SEDEX potential of the Tawallah Group, lower McArthur Basin

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The Palaeo-Mesoproterozoic McArthur Basin of northern Australia hosts world-class sedimentary 'exhalative' (SEDEX) McArthur-type Zn-Pb deposits. These deposits are largely hosted within the McArthur Group, a sequence of 1.64 Ga pyritic carbonaceous shales deposited in an extensional rift setting. A well known example of these is McArthur River (formerly known as HYC) Zn-Pb-Ag deposit. The older ~1.78 Ga McDermott and ~1.73 Ga Wollogorang formations of the Tawallah Group both contain carbonaceous shales deposited in similar environments. Our observations suggest the carbonaceous facies of the Wollogorang Formation were deposited under mostly euxinic conditions, with periodically high concentrations of sedimentary pyrite deposition. The carbonaceous shales in the older McDermott Formation contain considerably less early pyrite, reflecting a mostly sulfide-poor, anoxic depositional environment. Localised fault-bounded sub-basins likely facilitated lateral facies variations, evident from synsedimentary breccias in the Wollogorang Formation.

The presence of evaporitic oxidised facies within the McDermott and Wollogorang formations is a favourable criterium for SEDEX-style brine generation. Both formations overlie volcanic units that could have been sources of base metals. Detailed X-ray petrography and new geochemical data from historical drill cores indicate multiple intervals of stratiform and sediment breccia-hosted base metal sulfide within carbonaceous shale units, with high grade Zn concentrations in the Wollogorang Formation but not in the McDermott Formation. Lithogeochemical haloes and a close association between sphalerite and ferromanganean dolomite alteration in the Wollogorang Formation draws comparisons with younger SEDEX mineralisation at McArthur River. We therefore regard the Wollogorang Formation as prospective for base metals mineralisation, but have observed no evidence to suggest the McDermott Formation hosts any significant mineralisation.

Geological setting of Tawallah Group

The Tawallah Group of the Redbank Package is the lowermost and oldest stratigraphic unit of the southern McArthur Basin. It is mostly exposed southeast of the Batten Fault Zone (**Figure 1**). Deposited between ~1850 and ~1715 Ma, the Tawallah Group overlies basement volcanic units and is composed of basal conglomerate, basalts, varying shallow marine facies, fluvial and lacustrine facies, and basaltic and intrusive units. Within the marine sedimentary intervals, the McDermott and Wollogorang formations contain organic-rich mudstone and carbonate facies, potentially favourable for McArthur-type SEDEX mineralisation. Neither formation is thus far known to be significantly mineralised with base metals, but enrichments in Zn, Pb, and Cu have been identified at several stratigraphic levels (Jackson 1985, Donnelly and Jackson 1988, Kendall *et al* 2009).

In this study we analysed five open-file diamond drill cores that intersect shale-bearing units of the Tawallah Group: GSD7 and DD91DC1 (McDermott Formation); and DD91RC18, DD91HC1 and 14MCDDH002 (Wollogorang Formation; **Figure 1**).

McDermott Formation

The McDermott Formation is the oldest mudstone-bearing sedimentary unit within the Tawallah Group. It overlies the Seigal Volcanics and is overlain by the Sly Creek Sandstone (Jackson *et al* 1987, **Figure 2**). Accurate depositional ages for the McDermott Formation are not currently available, but an approximate age for deposition is derived from the maximum to minimum age of 1780 to 1760 Ma of the conformably underlying Seigal Volcanics (Rawlings 1999). The sedimentary succession consists of basal sandstone, interbedded carbonaceous siltstone and stromatolitic dolostone, and upper fluvial sandstones and red mudstones. The depositional environment ranged from shallow marine to shoreline.

Wollogorang Formation

The Wollogorang Formation is a laterally-extensive but relatively thin shallow marine to nearshore clastic sedimentary unit with a maximum thickness of around 150 m (Jackson 1985). It is both underlain and overlain by extrusive and intrusive volcanic units, and has a depositional age between 1730 ± 3 and 1729 ± 4 Ma from tuffaceous green clays (Page *et al* 2000). The sedimentary sequence consists of red-brown dolomitic mudstone with stromatolites, evaporites, and carbonaceous grey dolostone; dolomitic black carbonaceous siltstone; and dolomitic sandstone and quartz sandstone with minor dololutite (top). A key marker horizon in the Wollogorang Formation is the 'ovoid beds', a unit containing round diagenetic dolomitic nodules within black carbonaceous mudstone close to the base of the sequence.

McArthur-type SEDEX deposits

Stratiform 'sedimentary exhalative' (SEDEX) deposits are major sources of base metals such as Zn-Pb-Ag±Cu-Ni-Mo-Ba and are the primary sources of Zn and Pb (Large *et al* 2005). The McArthur and neighbouring Isa basins of northern Australia host numerous SEDEX deposits. As summarised in Large *et al* (2005), the main characteristics of SEDEX deposits in the McArthur-Isa basins are: laminated sphalerite and galena-bearing dolomitic siltstones; stacked mineralised lenses separated

