Lake Richmond - Microbialites, Microbial Mat Mapping and Hydrology Report

By Ryan Vogwill and Mike Whitehead

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Acknowledgements

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Cover Image

Couch grass, algae and charophytes smothering some of the best microbialite structures in Lake Richmond at the north end, looking west.

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Introduction

Lake Richmond (Figure 1) is located within the City of Rockingham (CoR) and is a perennial, currently freshwater lake situated less than 1km away from the Indian Ocean to the north and west. It occurs in a relatively small basin with elliptical shape, measuring 1.07km long in the NW-SE direction and reaching up to 0.67km wide, in the western portion of the Rockingham-Becher Plain. The Rockingham-Becher Plain is a 10 km wide beach ridge and dune system formed in response to a 2.5m relative sea level fall during the last 8,000 years of the Holocene (Searle & Woods, 1986) shown in Figure 2. The lake originated from a precursor marine embayment, which was cut-off from the sea during the progradation of a cuspate peninsula, behind a chain of Pleistocene islands (Searle & Woods, 1986).

Lake Richmond supports a diverse waterbird community including migratory wading shore birds protected under the JAMBA, CAMBA and RoKAMBA international migratory shorebirds agreements and hosts a critically endangered thrombolite community (Kenneally *et al*., 1987; English *et al*., 2003). Concerns exist over the effect of modern water chemistry on microbialite formation. Thrombolite (a type of microbialite) communities, are associated with microbial mat communities which are populations of phototrophic, chemotrophic and heterotrophic bacteria and archea that may be susceptible to changes in lake hydrology and water chemistry. Complex symbiotic and predatory relationships occur between prokaryote species within microbial colonies (Van Gemerden, 1993) and any impact on a single species may result in a cascade disruption of the entire colony function. English *et al*. (2003) state that this thrombolites community are unique and dependent on maintenance of water levels and quality within limits which were then unidentified.

Aim

The aim of this report is to:

1. summarise the available information on Lake Richmond, relevant to the origins and persistence of the microbial mats and microbialites;
2. map the current extent of microbial mats in 2017-18, compare to previous mapping and assess mat activity in terms of microbialite formation; and
3. make recommendations about how to maintain or preferably improve the microbial mats condition (in terms of water level and water chemistry) to allow accretion (growth) of microbialites into the future.

Figure 1 - Aerial photography of the Rockingham-Becher Plain in 1979 showing the well-defined beach-ridge trends and the north-south chain of Pleistocene islands on the left of the image (source: Landgate). Lake Richmond is in the Rockingham Peninsula, on the top-left of the image. See Figure 3 for the geological interpretation.

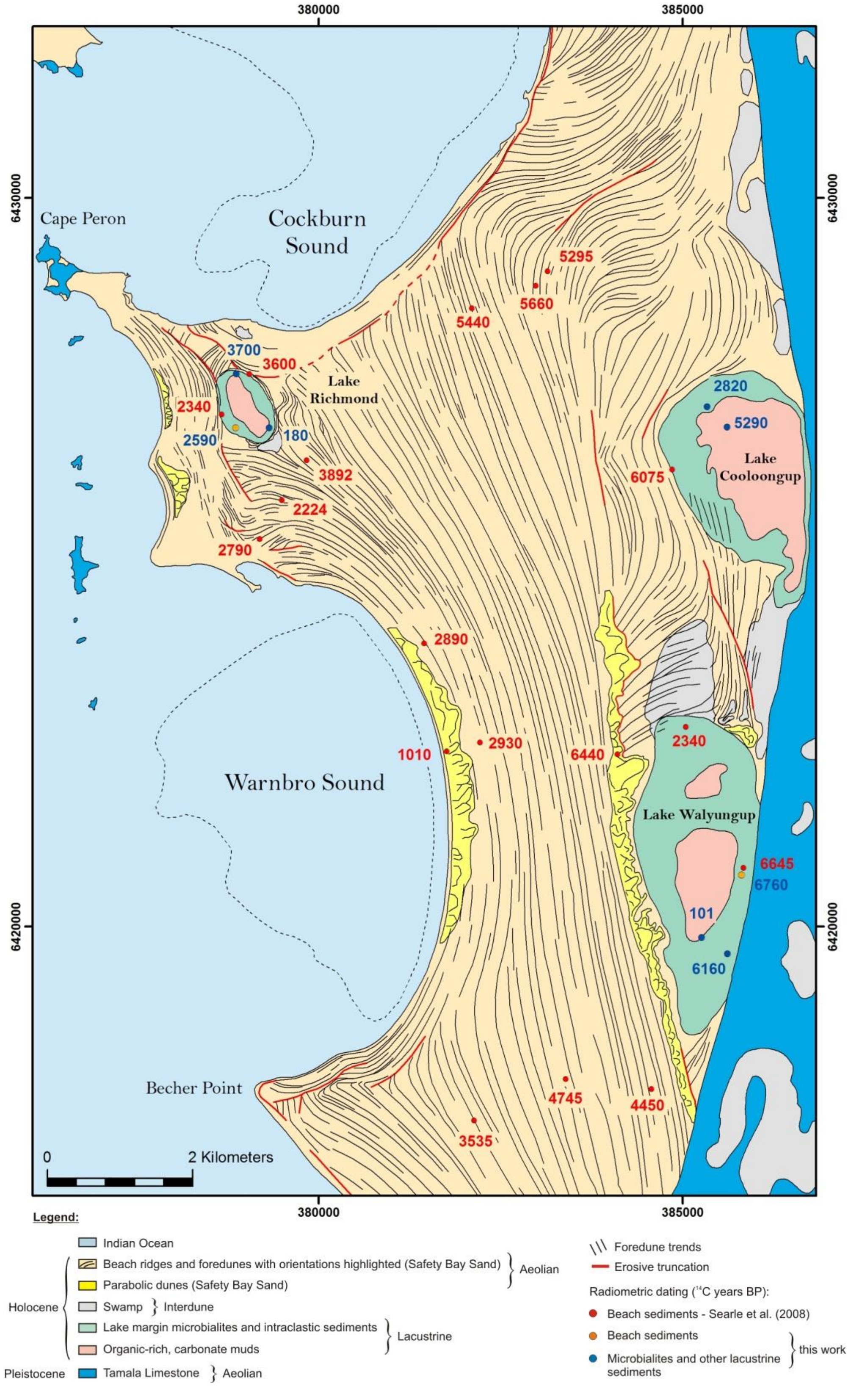

Figure 2 - Map of the Rockingham region illustrating the sedimentary units and configuration of the beach ridge and dune trends around Lakes Walyungup, Cooloongup and Richmond. Red circles are carbon-14 ages of beach sediments published by Searle et al. (1988). Additional beach sediment ages acquired during this work are shown as orange circles; dark blue circles are maximum and minimum ages obtained for lacustrine sediments (Guerreiro, in prep).

Geomorphology

The lake area can be divided into four concentric geomorphological domains according to bathymetry in relation to the lake level. These domains, from shallow to deep, are: a) the lake flat, b) infralittoral platform, c) the slope and d) central basin (Figure 3). The lake flat is a typically seasonally inundated area, characterised by a low-gradient (usually <2°) substrate elevation, which extends from the surrounding beach ridges to the mean low water level mark (LWL). The upper part of the lake flat contains a dense vegetation of sedges, rushes and weeds which grows over brown intraclastic sands with abundant phytoclasts (peat). The lower portion of the lake flat is characterised by sparse clumps of rushes, typically *Juncus pallidus, Baumea articulata* or *Typha orientalis* with vast areas dominated by Saltwater Couch (*Paspalum vaginatum*) grass in between. Depressions in the near shore littoral zone are dominated by a charophyte (*Nitella congesta*) with larger and more densely populated rush stands. In places the Couch grass intrudes on the emergent zone becoming interspersed with algae species (mostly *Rhizoclonium*) and often smothering microbial mats, microbialites and microbialite rubble. The central basin lies at the base of the slope, in the depocentre of the lake, and forms a slightly concave to planar area elongated in the NW-SE direction. Sedimentation in these two last domains consists predominantly of organic-rich, carbonate muds, reaching 15% total organic carbon (Guerreiro, in prep).

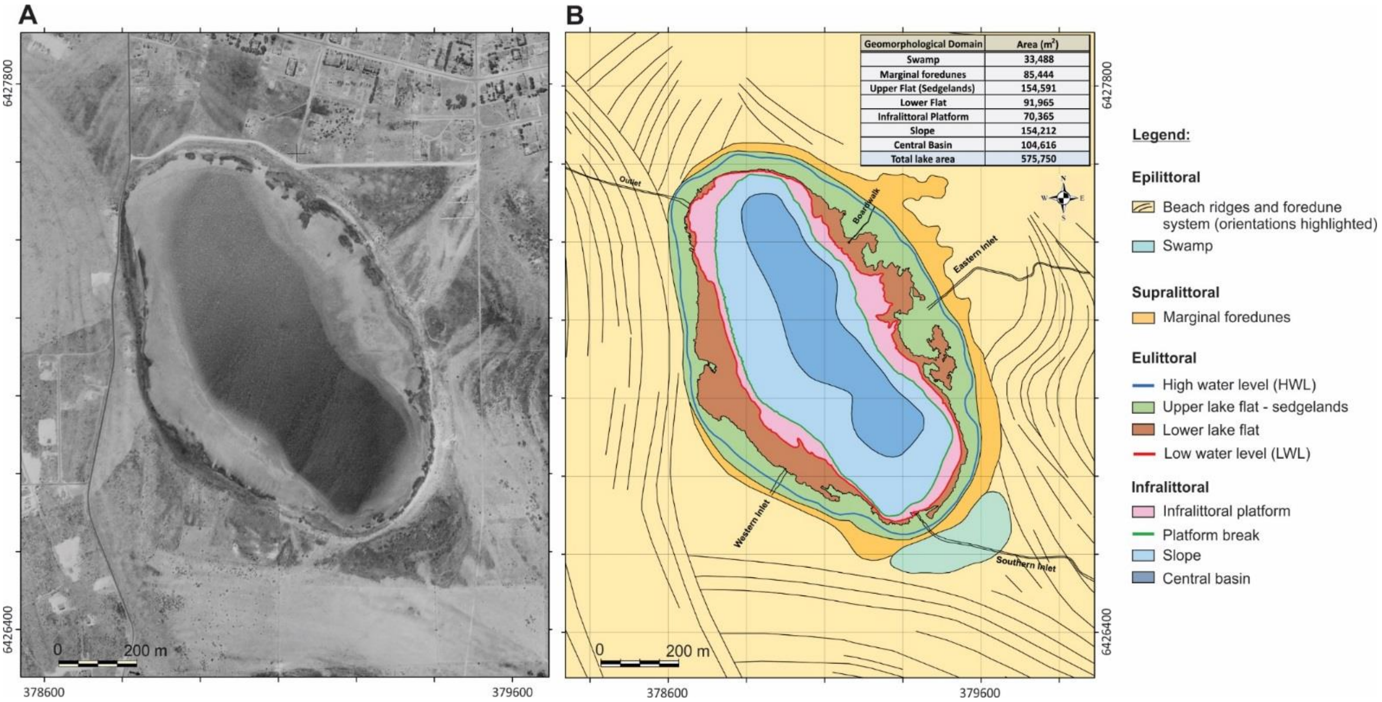

Figure 3 - (A) November 1953 aerial photography (source: Landgate) showing Lake Richmond area, surrounding beach-ridges and dunes prior to urbanisation. Note the wide lake flat and infralittoral platform along the east and west margins of the lake, in contrast to the narrow littoral on the north and south. (B) Map illustrating the geomorphic domains identified in the area and described in the text (Guerreiro, in prep).

Microbialite Distribution and Morphogenesis

Microbialites and broken down microbialite rubble form the majority of geologically recent sediment in the shallower portions of Lake Richmond. The variety of microbialite morphologies present reflects the way in which shallow groundwater flows have discharged to the lake, for example as surface flows through seepage above the lake waterline or as an up welling below the lake waterline and how this discharge has interacted with the microbial mats present at the time of carbonate deposition, (Whitehead and Vogwill unpublished research data. 2014,2015,2016). The various forms are found on all sides of the lake and occupy an area up to 150m wide, extending from the near shore seasonally inundated parts of the basin, down to at least 6m water depth (-5m AHD) in the middle slope. A widespread microbialite pavement covers much of this area and forms the substrate for the growth of bioherms with a wide range of shapes and sizes (Figures 4, 5 and 6). The north and south ends of the lake demonstrate the highest density of well developed microbialite structures while the east side contains low bioherms (mounds). Although the later currently show no activity they appear to be the historically most recently active formations. The west side is dominated by course carbonate material which is likely the result of breakdown of microbial carbonate but there is a lack of any modern or historical coherent structures (Figure 7).

The distribution and morphology of these microbialites reflect a series of environmental controls (both modern and historical) which relate to water depth, topography/bathymetry of the littoral zone and hydrodynamic conditions of the lake. Flat-topped and oblate structures, for example, preferentially occur in the shallower portions of the basin, where the water level restricts upward growth of the microbialites and induces lateral expansion. In contrast, deeper bioherms near the edge of the infralittoral platform tend to contain more rounded, subspheroidal shapes and form large columns with up to 60cm relief in the southern portion of the lake (Guerreiro, in prep).

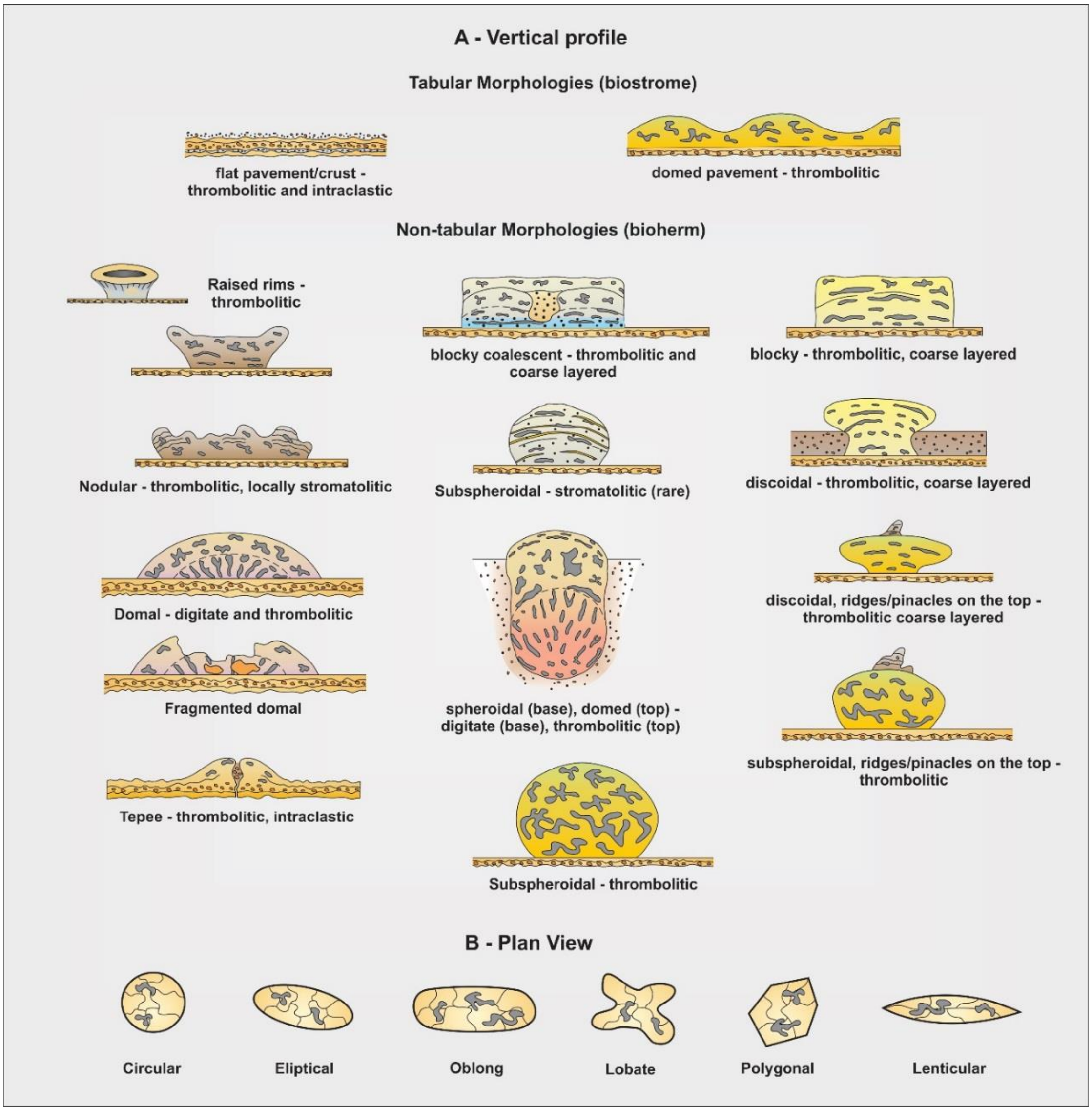

Figure 4 - Lake Richmond microbialite morphologies and fabrics classified according to their synoptic profile (A) and plan view (B) (Guerreiro, in prep).

Figure 5 – Microbialite morphologies. A) Spaced domal bioherms. B) Blocky structures elongated normal to the shore. C) Raised rim structures inside ponds, muddy sands in between. D) Coalesced subspheroidal bioherms, during abnormally low water level. E) Close–up of submerged subspheroidal bioherms. F) Submerged discoidal structures. G) Close-up of partially eroded tepee; eastern margin. H) Nodular bioherm with irregular shape. Scale given by hammer, GPS or scale bar (Guerreiro, in prep).

