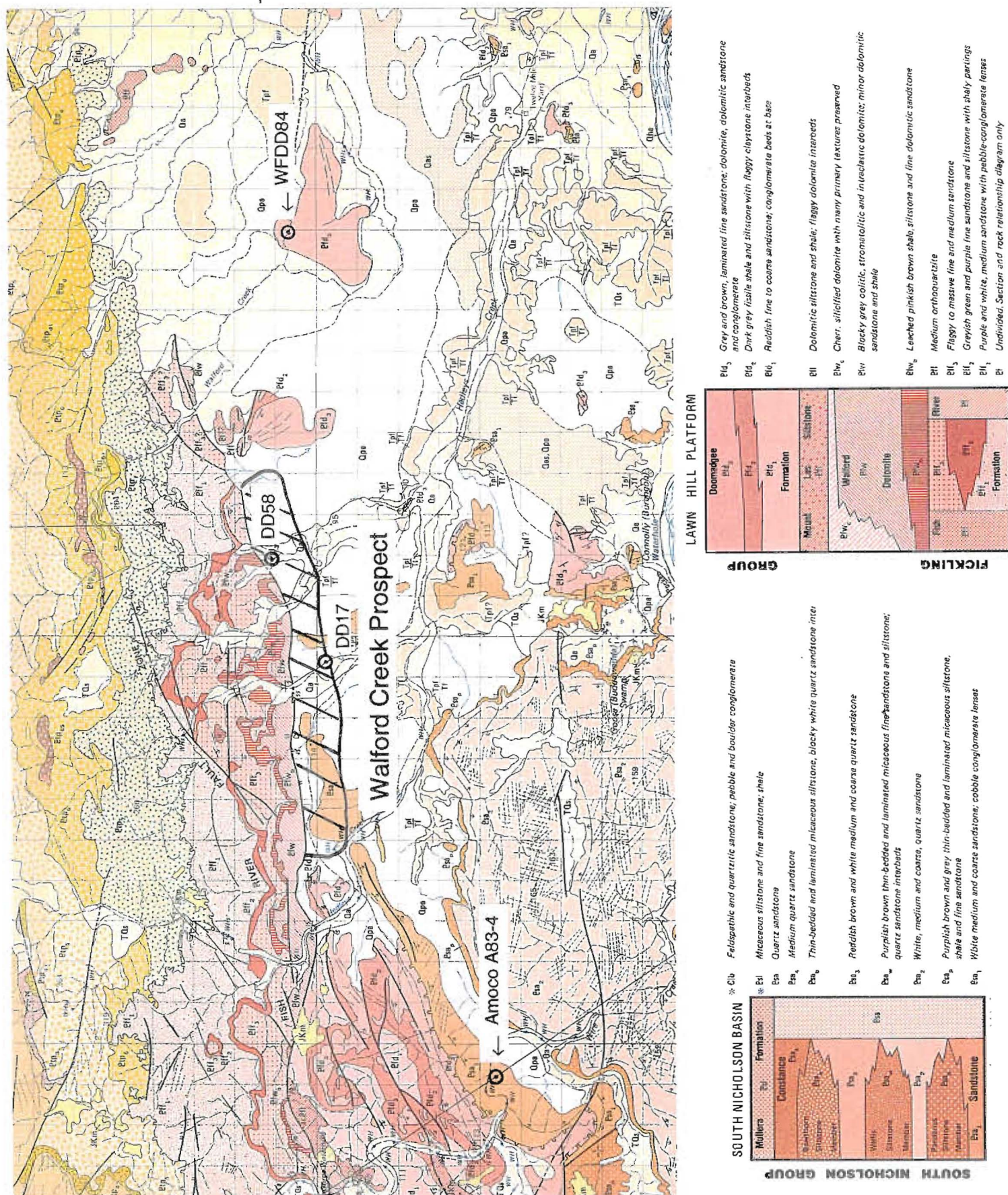


Figure 1. Portion of the Siegal-Hedleys Creek 1:100,000 geology map (Sweet et al., 1981) showing the location of drill holes sampled for this study.

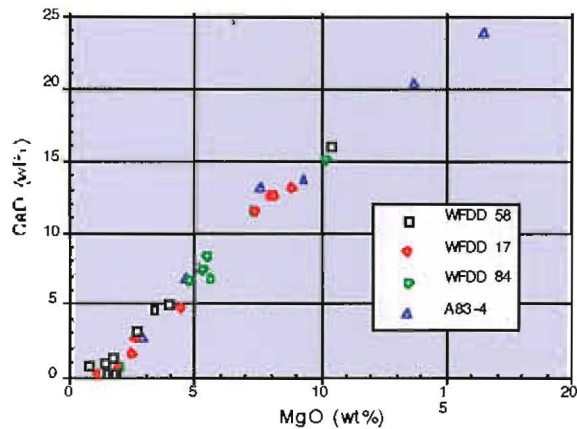


Figure 2. CaO/MgO relationships for 36 samples from the Mount Les Siltstone in the Walford Creek area.

A83 4, located 5 km to the E and SW, respectively, of the Walford Creek pyrite lenses, provided samples of Mount Les Siltstone remote from known mineralisation. The location of these drill holes and the geological setting of the prospect are illustrated in Figure 1.

Lithogeochemistry

Host rock carbonates

The CaO/MgO relationship for all samples (Fig. 2) indicates about three quarters of the samples contain significant carbonate, and that this carbonate is dolomite. Low carbonate samples have not been used for the MnO_d calculations (see below).

Zinc dispersion

Most of the samples from the two proximal holes contain between 10 and 100 ppm Zn (Figs 3 & 4), and similar levels are present in the two distal holes.

Alteration Indices

The Zn, SedexAI, AI3 and MnO_d interrelationships and down hole variations for the Walford Creek samples are displayed in Figures 3 and 4. Anomalous alteration indices are observed in three samples from the fringe position drill hole, but in none of the samples from the drill hole through the pyrite lenses. Several samples have elevated MnO_d values, but,

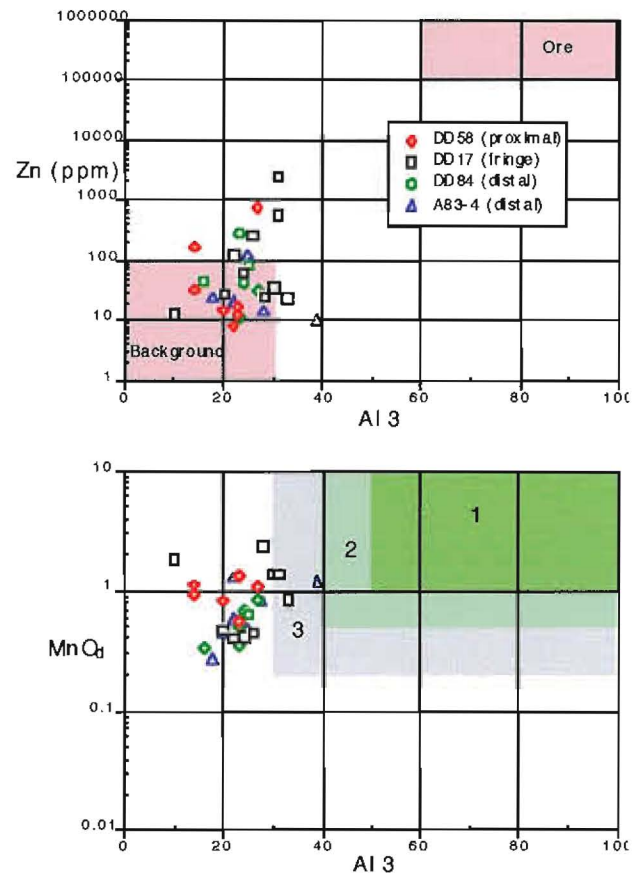


Figure 3. Zn/AI3 and MnO_d /AI3 cross-plots for samples from Walford Creek; low carbonate samples have been excluded from the MnO_d plots.

only just lie in the "Prospectivity 3" box of the AI3/ MnO_d plot (Fig. 3). In fact, the most prospective sample in terms AI3/ MnO_d comes from one of the distal holes (Amoco A83-4).

Thallium

Thallium in Walford Creek samples displays a similar pattern to the alteration indices, with all but three of the proximal samples containing background Tl levels, and these three are only weakly anomalous (5 to 6 ppm). The highest Tl value (16 ppm) was measured in a sample from a distal hole (WFDD 84).

Vectors to ore

The lithogeochemical data from Walford Creek indicate that this uneconomic, weakly mineralised system, produced little or no response in terms of the basket of indices developed for larger northern Australian deposits.

The poor response is interpreted to reflect the lack of large concentrations of base metal sulfides in the Walford Creek pyrite lenses, and could have been used to downgrade the prospectivity of the area at an earlier stage of drilling.

The response from the distal holes is more difficult to interpret, but may suggest other areas in the Hedleys Half Graben structure (Rohrlach et al., 1998) may still be prospective.

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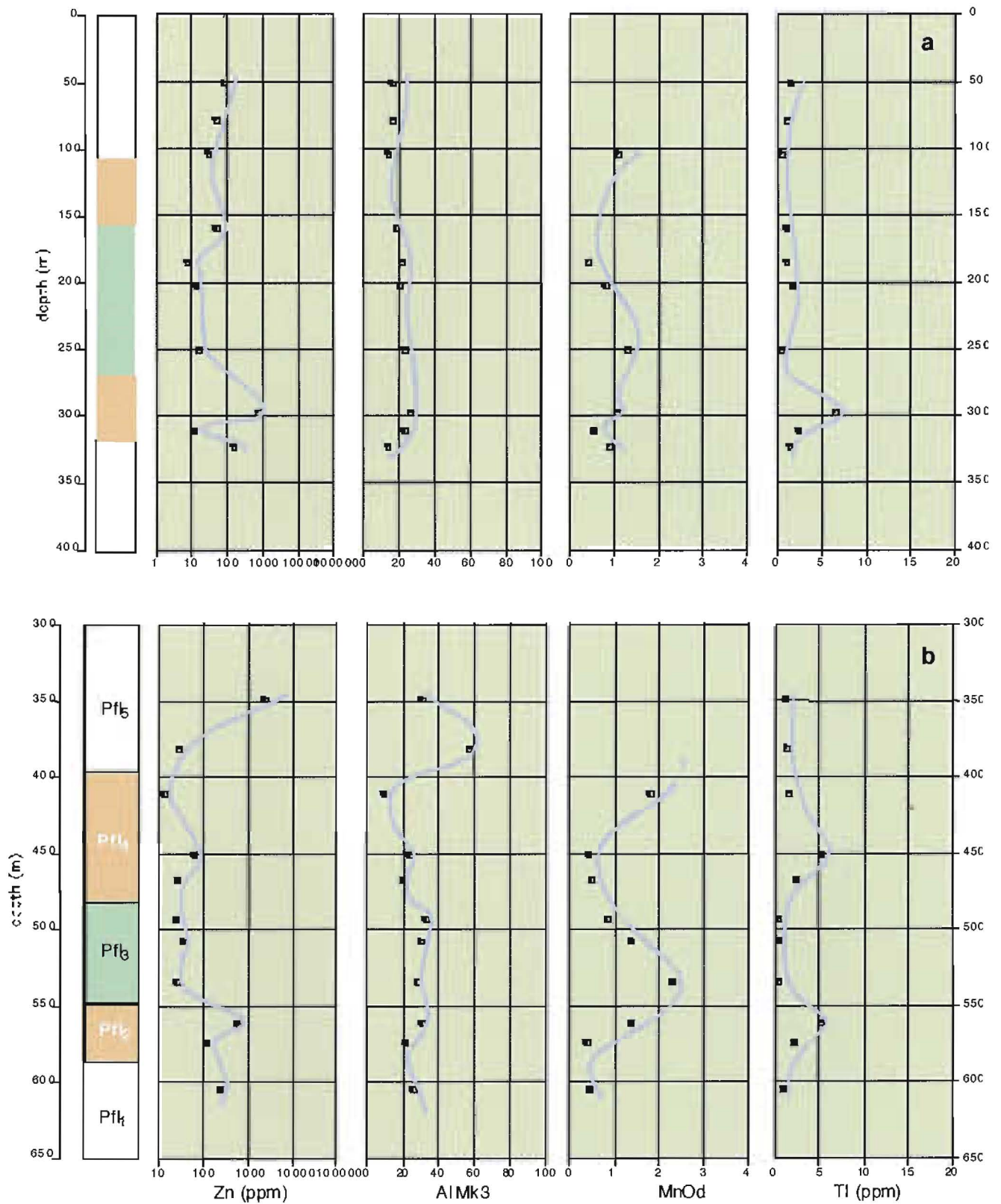


Figure 4. (a) The distribution of Zn, Al₃, MnO₂ and Tl in DDH WFDD58; mineralised pyrite lenses are present in this hole at the level of Pfl₄ and Pfl₂; (b) The distribution of Zn, Al₃, MnO₂ and Tl in DDH WFDD17; this hole was drilled through the southern fringe of the pyrite.

Walford Creek Deposit Summary

Regional Setting: The deposit occurs in late Palaeoproterozoic sediments of the Fickling Group at the northern edge of the Lawn Hill Platform (Sweet et al., 1981). The Fickling Group is correlated with the McNamara Group to the south and the McArthur Group to the north (Blake, 1987).

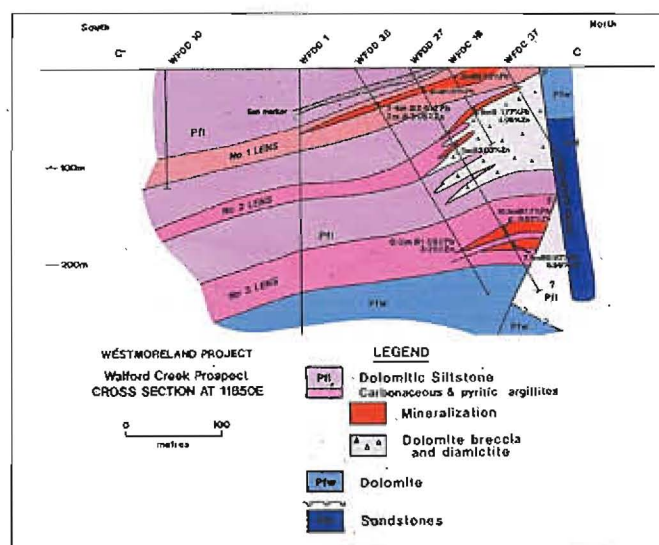
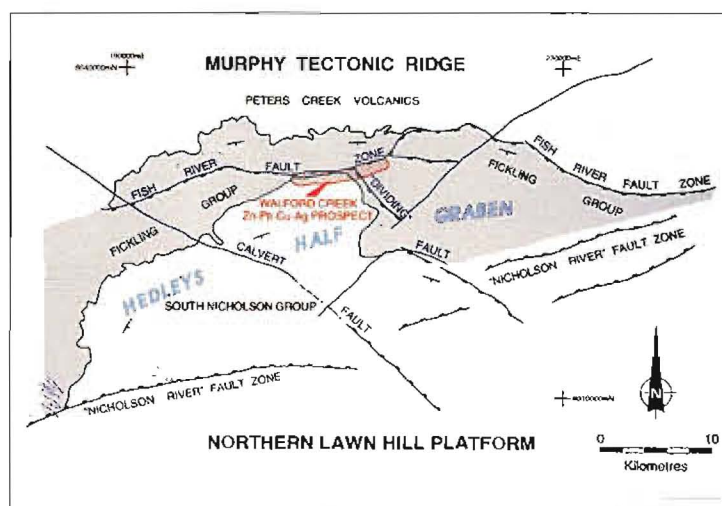
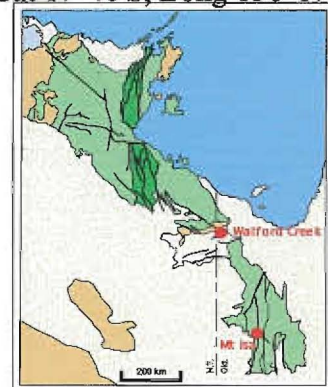
Host Rocks: Shallow S dipping, unmetamorphosed fine-grained dolomitic siltstones and shales of the Mount Les Siltstone. These are locally highly carbonaceous and pyritic. Three (stacked) syngenetic pyrite lenses occur proximal to the Fish River Fault. Talus breccias interfinger with the pyrite lenses and carbonaceous shales. Page and Sweet (1998) report a SHRIMP U/Pb age of 1640 ± 7 Ma from zircons from tuffs in the Mount Les Siltstone. The Mount Les Siltstone is unconformably overlain by clastic sediments of the Doomadgee Formation (a 1613 ± 5 Ma age was obtained by Page and Sweet (1998) for zircons in a unit 250 m above the unconformity).

Size and Grade: No resource estimate has been made for the Walford Creek deposit, but subeconomic mineralisation (2 to 5wt% Zn equivalent) is present over more than 8 km of strike length of the Mount Les Siltstone (Rohrlach et al., 1998). Discordant, Cu-rich mineralisation occurs close to the Fish River Fault. Best intersections reported by WMC were 7.5m @ 6.6wt% Zn, 9.2wt% Pb and 124 g/t Ag, and 6.3m @ 3.5wt% Cu and 5.9 wt% Zn.

Mineralisation: Two generations of syn-sedimentary pyrite and marcasite with a variety of textures (fine euhedral, colloform, spongy) are recognised (Rohrlach et al., 1998). Pyrite is re-worked to form clastic beds (debris flows). Sphalerite, galena and silica occur as porosity infill, impregnations, and replacement of Py1, Py2 and marcasite, and as infillings in the clastic Fe-sulfides. Chalcopyrite occurs in paragenetically late veins.

Genetic Models: Rohrlach et al. (1998) proposed a syndiagenetic model for Walford Creek in which the pyrite lenses formed as mounds with positive relief on the basin floor from hydrothermal fluids escaping from the Fish River Fault. Evidence from ore textures, and the absence of re-worked base metal sulfides in the debris flows, indicate that the base metal sulfides are a diagenetic overprint onto the pyrite lenses. Fluid inclusions suggest most of the base metals were deposited from saline (NaCl-rich) fluids with temperatures of about 180°C as a result of mixing with a cooler ($<60^\circ\text{C}$), dilute fluid. Prolonged fluid movements along the Fish River Fault produced later, discordant styles of mineralisation (including chalcopyrite veins) from a variety of saline fluids. This late mineralisation postdates deposition of some or all of the overlying Doomadgee Formation.

Lat $17^\circ 48'S$, Long $138^\circ 17'E$



References

- Blake, D. H., 1987, Geology of the Mount Isa Inlier and environs, Queensland and the Northern Territory: B.M.R. Australia Bulletin, v. 225, p. 83.
- Page, R.W., and Sweet, I.P., 1998, Geochronology of basin phases in the western Mount Isa Inlier, and correlation with the McArthur Basin: Australian Journal of Earth Sciences, v. 45, p. 219-232.
- Rohrlach, B.D., Fu, M. and Clarke, J.D.A, Geological setting, paragenesis and fluid history of the Walford Creek Zn-Pb-Cu-Ag prospect, Mt Isa Basin, Australia. Australian Journal of Earth Sciences, v. 45, 63-81.
- Sweet, I. P., C. M. Mock, and Mitchell, J.E., (1981). Siegel, Northern Territory, Hedleys Creek, Queensland. 1:100,000 geological map & commentary, Bureau of Mineral Resources, Australia.

