Buildups from the lower Cambrian Hawker Group, Arrowie Basin: construction, facies and geochemistry

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Archaeocyath boundstone from Wirrealpa Mine, upper Wilkawillina Limestone, scale bar = 4 cm.



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Declaration of Authorship

I hereby certify that the work in this thesis, "*Buildups from the lower Cambrian Hawker Group, Arrowie Basin: construction, facies and geochemistry*", has not previously been submitted for a degree to any other university or institution other than Macquarie University. This thesis is an original piece of research and any assistance received related to research or preparation has been appropriately acknowledged.

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Abstract

The lower Cambrian carbonates of the Flinders Ranges are richly fossiliferous and contain a highly diverse assemblage of archaeocyaths. Lower Cambrian buildups formed by the aggregation of archaeocyaths, cemented together by calcified microbes, occurred on shallow carbonate platforms in low latitudes. The development of these buildups provides an early example of ecosystem engineering by archaeocyaths. The rigidity of these buildups created topographic relief, while the heterogeneity produced internal cavities that enhanced habitat complexity within benthic ecospace.

In this study, buildup architecture is mapped to reveal the heterogeneity, structure and proportional relationship between archaeocyaths and calcified microbes. This centimetre-scale foundation provides contextual framework for deciphering the buildup architecture at millimetre- to micrometre-scale. This scale focuses on the biological composition of archaeocyaths, calcified microbes and associated faunas within the buildup. Additionally, this scale reveals the interaction between individual archaeocyaths and the calcified microbial support, with relevance to bioconstruction rigidity and the development of syndepositional cavities.

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1. Introduction

The lower Cambrian is a critical stage in evolutionary history, associated with the relatively rapid increase in metazoan diversity, appearance of bilateral body plans, expansion of ecospace into new niches and global changes in biogeochemical cycling (Bush et al., 2011, Butterfield, 2011, Budd, 2016). The triggers for these evolutionary innovations have been subject to extensive debate, with many environmental and biologically driven hypotheses proposed (Smith and Harper, 2013, Mángano and Buatois, 2014). However, an approach that has received less attention is the concept of ecosystem engineering.

Archaeocyaths are an extinct group of sessile, calcareous marine organisms, generally referred to as aspiculate poriferans (Rowland, 2001, Debrenne, 2007, Kerner et al., 2011, Botting and Muir, 2017). The calcite skeleton secreted by archaeocyaths consisted of two nested, often porous cones, forming an outer and inner wall (Wood et al., 1992, Zhuravlev, 1993). The aggregation of archaeocyaths cemented by calcimicrobial growths are the major biological constructors of early Cambrian buildups in low latitude marine shelf environments. These buildups created rigid structures with topographic relief and internal cavities that enhanced habitat complexity within benthic ecospace. This provides an early example of ecosystem engineering by archaeocyaths.

The different sedimentological features of buildups relate to ecology, growth, development and depositional facies (Gandin and Debrenne, 2010). These features have been applied to develop systematic buildup classifications that use detailed mapping of biological and inorganic constituents to constrain buildup type (James and Debrenne, 1980, Debrenne and James, 1981, James and Gravestock, 1990). Generally, these classifications are applied to studies of ancient and modern reefs. However, in the present study, buildup types will be observed in the frame of ecosystem engineering and niche habitat development.

1.1 Buildup Development

The buildup complexes of the early Cambrian were formed by the aggregation of living and toppled archaeocyaths, cemented together by a range of calcimicrobe "morphotaxa" (Rowland and Gangloff, 1988). These biogenic constructions created topographic relief and rigidity through cementation by calcimicrobes that increased wave resistance and generally occurred on shallow marine low latitude carbonate platforms with increased turbidity (Kerner and Debrenne, 2013).

The foundations of buildups follow a progressive sequence of biologically driven stages. The first is a pioneering or colonisation stage, with settlement of solitary archaeocyaths on the soft substrate; the second is a stabilisation stage, with the introduction of modular archaeocyaths forming framework with solitary archaeocyaths and lithification of the substrate; the third is a

diversification stage, which sees the arrival of encrusters, borers, cryptic faunas and cementing and encrusting by calcified microbes (Zhuravlev, 2001). The fourth stage of development is referred to as the climax stage, with buildup growth extending to the high-energy marginal peritidal zone (an alternative allocyclic fourth stage is destruction followed by recovery e.g. storm event) (Debrenne, 2007).

1.2 Ecosystem Engineering & Ecospace

An ecosystem engineer is defined as a species that actively modifies their environment, and subsequently alters resource availability for other species within that environment (Erwin, 2008). This modulation can be viewed as niche development, which is a feature of adaptive radiations and links biological constituents within ecosystems (Laland, 2010). Ecosystem engineering during the terminal Ediacaran likely provided the foundation for the subsequent ecological success of bilaterian clades (Zhang, 2014). During the early Cambrian, development of archaeocyath buildup framework led to the expansion of ecospace, which provides an early example of structural ecosystem engineering and may have played a key role in the Cambrian radiation.

An organism's ecological role can be considered in terms of their tiering position, motility and feeding strategy, providing a theoretical ecospace (Bush et al., 2011). Theoretical ecospace for marine animals define 216 potential modes of life with around two thirds occupied in modern marine systems, and only 30 modes of life during the early to middle Cambrian (Bambach et al., 2007). The rigid structures and tiering created by archaeocyath buildups led to the development of new topographic relief with complex internal cavities. This had a cascading effect on ecological structure and enhanced associated fauna habitat complexity within benthic ecospace.

1.3 Archaeocyaths

The variably open, irregular to narrow conical calcareous skeletons of archaeocyaths formed an inner and an outer wall surrounding a central cavity. The area between the two-walled structure, termed the intervallum, contained several skeletal structures: the taenia, tabula, vesicle and septum. Septa partition the inner and outer walls generally in radial-longitudinal compartments with pore development ranging from completely porous, sparsely porous to aporous (Debrenne et al., 2012). The varying degree of septal porosity and the diameter of the central cavity were associated with entrainment and reflects the energetic condition of the environment in which individuals formed (Zhuravlev, 1993, Savarese, 1995). The epitheca, at the base of the skeletal structure, allowed individuals to attach to substrate surfaces (Fig. 1).

Skeletal development was originally used to divide archaeocyaths into two subclasses, 'Regulares' (septal type) and 'Irregulares' (taenial type) (Zhuravleva, 1960, Debrenne, 2007).

However, this classification posed many identification problems including partial remineralisation during deposition and the morphology of juvenile taenial types (Gravestock and Jell, 1984). These subclasses have since been replaced by six orders that apply differences in structure and skeletal ontogeny to classification (Debrenne et al., 2012). Archaeocyaths exhibit a range of growth forms that include solitary, pseudocolonial (laminar or branching), uniserial erect (catenulate or pseudocerioid), and multiserial (encrusting or massive) forms (Wood et al., 1992). The present study is focused on buildup architectures. For this reason, archaeocyath growth forms will be discussed rather than taxonomic order.

Typically, archaeocyaths occur as isolated individuals, though often in close-knit clusters occupying a sessile epibenthic or pseudo-tiered filter-feeding ecospace. Due to their life habit, they were only able to form local, mostly decimetre scale (although occasionally larger, e.g, Moro Gorge locality) buildup framework rather than widespread rigid structures (Debrenne, 1991). Despite this, archaeocyaths were the major bioconstructors in early Cambrian bioherms. These buildups increased topography and structural rigidity due to widespread cementation by a range of calcified microbial taxa (James and Gravestock, 1990). The support of calcified microbial cement enabled archaeocyaths to accumulate within a rigid, spatially heterogeneous framework. New individuals often attached to hardgrounds of calcimicrobial layers or other skeletal components.



Figure 1. Typical archaeocyaths structures including inner and out walls, septum, intervallum, central cavity and epitheca. Adapted from Debrenne and Zhuravlev (1994).

The timing and spatial distribution of archaeocyath buildups reflect the emergence, peak and decline of archaeocyaths. The emergence of archaeocyaths during Terreneuvian, Stage 2, on the shallow carbonate platforms of the Siberian Plate coincided with the emergence of the calcimicrobes, *Renalcis* and *Epiphyton* (Riding and Zhuravlev, 1995, Debrenne, 2007). Subsequent increases in shallow water carbonate deposition and eustatic sea level rise during Stage 2 led to the dispersal of archaeocyaths to Europe, northern Africa, and Australia (Rowland and Gangloff, 1988, Brock et al., 2000). Archaeocyath distribution, abundance and diversity peaked during the Stage 2 in the tropical zone, followed by a rapid decline by Series 2, Stage 3 (Gandin and Debrenne, 2010).

Archaeocyath communities persisted in restricted low latitude environments due to higher carbonate deposition in warmer waters. However, archaeocyath buildups began to be replaced by stromatolite and thrombolite reefs. The eventual extinction of archaeocyaths during late Cambrian Stage 4 was potentially due to anoxia because of eutrophication and phytoplankton blooms, followed by marine regression, which led to restricted shelf areas of previously submerged platforms; continental breakup and drifting into higher latitudes; and the eruption of a Large Igneous Province in northern Australia (Adachi et al., 2015, Kruse and Reitner, 2014).