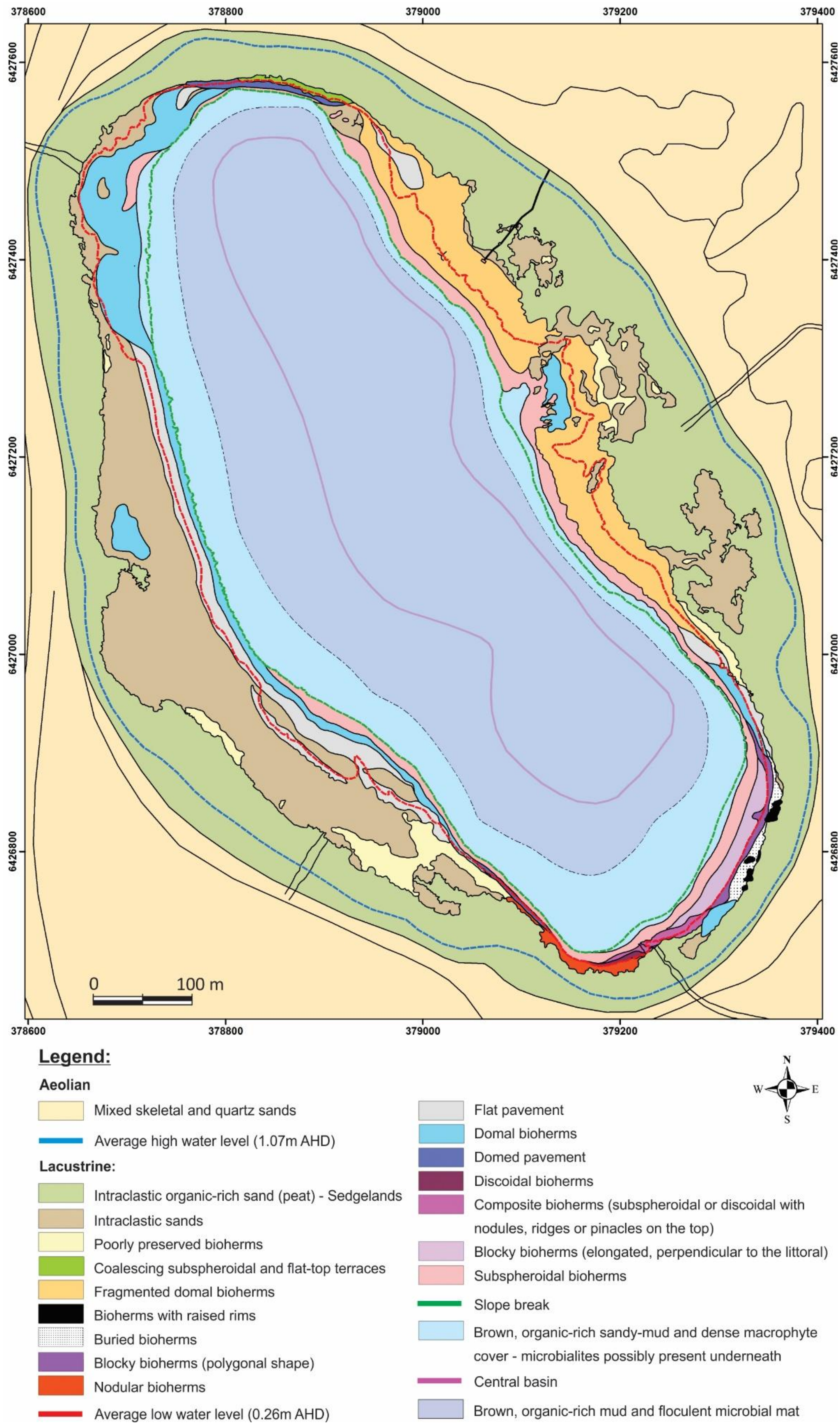

Figure 6 - Substrate map depicting the sediment distribution and diversity of microbialite morphologies in Lake Richmond (Guerreiro, in prep).

Figure 7 - Distribution and morphology of bioherms in different sides of Lake Richmond. A) Flat terraces forming reef-like deposits along the northern margin. Hammer for scale. B) Reef produced by the coalescence of subspheroidal bioherms along the southern margin. Notebook for scale. C) Partially eroded, domal bioherms along the eastern margin. Hammer for scale. D) Sandy lake flat along the western margin with flat pavement and rare domal bioherms buried by sediments. Hammer for scale (Guerreiro, in prep).

Microbial Mats

2013-14-15 Observations at the Macroscopic Level

During this period microbial mats proliferated along the lower portions of the lake flat and in the infralittoral platform, forming a soft cover on the surface of microbialites and over loose sediments. Whilst many environmental factors are known to influence the diversity, metabolism and aspect of the microbial mats, the availability of water is a critical control as mats require to be hydrated to persist. This can be through immersion in lake water or in areas where wet conditions are maintained by persistent groundwater discharge.

Permanently submerged areas in the infralittoral platform are colonised by green, smooth microbial mats, ranging from 2 to 5cm thick. They contain a laminated internal texture formed by the alternation of green and whitish organic laminae with cloudy patches of possibly organomineralized carbonate or sediment trapping/deposition (Figure 8). Radiocarbon dating of microbialites at the south eastern margin of the lake demonstrated that their historical approximate growth rate ranges from 0 to 1.2 millimetres per year (Figure 9) noting that radio carbon age dating cannot work on carbonate formed after 1950 due to the C^{14} introduced to the atmosphere by above ground nuclear testing which took place after that date. Hence C^{14} dating cannot ascertain if modern accretion is occurring.

In shallower areas at the lake flat microbial mats are poorly developed and ephemeral. Microbial communities are more extensive during winter when the lake level is high and mats in shallower areas tend to form green smooth microbial mats, similar to those in permanently submerged areas but thinner in cross section, usually less than 2cm. From the spring to early autumn, when the lake level falls, desiccation produces a well-defined sequence of transformations, first resulting in the formation of microbial mats with orange pigmentation, followed by black tufted mats and then shrinkage into dry microbial mat polygons (Figure 10). The colour changes have been identified by microscopic examination during the 2017-2018 study to result from changes in the dominant species present on the outer most surface in response to the change in environmental conditions. The high motility of the dominant species in the mat allows it to migrate to lower laminae exposing other species present and is discussed in detail in the microscopic examination section.) These dry microbial mat fragments are easily modified by the action of wind and waves when the water level rises again, reducing the chances of preservation in areas subject to seasonal exposure. A lag of reworked microbial mat fragments frequently accumulates in the littoral zone when the lake level rises at the beginning of the wet season.

It is unlikely that the microbial mats currently in the lake have resulted in all of the observed morphologies of microbialites, many of which have formed during the Holocene when water and solute balances of the lake would have been different. In 2013-14-15 the lake contained some areas of microbialite formation that may have been active but these are different to those during the recent geological past. Historically the lake's south and north littoral zones were most active, as evident from the density of well-formed structures in those locations, but more recently the eastern littoral zone appears most active. In summary recent microbialite formation appears to be of greatly reduced spatial extent and intensity as compared to during the Holocene (Guerreiro, in prep).

It should be noted that the formation process is seldom continuous as it relies on the establishment and maintenance of preferential water flow paths delivering sulfide compounds to areas of active mat where sulfur and carbonate reactions occur. When the localised carbonate cementation of the microbial mat's phototropic layer reaches a level which changes the resistance to discharge at the outlet point of a flow path, the flow then takes the path of least resistance. Then at least some of the flow will be diverted to another point, typically nearby. This is why multiple large structures often form in close proximity.

In relation to the age of the structures, formation activity may vary considerably over short time frames between structures in close proximity, seasonally or over longer time frames where little or no activity occurs for many years, followed by a significant accretion (growth) event. Cyclic changes to the near shore topography (through weather driven sedimentation for example) also may render the formation process inactive with activity restored when conditions become favourable again. This can occur in the long and short term. Reworking of carbonate material is also common in microbialite structures. For these various reasons it is difficult to accurately map the historic age or growth rates of microbialites at a useful resolution in relation to the later part of the Holocene period, specifically from approximately 2590 years ago when Lake Richmond was disconnected from the ocean (Guerreiro, in prep). The best indicator of historical activity is the size and density of the structures in a given area.

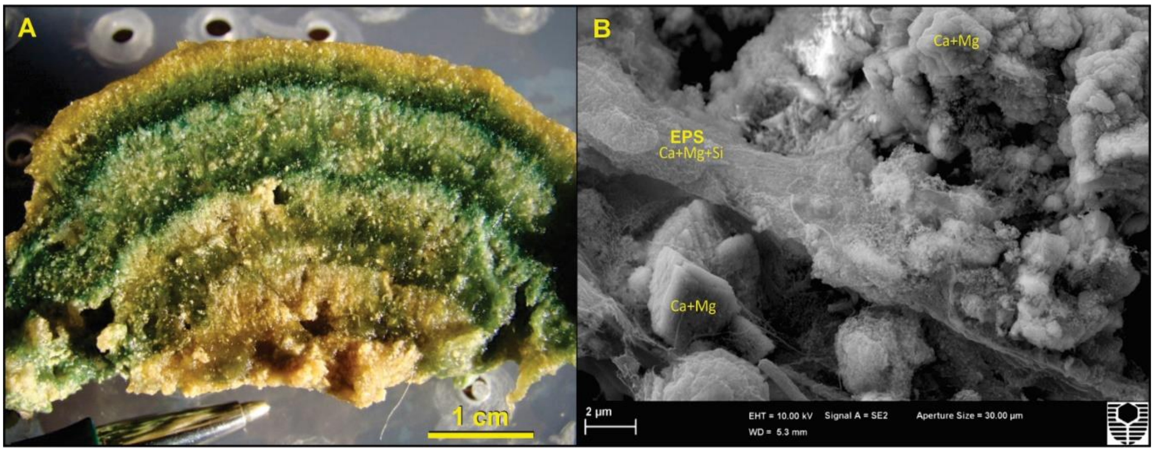

Figure 8 – Smooth microbial mat sample collected from a permanently submerged subspheroidal bioherm at the northern margin of the lake. (A) General view of the laminated internal texture formed by the alternation of green, organic laminae and whitish bands. (B) Scanning electron microscope (SEM) view of a whitish lamina showing organomineralization of the extracellular mucilage (Guerreiro, in prep).