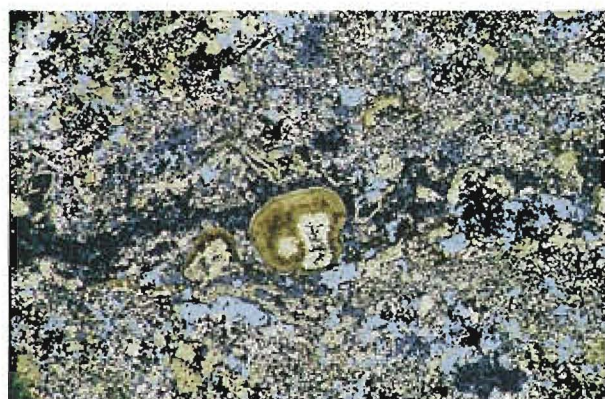


(a)

(b)



(c)



(d)



(e)



(f)



(g)

- a) Drill core from WFDD58 showing (badly decomposed) 'reactive' pyrite from No 1 and No 2 Pyrite Lenses.
- b) Laminated, 'reactive' pyrite from No 1 Pyrite Lens encased in epoxy resin.
- c) Filamentous and 'crinkly' pyritised microbial mat and replacive carbonate from No 3 Pyrite Lens (this sample contains minor chalcopyrite).
- d) Reflected light photomicrograph, field of view is 5 mm across; detrital pyrite sand with sphalerite and galena matrix; large pyrite grain in the centre of the photograph has been interpreted as an oncolite (Rohrlach et al., 1998).
- e) Reflected light photomicrograph, field of view is 2.5 mm across; pyrite/marcasite micro-stalactites and stalagmites oriented perpendicular to bedding within laminated pyrite; dark grey material is silica matrix.
- f) Reflected light photomicrograph, field of view is 2.5 mm across; detail from fine grained laminated pyrite band in No 1 Pyrite Lens.

Lithogeochemical studies of discordant, stratabound Proterozoic Zn mineralisation: Kamarga deposit, NW Queensland

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Centre for Ore Deposit Research

Summary

The Kamarga deposit is a large low grade Zn-Pb resource hosted in dolomitic and evaporitic sediments of the middle Gunpowder Creek Formation on the southern flank of the Kamarga Dome. The sulfides are stratabound (not stratiform) with veins and disseminations of pyrite, sphalerite and galena occurring as replacement and open space fillings. Most of the Zn-Pb resource occurs within 200 m of the Bream Fault, but low grade Zn is still present at least 800 m from the fault.

New samples from three diamond drill holes, and data from an unpublished thesis ((Jones, 1986)), were used to test the response of the Kamarga mineralisation in terms of the basket of geochemical and isotopic indices developed for northern Australian stratiform Zn-Pb-Ag deposits during the course of AMIRA Project P384/384A. Host rocks have a weak response in terms of alteration indices, MnO₂ and Ti. Furthermore, the alteration index and Zn relationships are quite dissimilar to that seen for large, stratiform deposits. The C and O isotope signatures of sparry dolomite associated with mineralisation are distinctly lighter than micritic dolomite in unmineralised Gunpowder Creek Formation carbonates (Jones, 1986).

The lithogeochemical studies of the Kamarga deposit summarised here are discussed in more detail in AMIRA P384 Final Report, pp 303–318, June 1995 and AMIRA P384 Report No. 5, pp 41–54, June 1994.

Introduction

Small discordant, vein-style and occasionally stratabound Zn-Pb deposits are known from several localities in Proterozoic rocks of the Lawn Hill Platform and the southern McArthur Basin (e.g., Coxco, Cooley 1, Burketown Mineral Field veins). In some cases they are spatially closely related to large stratiform Zn-Pb-Ag deposits. What (if any) genetic relationship they have to the stratiform deposits is more problematic. Similar primary lithogeochemical signatures in the discordant deposits and the stratiform deposits would implicate similar genetic processes in both styles of mineralisation.

From an exploration viewpoint, it would be useful if the discordant deposits had a recognisable unique lithogeochemical signature to discriminate them from the stratiform deposits. Lithogeochemical study of samples from drill core from Kamarga in NW Queensland (Fig. 1) provided an opportunity to test a large, low-grade, stratabound Zn deposit for the basket of indices developed for the stratiform deposits in AMIRA P384/384A (Large and McGoldrick, 1998; Large et al., 1998).

Deposit characteristics

Important features of the Kamarga deposit are summarised on Deposit Data Sheet #8 and examples of the sulfides are illustrated in Plate 7. No published account of the deposit is available, but comprehensive description and genetic model for the mineralisation is presented in a PhD thesis by Doug Jones (1986).

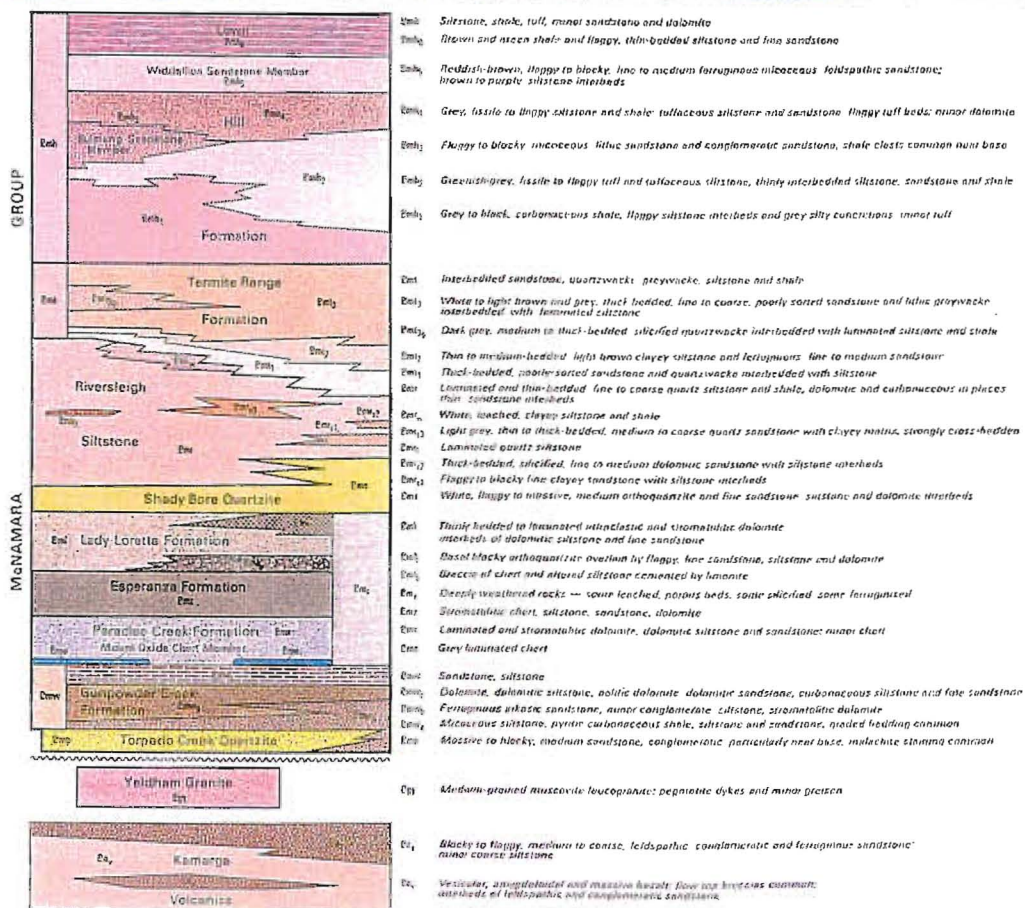
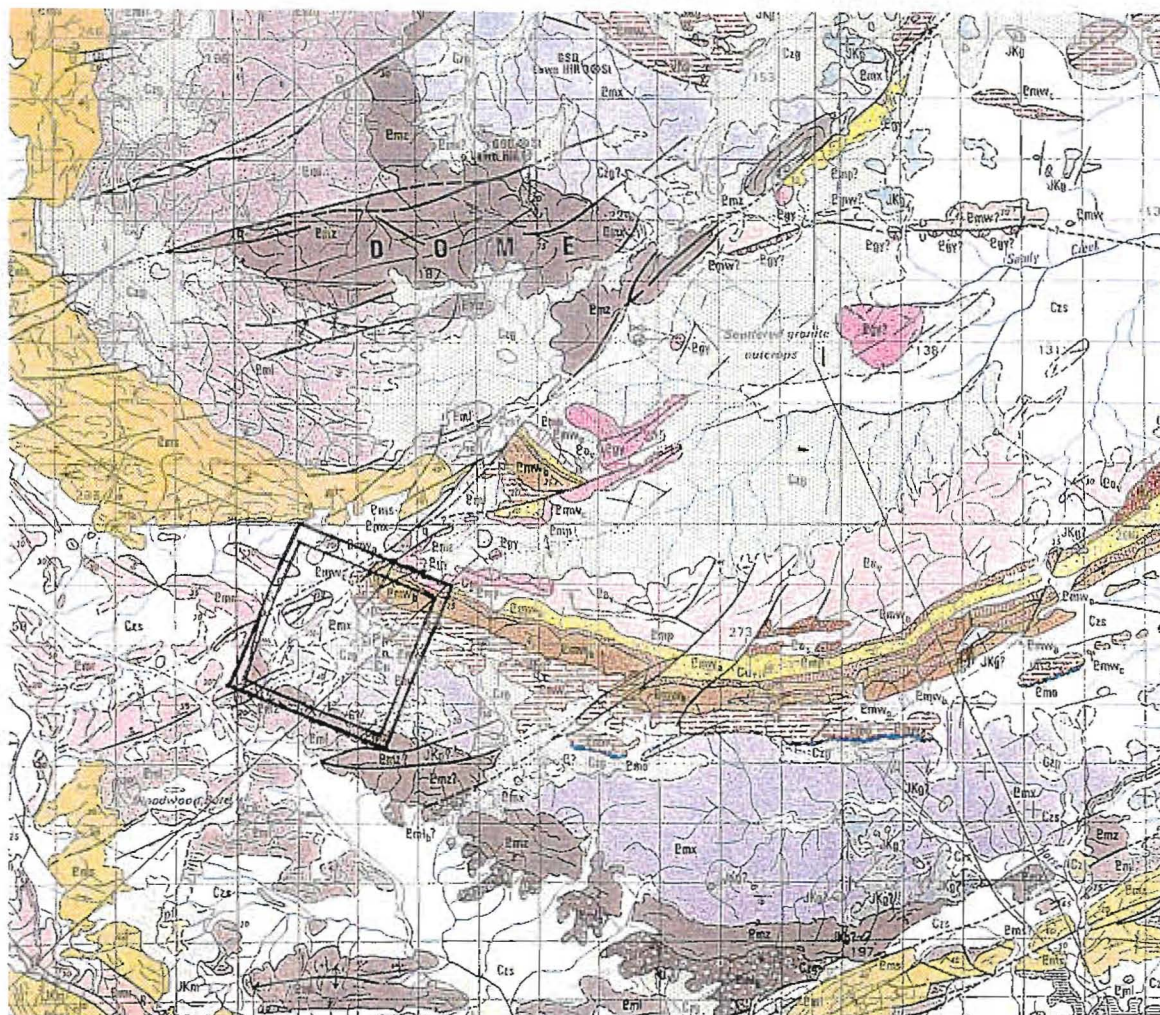


Figure 1. Portion of the Lawn Hill Region 1:100,000 geology map ((Sweet and Hutton, 1982)) showing the location the prospects.

Host rocks

The Gunpowder Creek Formation is a 400 m thick sequence of fine- to medium-grained siliciclastic, dolomitic and evaporitic peritidal sediments. Several shoaling upwards cycles capped by thin, synaeresis cracked carbonaceous mudstones can be recognised (Fig. 2). The Zn mineralisation is largely confined to strongly evaporitic dolomitic siltstones and sandstones in the middle of the section.

Sampling strategy

Sixty six samples from three diamond drill holes (Fig. 3) spanning an approximately 300 m true thickness of the interval from Member 1 to Member 6 were collected for geochemical analysis. Drill hole KD7 penetrated the main area of mineralisation (including 2.3 wt% Zn over about 80 m) about 100 m from the Bream Fault. Hole KD3, a 100 m further E was at its edge (1 wt% Zn over 50 m), and a third hole, WC1, over 1400 m from the Bream Fault, was the most distal available and only weakly mineralised (0.1 wt% Zn over 40 m).

Lithogeochemistry

Host rock carbonates

The CaO/MgO relationship for all samples (Fig. 4), and calculated Fe in carbonate ('FeOcarb') indicates about three quarters of the samples contain significant carbonate, and that this carbonate is dolomite in most samples. Three samples from KD7 with low CaO/MgO and high FeOcarb may contain both dolomite (or ankerite) and siderite (siderite pseudomorphs mush-textured evaporites in two of these samples). Low carbonate samples have not been used for the MnOd calculations (see below).

Zinc

The Zn, SedexAl, Al₃ and MnOd interrelationships and down hole variations for the grab samples from KD3 and WC1 are displayed in Figures 5 and 6. Very few samples are Zn anomalous, with most containing less than 100 ppm Zn. The mineralised parts of KD3 and KD7 contain a few anomalous samples with a few hundred to a few thousand ppm Zn.

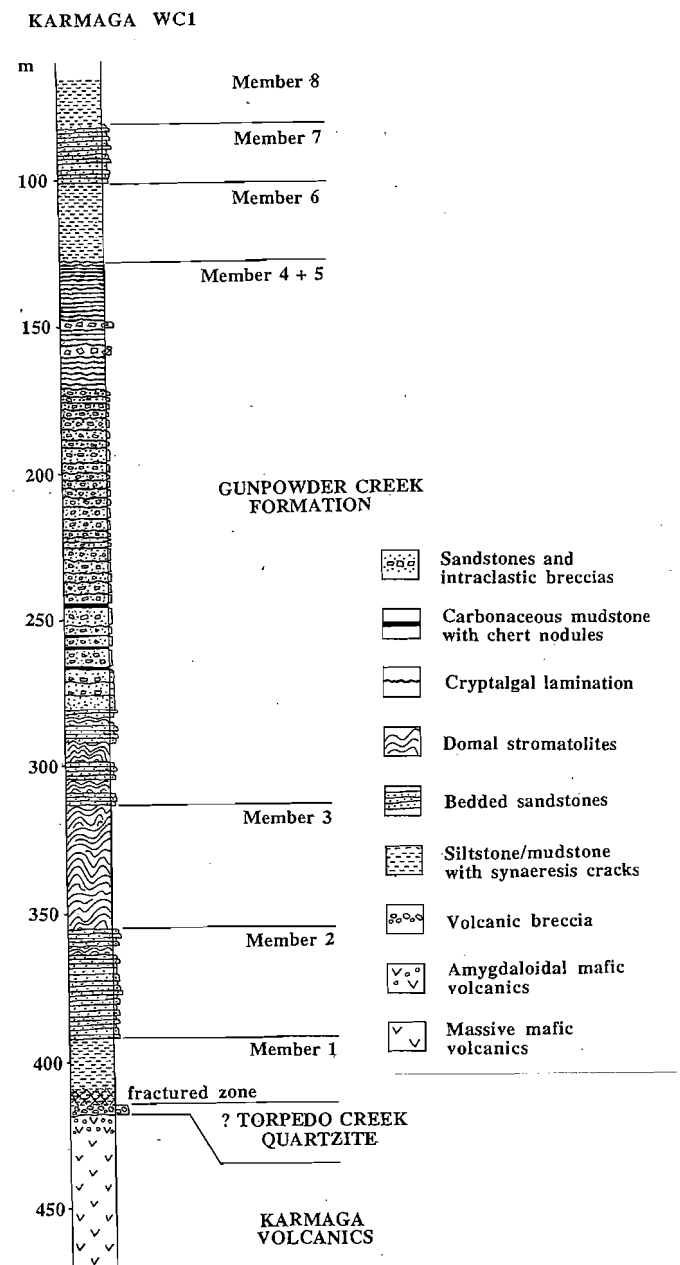


Figure 2. . Lithological log of DDH WC1 showing the facies variations in the Gunpowder Creek Formation at Kamarga.

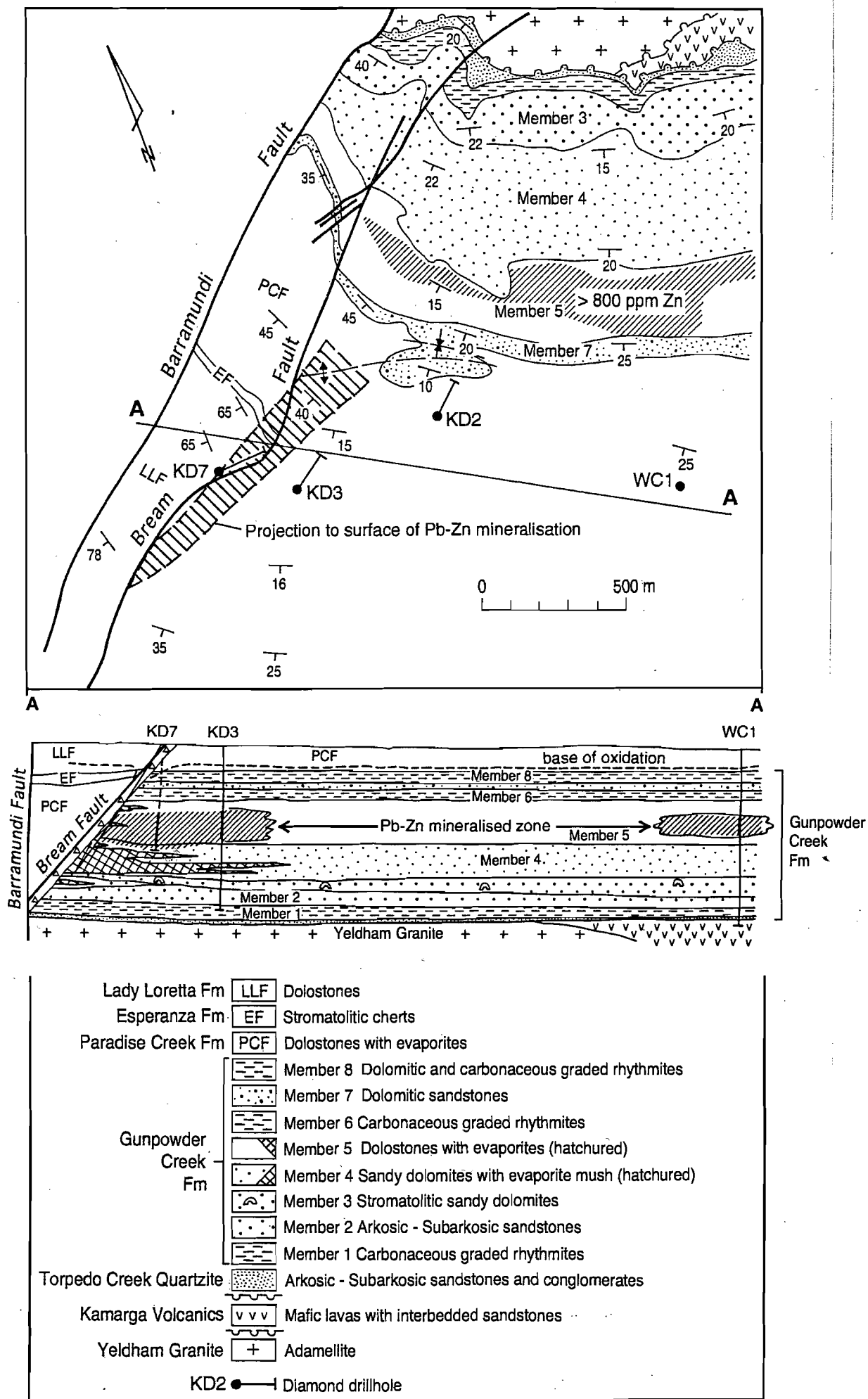


Figure 3. Geological plan and section from the Kamarga area showing the location of the mineralisation and drill holes sampled for this study.

