Sedimentology and carbon isotope chemostratigraphy of the Glyde sub-basin, McArthur Basin: Implications for base metals exploration

Marcus Kunzmann[1,2], Teagan N Blaikie[1], Galen P Halverson[3] and Susanne Schmid[4]

Introduction

The Palaeo- to Mesoproterozoic greater McArthur Basin (**Figure 1a**) in the Northern Territory is a 5–15 km thick mixed siliciclastic-carbonate succession with minor bimodal volcanics at the base (eg Plumb *et al* 1979a, b; Jackson *et al* 1987; Rawlings 1999). Together with the Isa Superbasin in Queensland, it represents one of the most important base metals provinces in the world (Leach *et al* 2005, 2010; Huston *et al* 2006). The ca 1640 Ma Barney Creek Formation of the McArthur Group (**Figure 2**) is the most important exploration target as it hosts the world class McArthur River Zn-Pb-Ag deposit and the Teena Zn-Pb prospect (eg Croxford 1975; Large *et al* 1998; Taylor *et al* 2017).

The Barney Creek Formation has been deposited in a basin with complex architecture characterised by palaeohighs and sub-basins (Davidson and Dashlooty 1993; McGoldrick *et al* 2010). This hinders basin-wide stratigraphic correlation. Furthermore, the most prospective organic-rich siltstone and shale facies is confined to sub-basins, highlighting the need for a detailed understanding of sub-basin development and architecture.

[1] CSIRO Mineral Resources; Northern Territory Geological Survey, GPO Box 4550, Darwin NT 0801, Australia
[2] Email: marcus.kunzmann@csiro.au
[3] Earth & Planetary Sciences, McGill University, Canada
[4] CSIRO Mineral Resources

Here we present a sedimentological, carbon isotope chemostratigraphic, and sequence stratigraphic evaluation of the Glyde sub-basin, a fault-bound depocentre in the southern McArthur Basin (**Figure 1b**), based on detailed logs of historical drill cores. We demonstrate that carbon isotope chemostratigraphy is a powerful tool to constrain basin-wide correlations in the greater McArthur Basin. Furthermore, we use the Glyde sub-basin as a case study for a multidisciplinary approach to gain insights into base metals systems in sedimentary basins. This approach can be applied in other parts of the McArthur Basin and in other sedimentary basins in general.

Geological setting

The greater McArthur Basin is part of a Proterozoic basin system on the North Australian Craton that likely formed in a far-field continental back arc setting with the postulated subduction zone to the south (in present coordinates; Giles *et al* 2002; Betts *et al* 2003; Betts and Giles 2006). The basin is divided into the northern and southern McArthur basins, separated by the east-west striking Urapunga Fault Zone (**Figure 1a**). The most important structural features are the Walker and Batten Fault Zones in the northern and southern McArthur Basin respectively (**Figure 1a**). These fault zones are north-south striking corridors, each about 20 km wide and 200 km long.