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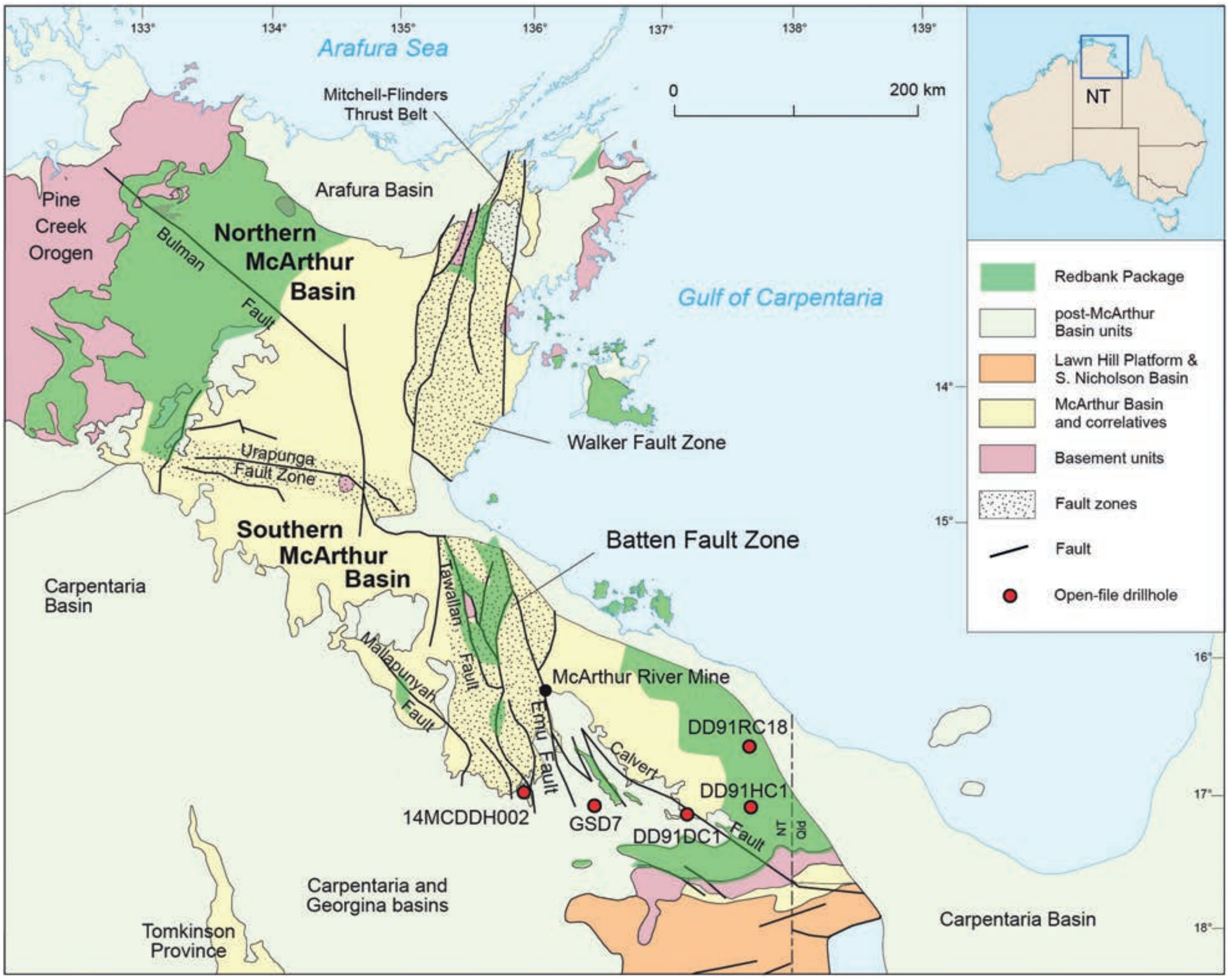

Figure 1. Simplified geological map of the McArthur Basin of Northern Australia (modified after Ahmad *et al* 2013 and references therein).

