Stromatolite Provinces of Hamelin Pool, Western Australia

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UNIVERSITY OF MIAMI

STROMATOLITE PROVINCES OF HAMELIN POOL, WESTERN AUSTRALIA

By

Erica Parke Suosaari

A DISSERTATION

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STROMATOLITE PROVINCES OF HAMELIN POOL,
WESTERN AUSTRALIA

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Hamelin Pool, Shark Bay, Western Australia, is home to the most extensive living stromatolite system in the world, providing an analog for Precambrian fossils that dominated the planet for over 80% of Earth’s history. Due to the remote location and restricted access of Hamelin Pool, which is a marine reserve within a World Heritage area, previous geospatial, microstructural and environmental studies in this area are limited in scope. Existing ground truth data comes mainly from the two iconic stromatolite locations located on the western margin (Flagpole Landing and Carbla Point). Additionally, many studies are out of date with current technology or simply inaccessible. As a result, there are significant gaps in knowledge regarding the distribution and morphogenesis of stromatolites throughout Hamelin Pool.

This dissertation research has taken an innovative approach involving intensive in situ observations to characterize and thereby better understand the living stromatolite system lining the shoreline of Hamelin Pool. Contrary to traditional mapping approaches, which classified stromatolites primarily on the basis of surface mat type, we mapped structures based on morphology. Seven
main facies divisions were identified, including: weakly lithified to non-lithified stratiform sheets, lithified discrete microbial buildups, pavements, sediments, beachrock, boulders and breccia. Each facies type was further divided into subfacies. In particular, discrete microbial buildups were classified as individual and merged, elongate, elongate-nested, composite/segmented, sinuous, elongate-clustered, seif and tabular structures.

A high-resolution map was generated showing the distribution of the newly identified facies. The new map is based on the most comprehensive ground truthing survey of Hamelin Pool to date. Mapping of structures revealed a unique distribution of morphologically distinct types of microbial buildups around the margins of the Pool. This result further led to the designation of eight Stromatolite Provinces, each with distinct patterns of stromatolite morphology and unique shelf physiography.

Additionally, high-density depth soundings were collected and used with a new generation of 30 m resolution satellite imagery to create a high-resolution digital elevation model (DEM). The new DEM model reveals previously unknown large-scale complexity within the Hamelin Pool embayment. Regional-scale physiographic features were exposed, facilitating a better understanding of the interaction of microbial buildups and their associated facies with the environment (ie: shelf vs. ramp, headland vs. bight, grade of slope into the basin, the location relative to the Faure Sill, etc.). Finally, coupling the new high-resolution facies map and bathymetry model with three years of environmental
monitoring data assisted in the interpretation of stromatolite growth and distribution.

Recognition of discrete Stromatolite Provinces in Hamelin Pool, each with unique stromatolite morphologies that do not correspond to broad surface mat types, suggests that varying energy regimes, sediment bed loads, and substrates interact to control stromatolite structure at the macro-scale. These observations linking morphology to physiography and environmental conditions in a modern system provide strong evidence that stromatolite morphology can be a powerful and potentially quantitative paleoenvironmental recorder.
DEDICATION

To my mother and my grandmothers.

Sarah Parke. You give more of yourself than anyone I have ever encountered in my lifetime. I am proud to have you as my mother and it is an honor to strive to be as selfless and loving as you are. Thank you for never giving up on me.

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Chapter 1  INTRODUCTION

1.1  Scope of dissertation
Stromatolite assemblages and the geologic formations they construct dominate the fossil record for more than 80% of the Earth’s geologic history (Kalkowsky 1908, Awramik 1992). Distribution and composition of modern stromatolite-building microbial communities, as well as the processes that influence growth are paramount to understanding ancient formations and contemporaneous environmental conditions (Grotzinger and Knoll 1999). Modern stromatolite systems, particularly within marine environments are no longer widely distributed. The most prolific and best-known location of active, modern marine stromatolites is the restricted marine system in Hamelin Pool, Shark Bay, Western Australia.

Hamelin Pool (Fig. 1.1) is a unique embayment with unusual environmental parameters located within the double-bay inlet system of Shark Bay, situated on Western Australia’s coastline about 800km north of Perth. Metahaline water floods through channels in the Faure Sill, a carbonate sand and sea grass bank that largely bars Hamelin Pool from the remainder of Shark Bay. Limited flushing of water through the sill, low rainfall and high evaporation result in hypersaline conditions, restricting many Eukaryotic organisms from thriving, resulting in reduction of grazing animals (Garrett 1970, Walter and Heys 1985), and competition for space (Fischer 1965). This creates a habitat capable of promoting extensive amounts of microbial growth. As such, Shark Bay was inscribed on the World Heritage List in 1991, with the stromatolites of Hamelin Pool having a significant impact on the decision.
The most spectacular heritage values include the diverse and abundant examples of stromatolites, microbial build-ups and unlithified microbial mats extending along the margin of Hamelin Pool for a total length of about 135 km. Additional values specific to Hamelin Pool consist of carbonate deposits and sediments (i.e.: Faure Sill), a hypersaline embayment promoting endemic or restricted sea life, Holocene deposits adjacent to Hamelin Pool (i.e.: Hamelin Coquina), evidence of ooid formation, submarine lithification and micritization. This combination of unique features resulted in Hamelin Pool’s “highly protected” Marine Reserve designation.

Stromatolites are a trace fossil recording the oldest forms of life on Earth and pioneering research has been carried out in Hamelin Pool over the last several decades to investigate one of the only places in the world containing comparable structures to fossils in ancient rocks (Logan et al. 1974, Hoffman 1976, Playford et al. 1976, Bauld, 1984, Golubic 1985, Burne and Moore 1987, Playford 1979, 1980 & 1990, Meischner 1992, Reid et al. 2003, Jahnert and Collins 2011, 2012 & 2013, Playford et al. 2013, Collins and Jahnert 2014 and others). Due to the remote location and extreme level of environmental protection, access to Hamelin Pool has been limited. Recent research regarding growth, distribution and life cycles of microbial deposits has been restricted to only a few studies.

This study is part of an overarching investigation examining the distribution, early diagenesis and petrophysics of Hamelin Pool. The role of this thesis focuses on identifying and defining mapping units, creating bathymetric and facies maps, collecting and evaluating environment parameters and synthesizing the information to capture heterogeneity and regional trends around the margin.
1.1.1 Research Objectives

The objective of this research is to characterize and map the living stromatolite system lining the shoreline of Hamelin Pool, Shark Bay, Western Australia. Results will address several key knowledge gaps regarding microbial-system development and paleoenvironmental interpretations of ancient stromatolites. The approach of this dissertation will include use of remotely sensed imageries, implementation of field studies including extensive ground truthing and in situ sampling, followed by quantitative laboratory analysis. Results from these studies will be used to better understand the biological, geological, and physical heterogeneity of restricted marine microbial carbonate systems.

This study will not only provide new insight and understanding of the largest modern marine microbial carbonate system, but also assist in improved interpretation of ancient formations observed extensively through the geologic record. Hamelin Pool is not only a window to the past, but additionally a good analog for hydrocarbon-rich subsurface localities, as Hamelin Pool is reservoir-scale basin. In addition to assisting interpretation
of ancient formations, a better understanding of the unique modern setting will also yield insight that will improve public awareness/education as well as assist managers and other vested stakeholders in the protection of the Hamelin Pool Marine Reserve. It is critical to gain an understanding of this living microbial carbonate system in Hamelin Pool as the scientific importance of the area and natural significance of the area has been internationally recognized by the United Nations (United Nations Educational, Scientific, and Cultural Organisation, 2005). It was designated in 1991 as a UNESCO World Heritage Area.

1.2 Background
1.2.1 Terminology
The definition of stromatolites has been controversial since the inception of the term. In 1908, in the Harz Mountains of Germany, Ernst Kalkowsky first discovered a series of layered rocks in the fossil record he proposed were of biological origin. Stromaliths, a word having a Greek origin: “stroma” meaning layered and “lithos” meaning stone, defined the “organogenic, laminated calcareous rock structures, the origin of which is clearly related to microscopic life which in itself must not be fossilized” (Krumbein, 1983, p. 499). The word stromatolite has since endured a number of definitions.

In 1976, Awramik et al. broadened the Kalkowsky definition to encompass all microbial deposits, including laminated and unlaminated structures. Semikhatov et al. (1979) circumvented the problem of identifying the biogenic origin of the fossil deposit by offering a descriptive definition for stromatolites indicating that the fossil must only be laminated, but not necessarily organic. Burne and Moore (1987) reverted to the Kalkowsky definition that indicated the biogenecity of the structure, coining the term
“microbialites - organosedimentary deposits that have accreted as a result of a benthic microbial community trapping and binding detrital sediment and/or forming the locus of mineral precipitation.” The broader term microbialite could be subdivided into smaller groups describing the degree of internal fabric lamination: stromatolites exhibit a laminated fabric, thrombolites exhibit a clotted fabric, dendrolites exhibit a dendritic or branching fabric and leiolites have an aphanetic fabric. Therefore, a commonly accepted definition describes stromatolites as laminated organo-sedimentary structures produced by trapping and binding and/or precipitation of mineral matter resulting from the metabolic activities of microorganisms (combined from Awramik et al. 1976, Walter 1976 and Burne and Moore 1987). In 2013, Playford et al. added “relief above substrate” as a critical element to the stromatolite definition. Previous usage of the definition does not require structures to have relief and therefore would also include flat microbial mats.

Although both laminated and unlaminated microbial deposits occur in Hamelin Pool, all structures will be referred to as stromatolites or discrete microbial buildups regardless of their internal structure to maintain consistency with previous studies. Historically, all microbial buildups with relief above the substrate in Hamelin Pool have been identified as stromatolites regardless of internal fabric/lamination, beginning with large scale studies in Hamelin Pool from the 1960’s forward (Loga 1961, Logan and Cebulski 1970, Logan et al. 1974, Read 1974, Hagan and Logan 1974). These studies resulted in a comprehensive AAPG Bulletin, with notable continued research conducted by Baas Becking (Burne and James 1986, Burne and Hunt 1990, Burne and Veitch 1990, Burne and Johnson 2012) and others (Playford 1979, 1980, 1990, Playford and Cockbain 1976, Playford et al. 2013, Reid 2003, Jahnert and Collins 2011, 2012 and 2013, and Collins
and Jahnert 2014). Although many studies have suggested that the internal fabric can be indicated by surface mat type and/or morphology, this study’s observations indicate that the internal fabric is heterogeneous and not predictable by surface mat.

1.2.2 Significance

Stromatolites are the first fossil evidence of microbial life and date back to nearly 3.5 billion years with the oldest known structures located in the Dresser Formation of Western Australia (Walter et al. 1980). Stromatolite reef complexes are built by microbial communities dominated by cyanobacteria and do not have a macroscopic “skeletal” framework. Instead, layers of bacterial mat grow sequentially on top of one another to form a three-dimensional framework cemented and lithified by metabolically induced carbonate precipitation within the active microbial mats, and further strengthened by diagenesis and continued cementation through time (Awramik et al. 1976, Awramik 1984, Burne and Moore 1987), producing distinct microbial buildups that have relief above the seafloor (Playford et al. 2013). As such, stromatolites make up the earliest reefs on Earth and are the first fossil record of macroscopic life; these structures dominated the fossil record for over 80% of Earth history (Awramik 1992, Figure 1.2). Well-preserved ancient stromatolites provide a window into ancient life (Grotzinger and Knoll 1999).

Although stromatolites have prevailed for almost 4000 million years, the highest populations and diversity were between 2800 and 1000 million years before present (Riding 2000). Stromatolite-building cyanobacteria are hypothesized to have modified the reducing atmosphere (<1% oxygen) composed mainly of methane, nitrogen and carbon dioxide, into the present day oxidizing atmosphere (>20% oxygen) (Dutkiewicz et
Figure 1.2: Diagram of stromatolite abundance through time, dominating the rock record for nearly 80% of Earth history (after Awramik 1992). A major decline in diversity and abundance is revealed from 1 Bya to 540 Mya possibly reflecting the evolution of higher animals in the Cambrian explosion.

Precambrian cyanobacteria were the first widespread photosynthetic organisms that expelled oxygen as a waste product. Free oxygen began to saturate the oceans and combine with dissolved ferrous iron causing ferric oxide or the “rusting of the oceans” resulting in the production of banded iron formations (BIFs) (Kopp et al. 2005, Dutkiewicz et al. 2006). Following the conversion of dissolved ferrous ions, the remaining free oxygen began to escape from the oceans and build up in the atmosphere.
Free oxygen accumulating in the atmosphere quickly underwent chemical reactions by causing iron oxidation on land and additional deposition of BIFs in sediments (Anbar et al. 2007). Many researchers believe that increasing levels of free atmospheric oxygen promoted the evolution of organisms and helped trigger the Cambrian Explosion (DesMarais 2000). A major decline in stromatolitic diversity is evident in the fossil record between 1 Bya to 540 Mya during the Phanerozoic reflecting evolution of higher animals and plants that were better competitors than the stromatolite-building cyanobacterial communities (1965, Awramik 1971, Garrett 1970, Monty 1973, Walter and Heys 1985, Andres and Reid 2006). Stromatolites may have been the culprits in their demise if the excess oxygen was responsible for evolution.

Modern day stromatolites were not believed to exist until they were discovered in Hamelin Pool, Shark Bay, Western Australia by Phil Playford in 1954, who identified them as “algal mounds”, built by blue-green algae (now known as cyanobacteria) and Richard Chase later identified them as stromatolites (Playford et al. 2013). In the 1980’s additional marine stromatolites were discovered by Jeff Dravis as small intertidal structures in the Schooner Cays on the margin of Exuma Sound (Dravis 1983) and then shortly afterwards by Bob Dill as massive subtidal structures in the Exuma Cays (Dill et al. 1986). Additionally, multiple stromatolitic assemblages have been discovered throughout the world in freshwater, brackish water, saline and highly alkaline lakes (Parker, et al., 1981, Grey, et al. 1990, Kempe et al. 1991, Defarge et al. 1994, Cohen et al. 1997, Desnues et al. 2008).
1.3 Study Area

1.3.1 Regional Geology of Shark Bay
Shark Bay lies within the Gascoyne sub basin found within the Carnarvon Basin. Faulted and folded Phanerozoic deposits are found over gneiss, schist, and granite Precambrian basement rock (Payne et al. 1987). The Gascoyne sub basin is an elongated N-S uplifted and westward tilted platform containing Devonian, Silurian and minor Carboniferous and Permian deposits (Hocking et al. 1988). Anticlinal folds in Quaternary and older rocks are responsible for the peninsulas and islands in the Shark Bay area. Folding occurred during the late Paleocene and Eocene and presumably into the Quaternary. Additionally, some of the anticlines are associated with reverse faults, localized by older normal faults.

The geological arrangement of the fault and fold systems allowed synclines to evolve into bays whereas the anticlines result in the emergent peninsulas such as the Peron Peninsula (Butcher et al., 1984, Playford et al. 2013) (Fig 1.3).

Hamelin Pool Marine Nature Reserve is situated within the Shark Bay Marine Park in Western Australia between 24°32’ - 26°40’S and 112°54’-114°30’W, approximately 800 km north of Perth. The Marine Park is a double-bay inlet system about 13,000 km² in area with an average depth of 10 meters, comprising Henri Freycinet Harbour and Hamelin Pool (Figure 1.1). The bay is protected from the open marine waters of the Indian Ocean by three main islands: Bernier Island, Dorre Island and Dirk Hartog Island, overlying anticlinal folds, formed 6k years ago when sea level rose.

Nanga Peninsula, the western margin of Hamelin Pool is composed of Pleistocene and Holocene Eolianites that overlay an anticline. Pleistocene Dampier (5e – time of open marine, containing abundant heads of colonial corals and the Carbla Oolite Member) and
Bibra (5e – time of open marine, containing beach ridge deposits with tidal flat and coralline algae deposits) Limestones are exposed in a few localities along the coast (Butcher et al. 1984), but is dominated by Peron Sandstone (red, poorly bedded, partly calcareous sandstone) covered by superficial red sands. The northern part of the peninsula is covered by transverse and parabolic dunes of Denham Sand. The Denham sand is unconsolidated sediment comprised of quartz and limesand grains of medium size, red in color due to a surfical cover of anhydrous iron oxide (Playford et al. 2013). The southern part of the Nanga Peninsula is covered by parabolic and undulating dunes of Nilemah Sand. The Nilemah Sand is composed of unconsolidated red quartz sand created by leaching of the Peron Sandstone. To the south of Hamelin Pool, the Nilemah Sands are a source of minerals containing: ilmenite, zircon, rutile and leucoxene (Playford et al. 2013). Birrida gypsum deposits are well formed on the Nanga Peninsula in low-lying interdune areas and can range from one meter in thickness to up to nine meters in thickness (Playford et al. 2013). These deposits are derived from seawater aerosol carried inland by winds (Playford et al. 2013).

The eastern margin of Hamelin Pool is composed mainly of calcretized Cretaceous chalk, greenish-white calcareous mudstone with flint nodules known as the Toolonga Calciulutite (more than 50% clay/silt-size transported carbonate grains – Grabau classification (1904). The Toolonga Calciulutite is the oldest rock unit outcrop and is exposed discontinuously along the easten margin between Flagpole Landing, to near Yaringa Homestead (Playford et al. 2013). In some areas Tertiary sandstone from the Paleogene and Neogene can also be observed as a green to grey calcarenite. Headlands are often rich with block fields of resistant Lamont Sandstone (Tertiary) which are
interpreted as lag deposits, having overlain the less resistant Cretaceous calcilutites that were eroded (example: Pt. Sweeney Mia) (van de Graaf et al. 1983).

Figure 1.3: Diagram A. displays the two main embayments of the Shark Bay Marine Park - Henri Freycinet Harbour and Hamelin Pool. Diagram B is a cross section spanning the Pleistocene Dirk Hartog Island on the west, Freycinet Reach which feeds Henri Freycinet Harbour, Plio-Pleistocene Peron Peninsula, Disappointment Reach, which feeds Hamelin Pool and L’Haridon Bight all overlying Tertiary Calcarenite, and the eastern boundary of Shark Bay which is dominantly Cretaceous Calcilutite. Diagram C depicts the falling sea level post Pleistocene (5e) interval where the carbonate materials were blown into dunes onto the underlying anticline (www.sharkbay.org).

Surrounding the Pool is a series of Holocene beach ridges composed of loose coquina shells *Fragum erugatum*, that are progressively cemented by percolating rain water (Playford et al. 2013). Nott (2011) counted as many as 26 beach ridges in southern Nilemah Embayment, linking them to successive tropical cyclones. This belt of coquina ridges forming the Hamelin Coquina are up to one kilometer wide and seven meters thick, nearly 11 meters at the highest elevation near Flagpole Landing, with the oldest dates recorded at 5316 ± 42 years BP (overlying a Birrida on the Nanga Peninsula) (Playford...
et al. 2013). The Hamelin Coquina is significant to petroleum research as it is regarded as a model for ancient coquinas that are prolific hydrocarbon reservoirs (Davies and Sherwin 1997).

1.3.2 Environmental Setting
In the last several thousand years, Hamelin Pool, the most eastern embayment in the Shark Bay system and the focus of this study, evolved into an environment extreme enough to promote stromatolite-building microbial communities. Hypersalinity, temperature, tides/exposure indices and energy regime in Hamelin Pool all influence the profuse development of stromatolites around the margin of Hamelin Pool. Seven-thousand years ago Hamelin Pool was a basin without a waterway connection to the Indian Ocean. About 6,000 years ago, as sea level continued to rise, it flooded the basin with waters of normal marine salinity (~35 ppt). About four-thousand years ago, sea level stood two meters higher than present and sea grass banks facilitated the growth and accretion of the Faure Sill at the mouth of the embayment. The sill restricted water exchange and due to arid climate, high evaporation and low precipitation, Hamelin Pool salinities rose to 1.5 times normal marine salinity (~52 ppt) (Logan 1961, Logan and Cebulski 1970, Logan et al. 1974 and Playford and Cockbain 1976). In the last 2,000 years, a relative sea level fall has been observed. Uplift has been measured on Faure Island of over 14.5 m in the last 3500 years (Playford et al. 2013), which could be an sign for local uplift in Hamelin Pool that would account for a relative drop in sea level.

Mitrovica (from supplemental material O’Leary et al. 2013) modeled a relative sea level fall in the Shark Bay area as a result of ocean siphoning. Collapse of glacial forebulges present during the last ice age resulted in modern isostatic adjustments that continued
long after all the meltwater from the glaciers was added back to the oceans. Peripheral areas surrounding former glaciers are still subsiding even though the global seawater volume entered stasis. This resulted in siphoning water toward the deepening areas near the poles. In addition, meltwater loading, filling in the areas of subsidence, also causes the areas in the peripherals of continents to flex downward. The combined affects of continental levering, ocean siphoning and meltwater loading are enough to cause a relative sea level drop of $> 0.5$ m (Mitrovica and Milne 2002, Kopp et al. 2009, O’Leary et al. 2013, Mitrovica pers. comm. 2014). Relative sea level is estimated to have been lowered about 2.5 meters from the Holocene high (maximum flooding 6800 U/Th years BP) (Logan et al. 1974, Jahnert and Collins 2011, 2012) or to present height (Figure 1.4). Additional accumulation of sediments on the Faure Sill further restricted flow and ocean recharge into Hamelin Pool resulting in increasing salinities that are currently, on average, nearly double normal marine salinity ($>70\%$).

Shark Bay seawater has a salinity gradient trending from normal marine salinity ($\sim35\%$) near the connection with the Indian Ocean to metahaline and hypersaline waters moving south and east. Hamelin Pool is home to the highest recorded salinities and is the only area within Shark Bay accommodating stromatolite growth. Extreme environmental conditions are suspected to contribute, if not control, microbial deposit accretion (Playford 1990).

The embayment area Hamelin Pool comprises south of the Faure Sill is just over 1200 sq. km with a maximum depth of 11 meters. As a result of the substantial size of the basin and minimal depth, the range of water temperature is large, closely mirroring air temperature. Tidal range averages around one meter daily, but ranges nearly two meters.
over the course of the year. Additionally, the basin’s only source of recharge is by the narrow channels through the Faure Sill resulting in long residence times (Davies 1970). Evaporation rates are nearly ten times precipitation rates (Playford and Cockbain 1976), resulting in average salinities greater than 68‰. Jahnert and Collins (2011) reported pH levels to range from 7.5-8.6.

Figure 1.4: Modified from O’Leary et al. (2013) displaying the sea level curve for Western Australia’s coastline over the last 40,000 years.

1.3.3 Hamelin Pool Stromatolites and Associated Facies

1.3.3.1 Stromatolites of Hamelin Pool
In July of 1954, Phil Playford first discovered the stromatolites and identified them as “algal mounds” while working for West Australian Petroleum Pty. Ltd. (WAPET) in the Shark Bay area. In November 1954, while working together in Hamelin Pool, Playford showed the structures to Dick Chase. In 1955, Chase was working on Proterozoic strata
of the Moora district with Brian Logan where ancient stromatolites had previously been discovered and identified. At this time, Chase made the connection between the modern algal mounds Playford had shown him in Hamelin Pool with the ancient structures and applied the term stromatolites to the structures (Playford et al. 2013). Later that year, Playford first sampled a stromatolite and sent it to the University of Western Australia (UWA) for analysis. Cyanobacteria (formerly known as “blue-green algae”), were identified in the structures. The discovery of stromatolites in Hamelin Pool was significant. Until that time, stromatolites were thought to be extinct.

Logan et al. (1974) identified three major microbial mat types in Hamelin Pool capable of building structures: pustular, smooth and colloform. Growth of the stromatolites was attributed to the microbial mats living on the surface of the structure, which trap and bind sediments and also undergo a variety of mechanical and diagenetic processes. In addition to structure-building mat types, non-structure forming microbial mats were also identified including: film, tufted, gelatinous and blister mat. Zonation of mat types was attributed to elevation and related to desiccation, tides, drainage and the position of the ground water table (Logan et al. 1974). All mats with the exception of film mat, which only forms a pelletoid rind, form in stratiform sheets. Smooth-mat, pustular-mat and colloform-mat can form ridge-rill structures, discrete columnar structures, calyx structures, ring and crescent structures and irregular masses, discs and columns. Additionally, each of the microbial mats were thought to generate a distinct fabric type with the exception of film mat (Table 1.1). In 1985, Golubic updated the mat type classification, stating that blister mat was an attribute any mat could display under the correct environmental conditions. Pincushion-mat and reticulate mat were added to the Logan et al. (1974) schema.
Expanding upon the structure-building microbial mats identified by Logan, Playford (1990, revised model 2013, Fig 1.5) developed a schematic cartoon depicting stromatolite growth along the margins of Hamelin Pool, depicting water depth as the primary control of mat type and stromatolite fabric. In Playford’s (1990) model, pustular-mat stromatolites are found completely in the intertidal zone and have an unlaminated fabric, similar to a thrombolite (Aitken 1967), with very coarse fenestrae and an irregular surface. The microbial mat assemblage responsible for creation of pustular-mat stromatolites is dominated by the coccoid cyanobacterium *Entophysalis major*. Smooth-mat stromatolites are found in the intertidal and upper subtidal and are characterized by laminated fabric with fine laminoid fenestrae. *Schizothrix helva* is reported as the dominant microbe responsible for formation of smooth-mat stromatolites. Playford’s Colloform-mat stromatolites are found wholly in the subtidal zone. Colloform-mat stromatolites are weakly laminated with coarse fenestrae and are commonly associated

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**Table 1.1:** Algal-mat types of Hamelin Pool, location in the tidal zone and type of fabric created (Logan et al. 1974).

<table>
<thead>
<tr>
<th>Mat type</th>
<th>Tidal Zone</th>
<th>Fabric type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Film</td>
<td>Supratidal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Upper Intertidal</td>
<td></td>
</tr>
<tr>
<td>Blister</td>
<td>Supratidal</td>
<td>Disrupted fenestral</td>
</tr>
<tr>
<td></td>
<td>Upper Intertidal</td>
<td></td>
</tr>
<tr>
<td>Tufted</td>
<td>Middle Intertidal</td>
<td>Scallop</td>
</tr>
<tr>
<td></td>
<td>Upper Intertidal</td>
<td></td>
</tr>
<tr>
<td>Pustular</td>
<td>Middle Intertidal</td>
<td>Irregular fenestral, grain-</td>
</tr>
<tr>
<td></td>
<td>Upper Intertidal</td>
<td>framework fenestral</td>
</tr>
<tr>
<td>Smooth</td>
<td>Lower Intertidal</td>
<td>Fine laminoid fenestral</td>
</tr>
<tr>
<td>Colloform</td>
<td>Subtidal</td>
<td>Coarse laminoid fenestral</td>
</tr>
<tr>
<td>Gelatinous</td>
<td>Lower Intertidal</td>
<td>Ribbon</td>
</tr>
<tr>
<td></td>
<td>Middle Intertidal</td>
<td></td>
</tr>
</tbody>
</table>
with *Acetabularia* sp. The microbes responsible for building colloform-mats are attributed to many different communities dominated by filamentous cyanobacteria such as *Microcoleus tennerimus, Schizothrix helva, Oscillatoria latet-virens, Oscillatoria foreavi, Johannesbaptista pellucida* and diatoms (Logan et al. 1974, Golubic 1985, Playford 1990, Playford et. al 2013). In Playford’s 2013 model (Fig. 1.5) an additional structure type termed “composite stromatolites” was added to the subtidal zone but a specific microbial community was not assigned to the structure (Playford et al. 2013). If stromatolite type, surface mat type (microbial community) and internal fabric are all intrinsically linked and related to water depth, then the same shoreward to seaward trends would be expected all along the Hamelin Pool margin.

Jahnert and Collins (2011 & 2012) modified the Playford model by removing the word “mat” from the name designation. Structures were identified on location in the tidal zone, surface mat, morphology and internal fabric. The different structure types included pustular, smooth, and colloform but also included two new designations: cerebroid and microbial pavement (Fig 1.6). Cerebroid structures, identified as cryptomicrobial, forming in domes, ridges or prismatic clubs, formed wholly in the subtidal and possess non-laminated structures that often display cerebrum morphology. Dominated by various coccoid cyanobacteria *Coccus* sp. (Jahnert and Collins 2011, 2012), the cerebroid structure type was negated by Burne and Johnson (2012) as a misidentification of a colloform-mat stromatolite morphotype. It is also possible that the Jahnert and Collins (2011, 2012) cerebroid structures and Playford et al. (2013) composite stromatolite structures are synonymous.
Figure 1.5: Traditional model for stromatolite growth updated from the 1990 version to include a new structure type solely in the subtidal typed composite. In this model mat, structure, and fabric type are determined by depth (Playford et al. 2013).

The new Jahnert and Collins (2012) schematic (Fig. 1.6), based on multiple transects surveyed, depicted distribution, morphology and internal fabric as a consequence of location within the tidal zone.

Figure 1.6: Microbial fabrics and variation of discrete head morphologies of Hamelin Pool structures. Pustular structures have a clotted fabric and can be termed thrombolites sensu Aitken (1967). Smooth and colloform structures exhibit a laminated fabric and are therefore termed stromatolites. Cerebroid and pavement have a cryptomicrobial fabric and are therefore neither stromatolite nor thrombolite. All types boast a variety of distinct and unique morphologies. Schematic highlights distribution, morphologies according to tidal zones and internal fabrics (Jahnert and Collins 2012).
All stromatolite fabrics are not homogenous. Internal fabric variations are caused as a result of falling sea level, shifting the tidal zone and changing the surface mats through time (Jahnert and Collins 2012).

1.3.3.2 Pavements
In addition to stromatolites, Hamelin Pool also features extensive microbial pavements throughout the subtidal that were first described by Jahnert and Collins (2011). Microbial pavement is described as either tabular or blocky. Tabular pavement is a flat substrate “being lithified as bioclastic grainstone that contains Fragum bivalves, serpulids, micro-gastropods, foraminifera and algae” (Jahnert and Collins 2011). Blocky pavement is similar in composition to tabular pavement but is disrupted or reworked producing disconnected blocks. Microbial pavement is found in the subtidal range between 2m and 6m in depth and is estimated to cover over 227 km$^2$ of the Hamelin Pool basin (Jahnert and Collins 2011 and 2012, Collins and Jahnert 2014).

1.3.3.3 Sediments
Studies on the sediments of Shark Bay were undertaken by Logan and Cebulski (1970) and Read (1974). Sediment constituents, mainly of biogenic origin, included: foraminifera tests, mollusk shells, coralline algae, bryozoans, serpulids, echinoids, sponges, codiacean algae and crustaceans. Although common to the area, previously documented components are not specific to Hamelin Pool. Due to the extreme environmental conditions in Hamelin Pool, the skeletal component of sediments is much less diverse than in the rest of Shark Bay. Hamelin Pool is a mud-poor system dominated by grainstone, floatstone and rudstone. The components that make up the sediment in Hamelin Pool were investigated and include: detrital quartz, eroded from the Peron
Sandstone (Davies 1970), peloids, irregular micritic grains, foraminifera tests, mollusk shells, ooids, bivalve shells, specifically *Fragum erugatum* (Logan 1970b, Playford et al. 2013), serpulid worm tubes, and *Acetabularia* sp. stalks. Many of these components are covered in a superficial carbonate coating (Giusfredi 2014) (Fig. 1.7).

Figure 1.7: Components of Hamelin Pool in thin section. A) quartz B) coated quartz C) peloids D) coated peloid E) irregular micritic grains F) foraminifera tests G) mollusk shells H) grapestone I) ooid J) Fragum erugatum K) serpulid tubes J) coralline algae (Giusfredi 2014).

1.3.4 Existing Hamelin Pool Maps

At the onset of this research, existing detailed maps of Hamelin Pool were limited or relatively inaccessible. Trying to locate bathymetric data from Landgate Australia resulted in no high-resolution depth surveys. There were “no navigational requirements” (personal communication, Royal Australian Navy, November 2010) in the Hamelin area.
One bathymetry map was generated to test a new approach using Landsat satellite imagery and spectral signatures (Bierwirth et al. 1993). Hamelin Pool was reportedly chosen for the study because of its shallow, clear waters, availability of detailed bathymetry data acquired from a closely spaced hydrographic survey (Australian Survey Office), and various bottom/facies types that had been described by Logan et al. (1974) (Bierwirth et al. 1993). Additionally, facies maps generated by Burne and Veitch (1990) became available to the science community in 2012 (Fig. 1.8a).

The Burne and Veitch (1990) 1:100,000 map included isolines based on previously recorded bathymetric survey and also classified the sea-floor (Fig. 1.8a). Classifications included: stromatolites, supratidal flats, sandy intertidal flats, slope deposits, grainstone and crusts, basin sediments, subtidal channel deposits, intertidal terrigenous sands, intertidal carbonate sands, organic ooze, carbonate ooze, ooid sands and land. An
expansive area of organic ooze was defined in the southwest area of the Nilemah Embayment, but iconic areas of stromatolite growth such as Carbla Point went unidentified.

Jahnert and Collins (2011) published initial results from data collected between 2008 and 2011 using remote sensing, underwater video, swath mapping and ground truthing. The publication documented large expanses of previously unrecorded subtidal deposits, and presented preliminary georeferenced maps recording the extent and variation of stromatolites. This divided Hamelin Pool into seven distinct mapping units: the Holocene limit, supratidal breccia & films, intertidal mats & heads, subtidal buildups, microbial pavement, bivalve shells & mud and seagrass carbonate bank (Fig. 1.8b).

Included with this publication were two high-resolution areas mapped with ground-truthing and aerial photography from Carbla Point and Flagpole Landing. Facies delineations of detailed maps were determined by using tonal variations from collected imagery.

In a subsequent publication, Jahnert and Collins (2012) published a highly detailed “sedimentary and organo-substrate” map based on coastal and marine ground truthing combined with samples and remotely sensed data (Fig. 1.8c). Mapping units were based upon “external organo-facies, composition and morphologies” (Jahnert and Collins 2012). Ground truthing was extremely limited, and focused primarily on the east side of the Pool, near Carbla Point and Flagpole. Limited ground truth data were available from the central basin (Jahnert and Collins 2012).
The Jahnert and Collins (2012) publication and map were released during the 2012 field season of the present study, with mapping boundaries based upon limited transects in the eastern section of the Pool and extrapolated, based on tonal variations visible in the aerial orthophotos. Field checking the facies boundaries of the Jahnert and Collins (2012) map by the team of this study, demonstrated many inaccuracies and indicated that the maps failed to capture the heterogeneity of microbial mats signifying mapping units, or type, shape and extent of microbial deposits in Hamelin Pool. Therefore these maps are deemed invalid.

1.4 Outline of Research & Objectives

1.4.1 Approach and Methods
Shark Bay Marine Park is a Protected World Heritage Area, and Hamelin Pool is a Marine Nature Reserve within that area. Hamelin Pool is the only Marine Nature Reserve in Western Australia providing the highest level of protection. The remote location and high level of protection results in many challenges regarding field work.

Research was conducted in Hamelin Pool for a total of six months over the course of three years: March and April, 2012; March and April, 2013; and March and April 2015. Additionally, two mini field campaigns were conducted in November of 2013 and 2014. Given the size of the Hamelin Pool basin, the goal was capture the heterogeneity at the megascale (identifying regional trends in mapping), macroscale (identifying and describing individual microbial buildups), mesoscale (identifying differences in microbial fabrics) and microscale (identifying microbial communities under the microscope and at a molecular level). Examination at multiple nested scales of this modern marine microbial system in the location of the best-known, active and most diverse structures
will result in the largest, most comprehensive study to date. Although research has been undertaken for decades, several knowledge gaps including basic knowledge of stromatolite locations, physiography of the basin, continuous environmental conditions, and composition of stromatolite building microbial communities, still exist. As part of a larger campaign, my research has focused on meeting the following objectives:

1. Identification of stromatolite morphologies, associated facies and landscape patterns (Chapter 2);
2. Integration of ground-truth data, photographic and video observations, bathymetry and structure identification to produce two maps, structure and bathymetric, combined with an extensive GIS database (Chapter 3);
3. Compilation and evaluation of environmental parameters including salinity, temperature, pressure and currents (Chapter 4);
4. Characterization and quantification of facies associations (Chapter 5);
5. Synthesization and integration of collected data to develop a better regional understanding of Hamelin Pool.

To meet the research objectives of this dissertation, the following methods and approaches were followed:

1. Extensive field campaigns: Three field programs (2012, 2013, 2014) were conducted over a three-year period to “ground-truth” remotely-sensed data, conduct detailed mapping of stromatolites and associated facies, deploy and collect environmental loggers, collect samples, gather sonar data and undertake real time kinematic (RTK) surveying. (Fig 1.9).
2. Integration of remotely sensed data: High-resolution satellite images and GIS tools were used to map and quantify lithofacies and create a bathymetric model. Geobodies, such as sheets, discrete microbial builds, sediments and coquina ridges, were extracted from the images and analyzed statistically using GIS tools. Oblique imagery captured by a PhD student Gumpei Izuno (2008) were generously provided to the study to better understand and quantify margin deposits. Georeferenced imagery included over 30,000 shoreline and underwater photos, underwater mosaics and high-resolution fluid-lensed imagery collected with a quadcopter. All imageries were used to help identify, describe and classify features. Extensive single-beam sonar data were collected in 2013 in east/west lines across the Pool connected with one north/south tie line. These data were integrated with satellite imagery to derive a bathymetry model.

1.6 Outline of Dissertation

Chapter 1: Introduction and background: This chapter focuses on the background information regarding stromatolites and Hamelin Pool. An overview of the approach, methods and goals of the dissertation is provided.

Chapter 2: Identification of microbial structures and associated facies: Previous maps of Hamelin Pool used the surface-mat type to classify the structures. This chapter identifies and classifies the various types of microbial buildup-structure morphologies and associated facies. All facies units used to map Hamelin Pool are described in this chapter.
Chapter 3: GIS database and mapping: Integration of facies elements described in Chapter 2 with remotely sensed data and ground-truthed data are presented in this chapter. Additionally, a bathymetry model derived from single-beam acoustics and satellite imagery is presented. In conjunction with this dissertation, a Hamelin Pool geodatabase was generated.

Chapter 4: Environmental pressures: Past research has emphasized the evolution of grazers resulting in the decline of stromatolite abundance and diversity in the rock record (Awramik 1971, Garrett 1970, Monty 1973, Walter and Heys 1985, Andres and Reid 2006). This chapter focuses on the extreme environmental parameters such as: fluctuating temperature, salinity, water-current, and subaerial exposure. These forces not only exclude a large grazing population, but also prevent higher life forms that would potentially outcompete the stromatolite-building cyanobacteria (following Fischer 1965).

Chapter 5: Stromatolite Provinces of Hamelin Pool: Comprehensive, regional investigation of Hamelin Pool combined with rigorous ground trutching of previously studied areas has uncovered an unanticipated amount of heterogeneity. Mat types, stromatolite structures and associated facies display undocumented diversity. This chapter explores the unique geographic distribution of morphologically distinct buildups and the associated facies, dividing Hamelin Pool into eight discrete provinces.

Chapter 6: Epilogue: The final chapter summarizes the results of the investigations undertaken in this research campaign relating to microbial structures and facies distribution and also, provides a roadmap for future investigation.
Figure 1.9: Ground-truth map resulting from three 2-month Hamelin Pool field campaigns undertaken 2012, 2013 and 2014. Comprehensive field-studies investigated the basin, sublittoral platform and tidal zone across Hamelin Pool, strengthening understanding of stromatolite distribution as previous research has principally focused heavily only on the eastern and southeastern margin. In addition to ground truth investigation, sample collection included 60 microbial mat samples, 40 pavement, 45 stromatolite heads, 150 sediment and 50 water samples. Single-beam sonar was obtained across the pool as well as side-scan sonar along transects.
Chapter 2 IDENTIFICATION OF FACIES TYPES

2.1 Overview

The stromatolites of Hamelin Pool are unique because they are one of only two known modern marine microbial systems. Hamelin Pool is the most extensive living stromatolite assemblage in the world and is the only restricted-marine system. Modern stromatolites offer vast scientific applications, including but not limited to, astrobiological, paleo-environmental and sub-surface petroleum reservoir interpretations.

Microbial carbonate sequences first appeared in Hamelin Pool between three thousand and four thousand years ago, when the pool reached hypersaline levels (Logan et al. 1974, Chivas et al. 1990). To date, stromatolite abundance and location was relatively unknown, except that these assemblages dominate nearly the entire 135 km of Hamelin Pool shorelines (Jahnert and Collins 2012, Collins and Jahnert 2014). Identification and location of structures around the margin is critical in understanding not only the modern system, but also ancient analogs. Previous studies have provided a strong baseline and road map for current and future studies.

Phillip Playford first discovered the stromatolites in Hamelin Pool in 1954, and the first major studies were undertaken by Logan (1961) and Logan et al. (1974). Original groundwork identified and described microbial mats present around the margins of Hamelin Pool, including the position of various mat types within the tidal zone. Microbial-mat biological communities were defined, and internal fabrics, created by continued accretion of various microbial mats, were described and attributed to specific mats.
Of the main types of microbial mats identified by Logan et al. (1974): film, blister, tufted, pustular, smooth, colloform and gelatinous (Table 1.1), only three were considered responsible for building structures: pustular-mat, smooth-mat and colloform-mat (Table 2.1).

- **Pustular-mat**, also termed cinder zone mat (Kendall and Skipwith 1968), convolute mat (Davies 1970) and mamillate mat (Golubic 1985, Burne and Johnson 2012) has a warty morphology of light-brown to dark-brown pustules with translucent centers. Pustular-mat is the most common microbial community in the intertidal zone. It occurs along wave-exposed coasts, as well as in protected environments where it is able to stabilize the underlying sediments forming extensive horizontal, flat, sheet mats.

According to Logan et al. (1974), pustular-mat is responsible for generating a poorly laminated to massive pellet packstone/grainstone fabric with irregular fenestrae. Penecontemporaneous lithification preserves fenestrae in the loose grain supported framework (Logan et al. 1974).

Pustular-mat structures included stratiform sheets, ring and crescent, ridge-rill, discrete elliptical to circular columns and irregular masses and discoid structures (Logan et al. 1974), elongate, ellipsoid and hemispherical morphologies (Jahnert and Collins 2011, 2012).

- **Smooth-mat** is identifiable by a characteristic flat, smooth, opaque, leathery surface. Smooth-mat can display beige (Jahnert and Collins 2011), beige-pink (Golubic 1985), or pale yellowish grey to brown (Logan et al. 1974) colors.
Found throughout the intertidal zone in various environments, smooth-mat generally dominates the lower intertidal and upper subtidal zones. Various locations can include such as high energy as wave-agitated headlands, but also low-energy environments such as protected tidal flats. This mat occurs as flat, stratiform sheets often forming on top of and stabilizing loose sediment or as a surface layer covering other stromatolites. Sub-spherical microbial buildups have also been attributed to accretion and subsequent lithification of smooth-mat (Logan et al. 1974, Golubic 1985, Allen et al. 2009, Jahnert and Collins 2011, 2012). Smooth-mats generally form continuous sheets except where interrupted by scouring action, or are ripped up as a result of underlying sediment mobility in high-energy environments (Logan et al. 1974).

Layers within the mat are composed of bound fine-grained sediment trapped by filaments, which combine with residual organic material. Smooth-mat internal fabric is generally dense, composed of sub-horizontal 0.5 to 5mm thick softly undulating laminae (Jahnert and Collins 2011). Fine laminoid fenestrae form at interlaminar boundaries initiated by oxidation of mat but maintained by syndepositional, incipient cements or lithification (Logan et al. 1974).

Table 2.1: Hamelin Pool structure-forming mat types are governed by location, biological composition, and fabric type. Information compiled (Logan et al. 1974, Golubic 1985, John 1993, Jahnert and Collins 2011, 2012, Burne and Johnson 2012 and Playford et al. 2013). The three main mat types attributed to stromatolite building: pustular, smooth and colloform that occur in distinct ranges within the tidal zone, possessing varying biological communities and corresponding with different internal fabrics, but various stromatolite morphologies transverse mat types.

<table>
<thead>
<tr>
<th>MAT TYPE</th>
<th>LOCATION</th>
<th>BIOLOGY</th>
<th>FABRIC</th>
<th>STRUCTURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pustular</td>
<td>Intertidal: wave exposed coasts and protected areas</td>
<td>Cocoid cyanobacteria: Entophysalis sp.</td>
<td>Poorly laminated to unlaminated with irregular fenestrae</td>
<td>Stratiform sheets, Ring and crescent, Ridge-rill, Discrete elliptical columns, Circular columns, Irregular masses, Discoid structures, Elongate, Ellipsoid, Hemispherical</td>
</tr>
<tr>
<td>Smooth</td>
<td>Lower intertidal to upper subtidal: wave exposed coasts and protected areas</td>
<td>Filamentous cyanobacteria: Schizothrix sp. and Microcoleus sp.</td>
<td>Sub-horizontal undulating laminae with fine laminoid fenestrae</td>
<td>Stratiform sheets, Ridge-rill, Discrete elliptical columns, Circular columns, Detached cryptalgal lumps, Linked columns, Domical, Club shaped, Conical</td>
</tr>
<tr>
<td>Colloform</td>
<td>Subtidal</td>
<td>Filamentous cyanobacteria: Microcoleus tenerimus and Symploca laete-viridis (shallow subtidal waters) Filamentous cyanobacteria: Schizothrix helva, Oscillatoria latet-virens, Oscillatoria foreavi and Johannesbaptista pellucida, and cocoid cyanobacteria Entophysalis sp., Chroococcus sp. and Gloeothecae sp. cyanobacteria in combination with diatoms (deeper subtidal waters)</td>
<td>Coarse, wavy laminoid structure</td>
<td>Individual structures to complex reefs, Elliptical columns, Circular columns, Compound masses, Branched, Prismatic elongate, Domical linked, Ellipsoid, Calyx, Compound Bladed</td>
</tr>
</tbody>
</table>

- Colloform-mat identification relies exclusively upon the physical characteristics of the mat: 1-2mm thick, pale yellowish-brown to gray mat with surface morphology possessing “hollow, contiguous convexities 1-3 cm in diameter” (Logan et al. 1974). Colloform-mats, as first described by Logan et al. (1974), are specifically described as “physically variable and biologically heterogeneous”. Colloform-mat and consequent colloform stromatolites make up the deepest of the microbial structures, covering subtidal structures and pavements.
Colloform-mats form 1-5 cm globular build-ups of fine-grained peloids and skeletal fragments that alternate with layers of micrite. This results in a coarse, wavy, laminoid structure, loaded with fine carbonate particles, and fenestrae that are often filled with sediment (Logan et al. 1974, Golubic 1985, Jahnert & Collins 2012). Laminations are composed of cryptocrystalline aragonite and mimic the domed undulations of the surface mat. Lamination is believed to be broken by *Acetabularia* sp. holdfasts. There are open fenestrae, but many are also infilled forming coarse laminoid fenestral fabrics: growth expansion of domal mats; binding of sediments, precipitation of aragonite and oxidation of organics (Logan et al. 1974).

Subtidal colloform-mat stromatolite morphologies are variable ranging from individual structures to complex reefs (Logan et al. 1974, Golubic 1985). Discrete structures often exhibit “elliptical to circular columns and compound masses” in places displaying a branched morphology (Logan et al. 1974). The morphologies include: prismatic-elongate, domical linked, ellipsoid, calyx and compound bladed structures (Jahnert and Collins 2011, 2012) Colloform structures are reported to decrease in height as they reach the lower depth limits (Burne and Johnson 2012).

The definitive morphologies of Logan et al. (1974) were revised by Jahnert and Collins (2011). Surface mat type remained their basis of stromatolite classification, but the word “mat” was eliminated. Two additional classifications, cerebroid and microbial pavement, both based upon morphology and lacking described surface mats, were included in the new classification. Cerebroid structures display ridges, spherical morphology, domical
morphology and compound bladed structures. Microbial pavement displays irregular, blocky, shelly, and tabular morphologies. Both newly described structures are located in the subtidal zone (Jahnert and Collins 2011, 2012).

The fundamental problems with classifying stromatolites by surface mat are:

1. Although the internal fabric is a record of a previous surface microbial mat, the current surface microbial mat may not be an indicator of the entire stromatolite fabric, as the structure may be a result of multiple types of microbial mats through time.

2. The internal fabric of a stromatolite is not known unless the structure is split open and physically observed.

3. Different surface mats can be found growing on top of and/or forming similar morphologies.

In addition to the problem of correlating and classifying microbial mats and internal fabrics with stromatolite morphologies, the majority of stromatolite data reported since the inception of research in Hamelin Pool are generally restricted to the east and southeast margins of Hamelin Pool (Logan et al. 1974, Hoffman 1976, Playford et al. 1976, Bauld, 1984, Golubic 1985, Burne and Moore 1987, Playford 1979, 1980 & 1990, Meischner 1992, Reid et al. 2003, Jahnert and Collins 2011, 2012 & 2013, Playford et al. 2013, Collins and Jahnert 2014 and others). Further investigation was warranted for exploration along the margins to determine the extent of microbial buildups. It is possible that not all stromatolites around the margin of the pool are similar to the structures already described.
Stromatolites and associated microbial buildups may be the focal point of research in Hamelin Pool, but as the structures form only along the margin of the 135 km shoreline, it is clear that additional, associated facies constitute a sizeable area of the 1300 sq. km in the embayment. Sedimentological studies in Shark Bay completed by Logan and Cebulski (1970) and by Read (1974) were not specific to Hamelin Pool, and sediment types were identified, but not described. Jahnert and Collins (2012) identified sediment types occurring in Hamelin Pool and were included within individual mapping units listing the sediment classification types as follows: red quartz sand; quartz and gypsum sand eroded from the Peron Sandstone (Pleistocene); coquina and quartz sand; bioclastic sand; quartz bioclastic sand; mud; peloids; ooids; bioclastic, shelly, oolitic sand; bioclastic, oolitic, peloidal and quartz sand; bivalve coquina; and microbial organic mud.

Giusfredi (2014) identified and described sediment components found within Hamelin Pool based on numerous sediment samples. The mud-poor sedimentological regime is comprised mainly of the following: detrital quartz, peloids, irregular micritic grains, foraminifera tests, mollusk shells, ooids, bivalve shells (specifically *Fragum erugatum*), serpulid worm tubes and *Acetabularia* sp. stalks. Many constituents were covered with a superficial carbonate coating.

Additional facies identified and mapped by Jahnert and Collins (2012) included under the substrate and sediments classifications included: limestone, calcrete and superficial deposits (Cretaceous/Quaternary), areas of encrusted serpulids, breccia, mega-ripples, ripples, a seagrass meadow domain and a sparse seagrass substrate. Previously described facies divisions interface geological, biological and physical domains such as microbial mat surface communities with seagrass domains, pavement structures and sediments.
2.2 Research Objective

Previous research in Hamelin Pool has focused primarily on stromatolites and associated microbial buildups. Stromatolites have been identified by the living microbial surface-mat community. Microbial surface mat communities are linked to internal fabric and can be found colonizing on the surface of a stromatolite and/or creating various structure morphologies. Identical stromatolite morphologies exhibit different surface-mat types. While geological structures may have a large biological and physical influence, the biology or transient physical influence is not a facies type. In order to develop a clear model of Hamelin Pool, biology must be separated from morphological facies divisions. Ultimately, creation of a geological facies map and a biological map including sea grasses, microbial mat types, live fragum beds, live mussel beds and other macroalgae might offer insight to how both aspects interact and influence each other. These maps, however, should remain separate.

At the mega-scale, previous maps of Hamelin Pool have been based on aerial photos. By combining data collected from ground-truthing the east and southeast iconic locations of stromatolite research, facies were derived for the remaining, understudied regions of the Pool. Historical mapping schemes have relied heavily on tonal variations in aerial photographs (Jahnert and Collins 2011 and 2012, Collins and Jahnert 2014). Aerial photography and satellite imagery are indeed a powerful tool in mapping, providing an initial way of discerning zonations, but it is critical to understand what the varying tones represent. The limits of remote sensing in Hamelin Pool reside in the varying microbial communities blanketing various geological facies, resulting in non-unique derivation of facies boundaries or lack of boundary placement due to biological influence. Therefore,
aerial imagery should be used in combination with comprehensive ground-truthing to identify different types of facies found in Hamelin Pool.

At the macroscale and mesoscale, stromatolites are found in a variety of shapes and sizes and internal fabrics are heterogeneous. The characteristics of internal fabric are unknown without examining stromatolite interior, resulting in descriptive inaccuracies when identifying structures by surface mats. Therefore, after examining information regarding surface-mats, internal fabrics and structure morphologies, the research objective evolved into creating a facies map based on different types of microbial structures and associated facies. Separating surface-mat type from internal stromatolite-structure type is contrary to the traditional approach. Therefore, identification and description of general structure types based on morphology will be created and used to describe the features of Hamelin Pool. This new system will identify and describe all structure types in Hamelin Pool. It will include those structures influenced and/or induced by microbial mats and those independent of microbial-mat influences. The new classification system seeks to create and define clear and concise mapping units.

2.3 Materials and Methods
During the 2012, 2013 and 2014 Hamelin Pool field seasons, a total of 20 predetermined transects were surveyed. Transects were chosen with the assistance of Phillip Playford with special attention to areas of interest on aerial photos, as well as in areas previously investigated but in need of further examination (Fig. 2.1). Tonal variations on aerial orthophotos were marked on the imagery and investigated from the land or by vessel to determine bottom type and identify structures.
Figure 2.1: Hamelin Pool map with surveyed transect locations selected with the assistance of Phillip Playford (Geological Survey of Western Australia, Perth). Transects ranged in length from around 1 km to over 8 km in length.
Facies types, including stromatolite and microbial buildup morphologies were determined using imagery combined with in-field evaluation. Sediment types were classified using the modified Dunham Classification (1962) system of carbonate rocks with additional classifying terms for skeletal/biogenic limestones by Embry and Klovan (1971) (Table 2.2). At each ground truth location, sediments were examined with major constituents identified and classified in the field. If sediment samples were collected, further analyses were completed on grain size in the laboratory.

Table 2.2: Table showing the Dunham classification (1962) of carbonate rocks with additional terms classifying biogenic limestones by Embry and Klovan (1971).

<table>
<thead>
<tr>
<th>Depositional Texture Recognizable</th>
<th>Original Component Not Bound Together During Deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contains Mud</td>
<td>Mud-Supported</td>
</tr>
<tr>
<td></td>
<td>Grain Supported</td>
</tr>
<tr>
<td>Lacks Mud</td>
<td>Grain Supported</td>
</tr>
<tr>
<td></td>
<td>Matrix Supported</td>
</tr>
<tr>
<td></td>
<td>Supported by components &gt; 2 mm</td>
</tr>
<tr>
<td>Original Components Bound Together During Deposition</td>
<td>Dehpositional Texture Not Recognizable</td>
</tr>
<tr>
<td>&lt; 10% grains</td>
<td>&gt; 10% grains</td>
</tr>
<tr>
<td>MUDSTONE</td>
<td>WACKESTONE</td>
</tr>
<tr>
<td>PACKSTONE</td>
<td>GRAINSTONE</td>
</tr>
<tr>
<td>FLOATSTONE</td>
<td>RUDSTONE</td>
</tr>
<tr>
<td>BOUNDSTONE</td>
<td>CRYSTALLINE CARBONATE</td>
</tr>
</tbody>
</table>

Aerial oblique photographs (taken from an airplane and provided by Australian National University (ANU) PhD student Gumpei Izuno) were used to locate and interrogate structures. Over 100 km of shoreline imagery was collected by our field team in ~ ten-meter increments at low tide using geo-tagged imagery from Canon D20 cameras. Underwater geo-tagged photos were also captured by our field team, resulting in a georeferenced photo library containing over 30,000 images. A quadcopter was flown nearly 650 km to collect imagery of targeted areas resulting in 14 km² of sub centimeter
scale imagery (Stanford University PhD student / NASA civil servant - Ved Chirayath). This imagery is the largest, highest-resolution, coastal data set in existence, to date. Stromatolite morphologies and associated facies types were discovered, targeted, examined and described using these resources.

2.4 Results
The new classification system for Hamelin Pool separates mat type from stromatolite morphologies and allows for isolation of various facies types, which were used as individual mapping units. Facies and sub-facies were classified (Fig 2.2) and described through extensive ground truthing (Fig. 1.11). Facies types now include: sheets, discrete microbial buildups (stromatolites), pavements, sediments, beachrock, breccia and boulders.

2.4.1 Sheets
Sheets are flat, stratiform microbial mats that develop in tidal flats in areas of low energy. They are un lithified to semi-continuously weakly lithified structures. Sheet extent can cover a few meters to hundreds of meters, often colonizing underlying sediments, breccia fields and other relict structures. