The ca 1640 Ma Barney Creek Formation in the McArthur Basin: Targeting diagenetic mineralisation and depocentre shift

Marcus Kunzmann[1,2,3] and Teagan N Blaikie[1,3]

Introduction

The ca 1640 Ma Barney Creek Formation is a dominantly fine-grained siliciclastic unit of the McArthur Group in the southern McArthur Basin (**Figures 1, 2**). It is of significant economic importance because it hosts the world-class McArthur River Zn-Pb-Ag deposit (eg Croxford 1975, Eldridge *et al* 1993, Large *et al* 1998, Ireland *et al* 2004a, b) and the Teena Zn-Pb prospect (Taylor *et al* 2017). In addition, it is one of the oldest active petroleum systems in the world and may be an important hydrocarbon source rock or unconventional reservoir (eg Jackson *et al* 1986, Summons *et al* 1988, Baruch *et al* 2015). The Barney Creek Formation is also an important archive of early life on Earth. Due to its generally low thermal maturity, it hosts the oldest unambiguous indigenous biomarkers in the world and represents a unique archive of mid-Proterozoic surface environments (eg Brocks *et al* 2005, Lee and Brocks 2011).

The Zn-Pb mineralisation in the Barney Creek Formation is typically stratiform and hosted by pyritic, organic matter-rich and dolomitic siltstones deposited in sub-basin depocentres. The timing of mineralisation is debated but generally considered to be syngenetic or diagenetic (eg Eldridge *et al* 1993, Large *et al* 1998). These characteristics highlight the need for detailed sedimentological, stratigraphic, and structural basin reconstructions for mineral exploration. Specific questions focus on the distribution and formation of sub-basins, on individual sub-basin reconstructions, and on understanding lateral and stratigraphic heterogeneity of the Barney Creek Formation. It is also important to develop sedimentological and stratigraphic models for targeting mineralisation that take into account the implications of syngenetic versus diagenetic mineralisation.

In this contribution, we extend our earlier work on the sedimentology and stratigraphy of the Barney Creek Formation from the southernmost Batten Fault Zone (**Figure 1**; Kunzmann *et al* 2018, 2019) to the entire Batten Fault Zone. We show that a significant shift in the depocentre occurred across the Batten Fault Zone from south to north at the Barney Creek–Reward transition (**Figure 2**). Considering new evidence for the timing of mineralisation (Taylor *et al* 2017, Spinks *et al* 2019), we propose to target mineralised strata by using a combination of sequence stratigraphy and facies maps.

[1] CSIRO Mineral Resources, 26 Dick Perry Avenue, Kensington WA 6151, Australia
[2] Email: marcus.kunzmann@csiro.au
[3] Northern Territory Geological Survey, GPO Box 4550, Darwin NT 0801, Australia