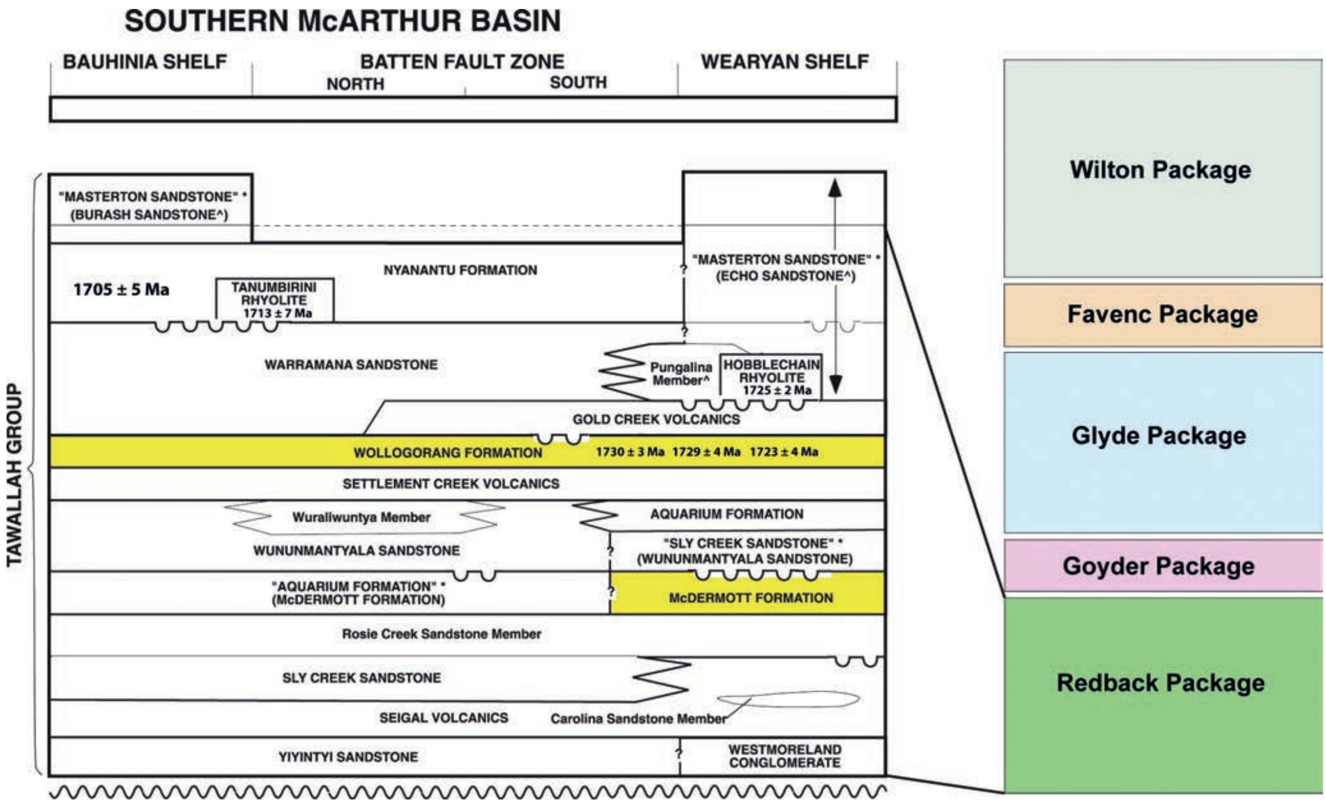

Figure 2. Stratigraphic framework of the southern McArthur Basin showing subdivisions by group and 'packages' (modified from Rawlings (1999).

by carbonaceous mudstones; base metals deposition adjacent to major faults; Fe-Mn dolomite alteration haloes; and no obvious vent or stringer zones. A generalised genetic model for deposition is of synsedimentary base metals sulfide precipitation facilitated by exhalation of metallic basinal brines from active fault zones (Large *et al* 1998, Large and McGoldrick 1998; Large *et al* 2005), or by syndiagenetic replacement of carbonate (Large *et al* 1998, Ireland *et al* 2004). Two distinct categories of SEDEX deposits were proposed by Cooke *et al* (2000) based on the mineralising brines, sedimentary basin and lithology type: McArthur-type (oxidised brines) and Selwyn-type (reduced brines). SEDEX deposits of the McArthur-type typically form by the following stages (Large *et al* 1998, Large and McGoldrick 1998, Cooke *et al* 2000):

1. oxidising brines descend from surface evaporitic environments into porous and fractured basin aquifers
2. basinal brines leach metals from underlying volcanics
3. sulfate-metal-bearing oxidised brines are released along fault zones into anoxic/euxinic basin floor or shallow subsurface
4. base metals sulfide precipitation through bacterial sulfate reduction or by interaction with biogenic H_2S.

The major known SEDEX deposits in the McArthur Basin (**Figure 1**) occur within the Barney Creek Formation of the McArthur Group (Glyde Package; **Figure 2**) such as the McArthur River Zn-Pb-Ag deposit (Large *et al* 1998, Large and McGoldrick 2000). The volcanic and oxidised clastic lithologies underlying the Barney Creek Formation are thought to have been critical in the formation of the oxidised metal-rich brines that formed McArthur River and other prospects (Cooke *et al* 2000) making the Barney Creek Formation the highest-priority ongoing exploration target. However, recent exploration attention has also been focused on shale-bearing units of the Tawallah Group such as the McDermott and Wollogorang formations, as they also overlie volcanic and oxidised clastic facies and contain pyritic carbonaceous shale. These underexplored and under-studied formations are the subject of this study.

Evidence for McArthur-type SEDEX mineralisation in the Tawallah Group

Base metals enrichment

The characteristic 'ovoid beds' of the Wollogorang Formation contain anomalous concentrations of SEDEX-related elements. Drill core 14MCDDH002 contains >2000 ppm Zn in a weakly mineralised zone with associated increases in Pb, Ag and Tl (**Figure 3**). The same interval from drill core DD91RC18 is mineralised and contains percent level Zn.

No significant mineralisation is observed in the McDermott Formation (**Figure 4**), although one section in drill core GSD7 contains anomalous percent level Zn.

Lithogeochemical haloes

At McArthur River there are pronounced lithogeochemical haloes associated with mineralisation which extend several kilometres from the deposit (Large *et al* 2000). Manganiferous dolomite alteration is measurable within the 'favourable unit' of the HYC Pyritic Shale Member in drill core 23 km laterally away, and perhaps further. SEDEX-associated element enrichments are also expressed as a laterally-extensive halo into the hanging wall sedimentary rocks at McArthur River (Large *et al* 2000). Through study of SEDEX host-stratigraphy in drill cores outwardly radiating from the main deposits, Large *et al* (2000) developed the SEDEX Indices as a vector to mineralisation. When applied to the sections of the McDermott and Wollogorang formations analyzed in this study, the SEDEX Indices show similarities with drill cores close to McArthur River (Large *et al* 2000; **Figures 3–6**).