1.4 Calcimicrobes

Calcimicrobes (calcified microbes) are typical in shallow marine carbonate environments. The main groups that occur through lower Cambrian buildups of the Flinders Ranges are *Renalcis*, *Epiphyton* and *Girvanella* (James and Gravestock, 1990). *Renalcis* exhibited a range of morphotypes including clotted, chambered, saccate and septate, and often developed as dense boundstones, or crust on the walls and within the intervallum of archaeocyaths (Pratt, 1984). *Renalcis* were the dominant framework builders of Cambrian buildups, likely due to growth being relatively uninhibited by higher sedimentation rates (Debrenne, 2007) (Fig. 2). *Epiphyton* exhibited a range of morphotypes including clotted, dendritic and septate (Pratt, 1984) (Fig. 2). Often *Epiphyton* grew in bush-like structures on or surrounding archaeocyath individuals (Debrenne, 2007). *Girvanella* exhibited a wider variety of forms than other calcimicrobes, which ranged from defined tubes to threads forming discontinuous, planar to arcuate crusts, either encrusting, dispersed or enrolled in morphology and generally inter-grown with other calcimicrobes (intraclastic) (Pratt et al., 2001) (Fig. 3).



Figure 2. Morphological variations of *Renalcis* and *Epiphyton. Renalcis* growths range from clotted and chambered intergrowths, saccate, chambered and septate. *Epiphyton* growths range from clotted, dendritic and septate. Adapted from Pratt (1984).



Figure 3. Morphological variations of *Girvanella*, ranging from encrusting, dispersed, enrolled and intraclastic. Adapted from Pratt (2001).

1.5 Buildup Associated Faunas

Lower Cambrian buildups contained generalist and opportunistic passive filter feeders and active suspension feeders. Associated calcified faunas contributed to carbonate accumulation of early Cambrian buildups and were primarily chancelloriids, calcareous sponges, brachiopods, hyoliths, and other shelly fossils (Zhuravlev, 2001, Brock, 2010). Microbioclastic spiculite are common in micrite-dominated buildups, with preserved fine silt-sized skeletal debris with numerous calcite spicules (James and Gravestock, 1990). The remains of these associated faunas often occur in the internal sediments of buildups, suggesting that these faunas lived on the surface or in the cavities of the buildup (Clarke, 1990).

1.6 Buildup Structures & Inorganic Constituents

Cavities are a key feature in carbonate reefs and are produced syndepositionally by the growth of structural ecosystem engineers; collapse of organic carbonate structures; or bioerosion from micro and macro boring metazoans (Kobluk, 1981, Kobluk and James, 1979, Erwin, 2008). Characteristic

buildup sedimentary structures such as fenestral fabric or stromatactis, appear as irregular cavities ranging from 10 mm to 200 mm in length (Flügel and Kiessling, 2002). Stromatactis are sparitic cement-filled cavities common in lower Cambrian buildups (Bathurst, 1980). These open space structures occur in millimetre- to centimetre-scale voids and are typical of subtidal environments (Flügel, 2013). The ceilings of these structures can be irregular and unsupported to partially or fully enclosed by archaeocyaths or *Girvanella* growths (James and Gravestock, 1990).

Cavities can form post-depositionally by chemical or physical erosion of carbonates such as the development of karstic surfaces. When resubmerged, the karst provide a new substrate for development of biogenic structures and allow associated faunas to colonise eroded cavities (Wood et al., 1992). The Flinders Unconformity, a potential karstic system, occurs through the Flinders Ranges, especially in shallow carbonate platform facies and can be observed in outcrop as a distinctive iron rich reddened crust, occasionally with micro-stromatolitic post-transgression pioneers growing directly on the karst surface.

Synsedimentary calcium carbonate cement was a key component in lower Cambrian buildups. Calcium carbonate precipitated on the sea floor and often filled pores and cavity spaces, which increased the rigidity of the buildups (Pratt et al., 2001). Through the Cambrian sediments of the Flinders Ranges, micritic, spherulitic and fibrous calcium carbonate cementation are the most common forms of inorganic carbonate input to buildup development (James and Gravestock, 1990).

2. Project Aims

This project has three main aims:

Aim 1. Detail the centimetre-scale architecture to reveal the structure and proportional relationship between archaeocyaths and calcimicrobes of the buildup and place Flinders Ranges buildups with previously documented Cambrian buildup types.

The centimetre-scale focuses on buildup architecture, especially the heterogeneity and distribution of organic and inorganic constituents, the structure and relief created by the buildup, and the proportional relationship between archaeocyaths and calcimicrobes of the buildup. Additionally, these data indicate the stage of bioconstruction development where appropriate (colonisation, stabilisation, diversification or climax) and help constrain the depositional environment. Once the centimetre-scale dynamics have been constrained, the millimetre- to micrometre-scale can be observed within a contextual framework.

H1: The architecture of sampled Flinders Ranges buildups will allow identification of buildup type.

H0: The architecture of sampled Flinders Ranges buildups will not provide sufficient data to confidently identify buildup type.

Aim 2. Detail the millimetre- to micrometre-scale architecture to reveal the biological composition and transition between individual archaeocyaths, calcimicrobes, associated fauna and inorganic constituents of the buildup.

The millimetre- to micrometre-scale focuses on the biological composition of archaeocyaths, calcimicrobes and associated faunas across the buildup. Additionally, this scale focuses on the transition between individual archaeocyaths and the calcimicrobial support, with relevance to buildup rigidity and the development of syndepositional cavities. These details will form a foundation for the potential development of new habitat niches for associated faunas. Mapping the cavities and the geopetal orientation of the sediment in-fill allows for greater understanding of the buildup orientation during life. Additionally, the secondary in-fill of the cavities and the post-depositional alteration reveal the diagenetic history of the buildup.

H2: Buildup architecture supported by archaeocyaths and calcimicrobes created new habitat niches for associated faunas.
H0: No clear habitat for associated faunas developed within archaeocyath and calcimicrobe buildups.

Aim 3. Describe the post-depositional alteration of buildup architecture, composition and the impact this has on the preservation of biological features.

Carbonates are highly porous and can potentially become severely altered over geological time through pore water fluid movement and remobilisation of minerals (Flügel, 2013). This feature of carbonates produces a challenge for interpreting fossilised reefs and buildups over deep time, by creating a diagenetic overprint of the original biological material that inhabited the environment. Understanding how this alteration can influence interpretations of community and species biodiversity, abundance and other palaeoecological factors is critical to studying these lower Cambrian buildups.

H3: Depositional buildup features will be concealed by diagenetic overprinting.
H0: Diagenetic processes and their impact on preservation of the depositional buildup features will not prevent interpretations of original biology.

3. Geological Setting & Biostratigraphy

The Flinders Ranges forms part of the Adelaide Rift Belt and contains a sedimentary succession of Neoproterozoic to lower-middle Cambrian (Fortunian Stage to unnamed Series 2, Stage 5) outcrops. These sediments were extensively deformed during the Late Cambrian (Furongian) to Lower Ordovician Delamerian Orogeny (James and Gravestock, 1990, Zang et al., 2004). Lower Cambrian strata from the Arrowie Basin are well exposed through the south Flinders Ranges and west to the Stuart Shelf of the Gawler Craton (Gravestock, 1995). The lower Cambrian Hawker Group is composed primarily of carbonates, variable in thickness, and with a range of complex facies (Haines and Flöttmann, 1998). These lower Cambrian carbonates have been subjected to varying stages of complex diagenesis related to diapirism, including patchy secondary dolomitisation (Haslett, 1976).

The samples described herein were collected from strata along previously measured stratigraphic sections through transgressive to highstand system tract deposits that crop out in the Bunkers and Mt. Scott Ranges in the Arrowie Basin (Gravestock, 1995, Gravestock and Shergold, 2001, Zang, 2002, Zang et al., 2004) (Fig. 4). These thick carbonate-dominated successions represent buildup (and inter-reefal) facies from shallow to mid-shelf deposits of the Wilkawillina Limestone and Ajax Limestone. The lower Wilkawillina Limestone, at least in shallow platformal settings around the Wirrelapa Hinge Zone, is subdivided into (in ascending order) the Mt. Mantell, Hideaway Well and Winnitinny Creek Members (Clarke, 1986, 1990). Archaeocyath buildups are particularly prevalent in the Hideaway Well Member, some measuring up to 100 m in lateral extent in the MORO section and are also prominent the Winnitinny Creek Member (Betts et al., 2014).



Figure 4. Sample localities through Cambrian outcrops of the Arrowie Basin, Flinders Ranges, South Australia. Moro Gorge (MORO); Balcoracana Creek (BALC); Ajax North, Mount Scott Ranges (AJXN); and Wirrealpa Mine (WIRM).

The buildups described herein span through all three new lower Cambrian shelly fossil biostratigraphic zones formally defined by Betts et al. (2016, 2017) based on the robust and repeatable stratigraphic ranges of a variety of key tommotiids, brachiopods, molluscs and bradoriids in the Arrowie Basin. The oldest zone, the *Kulparina rostrata* Zone, is entirely pre-trilobitic (globally). The *K. rostrata* Zone is characterised by a relatively low diversity shelly assemblage, typically containing five or six taxa including eccentrothecimorph and camenellan tommotiids and the paterinid brachiopod *Askepasma saproconcha* (Topper et al., 2013).