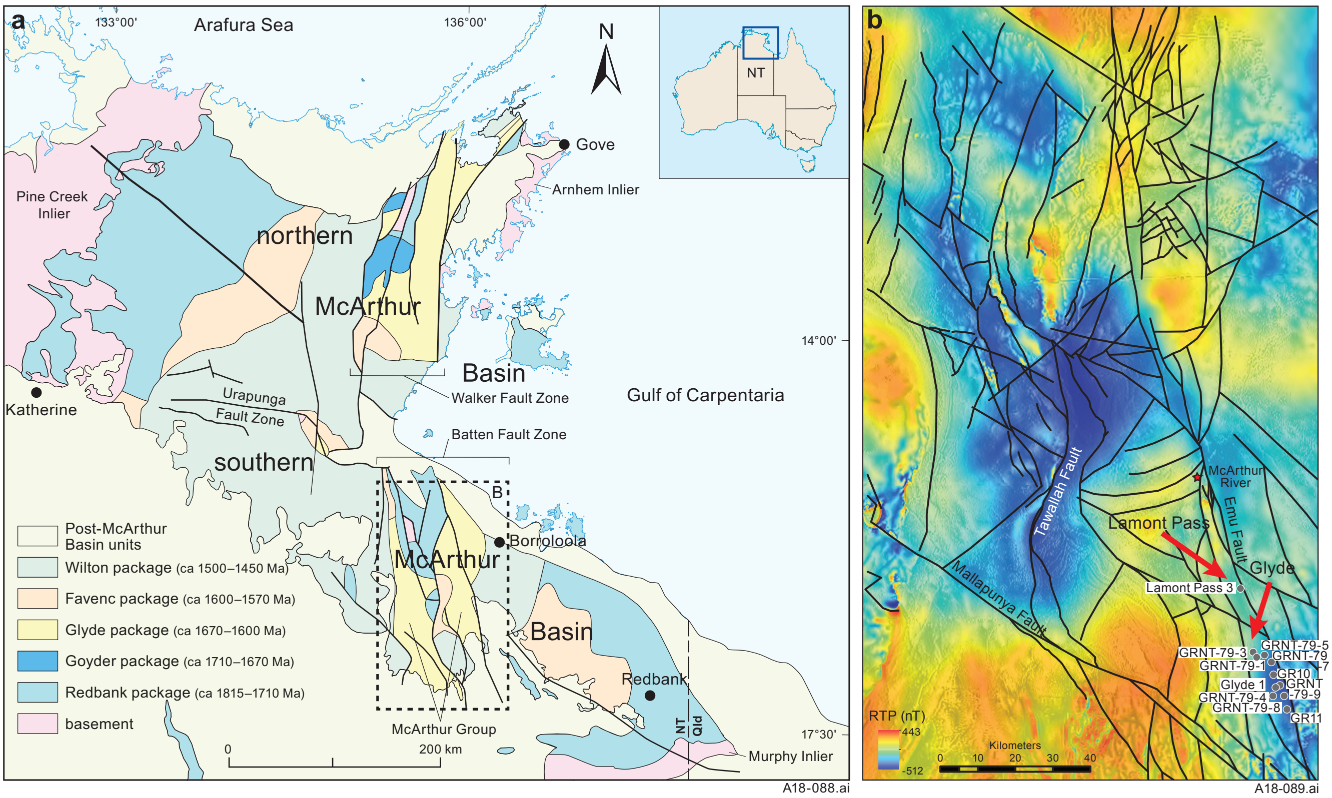

Figure 1. Simplified geological map of the McArthur Basin and magnetics of the Batten Fault Zone. (**a**) Spatial distribution of depositional packages across the McArthur Basin (modified after Ahmad *et al* 2013, Rawlings 1999). (**b**) Magnetics of the Batten Fault Zone showing the location of the Glyde sub-basin, Lamont Pass palaeohigh, and drillholes used in this study.

Rawlings (1999) divided the greater McArthur Basin stratigraphy into five informal and non-genetic packages. In the southern McArthur Basin, the ca 1670–1600 Ma Glyde package comprises the 1–3.5 km thick McArthur Group (**Figure 2**; Jackson *et al* 1987; Rawlings 1999). Organic-rich and dolomitic siltstones and shales of the ca 1640 Ma Barney Creek Formation are part of the middle McArthur Group and host the McArthur River Zn-Pb-Ag deposit.

Onset of Barney Creek deposition was accompanied by a change in the tectonic regime in the southern McArthur Basin. The depositional setting changed from a stable carbonate platform to a compartmentalised basin with numerous palaeohighs and sub-basins (McGoldrick *et al* 2010). Sub-basin formation was related to sinistral strike-slip along arcuate and broadly north-south trending fault systems. Whereas transpression occurred at east to west trending segments of the faults, transtension along north- to northwest-trending segments created accommodation space and led to sub-basin opening (McGoldrick *et al* 2010).