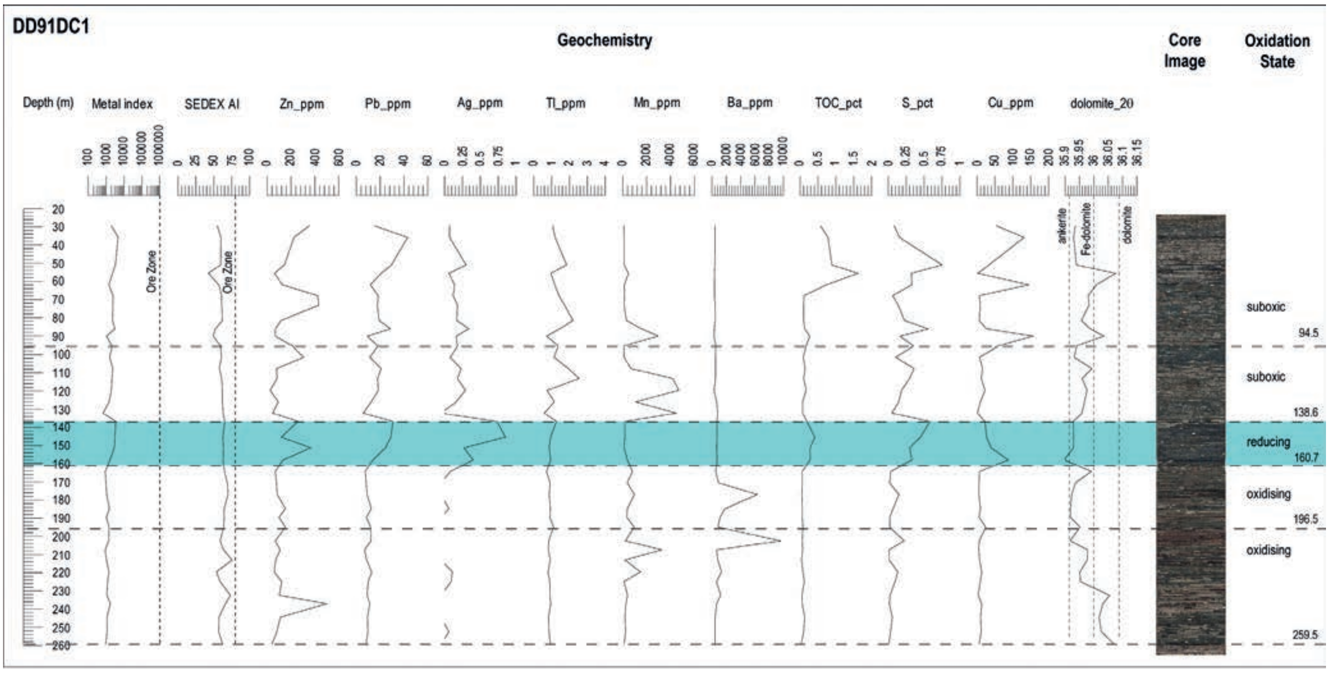

Figure 3. Composite log of drill core 14MCDDH002 including downhole geochemistry of Metal Index, SEDEX AI, Zn, Pb, Ag, Tl, Mn and Ba; composite core imagery, and lithology.

The relatively high SEDEX Metal Index values for the Wollogorang Formation lithologies are consistent with metal concentrations close to that of an orebody (**Figures 3, 4**). The SEDEX Metal Index considers the concentration of Zn, the limited dispersion of Pb and the widespread dispersion of Tl, with these factors increasing with proximity to an orebody (Large and McGoldrick 1998). Enrichments in SEDEX-related elements such as Pb, Ag, and Tl (**Figure 3**) in the Zn-mineralised 'ovoid bed' shale unit of the Wollogorang Formation are comparable with those observed in the favourable shale unit of the Barney Creek Formation about 15 km away from McArthur River (Large *et al* 2000). The pattern in Mn enrichment within the Wollogorang Formation is also consistent with that observed at McArthur River, with considerable enrichments above and below the mineralised zone (**Figure 3**). These enrichment patterns thus may represent haloes of distal SEDEX mineralisation within the ovoid beds.

The comparison of high SEDEX Metal Index factors in rocks of the Wollogorang Formation with those at McArthur River assumes that dispersion mechanisms of base metals at McArthur River and at potential orebodies in the Tawallah Group were similar. However, the genetic model of sphalerite deposition at McArthur River is one of both high-density metallic brines released from faults, depositing sedimentary sulfides, and later replacement of carbonate by sphalerite (Ireland *et al* 2004). Base metals mineralisation observed in the sedimentary rocks of the Wollogorang Formation in this study includes sulfides of primary authigenic sedimentary origin, and also diagenetic replacement products. The

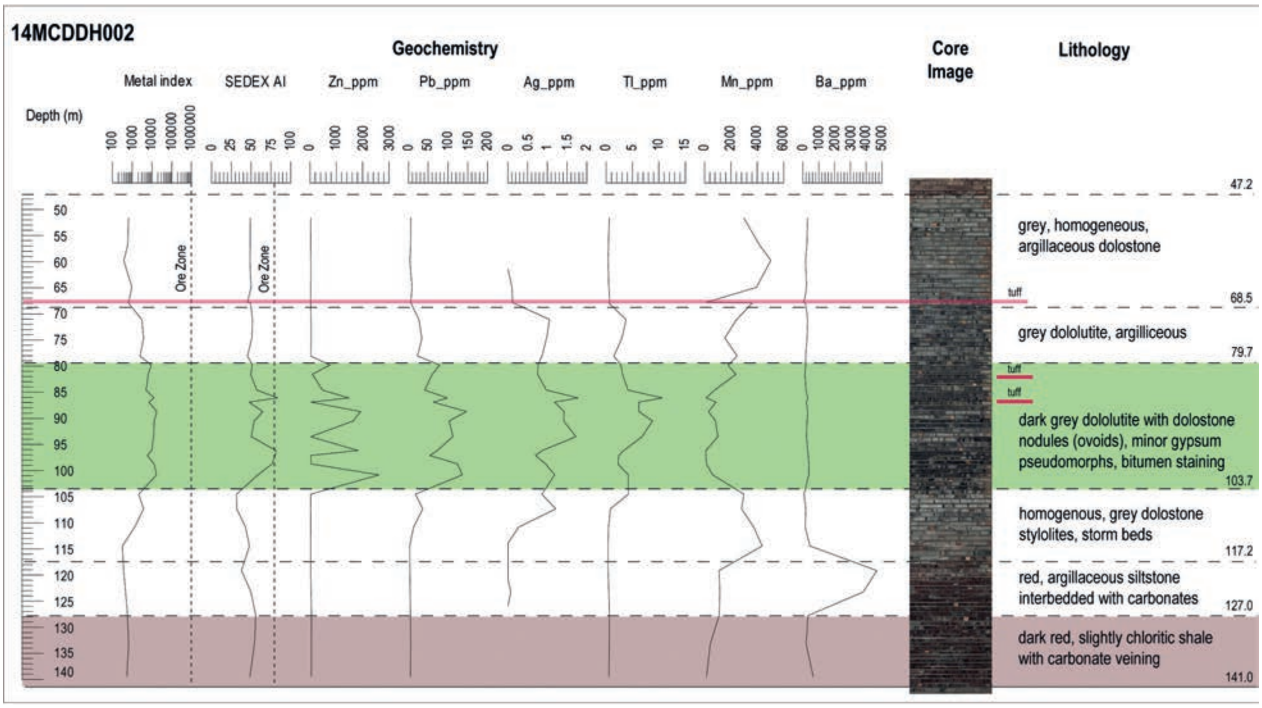

Figure 4. Composite log of DD91DC1 showing downhole geochemistry of Metal Index, SEDEX AI, Zn, Pb, Ag, Tl, Mn, Ba, TOC, S, Cu.

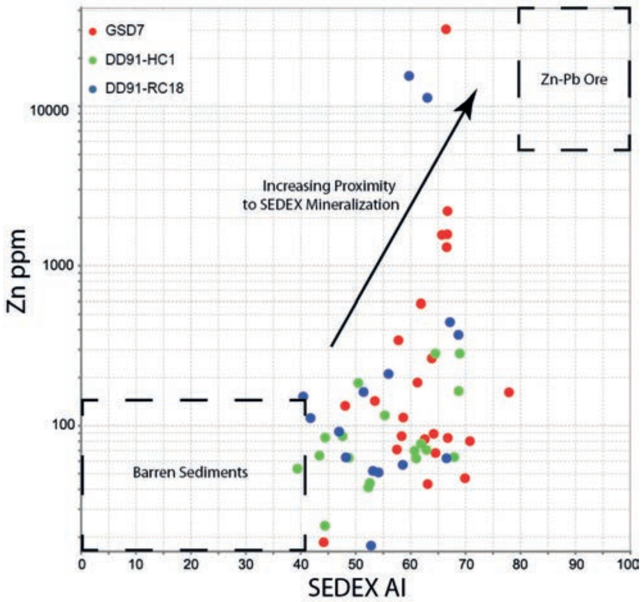

Figure 5. SEDEX Alteration Index versus Zn plot of drill cores DD91RC18, DD91HC1 (Wollogorang Fm.) and GSD7 (McDermott Fm.). Figure modified from Large *et al* (2000).

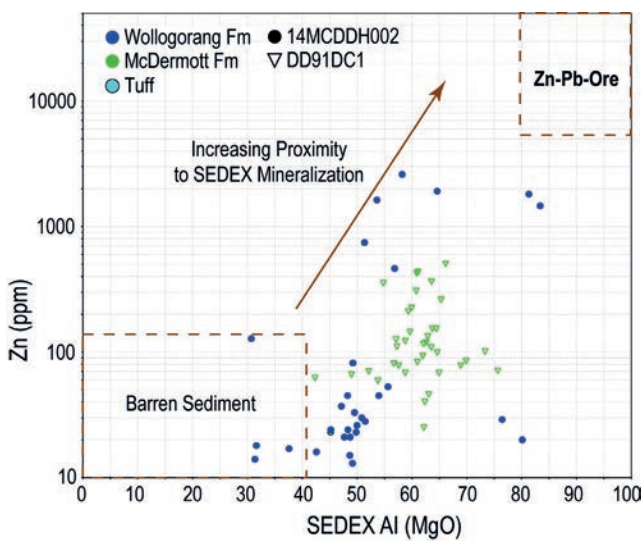

Figure 6. SEDEX Alteration Index versus Zn plot of drill cores 14MCDDH002 (Wollogorang Fm.) and DD91DC1 (McDermott Fm.). Figure modified from Large *et al* (2000).