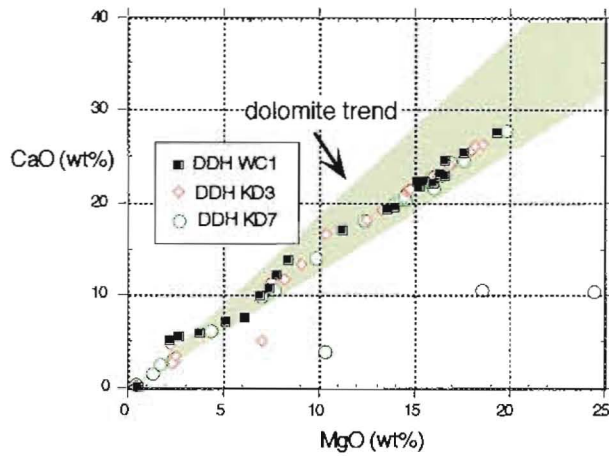


Figure 4. CaO/MgO relationships for 65 samples from the Gunpowder Creek Formation at

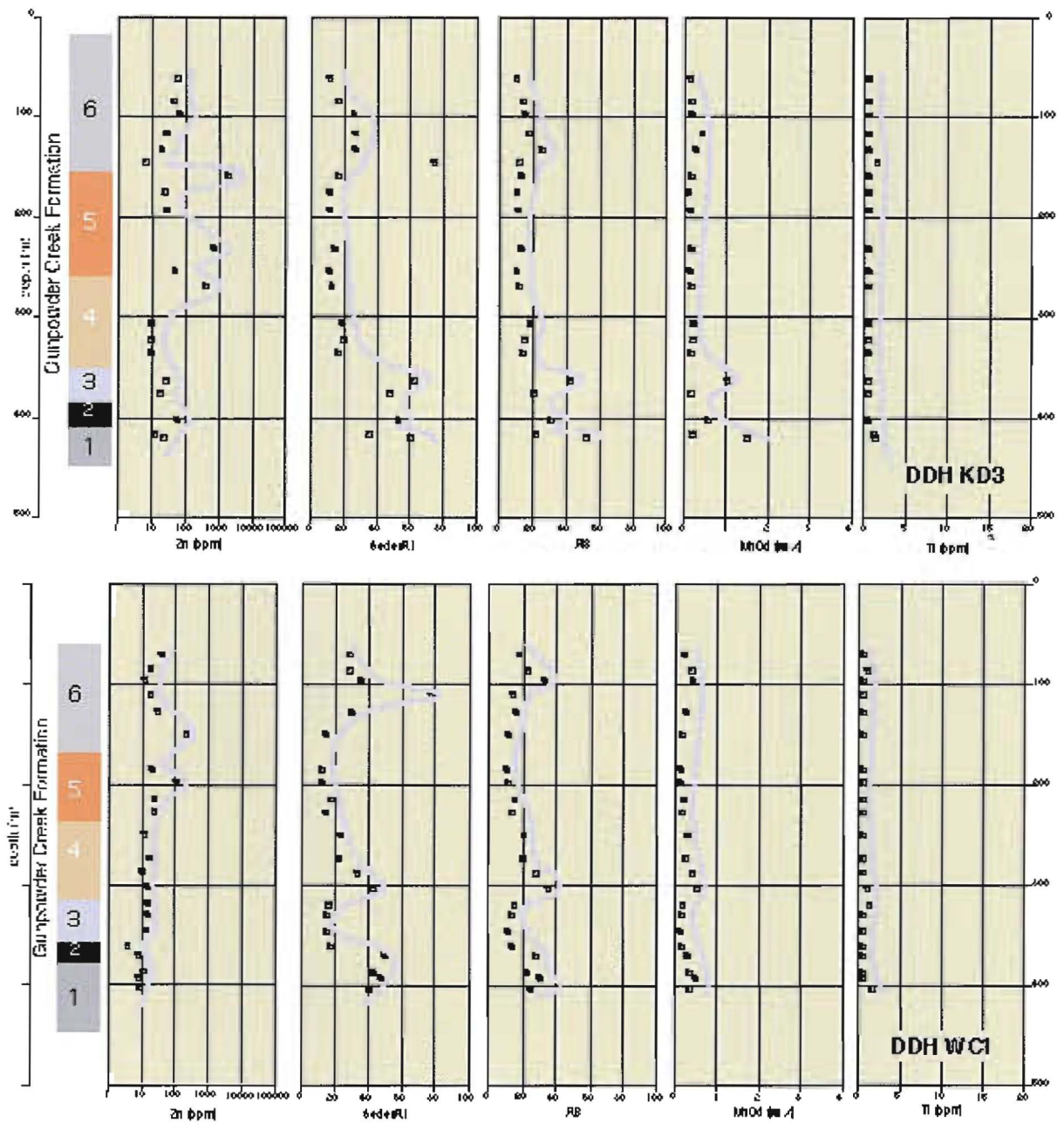


Figure 5: (a) The distribution of Zn, SedexAl, Al₃, MnO and Ti in DDH KD3; Zn mineralisation is present in this hole in the upper part of Member 4 and in Member 5; (b) The distribution of Zn, SedexAl, Al₃, MnO and Ti in DDH WC1.

Alteration indices

Almost all alteration index values (SedexAI and AI3) are within the background for host rocks to large stratiform deposits as defined by Large and McGoldrick (1998) and Large et al., (1998). A few weakly anomalous values are observed toward the bottom of KD3 and a carbonaceous mudstone at the Member 5/6 contact has a high SedexAI value due to the 'shale effect' (Large, 1994). Comparison of Zn to alteration index (Fig. 6) reveals an antipathetic relationship between Zn and alteration index (the 'Kamarga trend') quite unlike that observed in the large stratiform deposits (the 'Lady Loretta trend'). The Mn content of carbonate (MnO_d) in most samples is low, and MnO_d values lie outside the 'Prospectivity 3' box of the AI3/ MnO_d plot (Fig. 6). Two high MnO_d and high AI3 samples from KD3 are from well below the mineralised zone and contain siderite pseudomorphs of sulfate evaporites.

Thallium

There is no anomalous Tl in any of the Kamarga samples. Most are at or near the detection limit of 0.5 ppm, and all but one sample is less than the 2 ppm background for barren Lady Loretta Formation defined by Large and McGoldrick (1998).

Carbon and oxygen isotopes

A small amount of C and O isotope data was available from Jones (1986), and these results are compared in Figure 7 with new whole rock measurements from samples of the Paradise Creek Formation and Gunpowder Creek Formation from two nearby drill holes (BB1 and BB2 – see McGoldrick, 1998). Dolomicrite samples associated with mineralisation are indistinguishable from the whole rock samples. In contrast, dolospar veins and dolospar replacing evaporites has distinctly lighter carbon and lighter oxygen than the whole rock samples (Fig. 7).

Vectors to ore

Lithogeochemical investigations of the Kamarga mineralisation indicate that the 'basket of indices' developed for Lady Loretta and HYC cannot be used as guides to this style (discordant, stratabound, replacement) mineralisation. Grab samples of low-sulfide hosts rocks from within the mineralisation have little or no response in terms of Zn, SedexAI, AI3, Mn in carbonates and Tl. Nor do samples above, below, or in distal stratigraphic equivalents to mineralisation.

Sparry dolomite in the Gunpowder Creek Formation at Kamarga, including some associated with mineralisation, have distinctive (light) C and O isotopic signatures. However, micritic dolomite from mineralised samples has C and O that is indistinguishable from barren whole rock values.

Discussion: Jones (1986) suggested hot, reduced fluids were responsible for forming the Kamarga mineralisation. This contrasts to cool, oxidised fluids that are thought to form the large northern Australian Proterozoic stratiform Zn-Pb-Ag deposits (Cooke et al., 1998 in CODES AMIRA/ARC Project P384A Final Report, Volume 2.). This difference in metal-carrying fluid implies a fundamental difference in ore formation mechanism for Kamarga, which in turn may explain the lack of lithogeochemical response. None the less, from an empirical standpoint, the poor response from the Kamarga mineralisation could be used to downgrade the prospectivity of the Gunpowder Creek Formation on the southern side of the Kamarga Dome.

References

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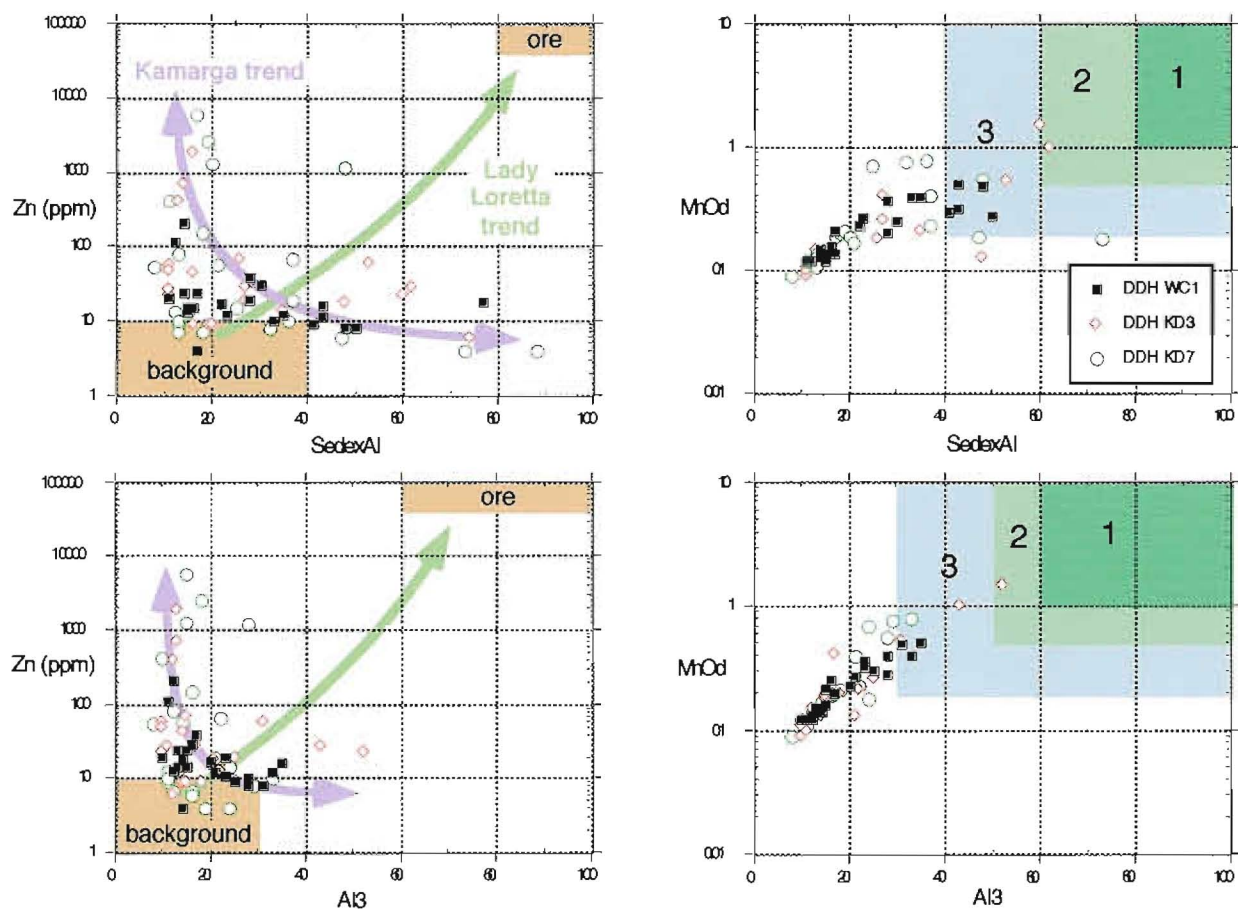


Figure 6. Zn/SedexAl, Zn/Al₃, MnOd/SedexAl and MnOd/Al₃ cross-plots for samples from Kamarga; low carbonate samples have been excluded from the MnOd plots.

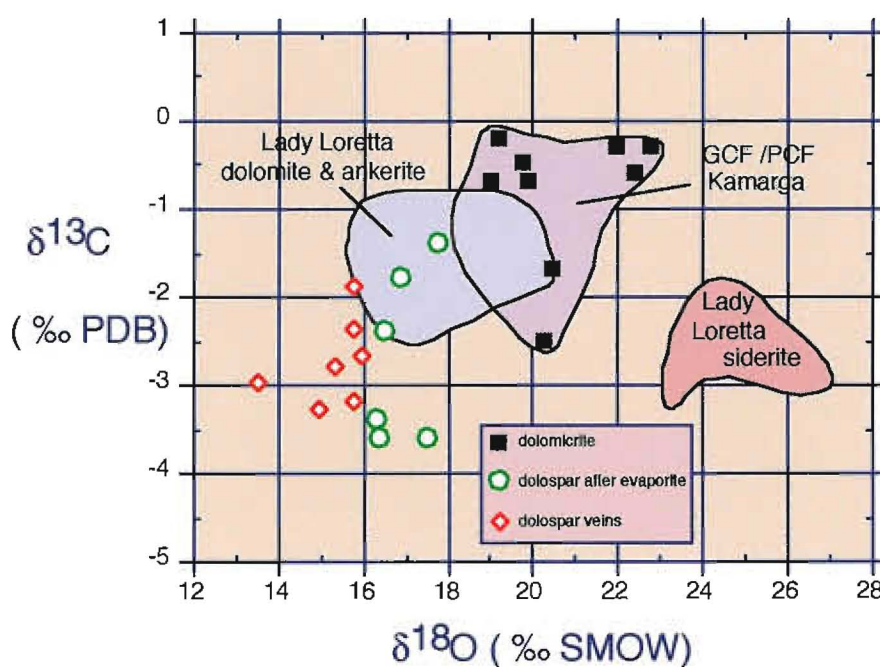


Figure 7. Carbon and oxygen isotope relationship for samples from the Lady Loretta Formation at the Lady Loretta deposit, and for samples from the Gunpowder Creek Formation and Paradise Creek Formation at Kamarga (data for dolomiticrite and dolospar are from Jones, 1986).

- Large, R.R., and McGoldrick, P.J., 1998, Lithogeochemical halos and geochemical vectors to stratiform sediment-hosted Zn-Pb-Ag deposits. Part 1: Lady Loretta deposit, Queensland, *Journal of Geochemical Exploration*, 63, 37-56.
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- Sweet, I. P., and L. J. Hutton, 1982, Lawn Hill Region: 1:100,000 geological map commentary.
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Kamarga Deposit Summary

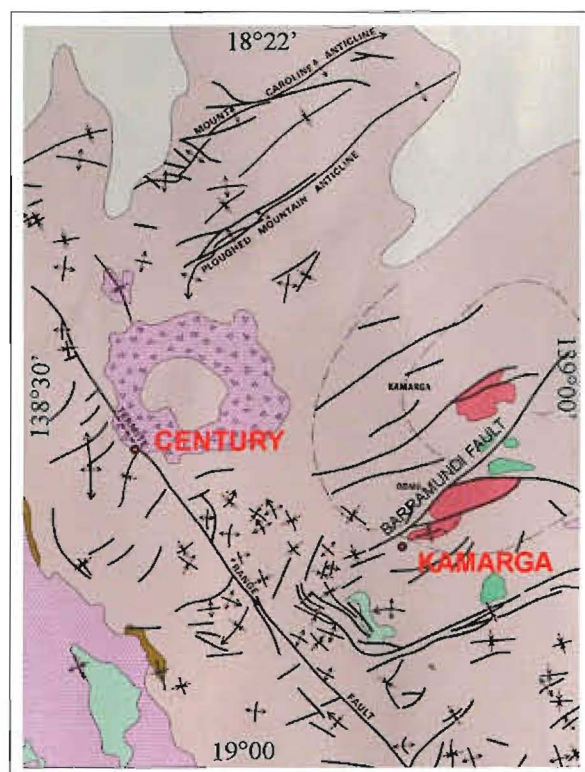
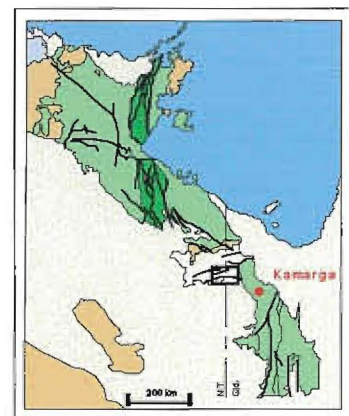
Regional Setting: The deposit occurs in late Palaeoproterozoic lower McNamara Group sediments on the southern side of the Kamarga Dome, in the central Lawn Hill Platform (Blake, 1987). It is adjacent to long lived regional scale NE – SW fault (the Barramundi Fault – Sweet and Hutton, 1982).

Host Rocks: Mineralisation occurs immediately adjacent to the Bream Fault (a splay off the Barramundi Fault) within shallow (20° to 25°) S dipping, unmetamorphosed, evaporitic, peritidal sediments of Members 4 and 5 of the Gunpowder Creek Formation (Jones, 1986). These are the stratigraphically lowest units that are strongly evaporitic at Kamarga. They include stromatolitic and algal laminated dolomites, dolomitic siltstones, sandstones and intraclastic sandy dolomites, and abundant pseudomorphs (silica, carbonate, sulfide) of nodular and mush-textured evaporites.

Size and Grade: A triangular mineralised area of about 2.5 square kilometres by 100 m thick contains a resource of approximately 50 million tonnes grading about 3% Zn + Pb. A higher grade zone (5-10% Zn+Pb) of about 10 million tonnes has been defined within the low grade zone (Jones, 1986).

Mineralisation: Pyrite and base metal sulfides occur as veins, breccia cements, irregular disseminated and massive zones, open space fillings and late stage open veins. Pyrite and sphalerite are the most abundant sulfides with lesser amounts of galena and chalcocopyrite (Jones, 1986 also reported minor jordanite – a Pb-As sulphosalt). Pyrite and chalcocopyrite are more abundant near the Bream Fault and decrease eastward. Non-sulphide minerals commonly associated with the mineralisation include (in order of decreasing abundance) dolospar, quartz, bitumen and fluorite.

Genetic Models: Sulfide - sediment relationships and the discordant nature of the mineralisation indicate that Kamarga mineralisation post-dates the deposition of the host sediments, and because diagenetic fabrics are over-



printed, also post-dates early stages of diagenesis (Jones, 1986). There is some evidence from fluid inclusions for highly saline (16 to 22 wt% NaCl_{eq}), high temperature (270° to 320°) fluids being responsible for sphalerite deposition (Jones, 1986). Sulfur isotopes indicate an evaporite sulfate source of the sulfide in the deposit (Jones, 1986). Jones (1986) proposed a model where deep circulating connate brines became heated, reduced and moderately acid and were expelled up the Bream Fault by seismic pumping. When this fluid first encountered carbonate-rich sediments (i.e., Members 4 and 5 of the Gunpowder Creek Formation), its pH increased thereby promoting sulfide and dolospar precipitation. Late stage fluorite and barite were deposited in response to declining temperature.

References

- Blake, D. H., 1987, Geology of the Mount Isa Inlier and environs, Queensland and the Northern Territory: B.M.R. Australia Bulletin, v. 225, p. 83.
- Jones, D. A., 1986, Stratabound zinc-lead mineralisation in the middle Proterozoic McNamara Group, NW Queensland: PhD thesis, University of New England, Armidale.
- Sweet, I. P., and L. J. Hutton, 1982, Lawn Hill Region: 1:100,000 geological map commentary.



(a)



(b)



(c)



(d)

Drill core from DDH WC1; yellow pencil is 14 cm long and points up hole (i.e., up sequence).

a) Massive and banded dolomite with minor (white) chert nodules (after anhydrite) and intraclast breccias from Member 4/5 of the Gunpowder Creek Formation.

b) Grey banded dolomite and brown (?sideritic) pseudomorphs of primary sulfate evaporite mush.

c) Low grade mineralisation in Member 4/5 of the Gunpowder Creek Formation replacing evaporite mush (above and to the right of the pen); most of the brown mineral is pyrite which occurs as veins, disseminations and overgrowths on dolomite clasts; host rock is dolomite breccia (probably partly hydrothermal and partly intraclast).

d) Lower two core runs contain low grade mineralisation (approximately 1.5wt% Zn) developed in dolomite breccias and evaporites; second core run from top is unmineralised evaporitic (now nodular chert) carbonaceous shale.