The 10–900 m thick Barney Creek Formation comprises three members: the W-Fold Shale, HYC Pyritic Shale, and the Cooley Dolostone (**Figure 2**; Jackson *et al* 1987). These members were defined in the sub-basin that hosts the McArthur River deposit; it is not well understood whether they represent basin-wide occurring lithostratigraphic units or lateral facies changes (Jackson *et al* 1987). This is particularly important for the Cooley Dolostone, which is mostly bound to local fault scarps and may thus not be a mappable unit.

The W-Fold Shale is generally described as green and red dolomitic siltstone and green vitric tuff (Brown *et al* 1978; Jackson *et al* 1987). The HYC Pyritic Shale Member consists of dolomitic and pyritic siltstones and minor silty shales, generally regarded to have formed in a deep subtidal environment (Bull 1998). The Cooley Dolostone is a locally, fault-derived, carbonate breccia that interfingers

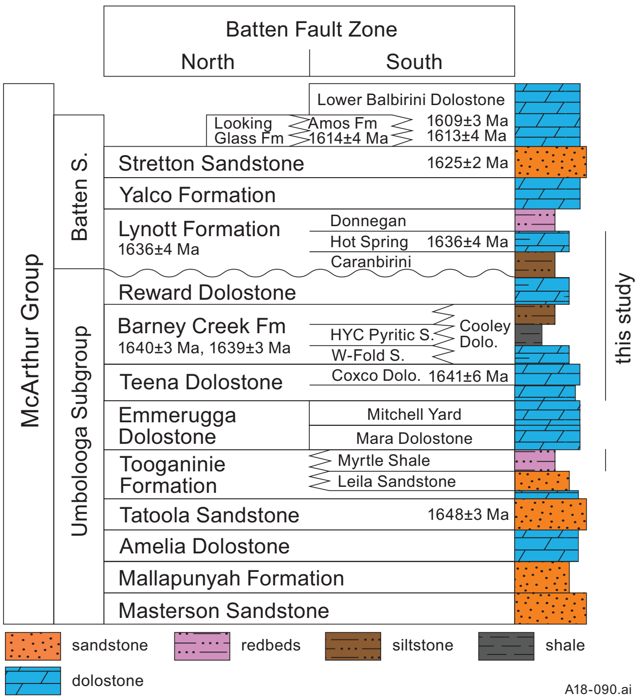

Figure 2. Stratigraphy and geochronology of the McArthur Group. Modified from Ahmad *et al* (2013).

with all parts of the Barney Creek Formation. The clasts are likely sourced from the underlying Teena and Emmerugga dolostones (Brown *et al* 1978; Ahmad *et al* 2013).

Principles of carbon isotope chemostratigraphy and sequence stratigraphy

Chemostratigraphy is the study of the variations in the chemical composition of sedimentary rocks. The chemical signals on which chemostratigraphy focuses are typically proxies for seawater compositions or environmental conditions at the time of deposition or during early diagenesis. One important application of chemostratigraphy is as a tool for intra-basinal and global correlations of stratigraphic units. When combined with radiometrically calibrated reference sections, chemostratigraphy can be used for indirect chronostratigraphy, comparable to biostratigraphy and magnetostratigraphy.

As biostratigraphy, arguably the most important stratigraphic tool in Phanerozoic successions, is only of very limited use in the Precambrian, basin-wide stratigraphic correlations in Precambrian basins are often difficult to unravel. However, the carbon isotopic composition of carbonate rocks ($\delta^{13}C_{carb}$) has been successfully applied in Proterozoic (mostly Neoproterozoic) basins around the world (eg Halverson *et al* 2005, 2010).

The carbon isotopic composition of unaltered marine carbonate rocks closely approximates the isotopic composition of the dissolved inorganic carbon (DIC) reservoir in seawater. Considering that the residence time of carbon in the modern ocean (about 200 000 years) is about two orders of magnitude longer than the mixing time of the ocean (1000–2000 years), coeval carbonate rocks in one basin (and even the global ocean) have the same isotopic composition (see Kump and Arthur 1999 for detailed review of carbon isotopes). This principle can be used for chemostratigraphic correlation if one important requirement is met – significant and systematic changes of the carbon isotopic composition of DIC, and thus carbonate rocks, through time. Otherwise, carbonate rocks from different stratigraphic units may have the same carbon isotopic composition, making it impossible to distinguish them.