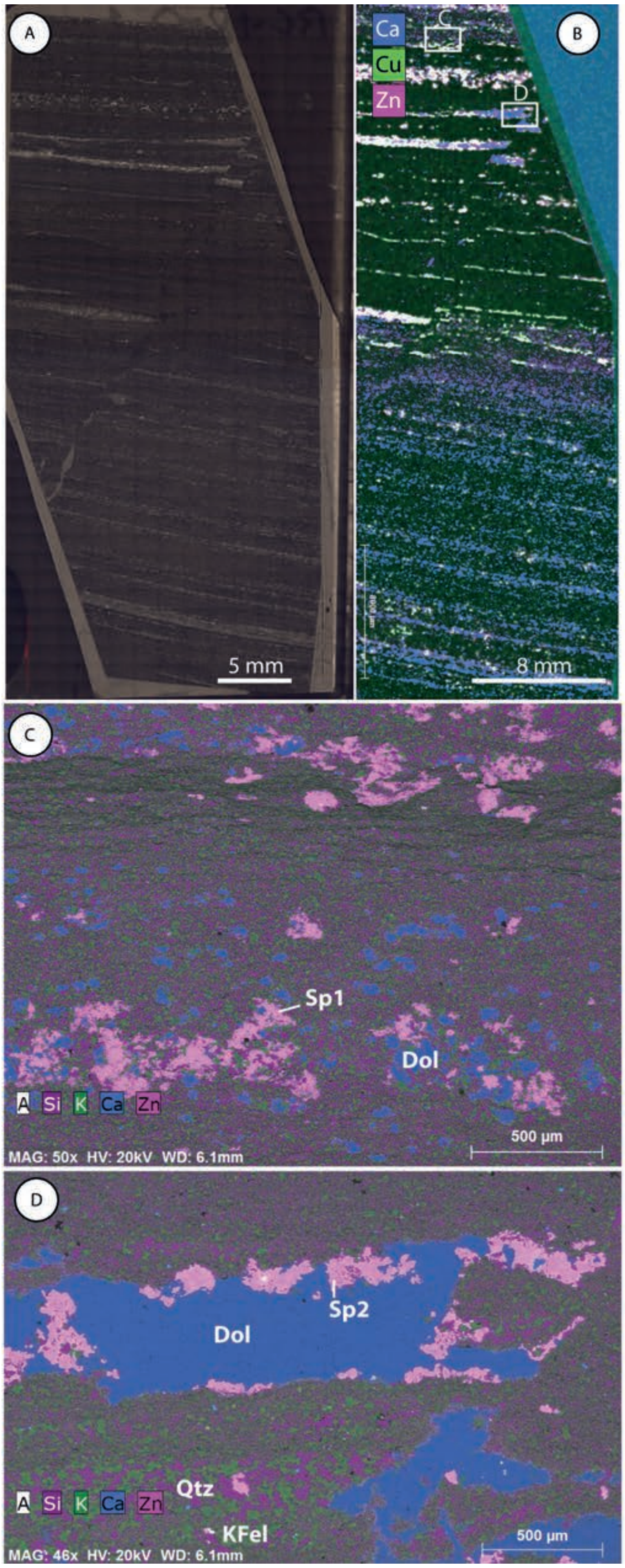

Figure 7. (**a**) Reflected light photomicrograph of section of laminated shale from drill core DD91RC18 at 267.5 m depth showing minor fractures and stratiform sulfide mineralisation. (**b**) XRF map of field of view in A, highlighting carbonate-associated sphalerite and minor chalcopyrite. Detailed element maps in C and D are highlighted by white boxes. (**c**) FEG-SEM element map highlighting the occurrence of primary (depositional) sphalerite associated with disseminated carbonate. Sp1=sphalerite texture 1, Sp2=sphalerite. texture 2, Dol=dolomite, Qtz=quartz. (**d**) FEG-SEM element map highlighting the occurrence of replacement sphalerite within carbonate laminae.

timing of these differing mineralisation styles remains unknown. They may represent events by which distal synsedimentary fault zones released metallic brines into the water column and the same fluids also migrated through porous facies in the subsurface. In both scenarios, oxidised metallic brines could have been reduced by biogenic H_2S in the water column or shallow sediments, or by early diagenetic/sedimentary pyrite in sediments.

SEDEX Alteration Index

The SEDEX Alteration Index (AI) is a means of mapping alteration haloes around SEDEX deposits, and is controlled by three primary factors: i) increased content of Mn and Fe in carbonate during replacement of MgO; ii) increased pyrite (FeO) in carbonaceous facies; and iii) increased shale/dolomite ratio (MgO). Large *et al* (2000) demonstrated that these three factors all increase with proximity to McArthur-type SEDEX deposits. When applied to the sections of the McDermott and Wollogorang formations analysed in this study, the SEDEX AI show similarities with drill cores close to McArthur River (Large *et al* 2000). SEDEX AI values of 80 to 100 are observed within ore-zone mineralised sedimentary rocks, whereas background barren sedimentary rocks have values of 0 to 40 (Large *et al* 2000). Increasing SEDEX AI values with concomitant increases in Zn are indicative of increasing proximity to SEDEX-type mineralisation. Many of the samples from the Wollogorang Formation plot close to the ore field, with some McDermott Formation samples showing high values (**Figures 5, 6**). The SEDEX AI is highest (>75) in the Wollogorang Formation in the mineralised shale unit (**Figure 3**), consistent with those observed close to McArthur River.

SEDEX-style mineralisation

Three distinct styles of base metals sulfide mineralisation are observed in the Wollogorang Formation that are comparable with occurrences distal to the large McArthur-type deposits such as McArthur River (eg Large *et al* 1998; 2000; 2005; Large and McGoldrick 1998; Cooke *et al* 2000; Ireland *et al* 2004). Chalcopyrite, not common at McArthur River, and sphalerite growth around early pyrite in mudstone clasts in sedimentary breccia zones implies the presence of metalliferous fluids before slumping. Laminated primary depositional sphalerite (**Figure 7**) comparable with Sp1 from McArthur River (Ireland *et al* 2004) occurs in the mineralised section in the Wollogorang Formation. Sphalerite apparently replacing carbonate lenses, comparable with SP2 at McArthur River (Ireland *et al* 2004) also occurs in close proximity to earlier sphalerite. Large concentrations of sphalerite also occur in the carbonate nodules characteristic 'ovoid beds' of the Wollogorang Formation (**Figure 8**). No significant base metals mineralisation was observed in the McDermott Formation.

Significance of euxinia for SEDEX potential

The emergence of oceanic euxinia (anoxic and sulfidic) is thought to have occurred at ~1.8 Ga; this age coincides with the disappearance of banded iron formations (BIFs) and, strikingly, the arrival of sedimentary SEDEX deposits in black shales (Lyons *et al* 2006). Previous assertions that the cessation of BIF deposition reflected deep oceanic oxygenation (Holland 2005), or widespread euxinic conditions (Canfield 1998), have been disputed with evidence for co-existence of ferruginous and euxinic conditions in the oceans from the Neoarchean to the Neoproterozoic (Planavsky *et al* 2011). There is an emerging model of euxinia occurring along continental margins (Poulton *et al* 2010) and localised intracontinental sub-basins, whereas the deep oceans may have remained ferruginous (Planavsky *et al* 2011). The sedimentary rocks analysed in this study are interpreted to have been deposited in such marginal marine settings, which raises the possibility of the development of euxinic bottom waters (Poulton *et al* 2010). Euxinic conditions are critical for the McArthur-type SEDEX deposits, providing a reduced sulfur source for liberated oxidised metal-bearing brines (Cooke *et al* 2000).

Palaeoredox proxies from the McDermott Formation are largely consistent with petrographic evidence for the sediments having been mostly deposited under moderately sulfidic anoxic conditions with intermittent high influx of marine sulfate into the basin at the site of deposition of the sediments. Euxinic sedimentary rocks occur close to the bottom of the analysed section of drill core GSD7, but sulfur concentrations apparently decreased as the basin shallowed, as is evident in the low S concentrations in the rock. The cause of this remains uncertain; it may reflect reducing flux of marine sulfate during deposition in that part of the basin.

Several factors may have affected the flux of sulfate to the McDermott Formation. The basal shales of drill core GSD7 are interpreted to have been deposited in a platform-type marginal environment, of which slightly older equivalents in the Animike Basin are thought to have been euxinic (Poulton *et al* 2010). Low sulfur concentrations in the evaporitic shale facies higher in the succession of GSD7 may reflect the development of a sulfur-poor shallow marine environment; however given the shallowing of the basin and progression to fluvially-dominated siliciclastic deposition, the possibility of the basin being closed to the open ocean and therefore to a sulfate source cannot be discounted. The paucity of sulfidic facies in the upper section of the basal McDermott Formation stratigraphy analysed in this study reduces the prospectivity for McArthur-type mineralisation in those rocks, whereas the sulfidic basal shales are considered more prospective.

Wollogorang Formation sedimentary rocks are rich in laminae of micron-scale euhedral pyrite crystals and clusters in the carbonaceous facies. Such textures are consistent with deposition under euxinic conditions; palaeoredox proxies similarly indicate abundant sulfur in the water column or