Most of the overlying *Micrina etheridgei* Zone is also pre-trilobitic (globally), but upper parts overlap with the lower boundary of oldest Australian trilobite (*Parabadiella huoi*) zone. The *M*.

etheridgei Zone is characterised by a high diversity shelly fossil assemblage that includes eccentrothecimorph and camenellan tommotiids, helcionelloid molluscs, bradoriid arthropods and lobopodians (Betts et al., 2016). The youngest shelly fossil biostratigraphic zone is the *Dailyatia odyssei* Zone, which overlaps the *Pararaia tatei*, *Pararaia bunyerooensis* and lowermost *Pararaia janeae* trilobite zones (Betts et al., 2017). Key shelly fauna occurring in the *D. odyssei* Zone include tommotiids, stoibostrombids and diagnostic brachiopod and bradoriid taxa (Betts et al., 2016, 2017).

The lower Cambrian Hawker Group contains two lithofacies sequences. Sequence 1 is identified as the lower part and contains transgressive siliciclastics and includes the Lower Wilkawillina Limestone, and equivalent units (James and Debrenne, 1980). Sequence 2 reflects a shallow carbonate platform, and includes the upper Wilkawillina Limestone, upper Ajax Limestone, and equivalent units (James and Gravestock, 1990).

3.1 Lower Wilkawillina Limestone (Hideaway Well Member) MORO Section, Moro Gorge [*K. rostrata* Zone]

Lower Wilkawillina Limestone outcrops through the MORO section, located 5 km south of Moro Gorge (Fig. 4). This section intersects strata that form the eastern limb the Arrowie Syncline in the northeast Flinders Ranges. These carbonate dominated sediments contain highly abundant archaeocyaths within large buildups and reflect a high-energy, shallow water environment (Betts et al., 2014). Samples were taken through the Hideaway Well Member, Lower Wilkawillina Limestone, which is part of the *K. rostrata* biostratigraphic zone (base of section at 30°43'36.96" S / 139°12'31.68" E; top of section at 30°43'27.54"S / 139°11'52.98"E (Betts et al., 2014, 2016) (Fig. 5).

3.2 Lower Wilkawillina Limestone (Winnitinny Creek Member) BALC section, Balcoracana Creek [*M. etheridgei* Zone]

The lower part of the BALC section is primarily stromatolitic, unfossiliferous, with breccia and dolomite. Poorly preserved archaeocyaths have been recorded 55 m from the base of the section (Skovsted et al., 2011). The upper part of the BALC section contains clean grey-white bioclastic limestone with well preserved, abundant and diverse shelly faunas and an absence of archaeocyaths and calcimicrobes. Occasional shell hash dominated by sclerites of the tommotiid *M. etheridgei* form in neptunian dykes at many levels. The top of the Wilkawillina Limestone at this section is disconformably overlain by poorly outcropping Billy Creek Formation. Samples were taken through the upper part of the section at Balcoracana Creek, 190 m from the base of section just below the iron-rich karst hardground 'reddened' horizon, which represents the regionally significant

Flinders Unconformity (base of section at 31°11'04.7" S / 138°52'36.8" E; top of section 31°11'03.2" S / 138°52'39.5" E) (Gravestock, 1995, Gravestock and Shergold, 2001). Samples from the upper part of the BALC section represent inter-reefal facies so provide a comparison to the buildup facies of the other three sections (Fig. 4 and 6).

3.3 Upper Ajax Limestone, AJX-N section, Mt. Scott Range [M. etheridgei Zone]

The Mount Scott Range in the northeast of the Arrowie Basin outcrops lower Cambrian sediments equivalent to the Lower Wilkawillina Limestone and Wirrapowie Limestone (James and Gravestock, 1990) (Fig. 4). This locality reflects Sequence 1 carbonate sediments with an intrashelf depression shallowing to a high-energy open-shelf setting (Betts et al., 2016). The base of the section is extensively dolomitized but contains rich shelly fossil assemblages of the *M. etheridgei* Zone, including widespread silicification. The reddened horizon of the Flinders Unconformity is not present in Mount Scott Range, reflecting its mid-shelf palaeodepth. Samples were taken in the upper Ajax Limestone, through the AJX-N section 150 m and 220 m from the base of the section (base of section at 30°35'38.69" S / 138°19'48.12" E; top of section at 30°35'38.1" S / 138°19'47.9" E) (Fig. 7).

3.4 Upper Wilkawillina Limestone, Wirrealpa Mine [D. odyssei Zone]

The Wirrealpa Mine locality is 2.7 km north of the Blinman-Wirrealpa road and is located near the margin of the Wirrealpa Diapir (Fig. 4). This locality contains upper Wilkawillina Limestone Sequence 2 high-energy open-shelf carbonate sediments that reflects two depositional cycles. The older, cycle 1 sediments contain primarily archaeocyath-dominated buildups, and the younger, cycle 2 sediments are dominated by oncolite rudstones, stromatactoid microbial clasts, stromatolites and decimeter buildup complexes (Kruse, 2016). The Flinders Unconformity is present at this locality and can clearly be identified in the iron-rich crust of the reddened horizon (James and Gravestock, 1990).

Samples were taken through Upper Wilkawillina Limestone, Sequence 2 (base of section at 31°04'17.1" S / 138°55'15.1" E; top of section at 31°04'28.3" S / 138°54'49.6" E), equivalent in time to Second Plain Creek Member which is only developed in the Bunkers Graben, some 20 km to the south. The buildups located above the Flinders Unconformity all occur within the *D. odyssei* biostratigraphic zone (Betts et al., 2016). Due to the excellent outcrop exposure and continuity of buildups at this section, samples were taken from the base of the section at the Flinders Unconformity, 37 m, 85 m, 113 m, 185 m and 210 m to map the local extent of these buildups (Fig. 8).



Figure 5. MORO section through the Hideaway Well Member, Wilkawillina Limestone in the Arrowie Syncline, Moro Gorge, northern Flinders Ranges. Archaeocyaths occur across the *Kulparina rostrata* and *Micrina etheridgei* Zones. A buildup sample was taken from the upper *K. rostrata* Zone, 470 m from the base of section.

BALC

(Balcoracana Gorge, Bunkers Range)



Figure 6. BALC section through the Winnitinny Creek Member, Wilkawillina Limestone, Balcoracana Creek, Bunkers Ranges, central Flinders Ranges. Inter-reefal samples were taken within the *Micrina etheridgei* Zone, 190 m from the base of the section.



Figure 7. AJXN section through the Ajax Limestone, Mount Scott Ranges, north-western Flinders Ranges. Archaeocyaths occur in the upper unit within the *Micrina etheridgei* Zone. Buildup samples were taken 150 m and 220 m from the base of the section.



Figure 8. WIRM section through the upper Wilkawillina Limestone in the central Flinders Ranges. Archaeocyaths occur in Sequence 2 sediments within the *Dailyatia odyssei* Zone. The Flinders Unconformity is a karstic erosional surface that divides the lower and upper Wilkawillina Limestone. Buildup sample section was taken from 0 m at the red crust, 37 m, 85 m, 113 m, 185 m and 210 m.

4. Buildup Types of the Lower Cambrian

Table 1. The various buildup types of the lower Cambrian include microbial, archaeocyath-sponge and archaeocyathcalcimicrobial buildups. The following table includes description and interpreted environment of deposition. Different building styles relate to the structural, depositional and compositional features and reflect associated facies. Buildup descriptions have been adapted from Rowland and Gangloff (1988) James and Gravestock (1990), Debrenne (2007) and Gandin and Debrenne (2010).

Туре	Description	Environment
Kalyptrae	Biconvex or concavo-convex mounds within a compound buildup, lenticular in cross section, with microbial framework, such as domal stromatolites.	Lower-energy, deeper water intra-shelf setting.
Calcimicrobial boundstone	This bioherm type is composed of >80% calcimicrobial framework, generally <i>Renalcis</i> , solitary archaeocyaths.	Lower-energy, deeper water intra-shelf setting.
Archaeocyath- <i>Renalcis</i> boundstones (<i>Renalcis</i> - dominant)	The <i>Renalcis</i> -dominated boundstones contain <10% small archaeocyaths, with small cavities, and generally form in isolated patch reefs or laterally continuous biostromes.	Lower-energy, inner-shelf setting.
<i>Girvanella- Epiphyton- Renalcis</i> boundstone	This bioherm type is primarily composed of <i>Girvanella</i> with some <i>Renalcis</i> and <i>Epiphyton</i> input with associated large, solitary archaeocyaths. Cavities occur throughout these bioherms, in-filled with sediments and fibrous calcite cement.	Medium- energy, inner- shelf.
Archaeocyath- Sponge buildup	These buildups contain highly diverse and abundant archaeocyaths from 10-50%, generally 30%, absent or few calcimicrobes present, numerous spar filled voids (fenestrae or stromatactis), and a distinctive red colouration through the matrix.	Mid-shelf, deeper water setting.
Archaeocyath- <i>Renalcis</i> boundstones (archaeocyath- dominant)	The archaeocyath-dominant boundstones contain archaeocyaths with a crust of <i>Renalcis</i> around the exterior wall of archaeocyath individuals that binds individuals together. This bioherm type contains approximately equal proportions of archaeocyaths (although archaeocyaths can reach up to 40%), calcimicrobial crusts, and growth cavities in-filled by either fibrous calcite cement or geopetal peloid sediments.	Higher-energy, platform setting.
Archaeocyath boundstones	This bioherm type contains archaeocyaths (mostly toppled, some <i>in situ</i>), with overgrowths of spongiomorphs, occasional <i>Renalcis</i> and cavities filled with fibrous calcite cement. The associated biota include reef dwelling and transported brachiopods, trilobite, sponge spicules,	Higher-energy, platform setting.

	phosphatic small shelly fossils, chancelloriids and echinoderm plates.	
<i>Epiphyton-</i> archaeocyath boundstones	<i>Epiphyton</i> composes ~50% of these bioherms with minor input from archaeocyaths and other associated biotas.	Higher-energy, platform setting.