Sequence stratigraphy defines a quasi-chronostratigraphic framework for sedimentary basins by defining stratigraphic surfaces that represent breaks in sedimentation or changes in depositional trends. Two major approaches of sequence stratigraphy exist: one defines sequence stratigraphic surfaces based on the theoretical base level curve (approximates relative sea-level curve); the other relies on observable, physical characteristics in the rock record to define sequence stratigraphic surfaces (eg Embry and Johannessen 2017). The latter approach defines transgressive-regressive (T-R) sequences (Embry 1993, 2009). We used this approach in the McArthur Basin because it requires less robust data and is generally easier to apply in structurally complex Proterozoic basins with limited or no available seismic data.

A T-R sequence is bounded by subaerial unconformities or the unconformable shoreline revinement surface in marginal and shallow marine settings, or by their deepwater equivalents, the maximum regressive surfaces (MRS). The sequence is divided into two systems tracts: a transgressive systems tract (TST), deposited during base level (relative sea-level) rise; and a regressive systems tract (RST), deposited during the subsequent base level fall. The TST and RST are separated by the maximum flooding surface (MFS). Refer to Embry (2009) and Catuneanu (2006) for a detailed introduction to sequence stratigraphy.

Results and discussion

The Barney Creek Formation thickens from ca 170 m in drillhole Lamont Pass 3 located on the Lamont Pass palaeohigh (**Figure 1b**) to ca 900 m in drillhole GRNT-79-7, about 17 km to the south in the northern Glyde sub-basin (**Figure 3**). Further to the south, the thickness ranges from ca 400 to 650 m. Thickening is also observable in west-east transects within the sub-basin, for example from ca 300 m in drillhole GRNT-79-3 to ca 900 m in GRNT-79-7. This threefold increase in thickness occurs over a distance of less than 10 km (**Figure 1b**). Importantly, whereas the Barney Creek Formation is conformably overlain by the Reward and Lynott formations in Lamont Pass 3, it is truncated by the sub-Cambrian unconformity in all drillholes in the Glyde sub-basin (**Figure 3**). The Barney Creek Formation is dominated by deep subtidal dolomitic siltstones in the Glyde sub-basin. In contrast, on the palaeohigh in Lamont Pass 3, it is composed of deep to shallow subtidal carbonate facies (**Figure 3**). This highlights that sedimentological and stratigraphic studies of the Barney Creek Formation must consider significant lateral facies changes.

Carbon isotope values show significant and systematic variation in the middle McArthur Group. In Lamont Pass 3, the high-resolution $\delta^{13}C_{carb}$ curve starts with ca -3.5 ‰ in the Myrtle Shale and values gradually increase upsection to ca -0.5 to 0 ‰ in the middle Barney Creek Formation, followed by an upsection decrease to ca -1.5 to -2.0 ‰ in the lower Lynott Formation (**Figure 3**). The Barney Creek Formation itself is characterised by a subordinate $\delta^{13}C_{carb}$ trend showing an increase from ca -1.5‰ at the base to ca 0 ‰ in the middle part of the formation, followed by values clustering around -1.0 ‰ in the upper Barney Creek Formation (**Figure 3**). The carbon isotopic composition and trend of the Barney Creek Formation is also observable in all of the ten studied drill cores from the Glyde sub-basin. Other distinctive carbon isotope signals are associated with the transition into the Barney Creek Formation and within the W-Fold shale respectively (**Figure 3**), and the contact between the Teena Dolostone and W-Fold Shale. These systematic and significant $\delta^{13}C_{carb}$ trends in the middle McArthur Group demonstrate that future application of carbon isotope chemostratigraphy will likely significantly improve our understanding of stratigraphic correlations in the greater McArthur Basin.

The Barney Creek Formation records two T-R sequences, herein named B1 and B2 (**Figure 3**). Sequence B1 starts at the Teena Dolostone-Barney Creek Formation contact or, in locations were the W-Fold Shale occurs, at the W-Fold Shale-HYC Pyritic Shale Member contact. It is characterised by a thin TST and a MFS that is composed of pyritic, organic-rich shale and silty shale in the Glyde sub-basin or sits within a tens of metres thick rhythmite in Lamont Pass 3. The RST represents a thick shoaling upward succession of dolomitic siltstone transitioning into silty dolarenite in the Glyde sub-basin and a shoaling to shallow subtidal dolarenite in Lamont Pass 3. Sequence B2 starts with renewed deepening to dark organic-rich dolomudstone in Lamont Pass 3 and dolomitic siltstone in the Glyde sub-basin. The thin TST culminates in a thick interval of dolomudstone (Lamont Pass 3) or pyritic and organic-rich shale and silty shale (Glyde sub-basin), representing the MFS. The overlying RST is composed of shallow subtidal dolarenite in Lamont Pass 3 and dolomitic siltstone and silty dolarenite in the Glyde sub-basin. The sequence boundary of B2 occurs in the Reward Dolostone (Lamont Pass 3). However, it is not preserved in the drill cores from the Glyde sub-basin due to truncation by the sub-Cambrian unconformity.

Whereas B1 is preserved in most of the Glyde sub-basin and is only truncated in the southern part, B2 is significantly truncated in the northern part of the sub-basin and absent in the south (**Figure 3**). This indicates that truncation below the sub-Cambrian unconformity increases towards the south. Importantly, the two MFS of both sequences are likely the most important intervals in the Barney Creek Formation to host base metals mineralization. Preliminary geochemical data suggest that both MFS were deposited under euxinic (anoxic and free H_2S/HS^-) conditions, which are ideal chemical traps, independent of models for syngenetic or early diagenetic models of mineralization. Furthermore, the McArhur River deposit sits stratigraphically at the level of the MFS in sequence B1. The absence of the MFS of sequence B2 in most of the Glyde sub-basin lowers its prospectivity. This highlights that sequence stratigraphy is a powerful tool in mineral exploration, similar to petroleum exploration.

Conclusion

We established a high-resolution carbon isotope curve for the middle McArthur Group in Lamont Pass 3. The same isotopic composition and isotopic trends observable in the Barney Creek Formation in Lamont Pass 3 are also observable in ten studied drill cores from the Glyde sub-basin. The observable systematic and significant stratigraphic changes in the carbon isotopic composition highlight the potential for carbon isotope chemostratigraphy to significantly improve our understanding of basin-wide stratigraphic correlation in the greater McArthur Basin. Considering that these analyses are also inexpensive and fast, we recommend to routinely use carbon isotopes in stratigraphic studies and mineral exploration in the greater McArthur Basin. This should be particularly helpful in underexplored areas where the stratigraphy is not well understood.

Using sequence stratigraphy, we were able to reconstruct the depositional architecture of the Glyde sub-basin. The Barney Creek Formation records two T-R sequences. However, the second sequence is significantly truncated or even entirely removed beneath the sub-Cambrian unconformity in the Glyde area. This observation is insofar important as the two MFS from both sequences represent the most important intervals for base metals mineralization in the Barney Creek Formation. This highlights that sequence stratigraphy is a powerful tool to identify and predict the occurrence of prospective intervals for base metals mineralization.

The results of this study will be integrated with geochemistry, and geophysical and numerical deformation fluid-flow models to strengthen our multidisciplinary approach to base metals exploration in sedimentary basins. Furthermore, these studies will be extended to the entire Batten Fault Zone in the next 12 months.