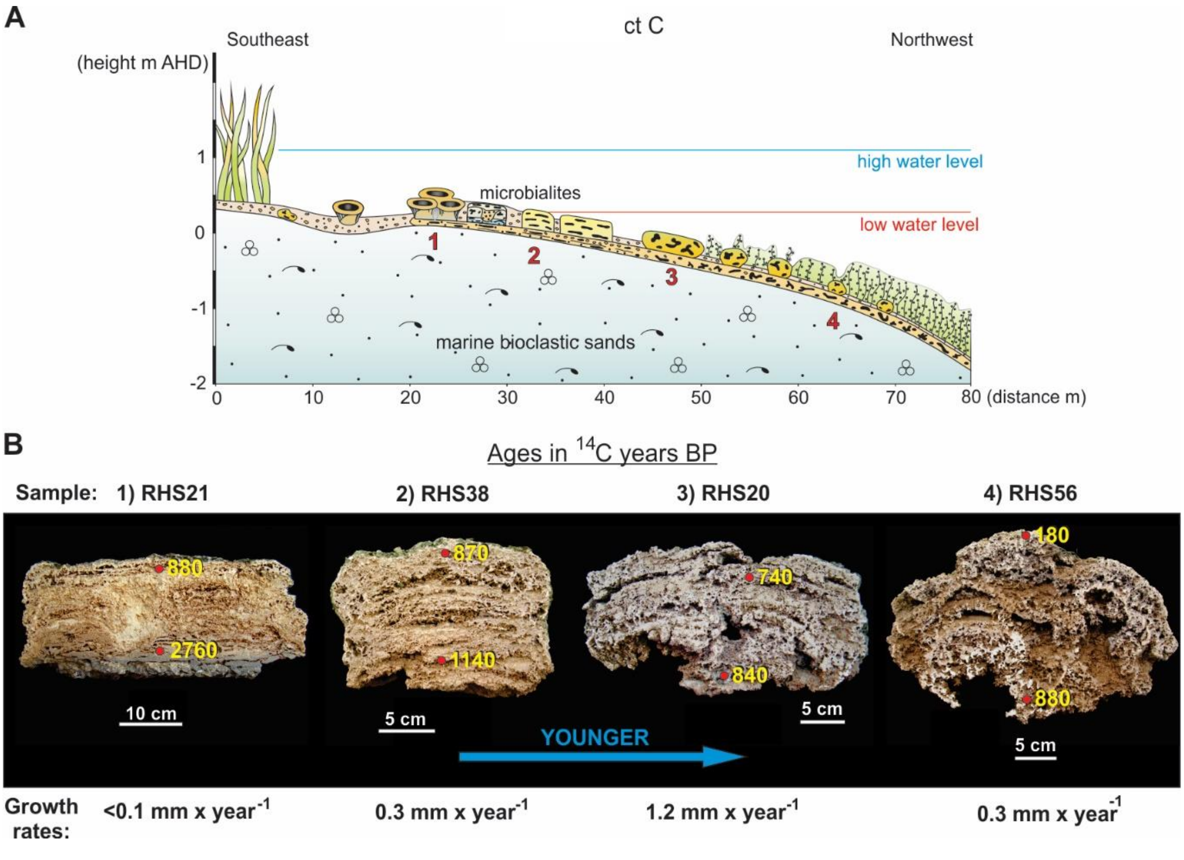

Figure 9 - (A) Transect at the southeastern margin of Lake Richmond; red numbers indicate the location of bioherms shown in (B). (B) Microbialite bioherms and respective radiocarbon ages in 14C years BP shown as yellow numbers. Calculated growth rates assume a linear growth rate between 14C dates which is likely a simplification (Guerreiro, in prep).

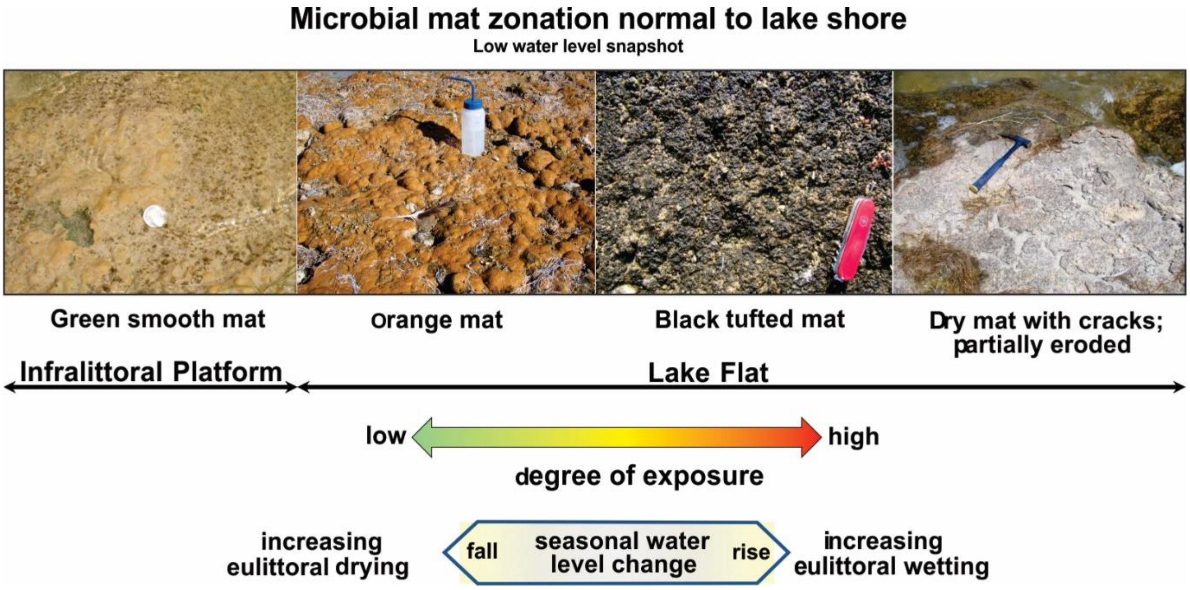

Figure 10 – Typical microbial mat zonation observed in the lake during the dry season. Gradual desiccation of the microbial mats in the lake flat produces a well-defined sequence of transformations that finishes with shrinkage into dry microbial mat fragments and reworking by the wind and waves (Guerreiro, in prep).

2017-18 Observations at the Macroscopic Level

During this period only the green, smooth microbial mats were seen across the littoral zone with no differentiated zones (growth patterns) caused by exposure to air as the lake water level never receded sufficiently for exposure to occur (this will be discussed in the hydrology section below). The high nutrient levels and fresh water quality currently occurring in the lake are triggering the proliferation of algae species to the detriment of the microbialites. Charophytes are particularly abundant in the deeper portions of the infralittoral platform and upper slope, forming a dense cover on the lake substrate. In these areas, the microbialites are often completely obscured and microbial mats are thin and poorly developed on relict (inactive) bioherms or pavements.

The examined microbial mats only contained loose granular carbonate which is associated with the entrapment of wind-wave reworked and suspended sedimentary carbonate that has become incorporated into the microbial mat matrix during the growth of the microbial colonies. This is a common feature of microbial mats in other carbonate rich lakes in the Yalgorup Lake system that are not associated with microbialite formation. It is an entirely different process to the calcification of the Extracellular Polymeric Substance (EPS) that forms microbialite structures, which was not observed throughout the duration of this study. This granular carbonate can be incorporated in structures during latter growth phases but typically becomes part of the lake sediments following the desiccation of microbial mats after seasonal expose to air and desiccation.

The limit of certainty on this statement is that due to the high water level throughout the year we were unable to access some of the deep formations which Guerreiro (in prep) identified as containing buried inactive microbialites and flocculant (chemotrophic) mat. Water quality indicators of EPS calcification (discussed below) were not present either. No calcification of the EPS produced by phototrophic cyanobacteria colonies examined during the duration of the study occurred. Additionally, none of the mats or structures we examined had any sulfur bacteria activity present in the lower laminas (Figure 11) and this strongly indicates that the formation chemistry has not been present for some time. The pK2 test (detail in the hydrology section later) developed by the authors during a study of the Lake Clifton thrombolites is a reliable indicator of microbialite carbonate deposition. This test was performed three times, two of which were at critical periods with regard to lake water level and the results were well outside the level that would occur under conditions of carbonate precipitation.