Geochemical data sets for northern Australian Proterozoic sedimentary rocks: background variations in lithogeochemical vectors to sedimentary Zn-Pb deposits

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As part of the continuing investigation of lithogeochemical halos to the northern Australian Sedex style Zn deposits an additional 450 high quality multi-element geochemical analyses of unmineralised sedimentary rocks were performed.

Approximately 150 samples were from unweathered surface outcrops and drill core from three areas in the southern McArthur Basin:

- (1) Drill core from the Berjaya prospect to the west of HYC (Winefield et al., AMIRA P384A Final Report v. 2)
- (2) Drill core from the Myrtle sub-basin to the north of HYC (Large and Bull, AMIRA P384A Final Report v. 2), and
- (3) Core and surface samples from the Gorge area south of the Abner Range (Winefield et al. AMIRA P384A Final Report v. 2)

In addition, 20 samples from a drill hole 2 km S of HYC (DDH Homestead 6) were analysed to complete the halo studies of the HYC deposit.

A further 270 of samples from the Western Succession of the Mount Isa were also analysed. These included sample sets for halo studies at :

- (1) Mount Novit (McGoldrick, 1996)
- (2) Grevillea (McGoldrick, AMIRA P384A Final Report v. 2)

and, unmineralised (or weakly mineralised) drill core for background geochemical studies, from:

- (1) Lady Loretta Formation, 4 km NNE of Lady Loretta mine, and from the Carrier area east of Riversleigh station
- (2) Paradise Creek Formation and Gunpowder Creek Formation at Bloodwood Bore (Kamarga).

All these data are included in AMIRA P384A Final Report v.2 on a PC format diskette as a series of Excel Worksheet and Excel text files.

A subset of these samples, representative of unmineralised McNamara Group sediments, has been combined with background data from AMIRA P384 (McGoldrick, 1994) to produce a set of analyses that can be used to gauge background variability in all the important fine grained rock types. Normative dolomite (calculated by assuming all CaO is contained in dolomite) has been used to subdivide the samples into four 'rock types': dolomite (>75% normative dolomite), shaley dolomite (50 to 75%), dolomitic shale (25 to 50%) and shale (<25%). The range shown for important pathfinder elements and element ratios, for each of these sample groups, is depicted on standard cross-plots (Large and McGoldrick, 1998) and as a series of box-plots in Volume 2 of AMIRA P384A Final Report.

References

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- McGoldrick, P., 1994, The geochemistry of 'barren' late Palaeoproterozoic sediments from the McNamara Group: background values for the Sedex Al, AI Mk3 and MnOd, AMIRA P384 Report 7, 141-148.
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Testing lithogeochemical vectors for northern Australian Proterozoic Sedex Zn deposits at the Sullivan deposit, Canada

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Many of the 'basket of indices' developed as vectors to northern Australian late Paleoproterozoic stratiform sediment-hosted Zn-Pb-Ag deposits require a reasonable amount (several percent or more) carbonate to be present in the rocks being tested (e.g., MnO₂ and MnO), while others (e.g., Tl, Sedex Metal Index) do not. Most of the host rocks to the Australian deposits meet this requirement, however, Sedex deposits elsewhere are hosted in siliciclastic sequences may not.

The Sullivan deposit in SE British Columbia was chosen to test the applicability of the lithogeochemical vectors developed for the Australian deposits to a siliciclastic turbidite-hosted deposit. The host rocks to Sullivan are (meta) greywackes and argillites and it was not anticipated that the 'significant carbonate' requirement would be met by many samples. Furthermore, differences in the nature of the Sullivan mineralisation and alteration (e.g., abundant pyrrhotite in the ores, intense tourmalinisation of the footwall rocks) to that seen in the northern Australian deposits suggests two fundamentally different fluids are involved in their formation (see Cooke et al., P384A Final Report v. 2). Hence, although several attempts to define lithogeochemical halos at Sullivan had met with limited success, it was decided to carry out a pilot lithogeochemical study using carefully located drill core from within a few kilometres of the deposit.

For this study 82 low-sulfide, greywacke and argillite samples from a fence of six drill holes extending E for about 8 km from the fringe of the Sullivan deposit were analysed for major and trace elements by XRF at the University of Tasmania. The samples were collected approximately every 10 m for a 200 m interval known to span the stratigraphic

interval containing the Sullivan mineralisation. These samples were supplemented with data further 68 samples from a Geological Survey of Canada regional lithogeochemical survey in the Sullivan area (Goodfellow, In press). This resulted in coverage of the orebody sequence at the fringe of the orebody, and 2, 4, 5 and 7 km away.

The analyses indicate little, if any response in terms of the northern Australian basket of indices for any of the Sullivan samples. There is some promise from Tl, which can be used to identify the Sullivan Sub-basin in the fringe position drill hole, and may have a subtle response in the more distal holes. This response is enhanced using Tl/(Tl+K) ratios. More work is needed to confirm the utility of Tl due to many samples having levels at or near the detection limit for Tl by XRF.

The variation in other elements is erratic; systematic trends that can be related to stratigraphic position are not observed. No multivariate analysis of the data was attempted.

An unexpected result from the study was the observation that many (about twenty percent) of the samples contained significant carbonate (>5wt% normative), and although some of the higher samples occur at the level of the ore position, others do not. A better understanding the nature of these carbonates may open up the possibility of using geochemical signatures from selective leaches of carbonate-bearing Aldridge Formation rocks to identify the Sullivan ore position.

Insights from chemical modelling on the likely composition of ore-forming fluids, metal and gangue associations for stratiform sediment-hosted Pb-Zn (SEDEX) deposits

David Cooke

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From the results of chemical modelling and geological investigations in AMIRA project p384, a two-fold subdivision for stratiform sediment-hosted Pb-Zn (SEDEX) deposits was proposed, based on fundamental differences in the chemistry of the mineralising brines (Cooke et al., 1995; 1998). The type of sedimentary basin from which the ore fluids are derived and the lithologies contained within the basin control these differences in fluid chemistry. The two brine types capable of transporting Zn and Pb are: (1) oxidised brines; and (2) reduced, acidic brines (Fig. 1).

McArthur-type deposits (eg. McArthur River, Mt Isa, Hilton, Century) precipitate from oxidised (SO_4^{2-} -predominant), near-neutral brines that evolve from sedimentary basins dominated by carbonates, evaporites and hematitic sandstones and shales. *Selwyn-type* deposits (eg. Sullivan, Rammelsberg, deposits of the Selwyn Basin) precipitate from acidic, reduced (H_2S -predominant) connate brines that evolved in reduced siliciclastic and shale basins.

Brine chemistry research in AMIRA/ARC project p384a has extended the results of P384 by considering theoretical solubility relationships and possible element associations (Cu, Fe, Mn, Au, Eu) associated with McArthur- and Selwyn-type brines. The redox state of the mineralised brines (sulfate- or sulfide-predominant) is a major controlling factor on minor element associations in the two classes of SEDEX deposits.

Oxidised brines may carry high concentrations of copper (Fig. 2), and there is potential for zoned Cu-Pb-Zn McArthur-type SEDEX systems to form from base metal-rich "super" brines, with Cu proximal to or within the feeder, and Pb-Zn in the distal stratiform position. McArthur-type brines can also precipitate

siderite and manganiferous carbonate as gangue and halo-forming minerals. They are incapable of carrying significant gold, tin and barium in solution, and as such, McArthur type deposits do not contain anomalous concentrations of these elements. Siderite and ferroan carbonate are stabilised in oxidised systems at temperatures below 200°C, and consequently McArthur-type deposits are inferred to form from low-moderate temperature brines.

Reduced, acid brines can carry high concentrations of barium, explaining the common barite lenses in Selwyn-type deposits. If reduced sulfur concentrations were sufficient in the mineralising brines, individual Selwyn-type deposits may contain anomalous or ore-grade gold (eg., DY, Vangorda). If the brines were highly reduced (pyrrhotite-stable), they may have carried high concentrations of tin (eg. Sullivan). Copper solubilities are low in reduced brines unless the waters are strongly acidic, and as such, there is less potential for a genetic association between Selwyn-type Pb-Zn deposits and copper mineralisation.

Iron solubilities are marginally affected by the redox state of the mineralising brines, and strongly affected by acidity. Consequently, Selwyn-type and acidic McArthur-type brines can carry Fe together with Pb-Zn in solution. However, if McArthur-type brines have near-neutral to alkaline pH values, then Pb-Zn may be transported in high concentrations, whereas Fe is insoluble and will not be mobilised in large quantities.

Positive europium anomalies have been considered by previous workers to be a fingerprint of reduced hydrothermal processes, and have been touted for their potential as an exploration vector. Our modelling has shown that europium is

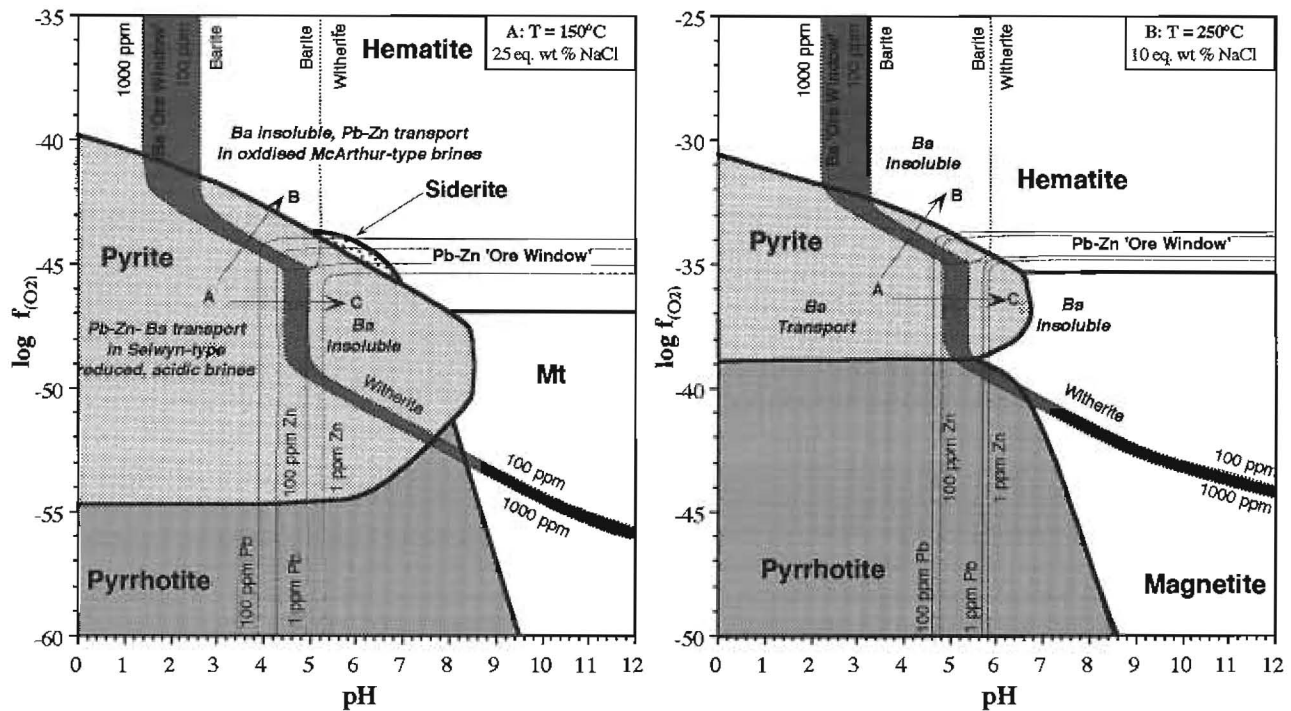


Figure 1. Log f_{O_2} -pH diagrams showing stability fields for Fe-oxides and sulfides, siderite, solubility contours and the 'ore-forming window' for galena and sphalerite, and for barite and witherite. (A) 150°C , 25 eq. wt. % NaCl; (B) 250°C , 10 eq. wt. % NaCl. Arrows indicate the most efficient reaction pathways for barite (A-B) and witherite deposition (A-C) from reduced, acidic (Selwyn-type) brines under isothermal conditions. McArthur-type brines cannot accommodate significant barium transport, due to the low barium solubilities in oxidised waters. Diagrams calculated for $\Sigma S = 0.001\text{m}$, $\Sigma C = 0.256\text{m}$, $m(\text{Na}^+) = 4.76$; $m(\text{Ca}^{2+}) = 0.31$; $m(\text{K}^+) = 0.46$. Thermodynamic data for aqueous Ba-species from Spycher and Reed (1990).

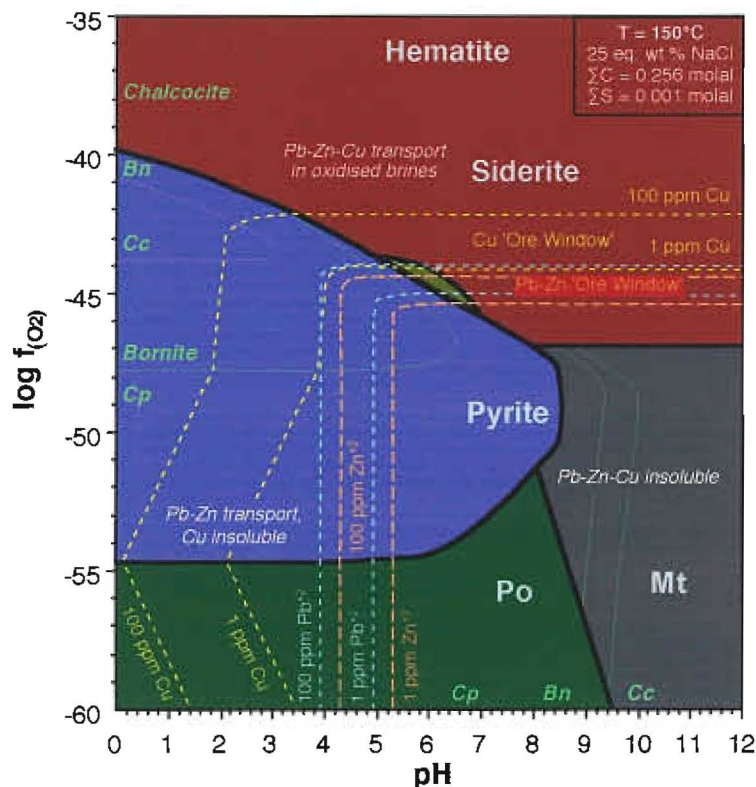


Figure 2. Log f_{O_2} -pH diagram showing stability fields for Fe-oxides and sulfides, siderite, solubility contours and the 'ore-forming window' for galena and sphalerite, and for chalcocopyrite, bornite and chalcocite, together with the solubility contours for copper at 150°C and 25 eq. wt. % NaCl. Diagram calculated for $\Sigma S = 0.001\text{m}$, $\Sigma C = 0.256\text{m}$, $m(\text{Na}^+) = 4.76$; $m(\text{Ca}^{2+}) = 0.31$; $m(\text{K}^+) = 0.46$. Thermodynamic data for aqueous Cu-species from Spycher and Reed (1990).

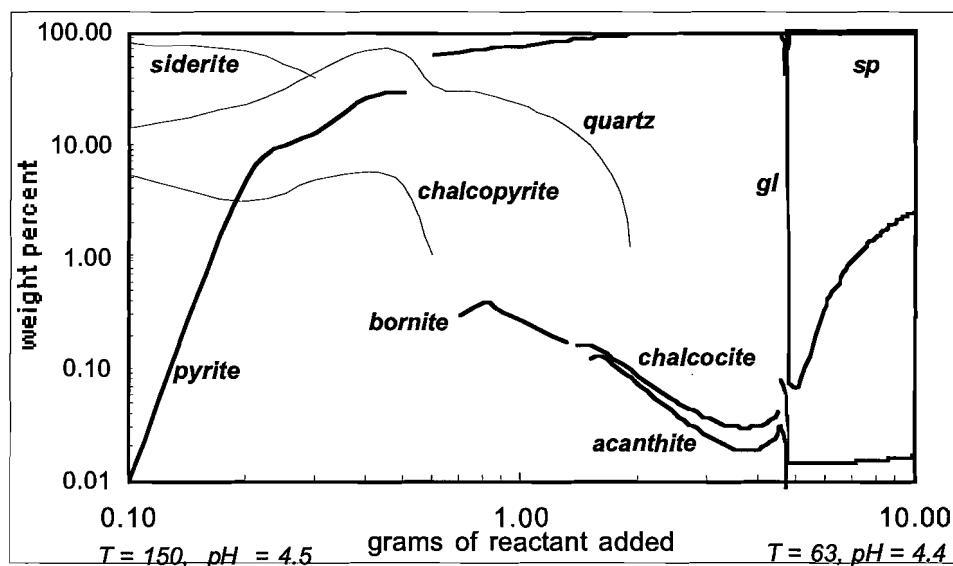


Figure 3. Predicted sequence of mineral precipitation when a 5°C H₂S-bearing seawater is incrementally mixed with a 150°C, 25 eq. wt. % McArthur-type brine with a pH of 4.5 and log $f_{O_2} = -43$. This process is predicted to precipitate zoned massive sulfide mineralisation (sphalerite and galena comprise more than 75% of the total precipitate) with a core of siderite, quartz, pyrite and chalcopyrite, an intermediate zone of galena, quartz, bornite and acanthite, and distal sphalerite and galena.

transported in the +2 valence state in both Selwyn- and McArthur-type brines, and as such has no potential to discriminate between the two brine types. Positive europium anomalies are not a good indicator of oxidation state in the hydrothermal environment, but may still discriminate hydrothermal activity from sedimentary and diagenetic processes.

With regards to depositional processes, temperature decrease and dilution (fluid mixing), addition of H₂S and pH increase can all be important for deposition of Zn and Pb from reduced (Selwyn-type) brines. In contrast, reduction and/or addition of H₂S (via fluid mixing or interaction with earlier-formed pyrite) will be the important processes for sphalerite and galena deposition from oxidised (McArthur-type) brines. Numerical simulations have demonstrated the effectiveness of mixing with reduced seawater (eg. Fig. 3) and interaction with hydrocarbon reservoirs for extracting Pb-Zn massive sulfide mineralisation from McArthur-type brines. Simulations of interaction of a McArthur-type brine with the Barney Creek Formation produces more

complicated gangue assemblages than observed at HYC, suggesting that wallrock replacement is not the principal depositional mechanism for Pb-Zn mineralisation. Cooling of McArthur-type brines produces barren quartz veins, which may be the typical mineral assemblage expected in faults that have acted as conduits for McArthur-type brines.

From an exploration perspective, oxidised sedimentary brines are more likely to produce large tonnage Zn-Pb-Ag deposits that have siderite or ankerite alteration halos and commonly lack barite lenses and vent complexes. They may also have anomalous or ore-grade copper nearby. In contrast, Selwyn-type deposits form in reduced siliciclastic and shale-dominated basins are more likely to be lower tonnage, and to contain barite, vent complexes and minor gold or tin credits. Copper is unlikely to be associated with Selwyn-type deposits. Consideration should be given to exploring for Selwyn-type Pb-Zn deposits in reduced sedimentary basins such as within the Lachlan Fold Belt, and for copper in the northern Australian zinc belt.

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Considerations concerning mineralising fluids within the McArthur Basin with particular reference to the HYC deposit

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Summary

An indicative study using relatively simple assumptions designed to evaluate possibilities and constraints on fluid requirements required to generate the HYC ore system in the McArthur Basin has suggested that gravity-driven or seismic-driven flow systems could circulate the volumes necessary. A seismically pulsed system is considered most likely in view of distance and scale to, and of, any topographic relief which may apply the head whether that relief be stable or undergoing uplift, continuous or pulsed. The complete argument is given by Leaman (1998a).

The ore body is finely layered and was formed in an interval of perhaps only one million years. These observations imply some site specific tectonic influences in association with host or precipitation requirements. There is also a consistency in mineral composition which suggests a fluid source which was not exhausted during ore body formation and which was of fairly consistent chemistry throughout.

The metal required might well have been supplied by volcanic elements of the section (especially the thicker, older sequence) at depth which have been interpreted in regional studies but which are rarely exposed in the McArthur Basin. The brines needed to carry the metals are, however, more special. These are considered to be neutral and oxidised, with temperature a non-critical factor, and may not need an evaporite as source; long term silicate exchanges may be sufficient. These conditions impose other limitations; the fluid and metal solution must be in place for a considerable period and may not be rapidly flushed in order to preserve and develop a homogenised character for supply during the critical

period. The homogenised volume must be very large and chemically quite uniform. A large storage is essential and any hydraulic feed which recycles a storage, or which may drain it quickly, cannot be considered either as a feasible source or reservoir. These constraints exclude many attractive formation options.

Although some background processes may well be applicable for flow control (gravity, perhaps convection) these can not guarantee large volume homogeneity upon sampling due to directed flow patterns (intake-to-points of discharge). Compactive expulsion is not a feasible mechanism. Gravity flow mechanisms can be diverted by fracture or aquifer systems which intersect the flow path and may allow circulation, replenishment or escape which can vary the homogenised chemical requirement. Additionally, the heads available from the two principal zones of active uplift at the time of mineralisation (Tawallah Ranges, Murphy Tectonic Zone) impose severe limitations on the circulation or supply possible.

Seismic processes superimposed on a background circulation system such as gravity flow can provide the required pulsing of local, large volumes; volumes comfortably in excess of those required and which can be isolated - long term - such that homogenisation are almost certain. Seismic withdrawal also focusses flow, radially, to the active structure - a characteristic which makes the entire local volume part of the flow system, a factor which reduces the flushing risks associated with background processes unless these can operate over hundreds of kilometres. Such a range of application is not possible for HYC due to applied head from the Tawallah Ranges nearby.

Density or convective circulation is not easily appraised as a mechanism but the volume and

homogenisation problem still applies: a large volume of fluid must have been available and retained for a long period in advance of the short, mineralising burst.

Estimates suggest, however, that brines of the type required may well have existed only within the thick volcanic sequences believed to be present deep in the basin and which constitute about half the volume of the basin rocks. The conjunction of regional thermal basin cells over long periods, continuing subsidence (host formation), active faulting and stress fields at the time are crucial elements (Leaman, 1998b). It is also likely that metals can be provided by the same volcanic units.

Thermal constraints are loose. Flow disturbance due to depth of circulation, convection or local young granitoids may all combine to vary flow patterns, convection, rate of release and even metal content but thermal conditions are essentially background components. A heat flow maximum near Barney Creek times might well be associated with particular tectonics in the area. It is likely, though, that the coupling of unusual, pulsed compressions (tectonic factor) with a heat flow maximum may fully account for the deposit - given the existence of an appropriate precipitating host. The absence of any of these factors would mean metal dispersion and no orebody. The disrupted character of host rocks adjacent to the Emu Fault is consistent with short term high flows, possible local boiling or over pressuring near the shallow sea floor.

Some additional information will be required before a complete geological, or mathematical, appraisal is possible. All formations known to be, or likely to be, within the section should be sampled for trace metal content and evaluated for their brine generation potential (not easy). Brine evaluation must not be limited to apparent evaporites. There also needs to be some evaluation of cross stratification flow and its potential contributions and whether convective cells are tightly constrained either by formation hydraulics, temperature or fluid density.

The ideas and conclusions generated were intended as feedstock for further observation, mathematical modelling and discussion.

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Numerical modelling of fluid flow systems in the McArthur Basin

Grant Garven and Stuart Bull

Johns Hopkins University and the Centre for Ore Deposit Research

Basins, fluids and lead-zinc ores

Despite the general understanding of stratiform ores in the Proterozoic basins of northern Australia, the hydrodynamic mechanisms causing hydrothermal fluid migration and related geochemical processes for metal transport, rock alteration and ore deposition are largely unknown. Fluid flow in sedimentary basins develop in several forms as a basin evolves geologically, and these include effects of compaction during burial, free convection caused by fluid-density gradients, flow caused by topography, and flow transients caused by tectonic deformation and seismicity (Garven, 1995). Many of these hydrologic concepts are introduced by Leaman (this volume) in his discussion of the HYC Zn-Pb-Ag deposit, Northern Territory.

Predictive numerical models of large-scale fluid migration have been developed and FORTRAN-based codes like JHU2D and RST2D built to quantify ore-forming processes in sedimentary basins (Garven and Raffensperger, 1997). These numerical models permit comparison and testing of conceptual models for fluid migration and ore genesis, which could aid exploration ventures in frontier basins. In this report, one simulation is presented as part of a palaeo-hydrologic study of the McArthur Basin. Conceptually, the numerical models compare different styles of fluid migration for ore genesis in

the McArthur rift, and explore the role of faults in controlling the transport of metal-bearing brines for both steady and transient flow systems (Figure 1). Large et al. (in press) present sedimentological, textural and geochemical arguments that favour a syn-sedimentary origin for the HYC deposit, and so this setting became the focus for preliminary calculations.

Numerical simulation of fluid flow

Numerical modelling requires casting the appropriate partial-differential equations governing fluid flow, heat transport, and geochemical mass transport in geologic media into numerical expressions for either fixed or deforming coordinates (compaction), for either steady or transient flow, and for either thermodynamic equilibrium or kinetic-controlled reactions. Fluid properties, formation properties, and chemical reactions create a strong coupling between the dependent variables of pressure, flow rates, temperature, and mass concentrations. In our models, the transport equations are solved with finite-element techniques that provide coupled predictions through time of fluid pressures, temperature, flow patterns, rates of fluid migration, concentrations of aqueous species and complexes, and masses of minerals dissolved or precipitated in a 2D flow system. Computer-generated maps, in either section or plan view, can be prepared to display the simulation results. Model parameters such as permeability, crustal heat flow, and initial ore-component concentrations are not well constrained, and so sensitivity studies are undertaken to explore the effects of model parameters and geologic boundary conditions.

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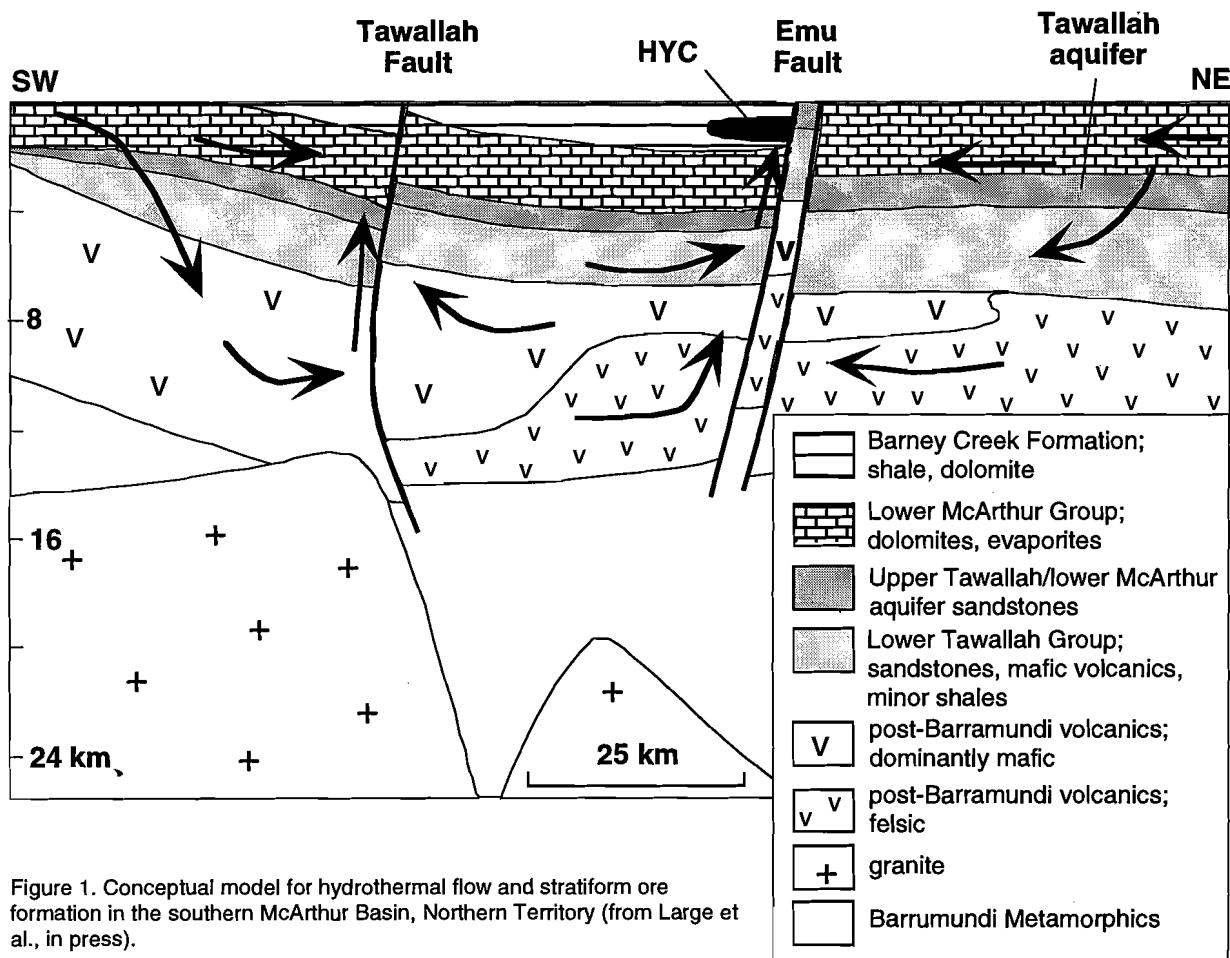


Figure 2 shows one simulation for the southern McArthur Basin, constructed to characterise the plumbing system during syn-sedimentary mineralisation in the Barney Creek Formation (about 1620 Ma). Our hydrogeologic profile extends SW-NE about 150 km across the Batten Trough near HYC (Fig. 2a): the stratigraphy is based on the interpretation of regional geophysics by Leaman (1998) and field observations by Bull and Rogers (1996). For this flow experiment, the sandstones of the upper Tawallah-lower McArthur Group Aquifer (Wununmantlyala, Masterton) comprise the largest porous reservoir (Unit 4), with horizontal hydraulic conductivity $K_x=100$ m/yr and vertical hydraulic conductivity $K_z=1$ m/yr. The thick lower Tawallah Group package (Yiyintyi-Sly Creek Sandstone; Unit 3) below the Upper Tawallah Aquifer is assumed to be cemented-lithified (Bull and Rogers, 1996) and one hundred-times less permeable. Other hydrostratigraphic layers are similarly assigned low

permeability. Two major faults zones, 250-m wide, cut across the stratigraphy. For this flow simulation, the Emu Fault $K_x=K_z=30$ m/yr and the Tawallah Fault $K_x=K_z=0.3$ m/yr. This cross section was discretised with a two-dimensional mesh (not shown) containing 39 rows and 89 columns of finite elements and results produced with the JHU2D basin flow software package licensed to the CODES SRC.

JHU2D calculates fluid-flow lines showing the pathways of fluid migration (Fig. 2b) and the focusing effects caused by the Upper Tawallah Aquifer and high-permeability Emu Fault. The flow system is assumed to be at steady-state, in a submarine environment, and therefore fluid migration is driven by density-driven free convection. Seawater recharges the basin subsurface across the entire rift, although at depth the pore fluids seep slowly (flow rates $q < 0.1$ cm/yr) across the McArthur Group, until they reach the oxidised Upper Tawallah Aquifer where metal concentrations increase and the brines are

driven more quickly ($q \sim 10$ cm/yr) toward the Emu Fault. The model predicts that about $250 \text{ m}^3/\text{yr-m}$ of fluid migrates through the basin annually, all of it rising up the Emu Fault at Darcy flow rates $q \sim 70$ cm/yr (Fig. 2c). These fluids discharge at or near the seafloor forming sulfide mineralisation in the Barney Creek Formation (Unit 6). Salinity increases linearly with depth, such that 20 wt.% equivalent NaCl brines exist at 5 km depth, although this increase in fluid density is partially offset by higher temperatures (Fig. 2d). Structural focusing of fluid discharge results in nearly isothermal temperatures of 120°C in the upper 3 km of the Emu Fault. Other numerical experiments show that a high-permeability Tawallah Fault zone acts mainly as a conduit for sinking (recharge) fluids. This ancient fault-controlled recharge-discharge pattern can be mapped as geochemical alteration halos according to Large et al. (this volume), and such halos could provide exploration vectors for targeting ore zones.

CONCLUSIONS

Hydrogeologic modelling of the McArthur Basin with JHU2D has shown that large fault zones have a major effect on flow patterns for both density- and topography-driven hydrothermal systems. Effects of transient flows associated with compaction and fault-release of overpressures have been modelled and these results will be reported elsewhere. New experiments are planned with the code JHU3D to explore three-dimensional basin plumbing for intersecting faults. The stage is set now for incorporating these hydrologic results into the geochemical reactive flow code RST2D to simulate patterns of rock alteration and mineralisation as the HYC hydrothermal system developed and evolved.

ACKNOWLEDGMENTS

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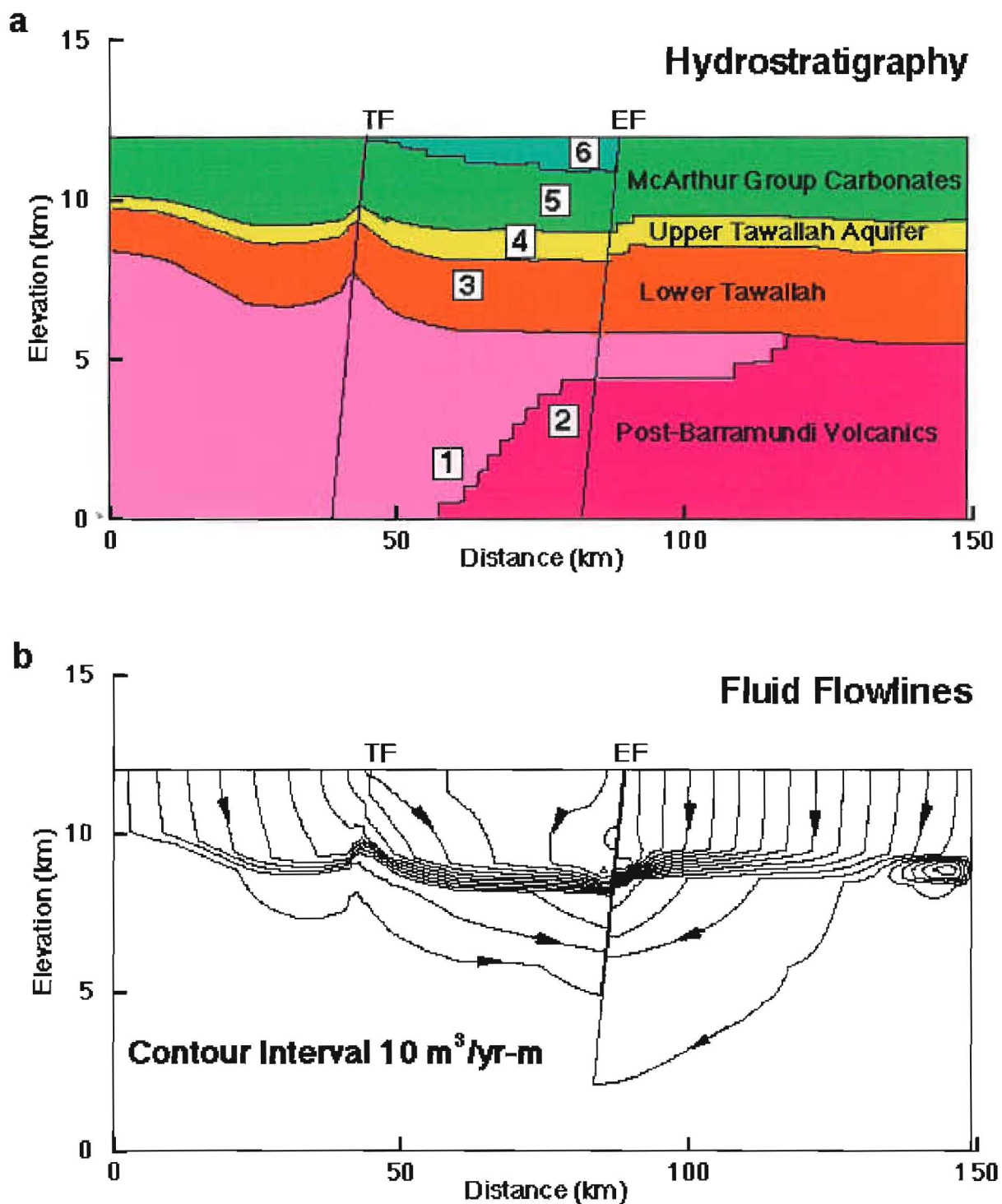
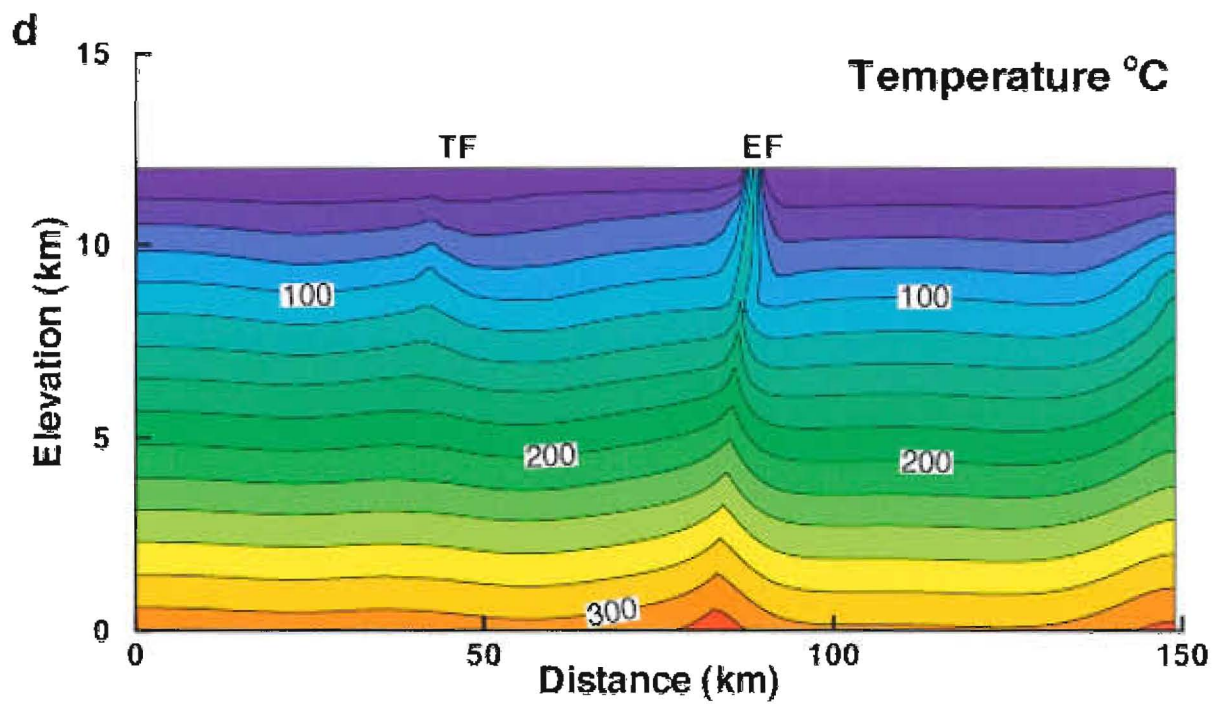
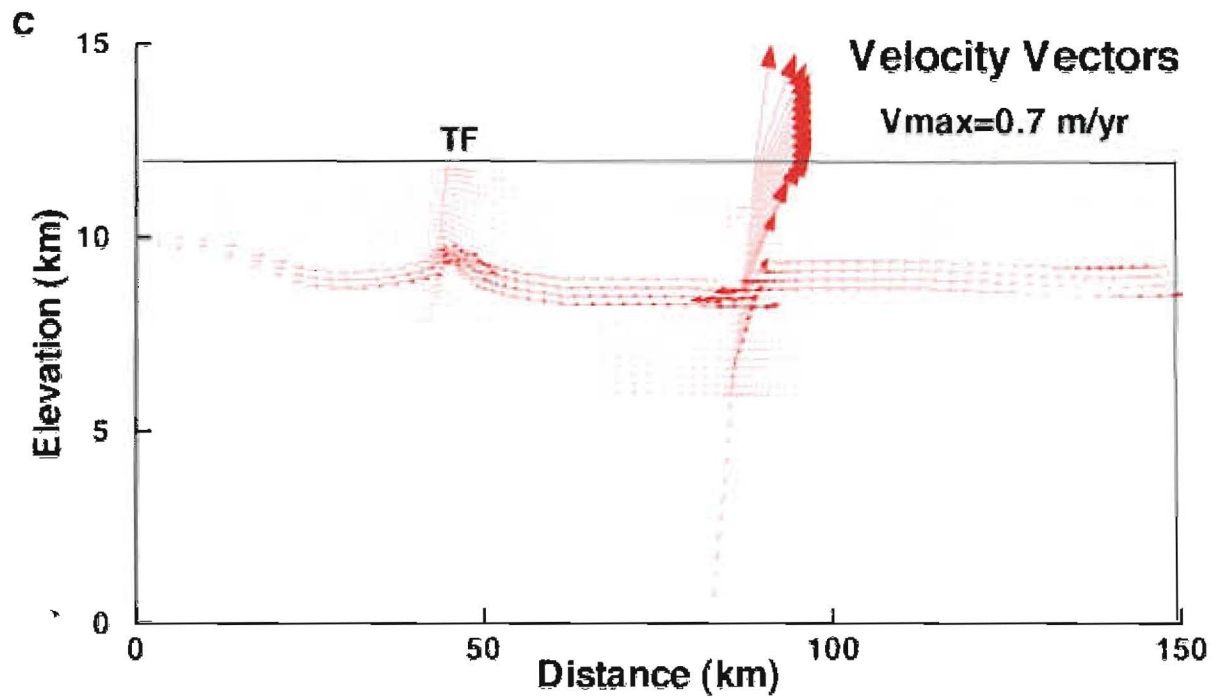


Figure 2. Numerical simulation of hydrothermal system driven by free convection in the McArthur rift near the HYC Zn-Pb-Ag ore deposit.