5. Materials & Methods

Buildup samples were collected at outcrop from the stratigraphic sections, MORO, AJXN and WIRM of the lower Cambrian Hawker Group. Samples represent buildups from three recently established biostratigraphic zones (Figs. 5, 7 and 8). Previous work on these sections is limited regarding buildup architecture and ecosystem engineering. Samples were chosen based on outcrop extent (AJXN section = poor; MORO section = reasonable; WIRM section = excellent). Samples were collected at outcrop from the BALC stratigraphic section (Fig. 6) of the lower Cambrian Hawker Group to represent inter-reefal facies.

Aim 1.

All buildup and inter-reefal slabs were cut perpendicular and parallel to the bedding planes. Cut slabs were polished using a sequential coarse to fine grain gradient of sandpaper and finished with tin oxide. Slabs were imaged using Hasselblad H4D-31 HC macro 120 mm lens with Phocus software. Images were coloured in Adobe Photoshop and percentage of colour was calculated using pixel count. Macro-photography and coloured images were used to show community relationships between the archaeocyath and calcimicrobial cement.

The cut slabs were imaged and analysed with Micro X-Ray Fluorescence using a Bruker M4 Tornado μ -XRF with a Rh anode tube operated at 50 kV and 200 μ A, and a dual Bruker silicon drift detector energy dispersive spectrometers. The poly-capolary X-ray optics analysed a 25 μ m spot size. X-ray maps were generated using the Bruker M4 Tornado acquisition software. Maps were acquired at 100 μ m steps at a 25 μ m spot size, higher resolution maps were taken at 20 μ m steps at a 25 μ m spot size, and minimum dwell time per point was 25 ms. μ -XRF was used to map and elementally analyse samples to show the relationship between the boundaries of the archaeocyath, calcimicrobes, cavities and associated faunas along with the inorganic material. Combined, the macro-photography, coloured images and μ -XRF were used to observe the centimetre-scale architecture of buildups and the composition of inter-reefal samples. The structure and proportional relationships of the buildup allow for Flinders Ranges buildups to be assigned to previously documented Cambrian buildup types.

Aim 2.

Blocks (28 x 48 mm) were taken at regular intervals from each slab, both perpendicular and parallel to the bedding plane. Blocks were made into polished 70 µm thin sections by the Palaeoscience Research Centre, University of New England. Selected polished thin sections were imaged using a petrographic microscope with a NIS-element viewer via a Nikon camera attachment. Images were produced using a 2x and 5x objective in both polarised and cross polarised light. Petrography was used to obtain millimetre- micrometre-scale and rock micro-fabric details.

The thin sections were then carbon coated and analysed with Scanning Electron Microscope (SEM) and Energy Dispersive X-Ray Spectroscopy (EDS) to reveal the elemental composition using Zeiss Evo MA 15 SEM equipped with an Oxford X-max 20mm² EDS Silicon Drift Detector (SDD). Analysis was carried out at 15 kV, 1 nA and a working distance of 12 mm. Data was collected using Aztec EDS software. SEM and EDS analysis was used in compliment with petrographic analyses to observe the biological composition and transition between individual archaeocyaths, calcimicrobes, associated fauna and inorganic constituents of each buildup. These data are important in regard to buildup rigidity and the development of syndepositional cavities, which may give rise to new habitat niches for associated faunas.

Aim 3.

Data collected from the μ -XRF (for Aim 1) and the SEM/EDS (for Aim 2) help to elucidate the post-depositional alteration of buildups and the impact this has on the preservation of biological features.

6. Results

Centimetre-scale buildup architecture obtained from macro-photography and µ-XRF analyses provides a foundation of buildup growth in terms of the difference in structural contribution by archaeocyaths and calcimicrobes, cavity development and inorganic calcite cementation. Once these data are collated, buildup type may be determined. The centimetre-scale data form a contextual framework for analyses of buildup architecture at an millimetre- to micrometre-scale of development. Petrographic and SEM/EDS analyses provides detailed data relating to the structural and compositional relationships between individual archaeocyaths, calcimicrobes, associated faunas and inorganic material as they relate to habitat development.

Combined, these data provide a comprehensive analysis of buildup growth and development across differing depositional environments. Additionally, elemental analyses using μ -XRF and SEM/EDS provide an indication of post-depositional alteration of buildups and the potential impact this has on interpreting the palaeoecology of early Cambrian environments.

6.1 Lower Wilkawillina Limestone (Hideaway Well Member) MORO Section Macro-photography

The buildups at the MORO section are the largest observed in the present study. At outcrop, these buildups occur for around 2 km along strike with structures that measure 100 m in lateral extent. A large slab, MORO-1 (28cm x 16cm) was taken 470 m from the base of section. MORO-1 contains ~12% archaeocyaths, primarily *in situ* solitary archaeocyaths in transverse section with some toppled individuals; ~7% chambered *Renalcis* growths, throughout the internal sediment and in association with archaeocyaths; and ~4% stromatactis cavities, up to 3 cm in diameter. Fibrous calcite cement in-fills the central cavity of the larger archaeocyaths and in the center of the largest stromatactis cavity (Fig. 9). Due to the large size of this slab, elemental analysis using μ -XRF was not possible.





Figure 9. MORO-1 a) photograph shows solitary archaeocyaths (A), minor development of stromatactis (St) and remineralised cavity (Cv) in-fill; b) coloured image showing archaeocyaths (blue), chambered *Renalcis* growths (green) and stromatactis (yellow); Section parallel with bedding plane; Scale bar = 4 cm.

SEM/EDS & Petrography

The MORO-1 buildup is primarily composed of sparitic cement with some micrite and small quartz veins. Chambered *Renalcis* growths occur throughout, isolated and in association with archaeocyaths. The internal cavities of archaeocyaths have largely been in-filled by fibrous calcite cement (Fig. 10). SEM and EDS analysis shows a concentration of calcium with a scattering of silicon and manganese through the internal sediment. Magnesium dominates chambered *Renalcis* growths, with a minor input of iron and carbon (Fig. 11).



Figure 10. MORO-1 thin-section photomicrographs a) archaeocyath (A) with calcite (Ca) in-fill within internal cavity; b) chambered *Renalcis* (R) growths within sparitic (S) cement; Sections parallel with bedding plane; Scale bar = $250 \mu m$.



Figure 11. MORO-1 a) SEM image of chambered *Renalcis* growth; b) backscatter image showing calcium through the internal sediment and magnesium through the chambered *Renalcis* growth; c) backscatter image showing iron concentrated through the chambered *Renalcis* growth; d) backscatter image showing carbon through internal sediment and concentrated in the chambered *Renalcis* growth; Section parallel with bedding plane; Scale bar = 500 μ m.

6.2 Lower Wilkawillina Limestone, BALC Section

Macro-photography & µ-XRF

Samples BALC-1 and BALC-2 contain a highly abundant assemblage of well-preserved faunas including brachiopods (*Askapasma toddense*), trilobites, hyoliths, and the shelly faunas *Micrina etheridgei* and *Pojetaia runnegari* Jell 1980, and lack archaeocyath and calcimicrobial input (Fig. 12). Elemental analysis using μ -XRF reveals a high concentration of magnesium, calcium and strontium through the internal sediment. Banding of silicon co-occurs with aluminium. Potassium occurs throughout and concentrated in association with silicon and aluminium banding. Shelly fossils are generally replaced with either iron or phosphorous (Fig. 13).





Figure 12. BALC-1 photographs a) faunas including *Askapasma toddense* (Ak), *Pojetaia runnegari* (Pj), hyoliths (Hy) and trilobitic thoracic hook (Tr). Absence of archaeocyath or calcimicrobial input; Sections perpendicular with bedding plane, oriented top to bottom; Scale bar = 1 cm; b) hyolith (Hy), trilobitic thoracic hook (Tr) and *Micrina etheridgei* (mitral) (Mi); Sections perpendicular with bedding plane, oriented top to bottom; Scale bar = 5 mm.



Figure 13. μ-XRF pseudo colour maps of BALC-1 showing silicon (Si), calcium (Ca), potassium (K), phosphorous (P), magnesium (Mg) and iron (Fe); Section perpendicular with bedding plane, oriented top to bottom; Scale bar = 2 cm.

Petrography

BALC-1 is composed of micrite and contains a diverse assemblage of hyoliths in cross sectional view as well as multiple cone-in-cone nesting and imbrication of shelly material (Fig. 14). Additional associated faunas include chancelloriids, *Askapasma toddense*, trilobites, and the shelly faunas *Micrina etheridgei* and *Pojetaia runnegari* Jell 1980. Archaeocyaths and calcimicrobes were not identified at this scale, nor were the common bioconstruction accessory faunas hexactinellid spicules.



Figure 14. BALC-1 thin-section photomicrographs a) nested hyoliths (Hy) in longitudinal section with a micritic (M) matrix; b) nested hyoliths (Hy) in longitudinal section with chancelloriid (Ch) with a micritic (M) matrix; c) hyoliths (Hy) in cross section; Scale bar = $500 \mu m$; d) isolated hyolith (Hy); Sections perpendicular with bedding plane, oriented top to bottom; Scale bar = $250 \mu m$.