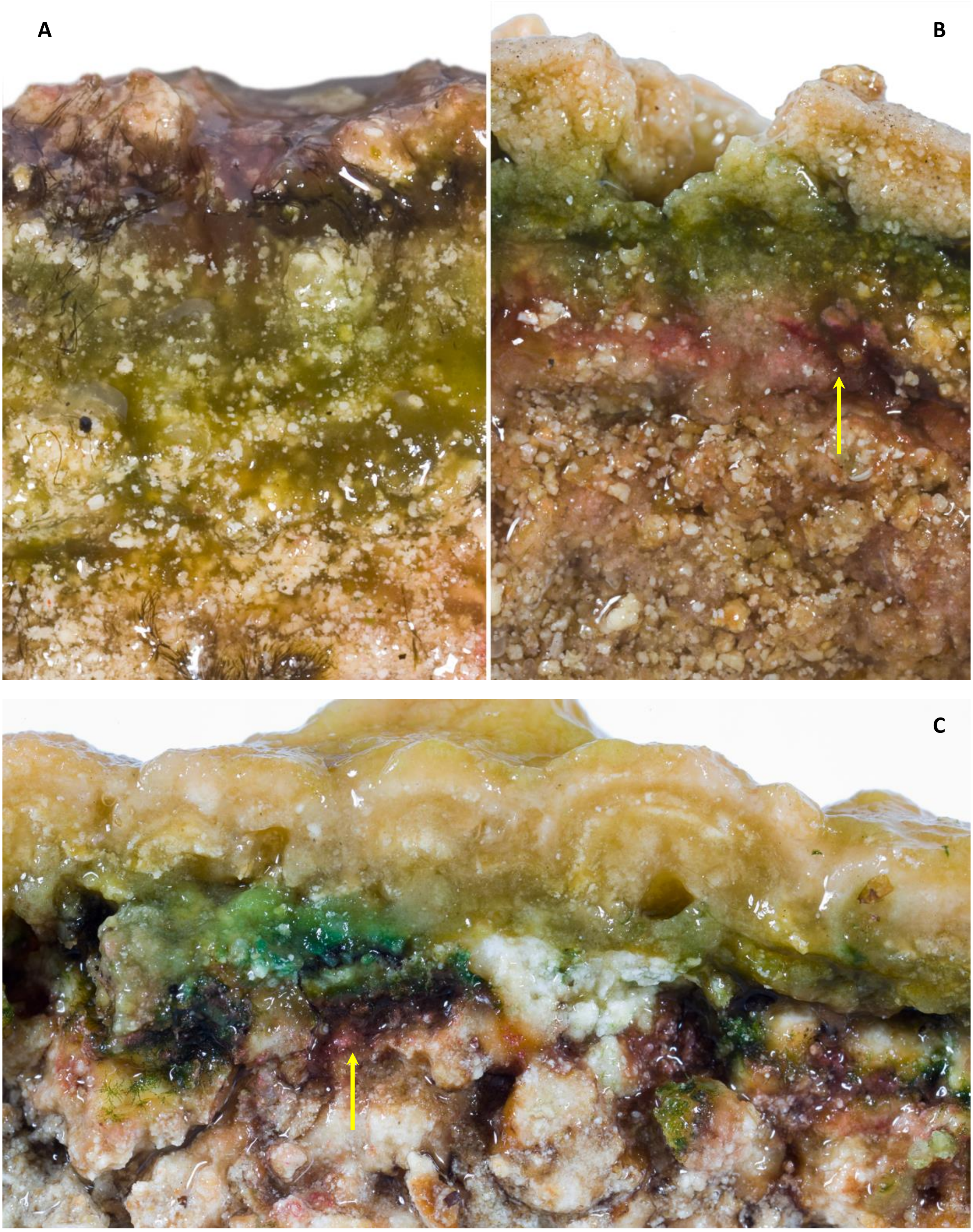

Figure 11 - A) Microbial mat cross section from Lake Richmond showing granular carbonate entrapment. B) Microbial mat cross section from Lake Clifton showing granular carbonate entrapment for comparison. C) A cross section showing the cemented top lamina of a microbial mat forming a new layer of microbialite structure at Lake Clifton. Note the purple colouring in the lower lamina caused by the presence of sulfur reducing bacteria (arrowed yellow).

Figure 12 shows the area of active microbial mat as mapped by field traverse with some air photo extrapolation in April-May 2018 with the 0.6mAHD lake level contour (minimum for 17-18) also shown for context. Comparison of this with Figure 6 shows how little of the microbialite community was exposed during the low lake level period. At 0.6mAHD the only significant area of mat exposed was on the west side of the lake, where structures do not occur.

Figure 12 - Area of active microbial mat, green shading is the area of phototrophic mat, purple shading is the area of flocculant chemotrophic mat. The 0.6mAHD and 0mAHD contours (red lines) are also shown. 0.6mAHD was the minimum lake water level in 2017-18. At 0mAHD the lake shoreline would expose the majority of the littoral zone microbial mat community. Note that 0mAHD is at the break of slope of the infralittoral platform.

Hydrology and Water Chemistry

Historical (pre-2013) Hydrology

Originally, prior to 1968, there were no surface drainages connected to the lake and the basin was predominantly sustained by the inflow of groundwater and direct rainfall. The hydrology, however, was significantly modified by the construction of one artificial outlet and three inlets in 1968 and runoff discharges are currently thought to represent the main source of water to the lake (Guerreiro, in prep). The available historical data (Figure 13) shows how water level fluctuations have changed in the lake post the use of the site for stormwater discharge with outlet control. There has been a reduction in lake level and in seasonal fluctuation of water levels. It's important to note in this context the lower frequency of data collection prior to 1978 wouldn't have captured the full seasonal fluctuation in lake level.

Unfortunately, no significant historical (pre-1968) water quality data for the lake exists. The only available historical water quality data is in Passmore (1970) who states that the total dissolved solids (TDS) fluctuated from 2000 mg/L in winter to 3,500 in summer when he investigated the lake in 1964-66 prior to installation of the stormwater drains. During this period chloride was typically the dominant anion (Passmore, 1970) with chloride (Cl^-) > bicarbonate (HCO_3^-) & carbonate (CO_3^{2-}) (undifferentiated) > sulfate (SO_4^{2-}). Cation abundances were sodium (Na^+) & potassium (K^+) (undifferentiated) > magnesium (Mg^{2+}) > calcium (Ca^{2+}). It should be noted that this was towards the end of a wetter than long term average period in Perth's rainfall which ended in 1968 (Yesertener, 2008). Hence the lake would likely have been fresher than during dry phases through the Holocene. Also, the lake was connected to the ocean until approximately 2590 years ago (Guerreiro, in prep) when it changed from marine (approximately 35,000 mg/L TDS) to lacustrine conditions. Given the maximum age of thrombolites in the lake is 3700 years old, it is likely that some of the microbialites began forming before the system was isolated from the ocean (Guerreiro, in prep).

In 1966 the groundwater levels to the east, south and west of the lake were higher than the lake nearly all of the time, indicating groundwater discharge into the lake. Groundwater levels to the north were lower except during the peak of winter, indicating discharge of aquifer water to lake occurred most of the year, hence Lake Richmond was primarily a groundwater discharge wetland (Passmore, 1970). In 2010-11 the lake was investigated by MHW (2011) the water levels fluctuated 0.85 to 0 mAHD noting this was a particularly dry year with an annual rainfall of only 407.6mm (2002-2018 mean 601.4mm) at Garden Island weather station (BoM station number 9256).

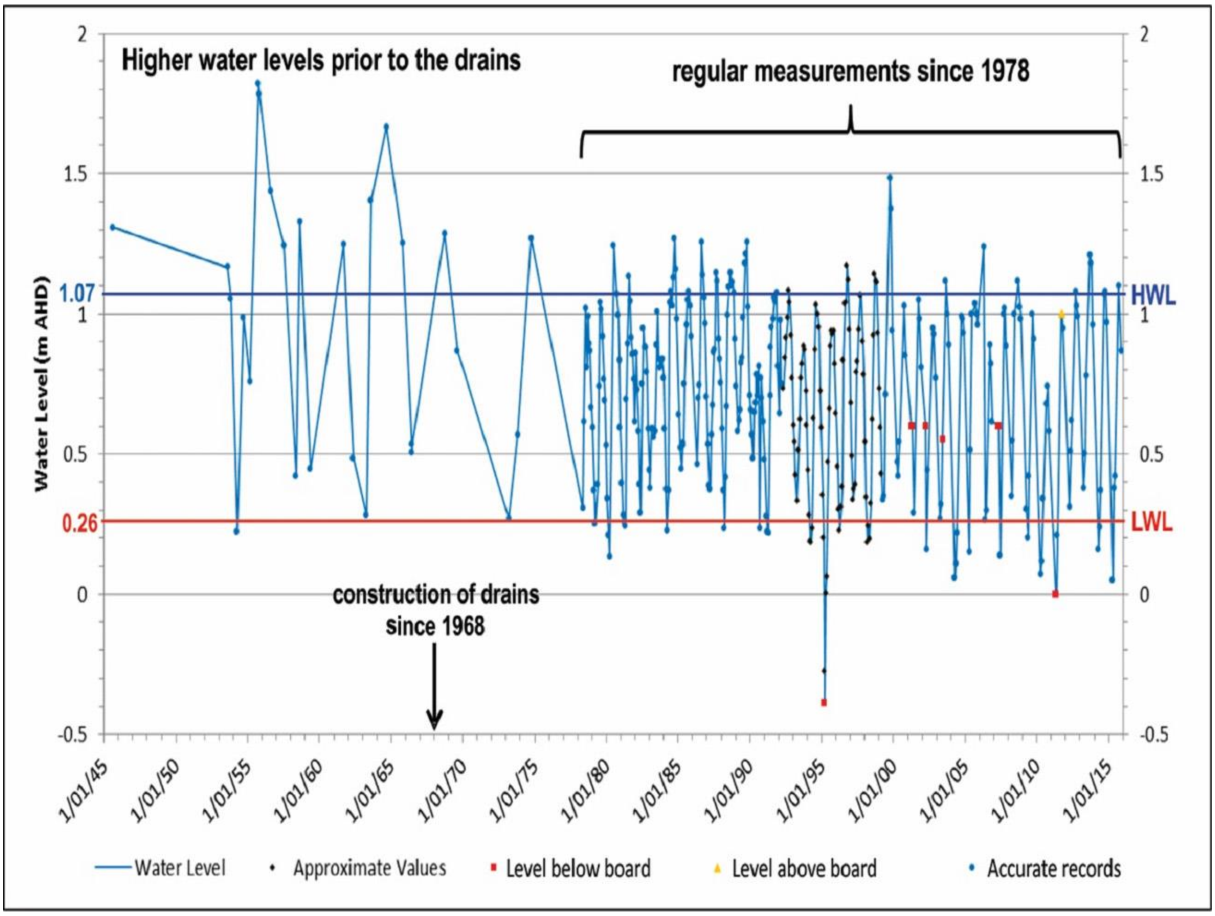

Figure 13- historical water level fluctuations in Lake Richmond from DWER data.

2013-14-15 Hydrology

In 2013-14-15 the interactions between the lake and adjoining aquifer were investigated through a network of 16 shallow piezometers installed around the lake. During the dry season, groundwater inflow occurs predominantly from southeast and east while seaward areas to the west and northwest constitute the main outflow zones. During winter however, the lake level tends to rise faster than the aquifer water levels due to drain stormwater inflow and the influx of groundwater is gradually reduced, becoming subordinate to runoff. Consequently, at the peak water levels the lake usually behaves as a groundwater recharge wetland, with surface water seeping into the aquifer in most directions, except to southeast where the hydraulic gradient is essentially flat so little to no exchange occurs. This is distinctly different to the historical surface water groundwater interaction regime from 1966 described above.

During 2013-14-15 Lake Richmond's water level (Figure 14) fluctuated on average 0.8m between the dry and wet seasons, with the minimum level of 0.25m AHD usually recorded in March-April and maximum of approximately 1.05m, coinciding with the end of winter in September-October. The flooded area is reduced by about 57% by the end of summer, resulting in the exposure of the microbial communities along the lake flat for a considerable period of the year. This process has a profound impact on the distribution, growth rates and preservation potential of the microbial mats, altering the balance of exposed areas in favour of microbialite erosion rather than accretion.