Criteria to determine recharge (downflow) and discharge (upflow) zones related to stratiform Zn-Pb-Ag deposits, McArthur Basin, N.T.

Ross R. Large, Stuart Bull and Grant Garven

Centre for Ore Deposit Research

Summary

Integration of fluid flow modelling with sediment geochemistry and isotope chemostratigraphy has demonstrated the possibility of identifying the key syn-sedimentary fault zones, or sections of fault zones, that are the conduits for Zn-Pb bearing ore fluids.

Hydrogeological modelling of basinal brines in a east-west cross-section through the McArthur basin, has highlighted the importance of faults as either recharge (downflow) zones or discharge (upflow) zones.

Barney Creek Formation sediments adjacent to discharge zones are characterised by low K_2O/Al_2O_3 ratios indicative of diagenetic illite >K-feldspar, and heavy $\delta^{18}O$ values in sedimentary dolomite. This suggests that discharge fluids were moderately acidic evolved connate brines.

In contrast, the sediments effected by recharge are characterised by high K_2O/Al_2O_3 ratios related to K-feldspar enrichment, and normal sedimentary dolomite $\delta^{18}O$ values. This suggests that recharges fluids were neutral to alkaline marine waters.

Application of the K_2O/Al_2O_3 ratio and isotope chemostratigraphy to all drill holes investigated in this study, indicates that some major faults have switched from acting as discharge conduits to recharge conduits during Barney Creek time.

The combination of this approach of fluid modelling and lithogeochemistry provides the exciting possibility for this line of research, to assist in focussing mineral exploration to fault zones, sub-basins and stratigraphic intervals where brine discharge has been most active.

Introduction

Hydrologic modelling of hydrothermal fluid flow in the southern McArthur Basin by Garven and Bull (this volume) has highlighted the importance of faults as either recharge zones where marine waters descend the basin stratigraphy, or discharge zones where the convected and evolved marine waters flow upwards and discharge to form the ore deposits (Fig. 1).

This modelling also shows that although discharge is confined to faults, recharge occurs throughout the basin but with focus along certain faults (Fig. 1). From both a genetic and exploration perspective it is important to be able to identify which of the syn-sedimentary faults in the McArthur Basin have acted as recharge conduits and which have acted as discharge conduits. In this respect it is relevant that any given fault, such as the Emu Fault, may not have acted as a discharge zone for the entire history of the basin, or along the entire length of the fault. For certain periods (e.g., HYC time) it has acted as a discharge conduit, but for other periods it may have been either a recharge conduit or have been sealed with no significant associated fluid-flow.

In the southern McArthur Basin, the evolving structural regime in the Batten Trough will control fault movements and play a role in determining fluid-flow directions within the faults. Thus detailed structural analysis may give some indication as to which faults had the potential to act as discharge or recharge zones at any given time during basin evolution.

An alternative approach, which we investigate here, is to study the sediment diagenesis and geo-

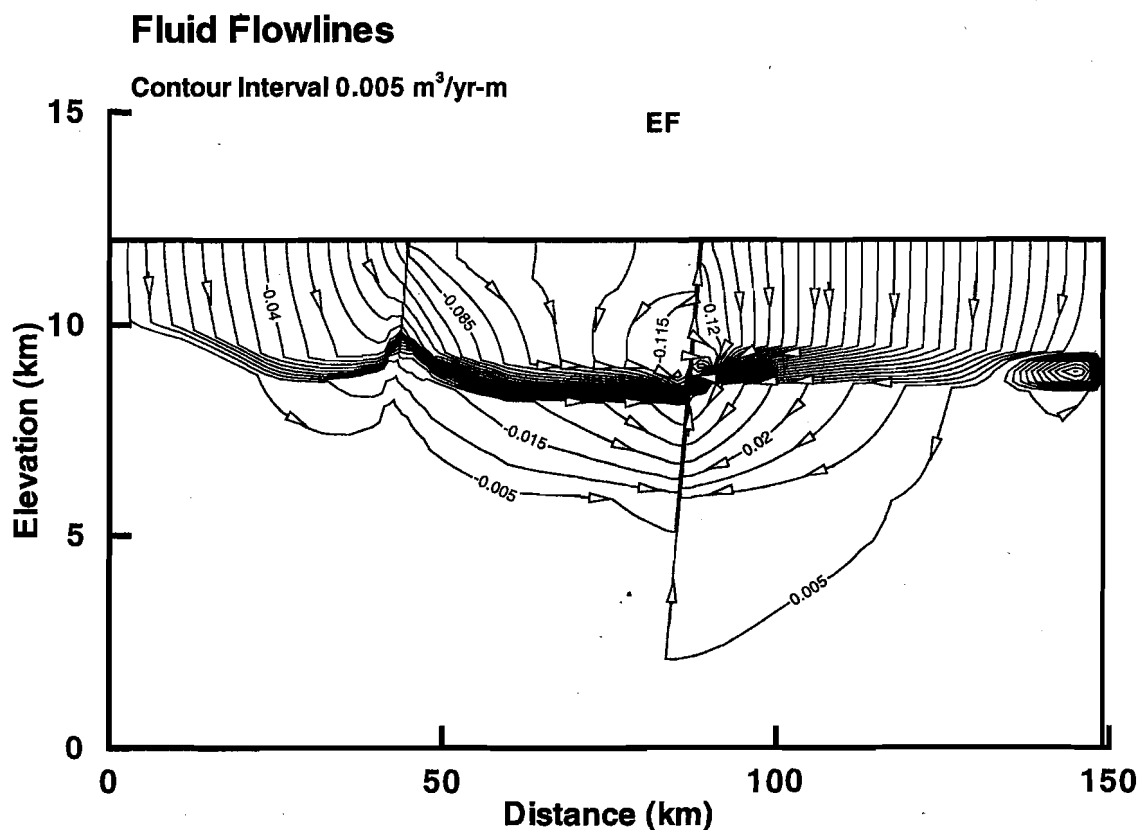


Figure 1. Fluid flow lines for a hydrogeologic cross section of the McArthur Basin at HYC time. Flow is assumed to be at steady state and driven by fluid density gradients in the subsurface (Garven and Bull, this volume).

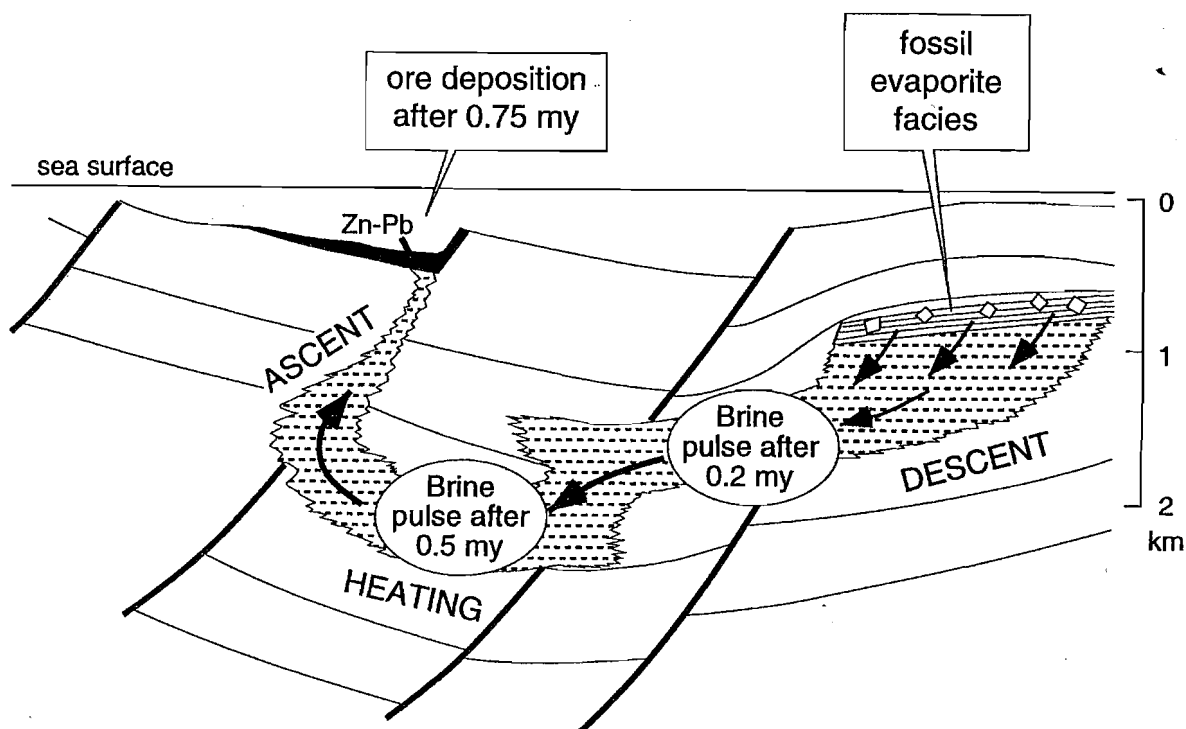


Figure 2. The 'brine factory' model for K-feldspar alteration and Zn-Pb mineralisation from Davidson (1998).

chemistry of the Barney Creek Formation and to interpret fluid/rock reactions that may relate to recharge of marine waters or discharge of hydrothermal fluids.

Sediment diagenesis and K_2O/Al_2O_3 relationships

The principal mineral assemblage in the carbonate and shale sediments of the McArthur Group is dolomite–illite–K-feldspar–quartz. Dolomite chemistry changes according to proximity to stratiform Zn–Pb–Ag mineralisation (Large, Bull and McGoldrick in previous AMIRA P384 reports), and is indicative of discharge of Fe, Mn bearing fluids associated with mineralisation.

In addition to these now well documented changes in dolomite chemistry, there are changes in illite and K-feldspar content of the sediments (Large and Bull, 1996) that probably relate to sediment diagenesis.

Beeson et al., (1989) were the first to recognise the importance of diagenetic K-feldspar in McArthur Basin sediments. They showed that the K_2O/Al_2O_3 ratio of sediments increased from the margins to the centre of the McArthur Basin, reflecting an increase in diagenetic K-feldspar toward the basin centre. Davidson (1995, 1998), in a detailed study of alkali alteration styles in the McArthur Group, suggested that the large scale early diagenetic stratabound K-feldspar metasomatism of volcanoclastic/clastic sediments related to descending brines sourced from overlying evaporites. By analogy with potassic alteration in some North American rift systems, he proposed that the regional stratiform K-feldspar alteration in the McArthur Basin signifies zones of descending brines (recharge) that evolved to form the ore fluid at HYC (Fig. 2).

K_2O/Al_2O_3 chemostratigraphy

Because K-feldspar and illite are the only significant K, Al bearing minerals in the Barney Creek Formation sediments, it is possible to use the whole-rock K_2O/Al_2O_3 ratio to estimate the ratio of K-feldspar to illite in the sediments. Illite has a K_2O/Al_2O_3 ratio of about 0.3 and K-feldspar has a value of about 0.9. Thus sediments which have a K_2O/Al_2O_3 ratio less than 0.6 will be dominated by illite, while those with a

ratio of greater than 0.6 will be dominated by K-feldspar*.

Downhole plots of K_2O/Al_2O_3 ratio for four drill holes through the Barney Creek Formation (BCF) at progressively greater distances from HYC are shown in Figure 3 and discussed below.

DDH Te 115 : This hole passes through the HYC ore zone from 290 to 440 m and has been discussed previously by Large and McGoldrick (1993). The downhole K_2O/Al_2O_3 variation (Fig. 3a) indicates that illite is the dominant potassic mineral through the ore zone and upper BCF. A narrow zone of K-feldspar-rich sediments is present at around 250 m downhole, in the hangingwall of the mineralised sequence.

DDH Homestead 6 : Illite is the dominant potassic mineral throughout the BCF in this drill hole close to HYC. K-feldspar becomes dominant ($K_2O/Al_2O_3 > 0.6$) in the lower part of the W-Fold Shale at the bottom of the hole.

DDH Barney 3: This drill hole is 15 km from HYC toward the outer edge of the carbonate alteration halo (Large and Bull, 1996). Illite is the dominant potassic mineral throughout the hole, except for two K-feldspar-rich tuff beds in the upper section.

DDH BMR 2 : At 23 km from HYC this hole is beyond the Fe-carbonate halo related to HYC. K-feldspar is the dominant potassic mineral present, with the K-feldspar to illite ratio varying from 0.7 to 1.0.

Summary: The drill hole chemostratigraphy indicates that illite is the dominant potassic phase through the ore zone and within the vicinity of HYC, giving way to K-feldspar beyond the discharge-related carbonate alteration halo (Fig. 4).

*These relationships only apply for sediments devoid of other alumina silicates such as albite and chlorite, which is generally the case for the McArthur Group.

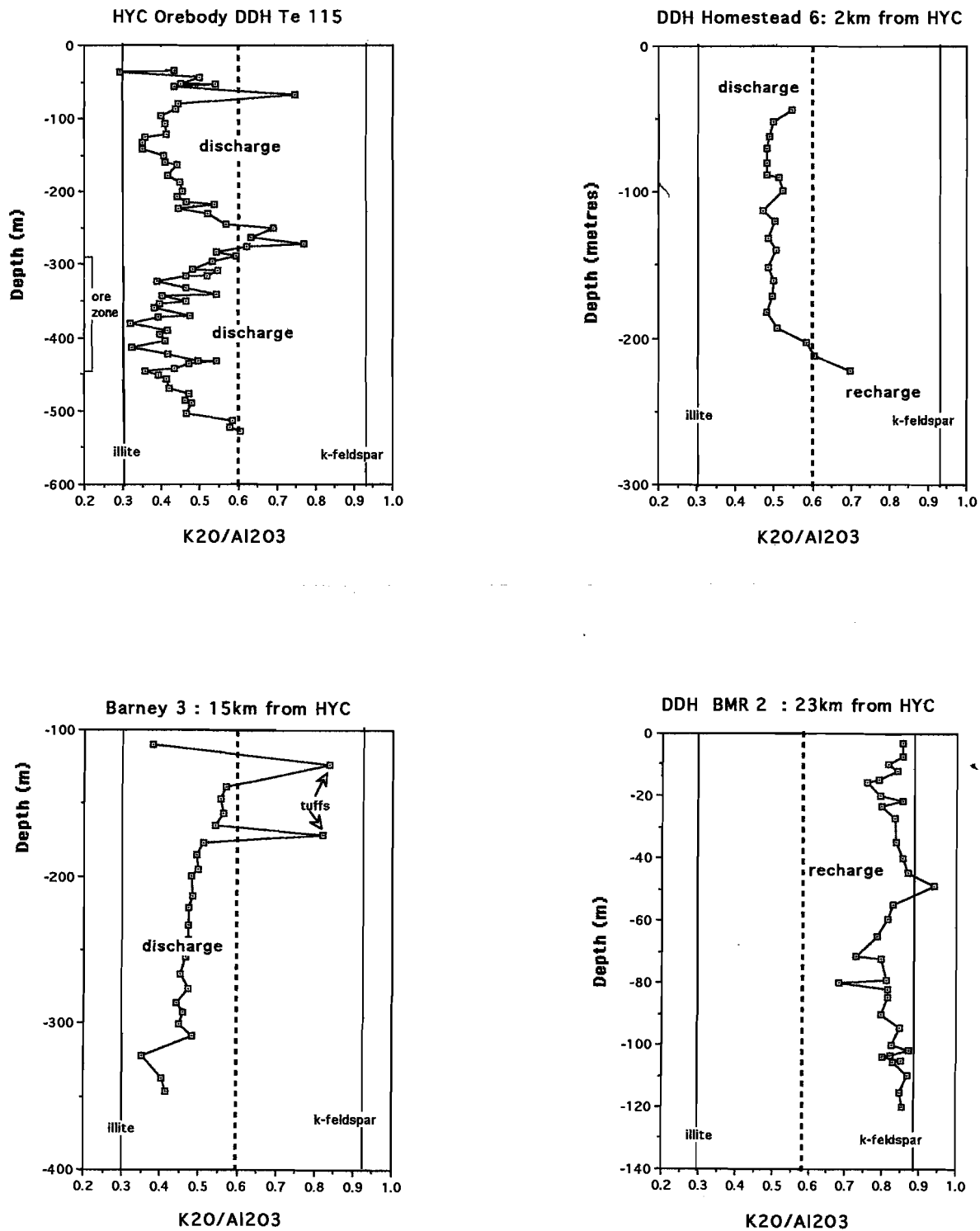


Figure 3. K_2O/Al_2O_3 chemostratigraphy in four drill holes through the Barney Creek Formation at successive distances from HYC (Fig. 4). (a) DDH Te 115 through the HYC orebody (data from Corbett et al., 1975); (b) DDH Homestead 6, 2 km south of HYC; (c) DDH Barney 3, 15 km SW of HYC; (d) DDH BMR 2, 23 km SW of HYC.