6.3 Upper Ajax Limestone, AJX-N Section

Macro-photography & µ-XRF

The buildup sample, AJXN-1, contains $\sim 7\%$ small (2 – 7 mm outer wall to outer wall diameter) toppled and *in situ* solitary archaeocyaths, with $\sim 3\%$ isolated chambered *Renalcis* growths and no clear cavity development (Fig. 15).



Figure 15. AJXN-1 a) photograph containing solitary archaeocyaths (A), chambered *Renalcis* (R) growths, no clear cavity development; b) coloured image showing archaeocyaths (blue) and chambered *Renalcis* growths (green); Section perpendicular with bedding plane, oriented top to bottom; Scale bar = 2 cm.

Two additional buildup samples were taken 220 m from the base of the section, AJXN-2 and AJXN-3. AJXN-2 contains a highly diverse assemblage of toppled, fragmented and re-worked archaeocyaths. Archaeocyath morphology within this assemblage are ~10% laminar pseudocolonial, ~13% multiserial encrusting and multiserial massive, with multiserial growths often surrounding or surrounded by stromatactis cavities. Stromatactis development is widespread and occurs through ~23% of the sample. Sparitic cement is prominent, with a distinctive red colouration. This buildup contains multiple cavities (up to 1.5 cm deep) in-filled with a mixture of bioclastic and intraclastic material (Fig. 16). Elemental analysis using μ -XRF indicates the internal sediment is dominated by calcium and strontium. A high proportion of aluminium, silicon and potassium occur in association throughout and in some instances, concentrated in the cavity within the inner wall of archaeocyath individuals. Minor amounts of iron and manganese and magnesium occur in association (Fig. 17).



Figure 16. AJXN-2 a) photograph containing toppled, fragmented and transported laminar pseudocolonial and multiserial (encrusting and massive) archaeocyaths (A) with stromatactis (St) and cavity (Cv) development; b) coloured image of pseudocolonial archaeocyaths (blue), multiserial archaeocyaths (red), stromatactis (yellow) and internal sediment (grey); Section perpendicular with bedding plane, oriented top to bottom; Scale bar = 2 cm.



Figure 17. AJXN-2 a) μ -XRF image b) RGB pseudo colour map showing aluminium (Al), silicon (Si) and potassium (K); Section perpendicular with bedding plane, oriented top to bottom; Scale bar = 1 cm.

AJXN-3 contains solitary and laminar pseudocolonial archaeocyaths that show evidence of some transportation and are remineralised (Fig. 18). This sample was distinctly more weathered than AJXN-2, even though both these samples were collected the same distance from base, along strike from one another. Elemental analysis using μ -XRF reveals iron and manganese crusts along major weathering cracks, and manganese encrusted exterior and interior walls of individual archaeocyath skeletons (Fig. 18). The internal sediment contains a high proportion of aluminum, silicon and potassium.



Figure 18. AJXN-3 a) photograph containing toppled, fragmented and transported solitary and laminar pseudocolonial archaeocyaths (A) with calcite cement occurring through weathered cracks and within major archaeocyath internal cavities, no clear microbial input present; b) μ -XRF RB pseudo colour map showing iron (Fe) and manganese (Mn); Section perpendicular with bedding plane, oriented top to bottom; Scale bar = 2 cm.

SEM/EDS & Petrography

AJXN-1 contains toppled and transported, but mostly intact, archaeocyaths with a few other taxa including chancelloriids and unidentifiable tubiform fragments. The internal sediment is primarily sparitic with minor micrite (most associated faunas occur within micrite) and fibrous calcite cement in-filling the cavity within the internal wall of larger archaeocyaths (Fig. 19). SEM and EDS

analysis shows that the internal sediment is dominated by calcium with traces of magnesium, silicon, manganese and aluminium. Iron and carbon occur in close association.

AJXN-2 contains fragmented archaeocyaths and associated faunal debris. Associated faunas include *Pojetaia runnegari* Jell 1980, hyoliths, *Cupitheca*, hyolithohelminthids, hexactinellid spicules, and unidentifiable tube fragments. The internal sediment is primarily composed of spar, with associated faunas generally occurring within micrite filled cavities. Major calcite vein occurs through these sediments (Fig. 20). SEM and EDS analysis shows the internal sediment is dominated by calcium and strontium, while archaeocyaths are enriched with magnesium.

AJXN-3 contains toppled, fragmented and transported archaeocyaths with a minor input of associated faunas including *Pojetaia runnegari* Jell 1980, *Askepasma toddense*, chancelloriids, hexactinellid spicules and hyolith fragments. The internal sediment is sparitic and micritic (most associated faunas occur within micrite), with major quartz veins (Fig. 21). SEM and EDS analysis shows the internal sediment is dominated by calcium with traces of strontium, aluminium, silicon and iron. Additionally, carbon is dominant through the internal sediment and within archaeocyaths. Archaeocyaths are enriched with magnesium (Fig. 22).



Figure 19. AJXN-1 thin-section photomicrograph a) faunal debris, including fragmented archaeocyath (A), chancelloriids (Ch) and tubiforms (Tu), internal sediment composed of spar (S) with some intraclasts (In); b) solitary archaeocyath (A) in latitudinal section; Sections perpendicular with bedding plane, oriented top to bottom; Scale bar = $250 \mu m$.



Figure 20. AJXN-2 thin section photomicrograph of archaeocyaths (A), spar (S) cement, calcite vein (Ca), minor micrite (M) and associated faunas (Fa) occurring within a micrite cavity (including a chancelloriid, hyolith and hexactinellid spicules; Section perpendicular with bedding plane, oriented top to bottom; Scale bar = 1 cm.



Figure 21. AJXN-3 a) thin-section photomicrograph of archaeocyath (A) in transverse with spar (S) between septal walls, in a micritic (M) matrix; b) archaeocyath (A) within a larger archaeocyath (A); Sections perpendicular with bedding plane, oriented top to bottom; Scale bar = $500 \mu m$.



Figure 22. AJXN-3 a) SEM image of solitary archaeocyath in latitudinal section; b) backscatter image showing strontium, aluminium, silicon, iron, calcium, magnesium and carbon; c) backscatter image showing calcium through the internal sediment and magnesium concentrated through the archaeocyath; d) backscatter image showing carbon concentrated through internal sediment and in the archaeocyath; Section perpendicular with bedding plane, oriented top to bottom Scale bar = 1 mm.

6.4 Upper Wilkawillina Limestone, Wirrealpa Mine, WIRM section

Macro-photography & µ-XRF

Buildup samples WIRM-1 (37 m), WIRM-2 (85 m) and WIRM-3 (113 m) contain major chambered *Renalcis* growths with small, solitary archaeocyaths. No shelly faunas could be identified across the three samples. WIRM-2 contains ~60% dense masses of chambered *Renalcis*, with <2% growths cavities and ~1% archaeocyaths.

Remineralised in-fill occurred in a few instances indicating potential cavity development (Fig. 23). Elemental analysis using μ -XRF reveals a high concentration of calcium and strontium through the internal sediment, within *Renalcis* growths and in archaeocyaths. Parts of the internal sediment that are depleted in calcium (but not strontium) are enriched with iron, manganese and magnesium. Minor input of silicon occurs through small cavity space and within the internal cavity of archaeocyaths.



Figure 23. WIRM-2 a) photograph showing dominant *Renalcis* (R) growths with isolated archaeocyaths (A) and minor cavity (Cv) development; b) coloured image showing archaeocyaths (blue) and *Renalcis* (green); Section perpendicular with bedding plane, oriented top to bottom; Scale bar = 2 cm.

Two buildup samples, WIRM-4 and WIRM-5, were taken 185 m from the base of the section. WIRM-4 contains two distinct phases of deposition. The lower (older) depositional phase represents a buildup containing a diverse assemblage of ~1% branching pseudocolonial and ~17% uniserial erect pseudocerioid archaeocyaths. Widespread fibrous calcite cement dominates the lower phase, comprising ~41% of the sample. Fibrous calcite cement surrounds and supports both the toppled and *in situ* archaeocyaths, as well as the margins of cavity spaces. The upper (younger) phase represents a debris flow supported by the change in internal sediment composition, high proportion of fragmented and transported archaeocyaths, and disarticulated shelly faunas (Fig. 24).

Elemental analysis using μ -XRF reveals the internal sediment of the lower phase is calcitedominated and the internal sediment of the upper phase is aluminosilicate mineral-dominated. Iron occurs scattered throughout the internal sediment of both the upper and lower phases, surrounding the exterior and interior walls of archaeocyaths, and around calcimicrobial growths. Strontium is concentrated through the lower depositional phase particularly in the internal sediment, and in the upper phase within the brachiopod shells *Askapasma toddense* (Fig. 25).

WIRM-5 contains ~4% branching pseudocolonial and ~21% uniserial erect pseudocerioid archaeocyaths in both toppled and *in situ* orientation. The buildup growth is supported by <5% *Renalcis* cement and ~29% inorganic calcite, with ~1% encrusting *Girvanella* growths. Cavities occur throughout this buildup, generally surrounded by inorganic calcite and in-filled by fibrous calcite cement (Fig. 26). Elemental analysis using μ -XRF reveals iron crusts around *Girvanella* growths and some archaeocyaths. Calcium has been replaced by magnesium in part, and strontium occurs in high concentration throughout the internal sediment (Fig. 27).