During the monitoring period, from February 2013 to April 2015, the salinity and pH measurements ranged from 550 to 700mg/L and from 8.5 to 9.0, respectively, with higher values generally recorded during summer. Daily fluctuations in dissolved oxygen (DO), pH and redox potential are significant in the lake and tightly coupled, emphasizing the importance of biological processes on the lake water chemistry. These parameters usually peak in the middle of the afternoon, when photosynthesis performed by the benthic microbial communities, phytoplankton and macrophytes is most intense. In contrast, an abrupt decline is verified during the night as a result of respiration.

During 2013-14-15 the proportion of anions in the lake water is HCO_3^- > Cl^- > SO_4^{2-} >> CO_3^{2-} and the proportion of cations is Na^+ > Mg^{2+} > Ca^{2+} >> K^+, with calcium occasionally higher than magnesium near the artificial drains. Calcium, bicarbonate and, to a smaller extent, magnesium are depleted in the lake water compared to the proportions in the groundwater and near artificial drainages, i.e. the main water sources of the basin. This could relate to either minor carbonate precipitation in the lake or carbonate dissolution during periods of high stormwater inflow with bicarbonate formed transported to the aquifer by lake water discharging to the aquifer.

The capacity of the lake to form and dissolve carbonate was investigated using geochemical modelling (PHREEQC - output in Figure 15) which predicts that the lake water can precipitate aragonite, calcite and dolomite most of the time. Near the drains, however, runoff discharges sometimes cause a sharp decrease in the saturation state of these minerals occasionally leading to under saturation and possible dissolution. The lake water pH and carbonate concentration were identified in PHREEQC modelling to be the most significant control on carbonate saturation with a negligible influence of calcium concentration.

Nutrient levels in lake water (up to 1.2 mg/L total nitrogen) normally remain well above the guidelines for freshwater ecosystems in Western Australia (ANZECC & ARMCANZ, 2000), consistent with the high concentrations verified primarily in the drains (up to 4.2 mg/L total nitrogen) and to a lesser extent in groundwater flowing into the lake (up to 1.2 mg/L total nitrogen). The nutrient concentrations rise during the winter when runoff discharges increase, and fall during the summer when the influx of drainage water is reduced and biota nutrient uptake increases. The phytoplankton and macrophyte productivity closely follow this trend and are visibly more abundant during the winter, when the availability of nutrients is higher.

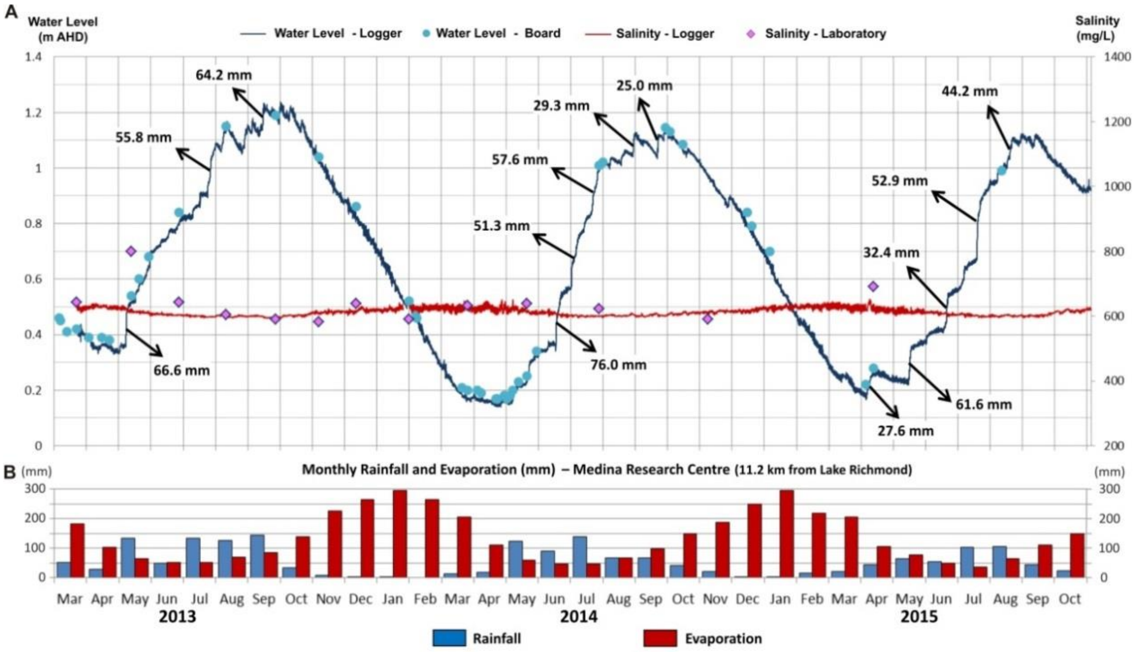

Figure 14 - Lake Richmond (A) water level and salinity at the northern margin of the lake from 2013 and 2015. The blue curve displays the high-frequency water level variations recorded with a logger while blue dots are manual measurements, using as reference a depth board from the Department of Water (DoW). Arrows indicate the volume of prolonged rainfall and storm events, accompanied by a rapid increase in lake water levels. The red curve represents the lake water salinity and was calculated from electric conductivity measurements performed by a logger. Pink dots are salinity values obtained through laboratory analyses of lake water samples. The lower part of the figure (B) presents the monthly precipitation and evaporation in the region, recorded at the Medina Research Centre (data provided by the Australian Government Bureau of Meteorology) (Guerreiro, in prep).

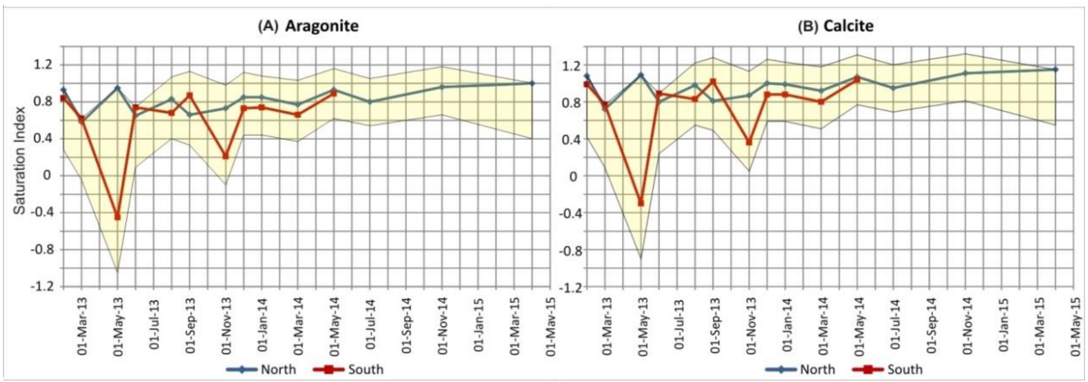

Figure 15 - Saturation indices for (A) aragonite and (B) calcite at the northern and southern margins of Lake Richmond. Most of the water measurements and sampling was carried out during the morning. The yellow shaded area was modelled to simulate diurnal variations resulting from a 0.6 pH unit fluctuation. Graphs show the lake water is, in general, saturated in relation to aragonite and calcite, but runoff discharges through the artificial drain at the southern margin of the lake can temporarily reduce the saturation state of lake water in nearby areas and eventually causes undersaturation, as observed in May 2013 (Guerreiro, in prep).

2017-18 Hydrology

Between June 2016 and December 2017 lake water level varied between 1.1 and 0.62mAHD (Figure 16) maintaining a persistently higher water level and reduced seasonal fluctuation relative to previous years. The presence of a large out of season rainfall event (107.6mm on the 16th of January) caused a nearly 0.3m increase in lake water level due to the effect of direct rainfall on the lake and stormwater inflow. This resulted in a lake level which stayed consistently high throughout the summer microbial mat growth period, approximately 0.4m higher than usual. The lake level was permanently above the outlet drain level in 2017-18, indicating that lake surface water outflow was constantly occurring.

This had a pronounced effect on the microbial mat community. Lake level never receded to the point where mats could be exposed to substantial groundwater discharge from the near shore sulfidic stores, a precursor to microbialite formation in some of our other sites (Lake Clifton, Lake Preston and Rottnest Island salt lakes in particular).

Water quality in 2017-18 was very similar to the 2013-14-15 data with anion relative abundances being HCO_3^- > Cl^- > SO_4^{2-} >> CO_3^{2-} and cations Na^+ > Mg^{2+} > Ca^{2+} >> K^+. Total Nitrogen varied from 0.8-1.7mg/L and total phosphorous was 0.12mg/L, and the laboratory certificates are shown in Appendix 1. To understand the capacity of the system to produce carbonate in 2017-18 we used data from our titrated alkalinity. The inflection point titrations of sampled shoreline lake water in proximity to existing microbialites was used to calculate the value of pK2 which is the pH value where dissolved bicarbonate and carbonate are at equilibrium. If sulfide compounds were being transported from the near shore pools in the sediment porewater and carbonate precipitation was taking place the value of pK2 would have been equal or less than the actual pH value of the lake water. On our three sampling dates the calculated pK2 value was well above pH10 while the actual lake water pH value was pH9 resulting in bicarbonate levels being an order of magnitude higher than carbonate levels. Significant carbonate precipitation has not occurred under these conditions and in fact lake water was likely net aggressive (i.e. predisposed for carbonate dissolution) all year round as was observed in the lake water near the drains in 2013-14-15. This will be further discussed below.