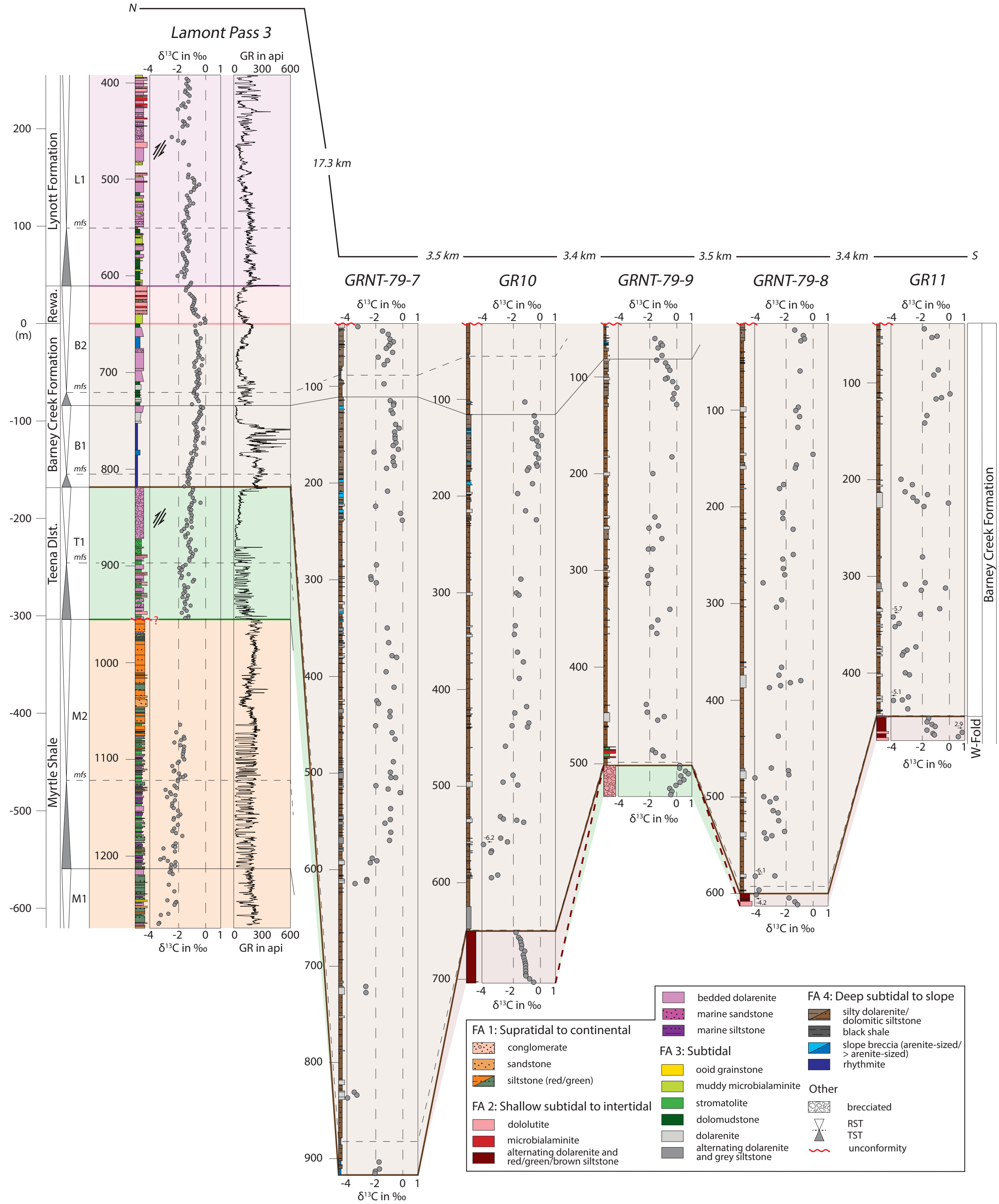

Figure 3. Litho-, chemo-, and sequence stratigraphy of the middle McArthur Group in the Glyde sub-basin. See **Figure 1** for location of drill cores.

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