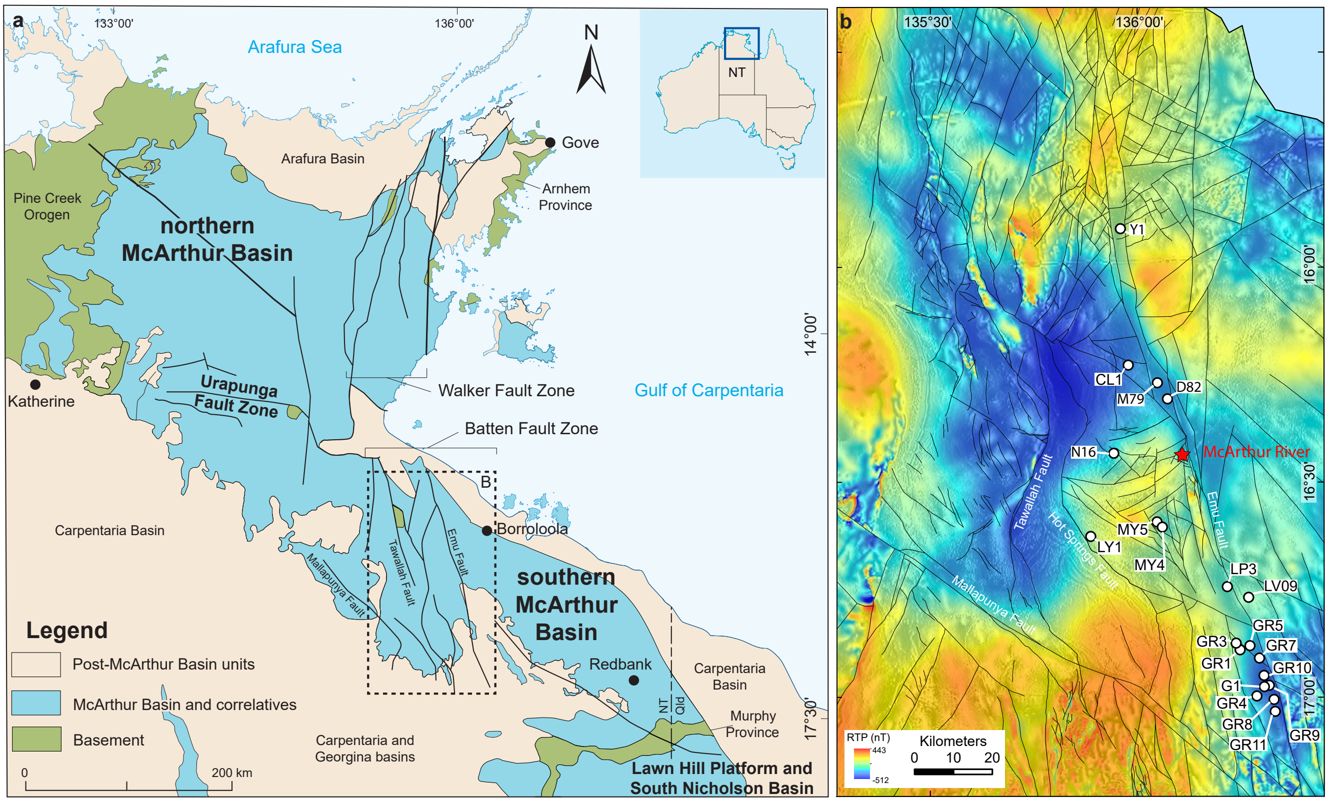

Figure 1. Simplified geological map of the McArthur Basin and magnetic image of the Batten Fault Zone. (**a**) Geographical distribution of McArthur Basin and equivalent stratigraphy, as well as basement inliers and younger sedimentary cover. (**b**) Reduced to pole magnetic image overlaid on the tilt-derivative of the Batten Fault Zone (location shown in **a**) highlighting the current structural complexity of the basin (modified from Kunzmann *et al* 2019). Also shown are the location of the McArthur River deposit and studied drill cores.

Geological setting

The greater McArthur Basin is part of a Proterozoic basin system on the North Australian Craton (eg Giles *et al* 2002, Betts *et al* 2003, Gibson *et al* 2017). It can be subdivided into the northern and southern McArthur Basin, separated by the east–west striking Urapunga Fault Zone (**Figure 1**). The most important structural features are the Walker and Batten Fault zones in the northern and southern McArthur Basin respectively (**Figure 1**). These fault zones are north-south-striking corridors, each about 80 km wide and 200 km long.

The ca 1670–1600 Ma McArthur Group is a mixed siliciclastic–carbonate succession (**Figure 2**) exposed in the southern McArthur Basin. The group is between 1 and 3.5 km thick. The Barney Creek Formation sits stratigraphically in the middle part of the McArthur Group and was deposited in a highly compartmentalised basin, characterised by km-scale sub-basins and paleohighs (eg McGoldrick *et al* 2010, Kunzmann *et al* 2019). Two types of sub-basins were recently recognised from the interpretation of geophysical data (Blaikie and Kunzmann 2019). Type 1 sub-basins are north–south striking transtensional sub-basins that developed along the north–northwest trending Emu Fault (**Figure 1**). In contrast, Type 2 sub-basins trend east–west and developed adjacent to east–west striking normal and north–northwest striking transfer faults located between the Hot Spring and Emu faults (Blaikie and Kunzmann 2019).

The Barney Creek Formation is 10–900 m thick and is subdivided into three members: the W-Fold Shale, the HYC Pyritic Shale, and the Cooley Dolostone (Jackson *et al* 1987). These members are overlain by the undifferentiated upper part of the formation (**Figure 2**). The W-Fold Shale represents the basal part of the formation and is composed of green or red siltstone, pink dololutite, or dolarenite with green or red siltstone laminae (Jackson *et al* 1987, Davidson and Dashlooty 1993, Kunzmann *et al* 2019). The HYC Pyritic Shale Member, which hosts the McArthur River deposit and Teena prospect, consists of dolomitic siltstones and minor silty black shale. Tuff beds in the HYC Pyritic Shale Member yielded SHRIMP U–Pb zircon ages of 1638 ± 7 Ma, 1640 ± 3 Ma, and 1639 ± 3 Ma (Page and Sweet 1998). The Cooley Dolostone is a locally developed carbonate breccia related to faults that interfingers with other members of the Barney Creek Formation (Jackson *et al* 1987). The undifferentiated upper part of the formation is dominated by dolomitic siltstones, carbonate mass-flow deposits, and dolarenite (Jackson *et al* 1987, Kunzmann *et al* 2019).

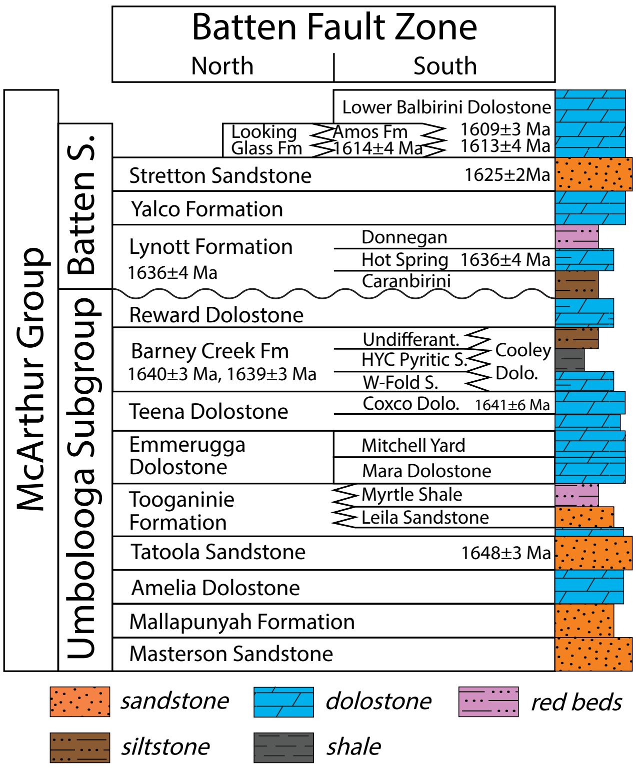

Figure 2. Stratigraphy, dominant lithology, and geochronological constraints of the McArthur Group. Stratigraphy modified from Ahmad *et al* (2013), radiometric ages from Page and Sweet (1998) and Page *et al* (2000).

The Barney Creek Formation comprises two 3rd-order transgressive–regressive sequences, referred to as sequences B1 and B2 (Kunzmann *et al* 2019). Sequence B1 comprises the W-Fold Shale, the HYC Pyritic Shale Member, and the lower half of the undifferentiated Barney Creek Formation. The transgressive systems tract (TST) records deepening of shallow subtidal and intertidal environments of the Coxco Dolostone Member of the underlying Teena Dolostone (**Figure 2**) to deep subtidal environments in the Barney Creek Formation. It culminates in a maximum flooding surface (MFS) in the HYC Pyritic Shale Member. This MFS is typically developed as bituminous dolomitic siltstone on palaeohighs and in shallow parts of sub-basins, but can be developed as highly pyritic black shale and silty shale in sub-basin depocentres (**Figure 3**; Kunzmann *et al* 2019). A thick regressive systems tract (RST) follows the TST and can record shoaling to subtidal environments on paleohighs. It is capped by a maximum regressive surface (MRS) as sequence boundary that sits within silty dolarenite turbidite deposits in sub-basins (Kunzmann *et al* 2019). Sequence B2 comprises the upper part of the undifferentiated Barney Creek Formation and most of the overlying Reward Dolostone (**Figure 2**). A thin TST records renewed deepening of the depositional environment and culminates in a highly pyritic black shale or silty shale in sub-basins or muddy dolostone facies on paleohighs (Kunzmann *et al* 2019). The overlying RST records shoaling to shallow subtidal and intertidal environments in the upper Reward Dolostone.

Methods

This work is based on detailed lithostratigraphic logging of 18 drill cores, supported by the interpretation of wireline data from two additional wells (**Figure 1**). A facies analysis of the middle McArthur Group, as well as a carbon isotopic and sequence stratigraphic framework of this succession, is discussed in detail in Kunzmann *et al* (2019). However, the stratigraphic interpretation in Kunzmann *et al* (2019) focuses only on the southern Batten Fault Zone. In this contribution, we extend it to the entire Batten Fault Zone to better understand the spatial variability of the Barney Creek Formation.