Figure 24. WIRM-4 a) photograph showing two distinct phases; the lower phase (*in situ* bioconstruction) contains branching pseudocolonial and uniserial erect pseudocerioid archaeocyaths (A) surrounded by fibrous calcite cement (FCC) minor calcimicrobial growths and multiple cavities (Cv); the upper phase (debris flow) contains fragmented archaeocyaths (A) and redeposited associated faunas including brachiopods (*Askepasma toddense*) (Ak); b) coloured image showing pseudocerioid archaeocyaths (blue), pseudocolonial archaeocyaths (red) and fibrous calcite cement (orange); c) photograph showing lower phase of buildup, archaeocyaths (A) surrounded by fibrous calcite cement (FCC); Scale bar = 2 cm; Sections perpendicular with bedding plane, oriented top to bottom; Scale bar = 4 cm.



Figure 25. μ -XRF image and RGB pseudo colour maps of WIRM-4 indicating strontium (Sr), iron (Fe) and silicon (Si); Section perpendicular with bedding plane, oriented top to bottom; Scale bar = 2 cm.



Figure 26. WIRM-5 a) photograph showing toppled and *in situ* branching pseudocolonial and uniserial erect pseudocerioid archaeocyaths (A), surrounded by fibrous calcite cement (FCC), *Renalcis* growths occur as a darkened rim surrounding archaeocyaths individuals, small encrusting *Girvanella* (Gi) laminae growths occur on fibrous calcite cement, and in isolation from archaeocyaths; b) coloured image of pseudocolonial archaeocyaths (blue), pseudocerioid archaeocyath (red), *Girvanella* (Gi), fibrous calcite cement (orange) and internal sediment (grey); Section parallel with bedding plane; Scale bar = 2 cm.



Figure 27. μ -XRF image and RGB pseudo colour maps of WIRM-5 indicating iron (Fe), magnesium (Mg) and strontium (Sr); Section parallel with bedding plane; Scale bar = 2 cm.

Two buildup samples (WIRM-6 and WIRM-7) were taken 210 m from the base of the section. The buildups at this level contain large cracks and appear very weathered. WIRM-6 contains solitary and uniserial erect pseudocerioid archaeocyaths with large finger-like growths of laminated encrusting *Girvanella* support, but no clear syndepositional cavity development. Elemental analysis using μ-XRF reveals a high concentration of calcium and strontium through the internal sediment, within archaeocyaths, *Girvanella* and *Renalcis* growths. Iron crusts form surrounding archaeocyaths, and iron with manganese, aluminium, silicon and potassium occurs concentrated along major post-depositional fissures (Fig. 28).

WIRM-7 contains solitary, laminar pseudocolonial and uniserial erect pseudocerioid archaeocyaths. This buildup is dominated by large finger-like growths of laminated encrusting *Girvanella* support, with minor chambered *Renalcis* growths throughout the internal sediment and

surrounding some archaeocyaths. There is no clear syndepositional cavity development. Elemental analysis using µ-XRF reveals a high concentration of calcium and strontium through the internal sediment, within archaeocyaths, *Girvanella* and *Renalcis* growths. Strontium was particularly dominant through *Girvanella* growths. Sulphur, magnesium and phosphorus occur scattered throughout the internal sediment. Aluminium, magnesium, manganese, silicon and iron occur in association surrounding *Renalcis* growths, the inner and outer walls of archaeocyaths and within *Girvanella* laminations (Fig. 29).



Figure 28. μ -XRF image and RGB pseudo colour map of WIRM-6 indicating potassium (K), iron (Fe) and silicon (Si); Section perpendicular with bedding plane, oriented top to bottom; Scale bar = 1 cm.



Figure 29. WIRM-7 a) photograph showing archaeocyaths (A), *Renalcis* (R) growths, and encrusting *Girvanella* (Gi) finger-like growths; b) μ -XRF pseudo colour map indicating iron (Fe); Section parallel with bedding plane; Scale bar = 4 cm.

SEM/EDS & Petrography

The internal sediment of WIRM-4 is primarily spar, with large growths of fibrous calcite cement, minor input of micrite and chert, and some secondary quartz veins. Fibrous calcite cement growths surround many archaeocyath individuals, with a minor presence of chambered *Renalcis* growths generally growing over fibrous calcite cement rather than archaeocyaths individuals.

Identifiable faunas in WIRM-4 include the bivalve *Pojetaia runnegari* Jell 1980, numerous hyoliths, hexactinellid spicules and chancelloriids (Fig. 30). The associated faunas that occur in the lower phase generally occur in concentration within micrite filled cavities. The faunas that occur in the upper phase (debris flow) are generally fragmented and difficult to identify. SEM and EDS analysis through the lower phase of the buildup show the internal sediment is dominated by calcium and magnesium, while these elements are absent within archaeocyaths. Iron, silicon, manganese, strontium and sulphur occur scattered through the internal sediment (Fig. 31).





Figure 30. WIRM-4 thin-section photomicrographs a) transition between archaeocyaths (A) individuals divided by spar (S) seam; b) archaeocyath (A) surrounded by spar (S); c) growth layers of fibrous calcite cement (FCC) (arrows show direction or growth) supporting the outer wall of an *in situ* archaeocyaths (A), small chambered *Renalcis* (R) growth overlying fibrous calcite cement; d) fibrous calcite cement (FCC) primarily overgrown by chambered *Renalcis* (R) and secondarily intruded by quartz veins; e) associated faunas: hexactinellid spicules (Sp), chancelloriid (Ch), *Pojetaia runnegari* (Pj); f) archaeocyath (A) primarily encrusted with fibrous calcite cement (FCC), secondarily intruded by quartz veins; Sections perpendicular with bedding plane, oriented top to bottom; Scale bar = 500 μ m (image a taken in polarized light, images b-f taken in cross polarized light).





Figure 31. WIRM-4 a) SEM image of archaeocyath in transverse section; b) corresponding backscatter image of archaeocyath showing carbon, iron, sulphur, manganese, magnesium, silicon and calcium; c) SEM image of archaeocyath in transverse section; d) corresponding backscatter image of archaeocyath showing manganese, carbon, iron, silicon, calcium and magnesium; e) SEM image of a chancelloriid; f) corresponding backscatter image of a chancelloriid; f) corresponding backscatter image of a chancelloriid; Sections perpendicular with bedding plane, oriented top to bottom; Scale bar = 500 µm.

The internal sediment of WIRM-5 is primarily spar, with some micrite and chert. *Renalcis* growths are prominent throughout, either growing in an isolated layered structure or encrusting archaeocyaths individuals. Identifiable faunas in WIRM-5 include numerous hyoliths, hexactinellid spicules, chancelloriids, trilobites and *Cupitheca*. Associated faunas tend to occur in concentration within micrite filled cavities, however hexactinellid spicules occur through (Fig. 32).





Figure 32. WIRM-5 thin-section photomicrographs a) archaeocyath (A) with *Renalcis* (R) growths in the cavity within the inner wall (polarized light); b) cementation of archaeocyath (A) by *Renalcis* (R); c) layered growth of *Renalcis* (R) arrows indicate direction of growth; d) associated faunas: *Cupitheca* (Cp), hexactinellid spicules (Sp), chancelloriid (Ch), with chambered *Renalcis* (R) growths; e) associated faunas: trilobite thoracic segment (Tr) with chambered *Renalcis* (R) growths; scale bar (a-e) = 500 μ m; f) associated faunas: hyoliths (Hy), hexactinellid spicules (Sp), chancelloriid (Ch); Sections perpendicular with bedding plane, oriented top to bottom; Scale bar = 250 μ m; (a and f images taken in polarized light, b-e images taken in cross polarized light).

7. Discussion

7.1 Cambrian Buildup Type

One archaeocyath-sponge buildup and four archaeocyath-calcimicrobial buildup types are represented through the lower Cambrian Hawker Group sections of the Wilkawillina Limestone and the Ajax Limestone, over three distinct biostratigraphic zones. Results show differences in buildup community structure, biological and mineralogical composition across the sections, which represent buildup construction across a range of facies on the carbonate platform. Buildups are discussed in ascending chronostratigraphic order:

Lower Wilkawillina Limestone (Hideaway Well Member), MORO Section [K. rostrata Zone]

The MORO-1 buildup is an <u>archaeocyath-dominant archaeocyaths-*Renalcis* boundstone (Table 1). This is supported by the proportion of archaeocyaths, toppled and *in situ* solitary (~12%), chambered *Renalcis* growths (~7%) and sparitic cement with stromatactis development (~4%). The boundstone is in a pioneering or colonising stage of bioconstruction development, due to the lower integration of archaeocyaths, and minor development of *Renalcis* growths and stromatactis cavities (Zhuravlev, 2001). These conditions suggest that the boundstone was deposited on a higher-energy, shallow platform setting.</u>

Lower Wilkawillina Limestone, BALC Section [M. etheridgei Zone]

Samples from the BALC section (samples BALC-1 and BALC-2) represent inter-reefal carbonate deposits that lack observable archaeocyaths and calcimicrobes. This section is dominated by abundant well-preserved hyoliths and the partial scleritomes of the tommotiids *Eccentrotheca helenia* and *Paterimitra pyramidalis* (Skovsted et al., 2011, Betts et al., 2016). This is consistent with previous studies that describe the BALC section as highly fossiliferous with well-preserved diverse and abundant shelly faunas (Brock and Paterson, 2004, Paterson and Brock, 2007).

Upper Ajax Limestone, AJXN Section [M. etheridgei Zone]

The AJXN-1 buildup is an <u>archaeocyath boundstone</u> (Table 1). This is supported by the toppled and *in situ* solitary archaeocyaths (~7%) with isolated chambered *Renalcis* growths (~3%) (Fig. 15). This bioherm appears to be in a pioneering or colonising stage of bioconstruction development, due to the presence of small solitary archaeocyaths and the lack of integration of bioconstruction components (Zhuravlev, 2001). Deposition of these Sequence 1 sediments likely occurred in the higher-energy open-shelf setting of the AJXN section (Betts et al., 2016).

The AJXN-2 buildup is an <u>archaeocyath-sponge buildup</u> (Table 1). This is supported by the dominate laminar pseudocolonial (~10%) and mulitserial (massive and encrusting) (~13%) archaeocyaths, microbioclastic spiculites, an absence of clear calcimicrobial input and major stromatactis development (~23%) (Fig. 16). Stromatactis-bearing buildups are associated with the deep red colouration of the internal sediment. This is caused by a ~1% concentration of iron oxide (Fe₃O₂) potentially detrital in origin or microbially precipitated or partially derived from the early cementation of the sponge components of the buildups (Bourque and Boulvain, 1993). This distinctive stromatactis fabric suggests the limestone is a red archaeocyath floatstone (James and Gravestock, 1990).

The AJXN-3 buildup is an <u>archaeocyath-sponge buildup</u> (Table 1). This is supported by solitary and laminar pseudocolonial archaeocyaths, most of which have been remineralised and

transported, microbioclastic spiculites, and an absence of calcimicrobial input. The biological constituents appear to have been partially obscured due to the extent of weathering of this buildup.

The archaeocyath-sponge buildups at the AJXN section appear to be deposited as talus on the side of a bioconstruction with transported archaeocyaths and therefore reflect flank facies. These buildups also contain associated faunas which have likely been transported or collapsed off the main bioconstruction in a debris flow. Both buildups were likely deposited in deeper waters, within an intra-shelf depression (Betts et al., 2016).

Upper Wilkawillina Limestone, Wirrealpa Mine, WIRM section [D. odyssei Zone]

Buildups from the Wirrealpa Mine locality in the upper Wilkawillina Limestone are the youngest sampled in this study and represent a range of depositional settings across a carbonate platform. Architecture and faunal composition vary considerably across sampling sites at this section. Typically, the WIRM section contains archaeocyath-*Renalcis* boundstones or archaeocyath boundstones, characteristic of Sequence 2 sediments in the Upper Wilkawillina Limestone (James and Gravestock, 1990).

The WIRM-2 buildup is a <u>Renalcis</u> dominant archaeocyath-<u>Renalcis</u> boundstone (Table 1). This is supported by the dense masses of chambered <u>Renalcis</u> growths (~60%), cavities (<2%), archaeocyaths (~1%) and no associated faunas (Fig. 23). This biological composition suggests this bioconstruction was deposited in a lower-energy, near shore (possibly lagoonal or inner-shelf) setting, protected by the outer-shelf (Gandin and Debrenne, 2010).

The WIRM-4 buildup is an <u>archaeocyath boundstone</u> (Table 1). This is supported by branching pseudocolonial (~1%) and uniserial erect pseudocerioid (~17%) archaeocyaths with two distinct phases of deposition (Fig. 24). The lower (older) depositional phase represents a stable, largely *in situ*, climax stage of development with peak archaeocyath diversity, dense clustering of toppled, transported and *in situ* archaeocyaths (Zhuravlev, 2001, Debrenne, 2007). The lower *in situ* phase of deposition contains widespread fibrous calcite cement development (~41%), which increase the rigidity of the bioconstruction. This boundstone composition is consistent with growth on a relatively high-energy, wave exposed position on the platform (James and Gravestock, 1990).

The upper (younger) phase exhibits a distinct change in internal sediment composition from calcite-dominated to aluminosilicate mineral-dominated, with a high proportion of fragmented and transported archaeocyaths, and disarticulated shelly faunas. This upper phase represents a high-energy transport event, such as a sheet debris flow of fragmentary shelly and intraclastic allochems deposited over the top of the *in situ* bioconstruction. Elemental analyses (Figs. 25 and 31) indicate the internal sediment of the debris flow is composed of aluminosilicate minerals, and has a lower concentration of strontium compared with the lower calcite-dominant phase (Banner, 1995).

The WIRM-5 buildup is an <u>archaeocyath boundstone</u> (Table 1). This is supported by an assemblage of archaeocyaths, primarily toppled and *in situ* branching pseudocolonial (~4%) and uniserial erect pseudocerioid (~21%). Archaeocyaths occurs in association with fibrous calcite cement (~29%), minor *Renalcis* (<5%) growths around archaeocyath individuals or in isolation, and *Girvanella* (~1%) growths through the internal sediment (Fig. 26). The large input of fibrous calcite cement increases bioconstruction rigidity. This bioconstruction composition is consistent with deposition on a high-energy platform setting. These conditions suggest the boundstone is in a climax stage of bioconstruction development (Zhuravlev, 2001).

The WIRM-6 and WIRM-7 buildups are *Girvanella-Epiphyton-Renalcis* boundstone (Table 1). WIRM-6 contains *in situ* and transported archaeocyaths solitary and uniserial erect pseudocerioid archaeocyaths with large finger-like growths of laminated encrusting *Girvanella* and no syndepositional cavities. WIRM-7 contains *in situ* and transported solitary, laminar pseudocolonial and uniserial erect pseudocerioid archaeocyaths, and large finger-like growths of laminated encrusting *Girvanella* support, minor chambered *Renalcis* growths, and no clear syndepositional cavity development. The comparable biological composition of WIRM-6 and WIRM-7 reflect a similar depositional environment. These sediments appear to have been deposited off the platform into the outer-shelf ramp zone, with medium-energy. These conditions suggest both boundstones are in a stabilisation stage of bioconstruction development (Zhuravlev, 2001). The *Girvanella-Epiphyton-Renalcis* boundstones are heavily weathered and poorly preserved, which is a stark contrast to the other boundstones documented lower in the WIRM section.

The bioconstruction architecture from samples taken from the base of the section to 113 m reflects *Renalcis*-dominant archaeocyath-*Renalcis* boundstone. The bioconstruction architecture from samples taken from 113 m to 185 m reflects archaeocyath boundstones. At 210 m, bioconstruction architecture reflect *Girvanella-Epiphyton-Renalcis* boundstone. The systematic sample collection through the WIRM section from the base of the reddened horizon to 210 m reflects a near shore to reef platform setting, followed by progressive deepening through the shelf (Fig. 33).



Figure 33. Reconstruction of the depositional environment for the WIRM section. The *Renalcis*-dominant archaeocyath *Renalcis* boundstone occurs 37 m to 113 m from base of section, reflecting the inner-shelf setting. The archaeocyath boundstones occur 185 m from base of section, reflecting the higher-energy platform. *Girvanella-Epiphyton-Renalcis* boundstone occur 210 m from base of section, reflecting deeper water outer-shelf setting. (sea level indicated as s.l.) Adapted from Gandin and Debrenne (2010).

7.2 Buildup Architecture & Habitat Development

Lower Wilkawillina Limestone (Hideaway Well Member), MORO Section

No associated faunas were identified through petrographic analysis. However, this is supported by previous work that notes a low diversity of shelly faunas within the *K. rostrata* biostratigraphic zone (Betts et al., 2016). Due to the absence of associated faunas sampled and the low percentage of cavity development, no interpretations could be made regarding the buildup architecture as it relates to habitat creation.

Lower Wilkawillina Limestone, BALC Section

The inter-reefal carbonate deposits from the BALC section (BALC-1 and BALC-2) are primarily composed of micrite. Dominate faunas are well-preserved hyoliths, the partial scleritomes of the tommotiids *Eccentrotheca helenia* and *Paterimitra pyramidalis*. Less abundant faunas including chancelloriids, *Askapasma toddense*, trilobites, and the shelly faunas *Micrina etheridgei* and *Pojetaia runnegari* Jell 1980.

These samples contain accumulated fragments of shelly faunas, including multiple cone-incone nested hyoliths, indicating relatively high-energy traction currents. Consistent orientation of geopetal in-fill of hyoliths along with a micritic matrix indicates deposition on a mid- to outer-shelf subtidal inter-reefal environment. The fragmentation and orientation of shelly faunas suggest post mortem transport and deposition so cannot indicate inter-reefal habitat development.

Upper Ajax Limestone, AJXN Section

The archaeocyath-sponge buildups (AJXN-2 and AJXN-3) were deposited as talus material, which indicates that the identification of habitats within syndepositional cavities is specious. Although associated faunas generally occur in cavities filled with micrite and with some faunas relatively intact, primarily these faunas are randomly oriented, disarticulated and fragmented. It is likely that faunas have been transported into the cavities post mortem.

Upper Wilkawillina Limestone, Wirrealpa Mine, WIRM section

The *Renalcis* dominant archaeocyath-*Renalcis* boundstone (WIRM-2) contains chambered *Renalcis* growths that form a dense framework, with solitary archaeocyaths, few cavities and no associated faunas (Fig. 23). Bioconstructions dominated by calcimicrobes provide limited relief from the sea floor. This is due to low diversity and abundance of archaeocyaths that would have created ecospace tiering (Bush et al., 2011). The absence of tiering created by archaeocyath reduces cavity development potential and these conditions create a more homogeneous habitat structure.