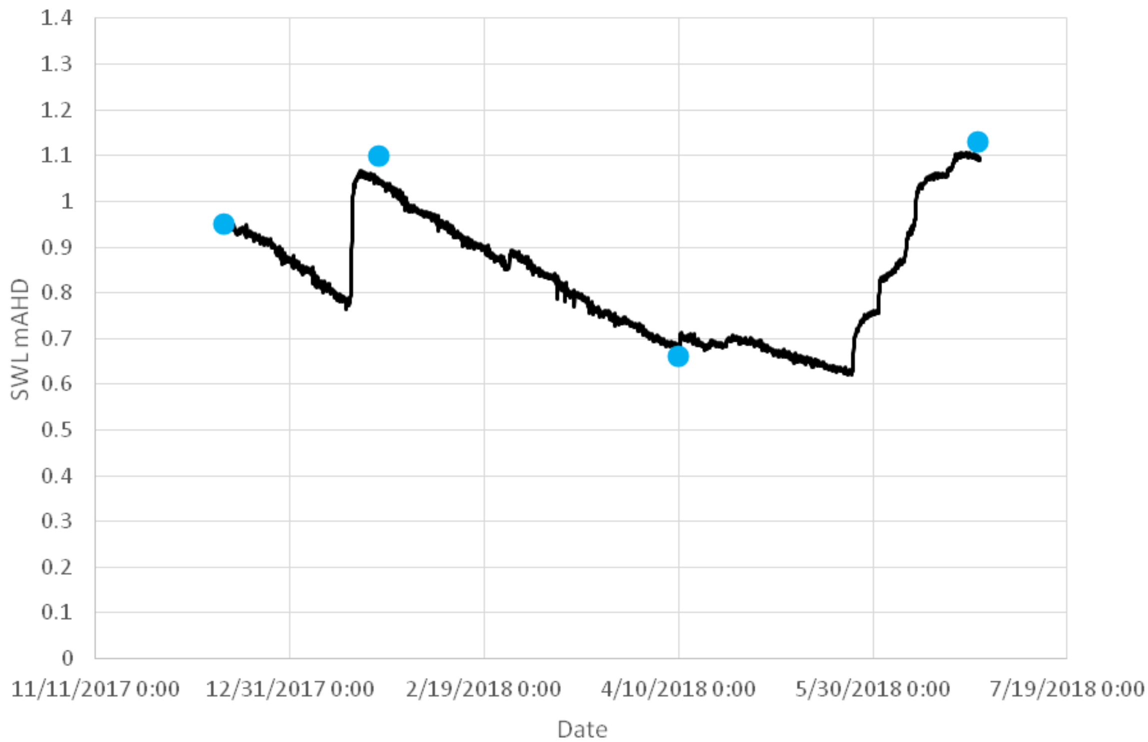

Figure 16 - Water level graph for 2017-18. Logger data is the black line and blue dots are manual depth board readings. Note the reduced fluctuation and perpetually high level compared to figures 13 and 14.

Discussion

An investigation of actively forming microbialites at sites on Lake Preston and Lake Clifton (Whitehead and Vogwill, 2014, 2015, 2016, unpublished data) revealed these localised formations shared specific and localised geomorphic, geochemical, hydrological and biological characteristics. The temporal and spatial convergence of the hydrological and biological components creates the specific conditions that promote the precipitation of carbonates and elemental sulfur within the EPS matrix of the microbial mats, causing the formation and growth of microbialite structures. Essentially microbialite formation requires the transfer of sulfide compounds to the mats via groundwater or surface water. The rarity of this combination of specific conditions is the reason microbialite formations are found in only a few lakes where often their occurrence is highly localised.

Some of these same characteristics occur in Lake Richmond, however the hydrological drivers were absent during this study. The lake water level increased to near the winter high following a large out of season rainfall event in January 2018 and remained high for the duration of summer (Figure 16). This perpetually high lake level inhibited groundwater discharge to the lake as groundwater and lake water were at similar heights throughout the year. When compared to some of the other sites where we have investigated microbialites, the absence of significant dune systems adjacent to the shoreline reduces the available hydraulic gradient to drive the hydrological component of the required characteristics at Lake Richmond for microbialite formation. This means the system is significantly more susceptible to disruption if minor changes to the remaining components of the microbialite formation process occur. As discussed in the observations section, only loose granular carbonate was seen on examination of the microbial mats and the usual basal lamina occupied by sulfur bacteria was completely absent. We also noted that where bacterial sulfur cycling in the sediments of the near shore pools did occur, the seasonal timing was too late to allow transport of the chemistry in pore water flows to the site of microbialite formation in relation to lake water level during this year. Additionally it appears that topographical changes through sedimentation facilitated by increased emergent vegetative growth has at least reduced the size of or eliminated the occurrence of the near shore pools in some areas (see Figure 3a). No detectable microbialite carbonate formation occurred during the duration of this study. This conclusion is supported by high pH in the near shore pools and carbonate speciation (pK2 verses pH) in the shoreline water.

The dominance of bicarbonate as an anion in lake water suggests that net dissolution of structures and carbonate generally in the lake are most likely occurring. In a rainfall dominated system (as this system was particularly in 2017-18) chloride would be expected to be the dominant anion as it was pre 1968 when the lake was only recharged by rainfall and groundwater inflow (Passmore, 1970). Note that the groundwater around the lake in 2013-14-15 was also highest in bicarbonate, likely due to groundwater recharge from the lake and carbonate mineral dissolution. In addition at other sites which are highly active in producing microbial carbonate, sulfate concentrations in the lake water decrease sharply relative to other ionic dissolved water components during the microbialite formation period. At Lake Richmond this did not occur in 2017-18 and in fact doesn't appear to have occurred in 2013-14-15 (Guerreiro, in prep) or in 2011 (MWH, 2011). This calls into the question the ability of this site to currently form microbial carbonate in anything other than a very small capacity as has been identified herein.

Despite these findings it should be noted that this does not exclude the possibility of continued formation of the Lake Richmond microbialites. While the Lake Clifton thrombolites receive addition carbonate deposition during spring in most years, the Lake Preston microbialites only form in years when the El nino weather cycle is present and at the onset of the rains in autumn. However, the absence of sulfur bacteria indicated by a pink to purple colouration in the second and third laminae of existing microbialites suggests the formation process has been inactive for at least three years.

An additional impact of the January rainfall event was that the microbial mats did not complete a normal seasonal growth cycle to a final stage of desiccation on exposure to air due to receding lake water level. The mats remained mostly submerged with only narrow shoreward band being exposed to air at the end of summer and never drying to the point of desiccation. We do not expect this to reflect any change to the mapping of the mats as the growth area is expected to remain consistent with other years governed by the winter high lake water level. While chemotrophic and heterotrophic bacteria can theoretically form mats at any depth, the phototrophic cyanobacteria associated with microbialite formation are limited in their distribution by the penetration of sunlight through the overlying water column. At Lake Richmond the mats occupied by phototrophic cyanobacteria occur around the shoreline in 50mm to 700mm water depth where their occurrence declines due to limited sunlight exposure. The recession of the water level into the summer months results in an extension to their range as they follow the depth profile and increased light allows increases in productivity in previously deeper areas. Mapping therefore reflects the zone of productivity over a yearly growth cycle. They are most productive in the 300mm too 400mm depth zone. Microscopic examination of mat samples taken from regular intervals between the shoreline and 700mm depth revealed that while colony numbers of individual species increased during the summer, the species composition of the mats remained unchanged. Changes in species dominance of the surface layer which imparts colour variation over the seasonal growth cycle did not occur to the extent recorded in dryer years by Guerreiro, (in prep).

Conclusions and Recommendations

To return to the aims of this report, the first was to summarise the available information relevant to microbial mat and microbialite formation at Lake Richmond, which has been presented. Although not comprehensive, enough data exists to allow us to complete the second two aims. The second aim was an assessment of the microbialite formation potential/status at Lake Richmond. In 2017-18 there was no apparent calcification of the microbial mats as the lake's physical and chemical conditions were not suitable for structure accretion as described above. During the 2017-18 growth season conditions are most likely net dissolving carbonate due to the dominance of runoff/stormwater throughout the summer. The prospects for ongoing formation of structures were better in 2013-14-15 but were still less than ideal and only minor carbonate formation is believed to have occurred during those years. Water chemistry promoting the dissolution of structures was only present in the southern end of the lake, near the main drain inflow, during the main microbialite formation period (summer) unlike in 2017-18.

In terms of alteration to the lake hydraulic regime to improve the potential for microbialite formation a number of factors need to be changed:

1. Lake level - The current lake level regime is heavily modified due to the influx of stormwater. Pre stormwater drainage inflow modification of the lake it had a higher lake level and a greater seasonal fluctuation. The lack of a surface water outflow was also important pre modification as this maintained higher lake levels for a longer period and allowed evapo-concentration of TDS to occur. The presence of this outflow allows some of the water solutes to discharge maintaining the lake as a freshwater system (<1000mg/L TDS). In 2017-18 the lake level never receded to the point where outflow would stop (at 0.58mAHD). In

2013-14-15 it did recede to below the level at which discharge would stop, but the outflow and altered surface water-groundwater interaction meant that TDS stayed continuously low. Under the current regime of inflows and outlet control an annual lake level low of 0mAHD or lower would be preferable to facilitate groundwater discharge, some increase in lake TDS and lakeward transport of sulfide compounds. It would be preferable to restore the lake to its pre modification hydrologic regime (i.e. lake level fluctuating between 1-2 mAHD) but it is unclear if this is feasible given the constraints imposed by use of the lake for stormwater disposal. As discussed previously, the temporal convergence of biological and hydrological components of the formation process is required for continued carbonate deposition to support microbialite growth and this synchronization would need to be restored and optimised to encourage continued microbialite formation.

2. Groundwater level verses surface water level - Pre-modification the lake level was typically lower than groundwater levels (except on the north side) which would have caused an increase in lake TDS, with the lake behaving predominantly as a groundwater discharge feature. The groundwater levels appear to now be lower than they were pre-modification, causing the lake to be discharging to the aquifer for much of the year, followed by return of that primarily lake stormwater originated groundwater to the lake once the levels recede. It is preferable that the groundwater level be higher than the lake level for the majority of the year to help elevate TDS and allow a lakeward gradient in groundwater to develop.