Results and Discussion

Targeting diagenetic mineralisation and fluid pumping

The HYC Pyritic Shale Member and the undifferentiated upper part of the Barney Creek Formation are generally pyrite- and organic matter-rich. However, the maximum flooding surfaces of sequences B1 and B2 have even higher pyrite and organic matter contents, in particular in sub-basin depocentres where they can be developed as silty and black shales (Kunzmann *et al* 2019). This suggests that they represent the most suitable chemical traps for oxidised base metal brines. Therefore, we had previously proposed to target these intervals in sub-basin depocentres for Zn-Pb mineralisation (Kunzmann *et al* 2018). This targeting concept focused on syngenetic models for mineralisation. However, recent microanalytical results from the McArthur River deposit suggest that the mineralisation postdates earliest diagenesis and highlights the importance of carbonate replacement (Spinks *et al* 2019). This implies that the host rocks were already buried at the time of mineralisation. Constraining the depth below the seafloor at which the mineralisation occurred is challenging though. Based on the paragenetic relationships observed at McArthur River (Spinks *et al* 2019), it seems likely that the burial depth was on the order of ten to a few hundred meters. We suggest that the maximum flooding surfaces, where developed as silty and black shales, would have already been compacted and lithified at such depths, thus significantly reducing their porosity and permeability. For this reason, we suggest that the shale facies of the maximum flooding surfaces would have acted as physical traps (seals) to ascending base metal brines.

The new model for the mineralisation at McArthur River is consistent with observations from Teena (Taylor *et al* 2017) and has implications for exploration. Of particular importance is the maximum flooding surface of sequence B1 because the mineralisation at McArthur River and Teena occur in the HYC Pyritic Shale Member (eg Eldridge *et al* 1993, Taylor *et al* 2017). Instead of targeting the maximum flooding surface for mineralisation, the transgressive deposits below should be the target. Their stratigraphic occurrence, and that of the capping maximum flooding surface as physical trap (seal), can be predicted with sequence stratigraphy. Ideally, this should be coupled to facies maps that show where in the basin the maximum flooding surface in the HYC Pyritic Shale Member is developed as shale (and not as siltstone) to provide ideal seal properties. This model should be testable with detailed stratigraphic studies of mineralised sub-basins. At Teena, the most carbonaceous and pyritic interval (ie maximum flooding surface?) occurs above the mineralised zone of the HYC Pyritic Shale Member (Taylor *et al* 2017), which is generally consistent with our model.

A syngenetic model for the mineralisation implies that fluid pumping occurred at the time the host rocks of the HYC Pyritic Shale Member were deposited. This means the pumping of fluids would have happened during extension and deepening of sub-basins (McGoldrick *et al* 2010, Blaikie and Kunzmann 2019). However, numerical fluid flow modelling

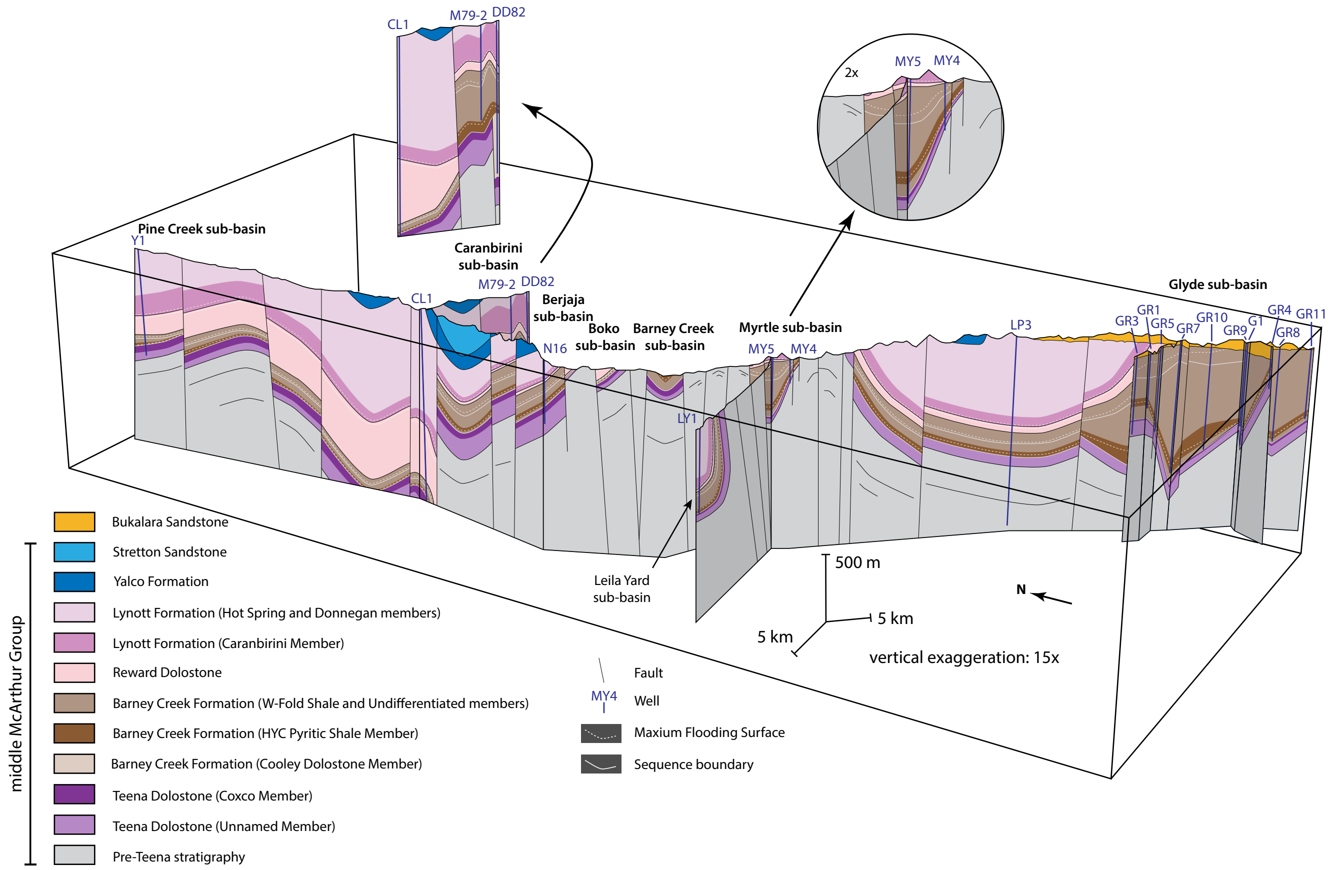

Figure 3. Three-dimensional geological cross-section across the Batten Fault Zone. In the southern and central part (south of well CL1), the Barney Creek Formation is thick but the overlying Reward Dolostone is thin. The opposite relationship is observable in the northern part of the Batten Fault Zone.

demonstrates that extensional deformation is generally not conducive to support upward flow of fluids (Sheldon *et al* 2019). In contrast to models of syngenetic mineralisation, diagenetic models suggest fluid pumping after the host rocks were deposited. One hypothesis is that fluid pumping occurred during deposition of the upper Barney Creek Formation. Our detailed logging shows that carbonate mass flow breccias are common in this stratigraphic interval, indicating instability of shallow depositional environments potentially linked to a short-lived compressional event. This event may be related to accretion of the Warumpi Province at the southern margin of the North Australian Craton or intraplate instability associated with broader scale plate reorganisation (Blaikie and Kunzmann 2019).

Depocentre shift

Core logging on a regional scale across the Batten Fault Zone shows a shift in the depocentre at Barney Creek–Reward time (**Figure 3**). In the central and southern part of the Batten Fault Zone, the Barney Creek Formation is relatively thick, whereas the overlying Reward Dolostone is thin. Furthermore, the Reward Dolostone comprises shallow marine facies. In contrast, in the northern part of the Batten Fault Zone, the Barney Creek Formation is much thinner, whereas the Reward Dolostone is very thick and represents hundreds of meters of deep marine strata. In this area, the overlying Caranbirini Member of the Lynott Formation also seems to be thicker than further to the south.

The observed depocentre shift indicates that major extension in the northern part of the Batten Fault Zone occurred later in the basin's history when compared to the southern and central region. The Caranbirini Member is lithologically similar to the Barney Creek Formation and shows excellent metal host compositions (Kunzmann *et al* 2019). Therefore, the Caranbirini Member may be a potential exploration target, depending on the timing of fluid pumping, availability of a metal source, and the structural framework and evolution.

Conclusions

Based on a diagenetic model for the mineralisation at Teena and McArthur River (Taylor *et al* 2017*,* Spinks *et al* 2019), and on our sedimentological and stratigraphic insights, we propose to target Zn-Pb mineralisation in the Barney Creek Formation by integrating sequence stratigraphy and facies maps. Furthermore, our regional scale study of the middle McArthur Group demonstrates that a depocentre shift occurred across the Batten Fault Zone at Barney Creek–Reward time. A thicker Caranbirini Member in the northern part of the fault zone may be an exploration target.

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