The archaeocyath boundstone (WIRM-4) contains two phases of deposition, the lower *in situ* phase represents climax bioconstruction development, and the upper phase represents a debris flow. The lower phase contains cavities that are interpreted as syndepositional since cavity walls are created by archaeocyaths or other bioconstruction constituents, but contain no observable micrite. Additionally, associated faunas (e.g. hexactinellid spicules, chancelloriids, *Pojetaia runnegari*) occur within cavity space (Fig. 30). This suggests that the archaeocyath supported syndepositional cavities led to habitat development. Although no associated faunas are attached to cavity walls, so life position cannot be confirmed, and skeletal material may have been transported post mortem.

The archaeocyath boundstone (WIRM-5) contain multiple cavities that are interpreted as syndepositional due to fibrous calcite cement generally covering the ceilings, and on occasion the walls of cavities are created by archaeocyaths or *Renalcis*. Associated faunas (e.g. hyoliths, chancelloriids, *Cupitheca*) occur within cavity space (Fig. 32). Syndepositional cavities with associated faunas may suggest habitat development. However, as with WIRM-4, no associated faunas attach to cavity walls, so life position cannot be confirmed. Both archaeocyath boundstones from the WIRM section contain elaborate fibrous calcite cement development with a greater proportion of cavities compared with other bioconstruction types observed in the present study.

The *Girvanella-Epiphyton-Renalcis* boundstones (WIRM-6 and WIRM-7) do not contain clear syndepositional cavities. However, both *Girvanella-Epiphyton-Renalcis* boundstones are largely weathered, which may obscure identification of cavity development.

7.3 **Post-Depositional Alteration**

The seawater of tropical shallow marine environments is supersaturated in calcium carbonate, which is largely related to sea surface temperature (Wood, 1998). The super saturation of calcium carbonate in seawater, the porosity of carbonate rocks and heterogeneity of buildup architecture leaves these structures susceptible to diagenetic alteration (Flügel, 2013). The degree of alteration is a particular challenge when interpreting buildups of Cambrian age. Geochemical and petrographic data collected to interpret buildup architecture and composition can also help elucidate post-depositional processes. Identifying the potential for overprinting and how this alteration can affect palaeoecological interpretations of original architecture is essential for understanding these lower Cambrian buildups.

Lower Wilkawillina Limestone (Hideaway Well Member), MORO Section

The archaeocyath-dominant archaeocyaths-*Renalcis* boundstone (MORO-1) is a well preserved bioconstruction that appears to have undergone only minor alteration. The inner cavity of larger archaeocyaths has been infilled with remineralised calcite, but overall, no overprinting of bioconstruction architecture and composition. Calcium is dominant through the internal sediment, while magnesium is dominant through the chambered *Renalcis* growths (with a minor input of iron and carbon) (Fig. 11). This is consistent with preservation of calcified microbial growths and reflects ambient seawater temperature along with other environmental parameters, and is not an indication of alteration (Flügel, 2013).

Lower Wilkawillina Limestone, BALC Section

The inter-reefal samples (BALC-1 and BALC-2) are relatively well preserved, with some cracks that contain in-fill of iron suggesting minor post-depositional alteration. Shelly fossils have largely been replaced with iron and phosphorus, but overall, shelly fossil material is only partially fragmented and generally well preserved (Fig. 13).

Upper Ajax Limestone, AJXN Section

The archaeocyath boundstone (AJXN-1) is a very well preserved bioconstruction, with no clear indication of weathering or alteration. This contrasts to the deeper water samples (AJXN-2 and AJXN-3) from the AJXN section, which display a higher degree of alteration.

The archaeocyath-sponge buildup (AJNX-2) contains major input of K-feldspars through the internal sediment and in the cavities between the septa of the inner walls of archaeocyath individuals (Fig. 17). The K-feldspar appears to be secondarily precipitated in association with fabric-retentive dolomite, reflective of high-energy to low-energy facies (Jiang et al., 2016). The presence of dolomite through the lower part of the AJXN section is consistent with previous work (James and Gravestock, 1990), while the secondary K-feldspar in association with dolomite indicates that the buildup has undergone diagenetic alteration. The dull red colour associated with fabric-retentive dolomite overprints some of the biological composition.

The archaeocyath-sponge buildup (AJXN-3) is heavily weathered with iron and manganese crusts forming through major cracks and archaeocyaths (Fig. 18), overprinting some of the biological composition. Secondarily precipitated K-feldspars occurs as thick bands, and the orange-red colouration further reduces the clarity of buildup features (Jiang et al., 2016). However, both archaeocyath-sponge buildup were deposited in flank facies and do not reflect a bioconstruction.

Upper Wilkawillina Limestone, Wirrealpa Mine, WIRM section

The *Renalcis*-dominant archaeocyath-*Renalcis* boundstones (WIRM-1, WIRM-2 and WIRM-3) and archaeocyath boundstones (WIRM-4 and WIRM-5) are well preserved bioconstructions with only minor indications of post-depositional alteration.

The lower calcite-dominant *in situ* growth phase of the archaeocyath boundstone (WIRM-4) contains high concentrations of strontium, reflecting ambient seawater, whereas the upper phase is dominated by aluminosilicate mineral and reflects a debris flow (Banner, 1995) (Fig. 25). The concentration of aluminosilicate minerals in the upper phase suggest that this phase was deposited quickly over an active bioconstruction. This event or series of events likely sealed in the buildup below, ensuring a high degree of preservation.

The archaeocyath boundstone (WIRM-5) is also a well preserved bioconstruction with only minor indications of post-depositional alteration. This is seen in secondarily formed iron crusts around *Girvanella* growths and on the exterior and interior walls of archaeocyaths (Fig. 27). However, this occurrence is low, and only obscures minor bioconstruction architecture and composition.

Major fibrous calcite cement development occurs through both the archaeocyath boundstones (WIRM-4 and WIRM-5). Some proportion of the fibrous calcite cement growth is synsedimentary, while some is a post-depositional artifact. The secondary formation of fibrous calcite cement occurred due to fracturing, dissolution and remobilisation or pore water fluids (James and Gravestock, 1990).

The *Girvanella-Epiphyton-Renalcis* boundstones (WIRM-6 and WIRM-7) are heavily weathered and cracked, with iron crusts around archaeocyaths, and along major post-depositional fissures. In WIRM-6, these fissures also contain concentrations of manganese, aluminium, silicon and potassium (Fig. 28). In WIRM-7, aluminium, magnesium, manganese, silicon and iron occur in association with *Renalcis* growths, archaeocyaths and *Girvanella* laminations (Fig. 29). Although these boundstones have undergone alteration, bioconstruction architecture and composition details can be identified.

8. Conclusion

In the present study, one archaeocyath-sponge buildup and four archaeocyath-calcimicrobial buildup types were identified through the lower Cambrian Hawker Group sections of the Wilkawillina Limestone and the Ajax Limestone, over three distinct biostratigraphic zones. The centimetre-scale bioconstruction growth, structure and proportional relationship between archaeocyaths and calcimicrobes was used to determine the depositional environment and rigidity of construction, which supports the assignment of bioconstruction types. This indicates the null hypothesis can be rejected.

The buildup types described in the study are presented in ascending chronostratigraphic order. The MORO section from the *K.rostrata* Zone is an archaeocyath-dominant archaeocyath-*Renalcis* boundstone. Both the BALC and AJXN section occur through the *M. etheridgei* Zone. The BALC section and represents an inter-reefal environment. The AJXN section contains an archaeocyath boundstone and archaeocyath-sponge buildups, reflecting flank facies. The WIRM section from the *D. odyssei* Zone contains *Renalcis*-dominant archaeocyath-*Renalcis* boundstones, archaeocyath boundstones and *Girvanella-Epiphyton-Renalcis* boundstones.

At centimetre-scale, it is difficult to distinguish bioconstruction features such as the growth form of calcimicrobes, associated faunas and internal sediment fabric. The millimetre- to

micrometre-scale component of the study allows for these features to be confidently identified and placed in context of the overall bioconstruction and provides higher resolution of interactions between archaeocyaths, calcimicrobes, and associated faunas. Additionally, the millimetre- to micrometre-scale architecture details the biological composition, transition between individual archaeocyaths, calcimicrobes, associated fauna and inorganic constituents of the buildup in relation to the creation of new niche habitats.

Archaeocyaths could be viewed as structural ecosystem engineers of the lower Cambrian, a role that may have been a key feature of the adaptive radiation (Erwin, 2008). In this study, associated faunas are identified within cavities and on the surface of buildups. The focus on cavity development and the associated faunas that are preserved within these spaces, may indicate these faunas occupied this niche during life. However, across all buildup types, (which reflect hydrodynamics, position on platform, and biological and inorganic constituents) no associated fauna could be identified in life position, and faunas are generally disarticulated and display varying degrees of fragmentation. This could indicate that faunas were transported post mortem. As a result, the null hypothesis cannot be rejected.

Finally, analysis of the bioconstruction geochemistry indicates varying stages of alteration across bioconstructions, which can potentially overprint the biological features. Although the sampled buildups are diagenetically altered, original palaeoecology details could be collected from each sample. This indicates the null hypothesis can be rejected. However, these data can only indicate the superficial extent of diagenesis and more robust analyses including isotopic values and thermal maturity parameters, e.g. biomarker ratios, are required to constrain the degree of alteration.

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