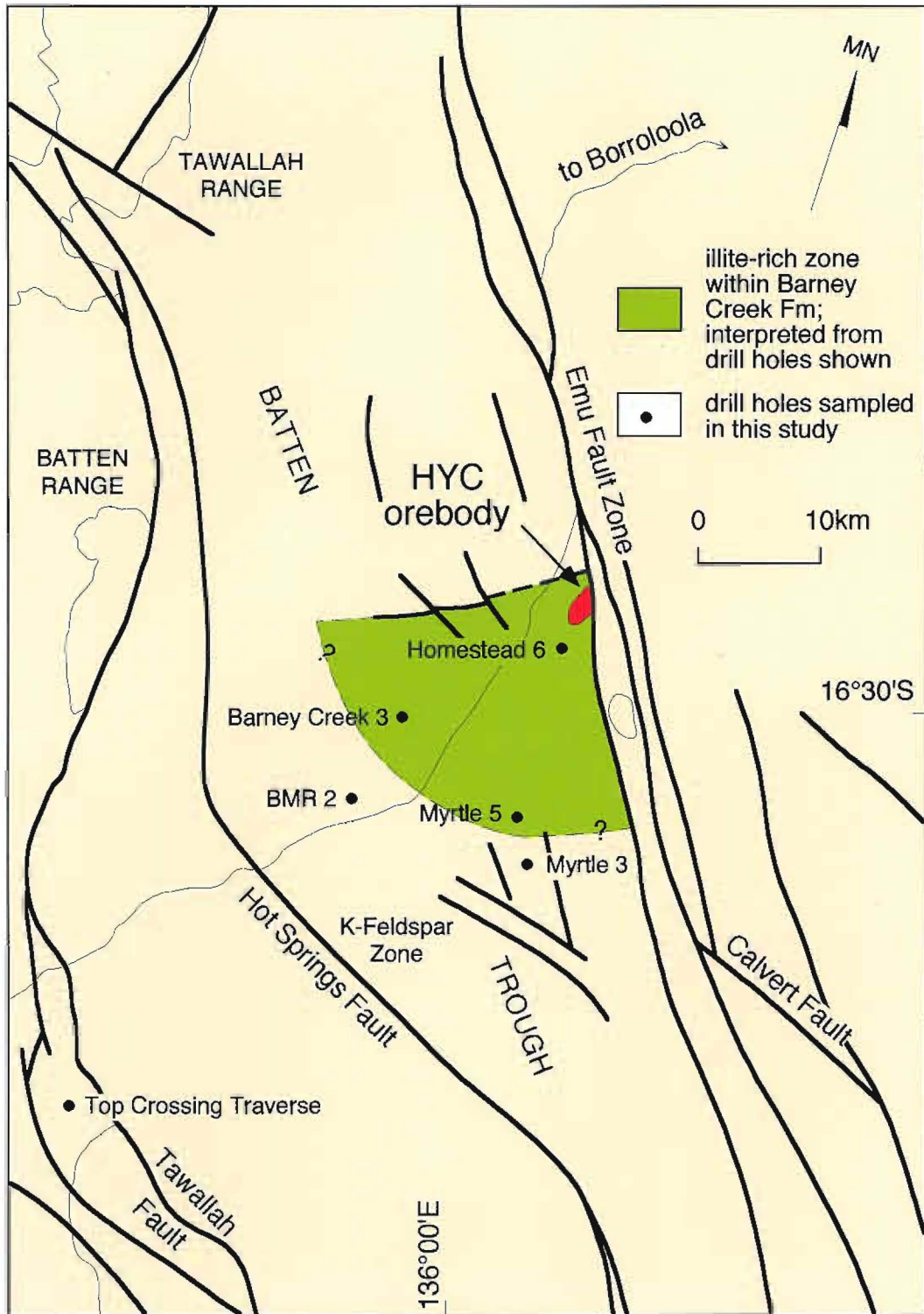


Figure 4. Location of the four drill holes shown in Figure 3, and the limit of the illite-rich zone in the BCF.

This suggests that the discharge fluids related to HYC were in equilibrium with illite while recharge fluids beyond the discharge halo were in equilibrium with K-feldspar. From a chemical viewpoint this means that the discharge fluids possessed a higher a_{K^+}/a_{H^+} ratio, and were thus likely to be more acidic than the recharge fluids (Fig. 5).

Petrography and FTIR Studies

Thin section and FTIR studies were undertaken on the drill samples to check the illite — K-feldspar relationships interpreted from the whole-rock geochemistry. A good correlation between K_2O/Al_2O_3 ratio and FTIR spectra confirmed the K-Al mineral relationships. Preliminary assessment of the FTIR spectra indicates that the illite is an Fe, Mg rich variety, with a composition similar to a phengitic muscovite (i.e., $K_2Al_3Fe_{0.5}Mg_{0.5}[Si_7AlO_{20}](OH,F)_4$). Petrographic studies indicate that both the illite and K-feldspar are very fine-grained, making it extremely difficult to estimate percentages. Figure 6 shows some typical textural relationships of the illite and K-feldspar bearing sediments. A major difference between these two types is that the K-feldspar rich sediments in DDH BMR show very fine recrystallization of carbonate, quartz and K-feldspar (Fig. 6) producing a rock with an interlocking texture of very low porosity. By contrast the illite-rich sediments have a more typical sedimentary texture produced by clay-silicate interlaying.

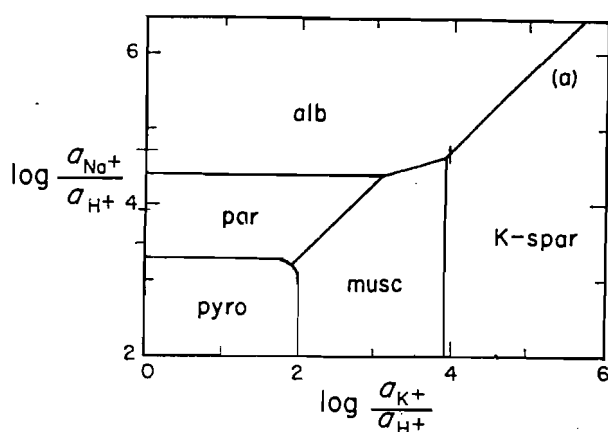


Figure 5. Activity diagram showing that muscovite (illite) is stable at lower a_{K^+}/a_{H^+} ratio than K-feldspar.

Calculation of mineral percentages

The MINSQ computer program developed by Herrmann and Berry (in prep.) was used to calculate the percentage of illite (phengite) and K-feldspar from whole-rock analyses of sediments in selected drill holes in the McArthur Basin study.

This approach shows that the whole-rock K_2O/Al_2O_3 ratio is a good estimate of the relative proportions of illite and K-feldspar in the BCF. In Figure 7 the calculated mineral proportions using MINSQ of sedimentary samples from the four drill holes studied are compared together. Phengite is the dominant K-Al silicate in the holes close to HYC (DDH Te 115, Homestead 6 and Barney 3), whereas K-feldspar is dominant in the most distal hole (BMR 2). Through the ore zone, in DDH Te 115, the HYC Pyritic Shale varies from 10–45 wt% phengite (illite) and 0 to 5 wt% K-feldspar. In contrast the equivalent sequence in DDH BMR 2 contains 1–15 wt% phengite and 15–55 wt% K-feldspar.

Oxygen and carbon isotope anomalies at discharge sites

Our previous work (Large and Bull, 1996) has identified an extensive halo of oxygen and carbon isotope anomalism in the sedimentary/diagenetic dolomite surrounding the HYC deposit. The isotope halo extends for about 20 km south west of HYC (Fig. 8) and is marked by dolomitic sediments which contain heavy oxygen ($\delta^{18}O = 22.5$ to 26‰) and light carbon ($\delta^{13}C = -2$ to -3.5‰). This heavy isotope signature is similar to that reported previously at the Lady Loretta deposit (Large et al., 1995; McGoldrick et al., 1998) and is considered to relate to the discharge of hot, saline brines that are of evolved connate origin sourced from deep in the basin – probably from the upper Tawallah-lower McArthur Group aquifer (Fig. 1). Sedimentary/diagenetic dolomite growth surrounding HYC has occurred in equilibrium with this discharge brine, leading to the heavy oxygen isotope signature. The oxygen isotope halo is therefore clear evidence of the extent of the discharge brines related to the HYC deposit.

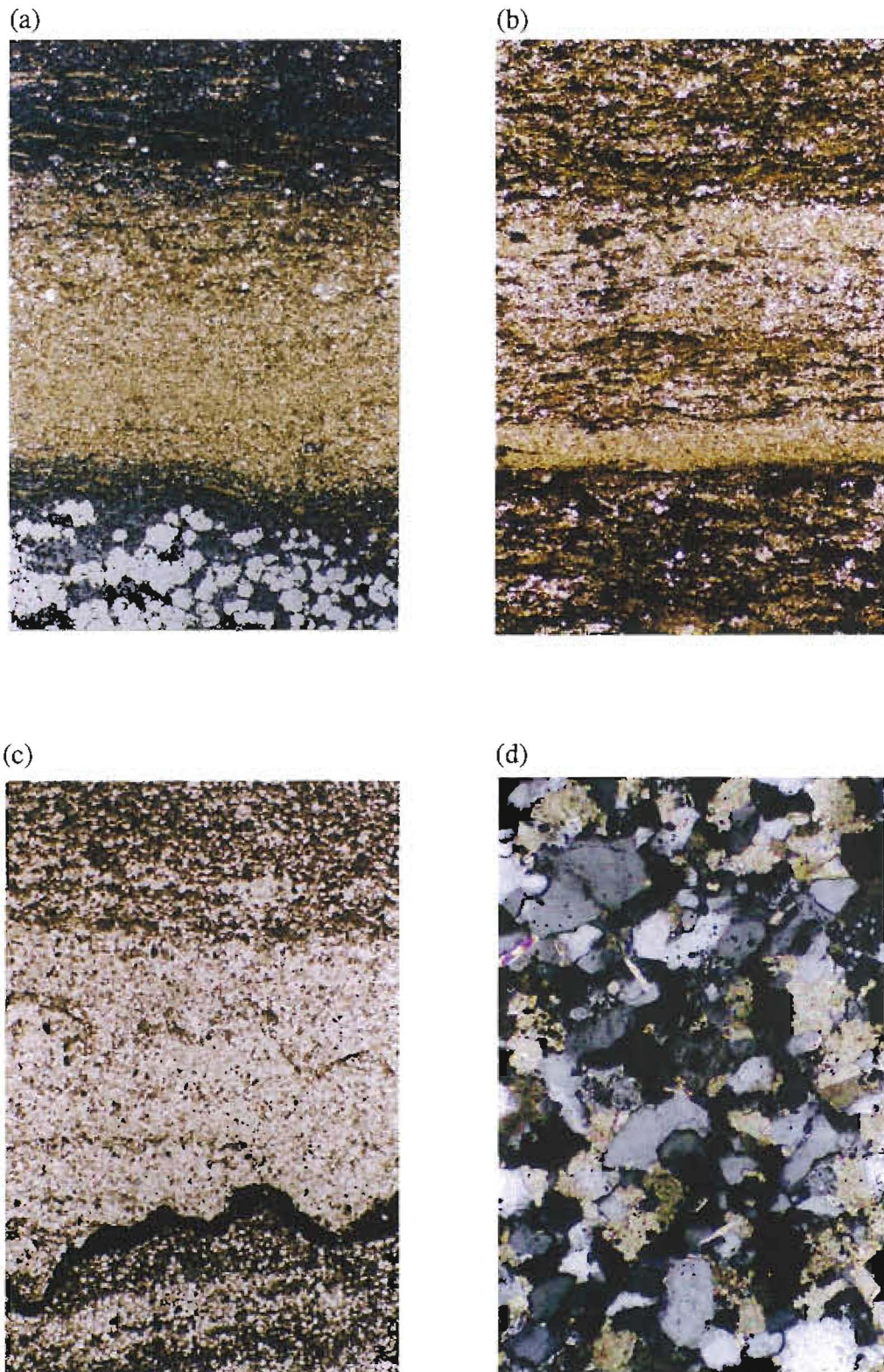


Fig 6 : Photomicrographs of Barney Creek Formation: black dolomitic siltstones showing illite and K-Feldspar bearing examples.

a. Illite bearing siltstone layer, HYC No.2 orebody.

b. Illite and organic(dark) bearing siltstone/mudstone, DDH Homestead 6, 51.6m.

c. K-Feldspar bearing silt-sand size layer in dolomitic black shales, DDH BMR2, 52.3m. (X25).

d. Higher magnification (x200) of quartz-K-Feldspar-dolomite intergrowth texture developed in Kspar rich sediments - same sample as c.

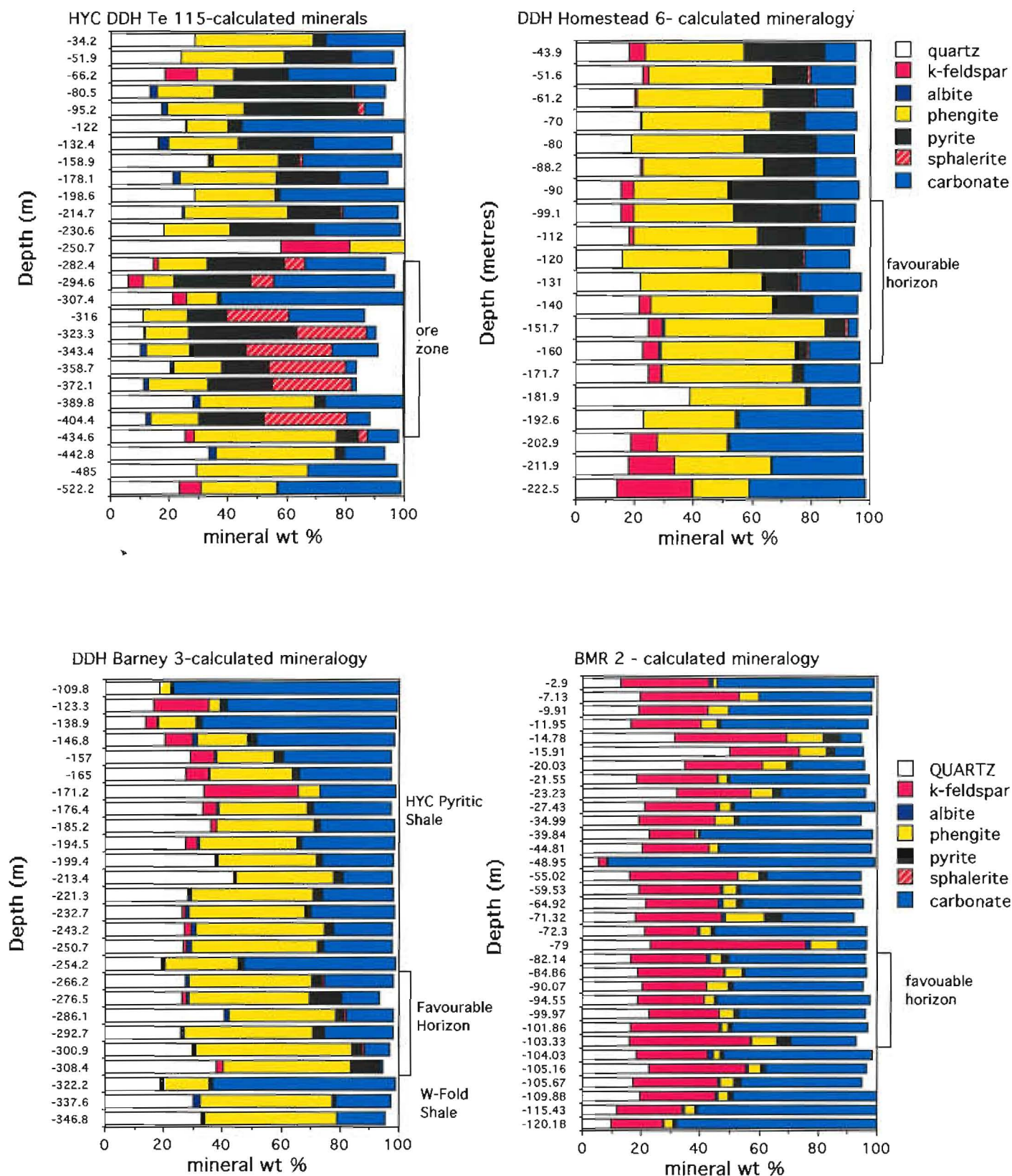


Figure 7. Calculated mineral proportions in samples from four drill holes through the BCF, using the MINSQ program (Herrmann and Berry, in prep.).

C/O isotopes and K_2O/Al_2O_3 relationships

By combining oxygen and carbon isotope data on the sedimentary carbonates with whole-rock K_2O/Al_2O_3 on the silicates it is possible to clearly discriminate the rocks affected by hydrothermal discharge from those affected by marine water recharge.

In Figure 9a the fields for fluid discharge and fluid recharge are clearly outlined:

Fluid Discharge (samples from Homestead 6 and Barney 3):

$\delta^{18}O$ dolomite $> 22.5\%$
 $K_2O/Al_2O_3 < 0.6$
 i.e., illite $>$ K-spar.

Fluid Recharge (samples from BMR 2):

$\delta^{18}O$ dolomite $< 22.5\%$
 $K_2O/Al_2O_3 > 0.6$
 i.e., K-spar $>$ illite.

This data indicates that discharge fluids are mildly acid, in equilibrium with illite, and have a heavy oxygen isotope signature indicative of an evolved connate origin. In contrast, recharge fluids are neutral to alkaline, in equilibrium with K-feldspar, with a normal sedimentary/diagenetic oxygen isotope signature indicative of a marine origin.

The relationships in Figure 9b are not so clear as the carbon isotope fields overlap. The boundary between the discharge field and recharge field approximates to $\delta^{13}C = -1.5$, however a proportion of the samples overlap this boundary. Consequently our future discussion will not involve carbon isotopes in the discrimination of recharge and discharge sites.

Summary

A combination of oxygen isotopes of carbonates and K_2O/Al_2O_3 ratio of silicates in dolomites and shales of the BCF (and related sedimentary units), can be used to identify zones and faults related to fluid discharge (upflow) from those related to recharge (downflow). These relationships are shown in a conceptual model in Figure 10.

Application of this approach to the Top Crossing area

Samples previously collected along a surface traverse to study BCF lithogeochemistry in the Top Crossing area (Large, 1994; Large and Bull, 1996) have been re-evaluated using the approach outlined above.

This is an important traverse, as it samples the BCF adjacent to the Tawallah Fault (Fig. 4), a major north-south structure within the Batten Trough. Our objective here is to test whether the Tawallah Fault, at this locality, has acted as a discharge or recharge conduit during BCF deposition.

Plots of K_2O/Al_2O_3 and $\delta^{18}O$ carbonate along the traverse (expressed as sediment thickness above the base) are shown in Figure 11. This plot indicates that the lower BCF (0 to 60 m above base) has elevated K_2O/Al_2O_3 and light oxygen isotopes. This is indicative of a K-spar rich sedimentary sequence typical of a recharge (downflow) zone. However above 60 m, the upper BCF switches to show the characteristics of a discharge (upflow) zone, with generally heavy $\delta^{18}O$ values ($>22.5\%$) and $K_2O/Al_2O_3 < 0.6$ indicative of an illite dominated sequence.

This switchover, from a lithogeochemical signature indicative of recharge to a signature indicative of discharge, may indicate a change in the structural regime of the Tawallah Fault midway through BCF time. Consequently, there may be potential for stratiform Zn-Pb-Ag mineralisation in the upper part of the BCF along this section of the Tawallah Fault. This interpretation is supported by plotting the Top Crossing data on the discharge-recharge discrimination diagram developed for HYC (Fig. 12).

Conclusions

During the deposition of the BCF in the southern McArthur Basin, some major syn-sedimentary faults have acted as recharge (downflow) conduits and others have acted as discharge (upflow) conduits. By combining carbonate isotope data with whole rock K_2O/Al_2O_3 data on the sediments adjacent to these faults, it may be possible to distinguish discharge zones from recharge zones and thus focus exploration to the highest priority sites.

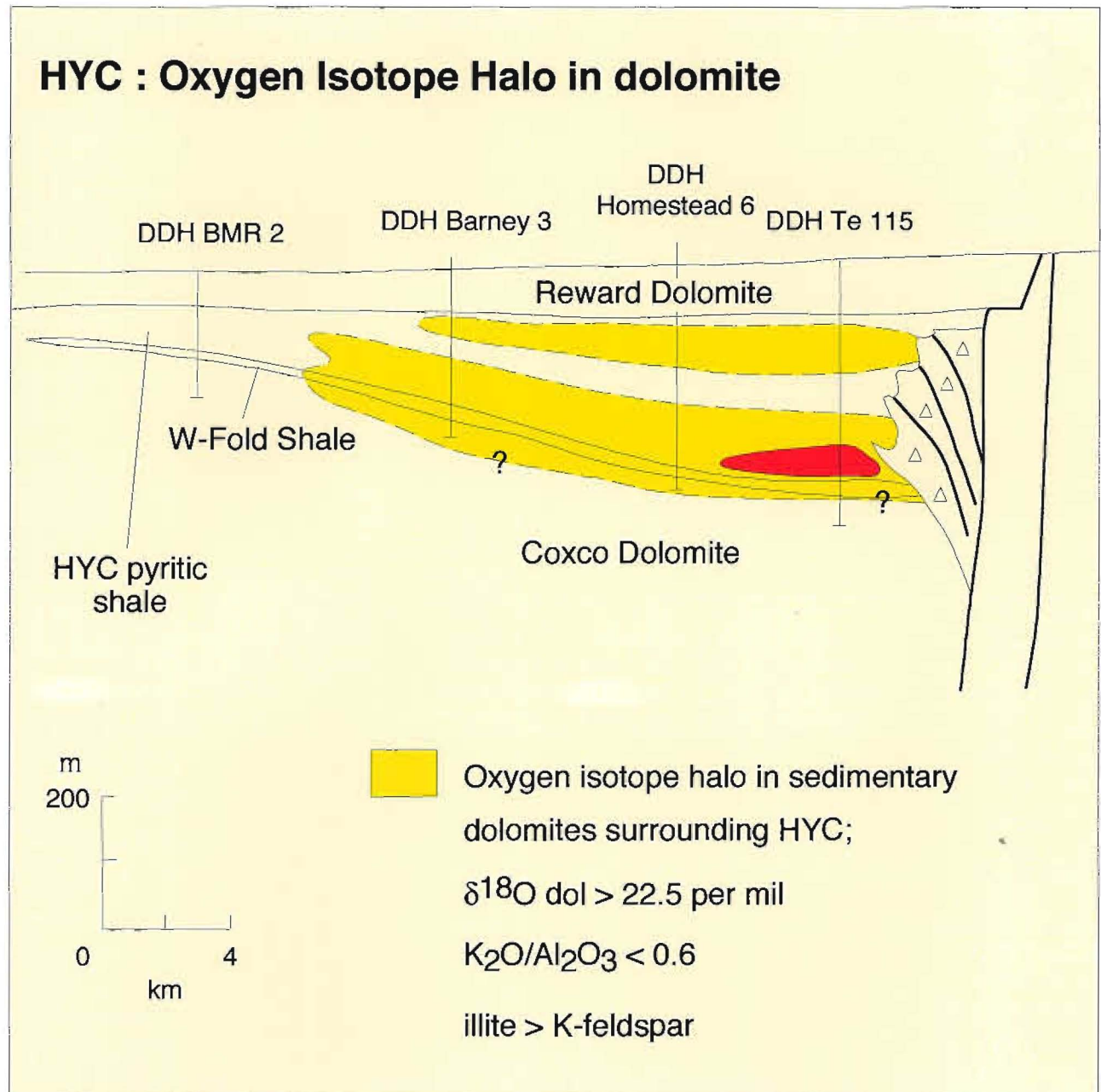


Figure 8 . Oxygen isotope halo to HYC, based on data from the orebody, plus DDH Homestead 6, DDH Barney 3 and DDH BMR 2 (Large and Bull, 1996).

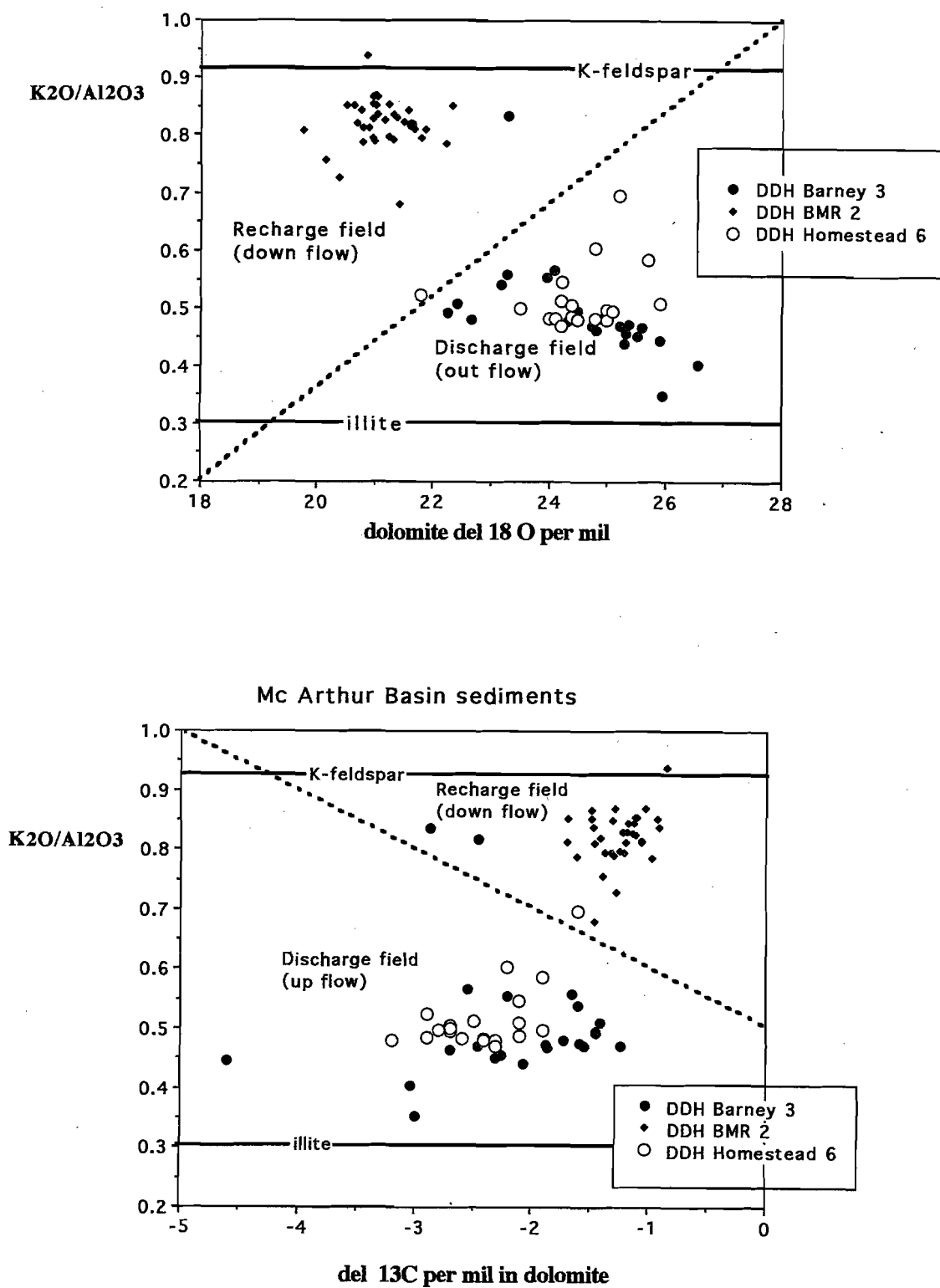


Figure 9. Recharge and discharge fields for BCF sediments based on dolomite C/O isotopes and silicate K₂O/Al₂O₃ ratios.

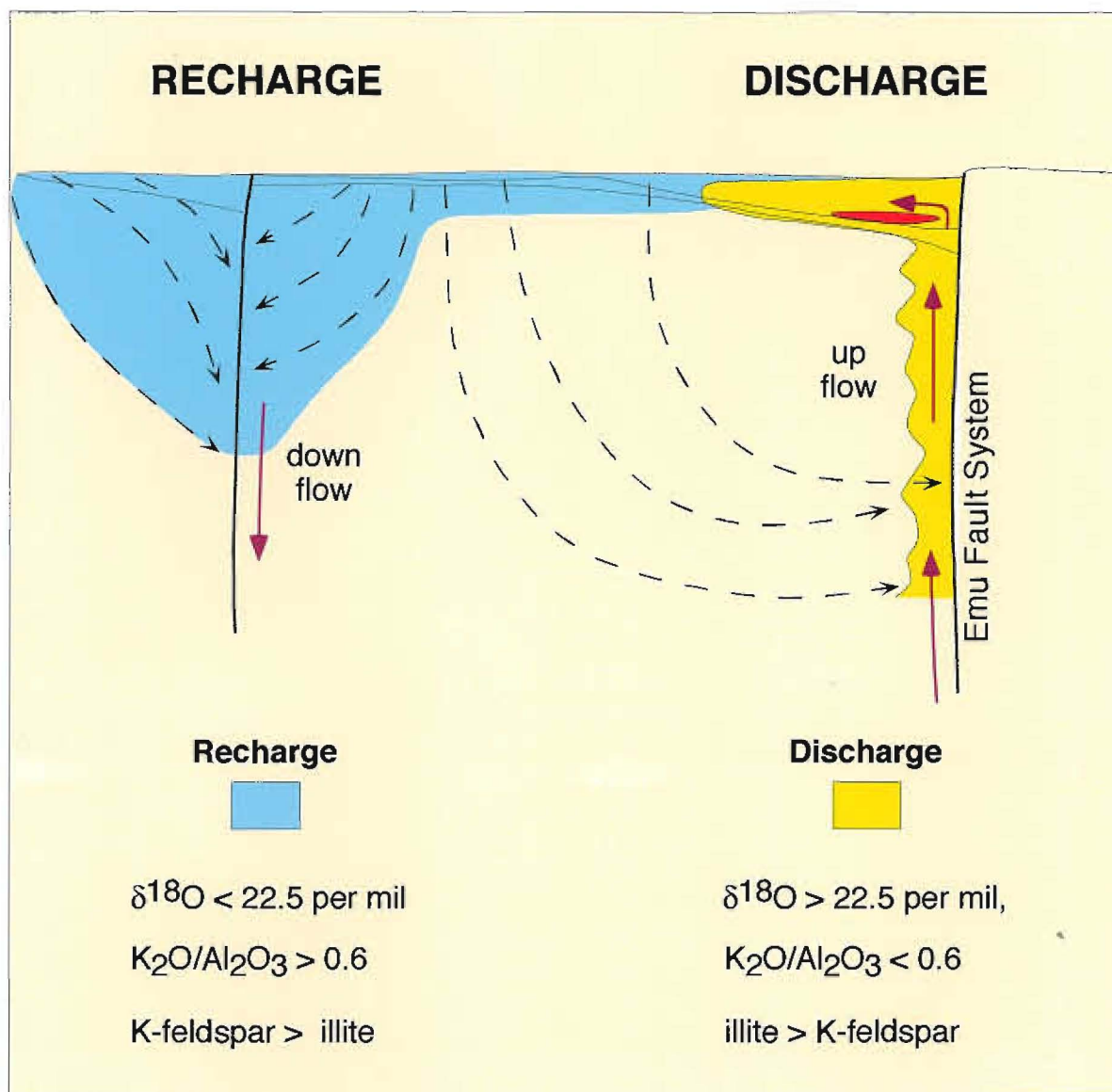


Figure 10 . Model showing the geochemical discrimination of fluid recharge zones from discharge zones related to stratiform Zn-Pb-Ag deposits in the McArthur Basin, N.T.

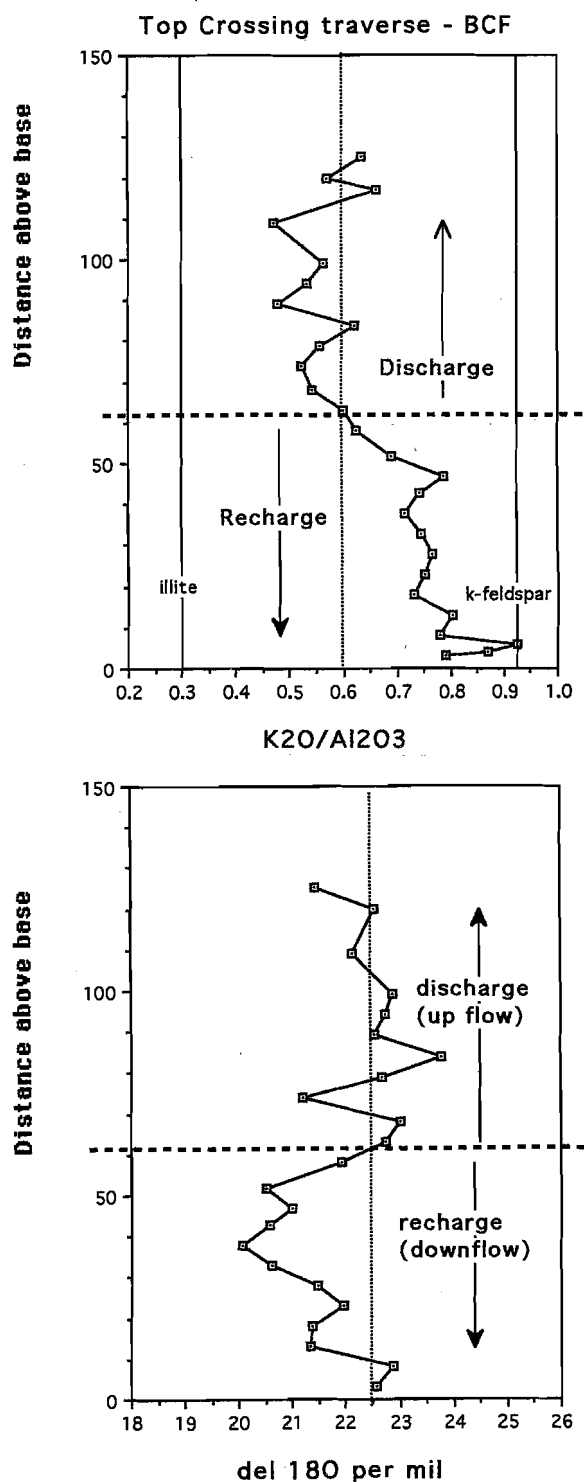


Figure 11. K₂O/Al₂O₃ and carbonate oxygen isotope chemostratigraphy in the Top Crossing area through the BCF.

Our work suggests that discharge zones related to SEDEX mineralisation are characterised by heavy carbonate oxygen isotopes (>22.5 per mil) and illite dominated assemblages (K₂O/Al₂O₃ <0.6). In contrast, recharge zones have K-spar dominated assemblages with light carbonate oxygen isotopes.

Our research also suggests that chemostratigraphy has the potential to identify where certain major syn-sedimentary faults have switched from recharge conduits to discharge conduits during BCF deposition. By combining this approach with our previously identified basket of indices (SEDEX AI, AI₃, MnO_d, Tl, Zn, Pb), it is possible to target favourable horizons within discharge zones for maximum exploration benefit.

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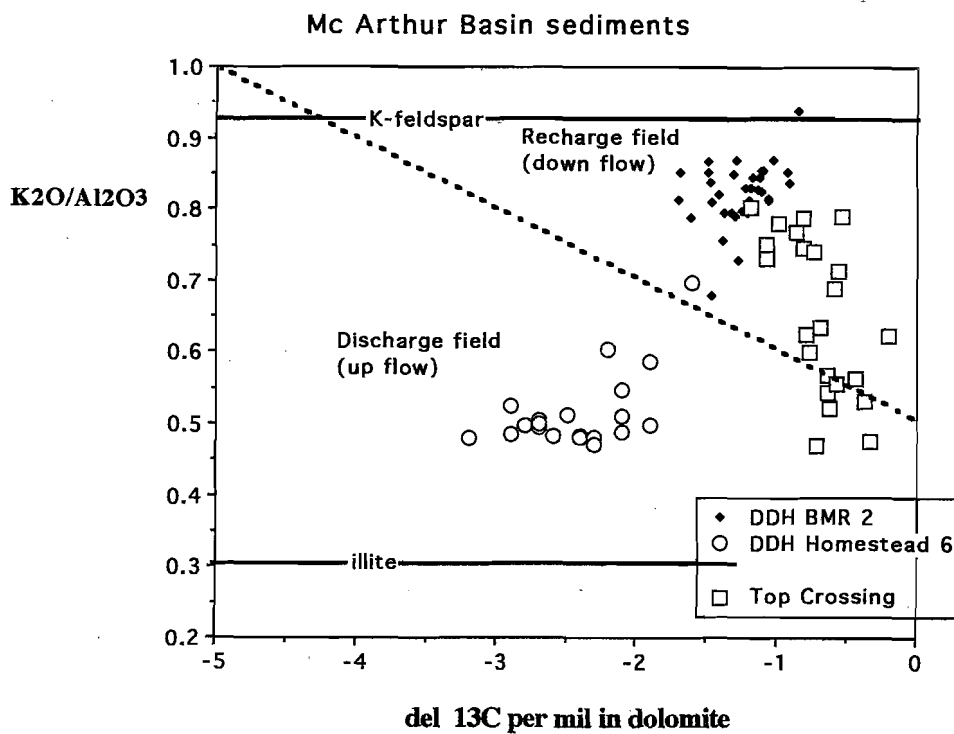
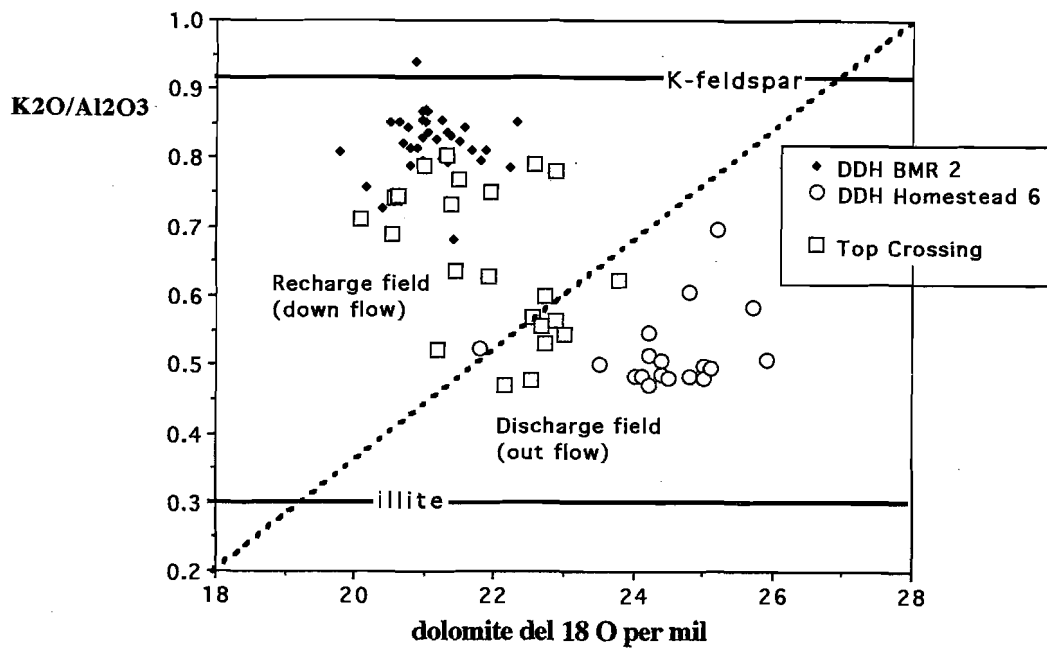


Figure 12. The Top Crossing data set plotted on the discharge-recharge discrimination diagram. Only samples from the Upper BCF plot within the discharge field.