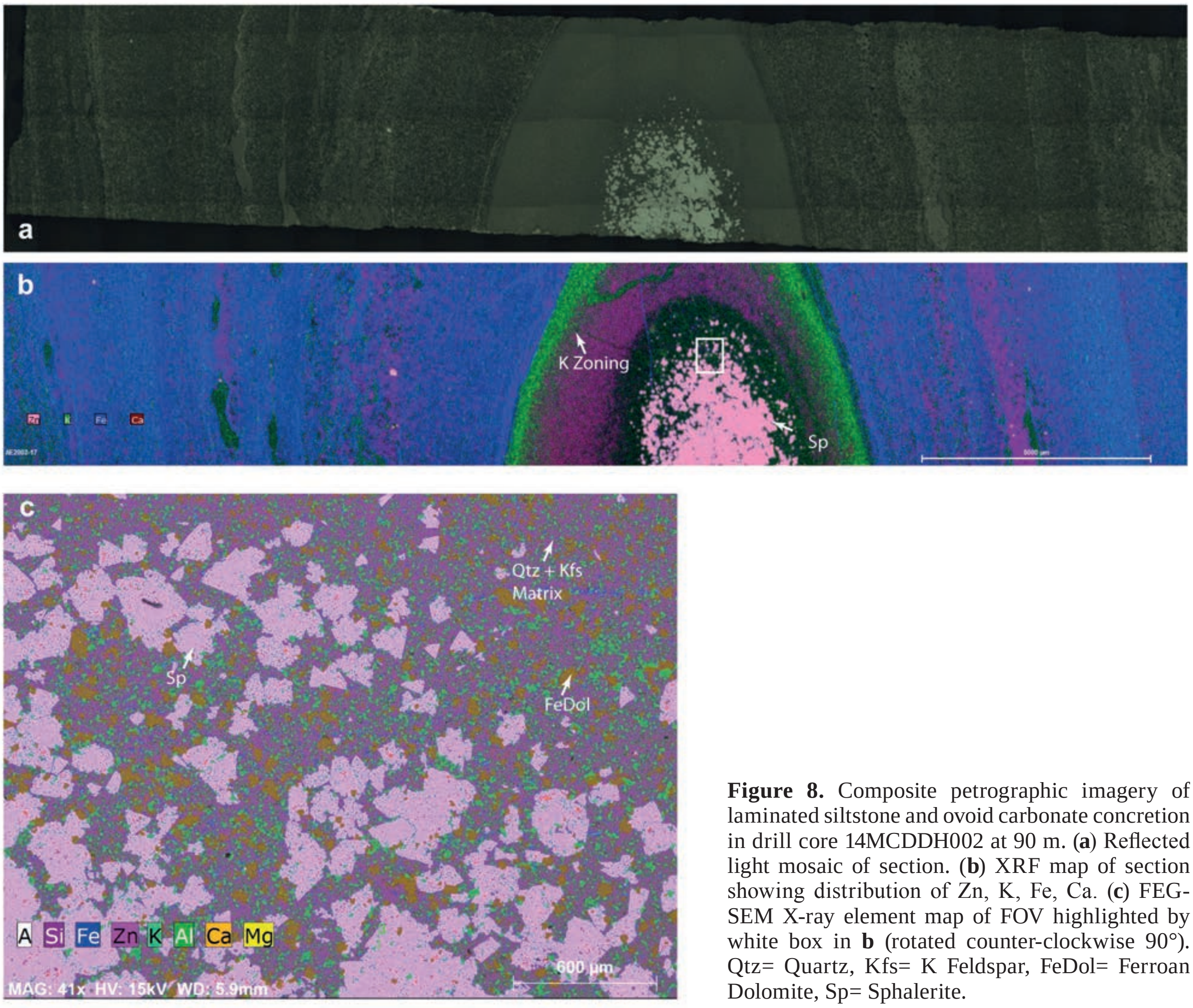

Figure 8. Composite petrographic imagery of laminated siltstone and ovoid carbonate concretion in drill core 14MCDDH002 at 90 m. (**a**) Reflected light mosaic of section. (**b**) XRF map of section showing distribution of Zn, K, Fe, Ca. (**c**) FEG-SEM X-ray element map of FOV highlighted by white box in **b** (rotated counter-clockwise 90°). Qtz= Quartz, Kfs= K Feldspar, FeDol= Ferroan Dolomite, Sp= Sphalerite.

pore fluids. Enhanced Mo concentrations relative to Re and V in analysed sections of carbonaceous shales signal uptake of Mo into authigenic sulfides and organic matter under euxinic conditions. Although not all of the analysed sections of the Wollogorang Formation display trace element and petrographic evidence for extremely euxinic conditions, none are sulfur-poor. This may be the result of a restricted marine environment that was not permanently linked to the open ocean or a localised sulfate source, with episodic influxes of sulfur. This implies that euxinia had become established in the shallow shelf environments of the McArthur Basin by 1.73 Ga during the deposition of the Wollogorang Formation, thus providing a strongly-reducing buffer and sulfur source for potential exhaled metallic brines and subsequent primary SEDEX deposition.

Conclusions

The analysed sections of the McDermott Formation contain little evidence for proximal base metals mineralisation. However, downhole Zn-Pb-Tl-Mn concentration patterns in the Wollogorang Formation are comparable with those observed close to the McArthur River deposit. The carbonaceous shales of the Wollogorang Formation also contain sphalerite mineralisation with similar textures to those observed at McArthur River. Synsedimentary brecciation and euxinia provide further indicators of a possible SEDEX system within the Wollogorang Formation. The lithological and tectonic conditions for oxidised metallic brine generation and subsequent 'exhalation' from synsedimentary faults into a reducing basin, existed during Tawallah Group times (~1.78 to ~1.73 Ga). The Wollogorang Formation, in particular, could have acted as an efficient reductant and sulfur source for metallic brines, and may be a favourable unit for SEDEX deposition. The Redbank Cu deposits, which likely represent mineralisation of metals remobilised from underlying rocks such as the Wollogorang Formation, are further evidence for the mineralisation potential of the Wollogorang Formation. The combination of these factors leads us to conclude that the Wollogorang Formation can be considered favourable for mineralisation styles similar to McArthur-type SEDEX deposits.

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