3. Lake TDS - The only pre-modification lake TDS data suggests the lake fluctuated between 2000-3500 mg/L, considerably higher than currently where it is constantly well below 1000 mg/L. Alteration of the lakes TDS to revert to these historic levels would support the microbial mats and microbialite formation as it would exclude a number of the freshwater species which are currently competing with the mats and in the case of macroinvertebrates, consuming the mats as they form, while encouraging the productivity of more cyanobacteria species that promote microbialite formation. Note that an elevated TDS would also help control other invasive weeds, many of which are not tolerant of brackish water. It is unclear if structures were forming in 1968, but we consider the likelihood much higher than under the current lake TDS, hence would recommend trying to reengineer the lakes hydrology to achieve these levels. It is outside of the scope of this project to determine how this could be accomplished, which would be a complex stormwater engineering, water and solute balance project in its own right.

4. Lake nutrient concentrations - The levels of nutrients measured in Guerreiro (in prep) and in this study exceed ANZECC and ARMCANZ (2000) guideline values. Our observations for 2017-18 are that this is having determinantal consequences for the microbial mats ability to form microbialites. The elevated nutrients are causing a proliferation of algae and aquatic vegetation, particularly abundant in the deeper portions of the infralittoral platform and upper slope, forming a dense cover. In these areas. The substrate has been completely obscured in many areas and was devoid of microbial mats on microbialites in many cases. Similar observations we made in 2013-14-15. The nutrient levels are high but not excessive. If the water TDS was elevated as per the previous recommendation we believe they would pose a greatly reduced threat as many of the problem organisms would be excluded by brackish water quality.

5. Inflow of sulfide compounds to the littoral zone is an important part of the hydraulic regime supporting microbialite formation in other systems but has been absent at Lake Richmond between 2011 and 2018. For sulfide inflow to occur you need an external sulfur source and a hydraulic gradient driving water flow to the littoral zone where the biologically mediated chemistry of microbialite formation occurs. In 2017-18 we looked at the areas above the shoreline where sulfide sources (primarily pyrite in potential acid sulfate soils such as organic lake deposits or gypsum resulting from the carbonate neutralisation of acid sulfate reactions) could be present and we believe that there are still some sources adjacent to the lake. For these to produce sulfate which is then converted to sulfide, they need to be oxidised through prolonged drying, which isn't occurring due to elevated summer lake levels keeping these areas wet and limiting oxidation. Restoration of a hydraulic gradient that facilitates the transport of sulfur species into the lake at the optimum time would benefit future microbialite formation. The groundwater level verses surface water level regime described above are likely to encourage this to occur.

As a final note in terms of indicators of a system actively forming microbialite the presence of an annual dip in lake water sulfate concentrations during the microbialite formation period is an important criterion at other sites and would likely also be the case here if the pre-modification hydrology was restored. The alkalinity verses pH (pH greater than pK2 in an alkalinity titration) criterion is also important. These simple indicators could be used to indicate success once the lakes hydrology has been altered to better reflect the conditions descried above. If the City of Rockingham desires to recover the health of this system we recommend the following work is undertaken:

1. A study assessing options to reengineer the stormwater system to achieve lake water and solute balances by reducing (or diverting) stormwater inflows to return the lake to more of a pre-1968 water level and water quality regime. This would involve the seasonal diversion of significant amounts of stormwater around Lake Richmond and the outlet level being controlled to restore the historic seasonal lake level variation (of approximately 1.5-2m). The outlet gate would need to be sequentially lowered to achieve the desired level reduction, mimicking the timing and magnitude of historic water level fluctuations. Historically water level fluctuations would have been a function of loss through evaporation and groundwater exchange. It should be noted that increasing the lake level will also increase the level of water in the drains and local groundwater levels. Any study would need to address any impacts this may have on the surrounding area including acceptable flooding level in stormwater drains, the time it would take for the system to re-equilibrate and restore relevant hydraulic gradients for sulfur transport in the lake. Hence the precise mAHD of seasonal lake level required is currently unable to be determined and requires further study.

2. Experimentally determine the benefit of increased TDS on the microbial mats, pest algae and charophytes.

3. Testing of the viability of current mats to form structures by experimentally assessing their response to the formation chemistry.

4. Mapping the lakes littoral zone and surround areas for the presence of sulfide sources. The areas immediately downgradient of these sulfide deposits will be most prospective for future structure formation and/or growth following restoration of the hydraulic gradient.

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Appendix 1 - Laboratory Certificates

LABORATORY REPORT

Job Number:	18-10543
Revision:	00
Date:	24 July 2018

ADDRESS: HGE
16 Ritford Place
Carine WA

ATTENTION: Ryan Vogwill

DATE RECEIVED: 13/07/2018

YOUR REFERENCE: HGE

PURCHASE ORDER:

APPROVALS:

Douglas Todd
Laboratory Manager

Sean Sangster
Inorganics Supervisor

REPORT COMMENTS:

This report is issued by Analytical Reference Laboratory (WA) Pty Ltd
Samples are analysed on an as received basis unless otherwise noted.

METHOD REFERENCES:

Methods prefixed with "ARL" are covered under NATA Accreditation Number: 2377
Methods prefixed with "PM" are covered under NATA Accreditation Number: 2561

ARL No. 29/402/403	Metals in Water by AAS/ICPOES/ICPMS
ARL No. 029	Metals in Water by AAS
ARL No. 330	Persulfate Method for Simultaneous Determination of TN & TP
ARL No. 308	Total Phosphorus in Water by Discrete Analyser
ARL No. 305	Chloride in Water by Discrete Analyser
ARL No. 301	Sulfate in Water by Discrete Analyser
ARL No. 309	Filterable Reactive Phosphorus in Water by Discrete Analyser
ARL No. 303	Ammonia in Water by Discrete Analyser
ARL No. 313/319	NOx in Water by Discrete Analyser
ARL No. 311	Nitrite in Water by Discrete Analyser
ARL No. 037	Alkalinity in Water

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LABORATORY REPORT

HGE

ARL Job No: *18-10543* *Revision:* *00* *Date:* 24 July 2018

Metals in Water Sample No: Sample Description: Sample Date:	LOR	UNITS	18-10543-1 RB1-1 5/12/2017	18-10543-2 RB1-2 23/01/2018	18-10543-3 RB1-3 10/04/2018
Aluminium - Dissolved	0.1	mg/L	<0.1	<0.1	<0.1
Calcium - Dissolved	0.1	mg/L	26	25	25
Iron - Dissolved	0.01	mg/L	<0.01	<0.01	<0.01
Potassium - Dissolved	0.1	mg/L	7.6	6.9	7.0
Magnesium - Dissolved	0.1	mg/L	50	50	52
Sodium - Dissolved	0.1	mg/L	87	88	100

Total Nitrogen in Water Sample No: Sample Description: Sample Date:	LOR	UNITS	18-10543-1 RB1-1 5/12/2017	18-10543-2 RB1-2 23/01/2018	18-10543-3 RB1-3 10/04/2018
Total Nitrogen	0.2	mg/L	1.1	0.8	1.7
Total Kjeldahl Nitrogen	0.2	mg/L	1.1	0.8	0.4

Total Phosphorus in Water Sample No: Sample Description: Sample Date:	LOR	UNITS	18-10543-1 RB1-1 5/12/2017	18-10543-2 RB1-2 23/01/2018	18-10543-3 RB1-3 10/04/2018
Total Phosphorus	0.01	mg/L	0.12	0.12	0.12

Ions by Discrete Analyser Sample No: Sample Description: Sample Date:	LOR	UNITS	18-10543-1 RB1-1 5/12/2017	18-10543-2 RB1-2 23/01/2018	18-10543-3 RB1-3 10/04/2018
Chloride	5	mg/L	150	160	170
Sulfate	1	mg/L	55	52	60
Filterable Reactive Phosphorus	0.01	mg/L	<0.01	<0.01	<0.01
Ammonia-N	0.02	mg/L	<0.02	<0.02	0.05
Nitrate-N	0.01	mg/L	0.02	<0.01	1.3
NOx-N	0.01	mg/L	0.02	<0.01	1.3
Nitrite-N	0.01	mg/L	<0.01	<0.01	<0.01

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Telephone: 08 6253 4444 Facsimile: 08 6253 4440 www.arlgroup.com.au

LABORATORY REPORT

HGE

ARL Job No: *18-10543* *Revision:* *00* *Date:* 24 July 2018

Physical Parameters Sample No: Sample Description: Sample Date:	LOR	UNITS	18-10543-1 RB1-1 5/12/2017	18-10543-2 RB1-2 23/01/2018	18-10543-3 RB1-3 10/04/2018
Alkalinity	5	mg$CaCO_3$/L	210	190	210
Bicarbonate	5	mg$CaCO_3$/L	160	150	160
Carbonate	5	mg$CaCO_3$/L	52	41	52

Ionic Balance (Calculated) Sample No: Sample Description: Sample Date:	LOR	UNITS	18-10543-1 RB1-1 5/12/2017	18-10543-2 RB1-2 23/01/2018	18-10543-3 RB1-3 10/04/2018
Ionic Balance (Calculated)		%	3.1	3.6	2.0

Result Definitions

LOR Limit of Reporting [NT] Not Tested [ND] Not Detected at indicated Limit of Reporting

* Denotes test not covered by NATA Accreditation

FOR MICROBIOLOGICAL TESTING - The data in this report may not be representative of a lot, batch or other samples and may not necessarily justify the acceptance or rejection of a lot or batch, a product recall or support legal proceedings. Tests are not routinely performed as duplicates unless specifically requested. Changes occur in the bacterial content of biological samples. Samples should be examined as soon as possible after collection, preferably within 6 hrs and must be stored at 4 degrees Celsius or below. Samples tested after 24 hrs cannot be regarded as satisfactory because of temperature abuse and variations.

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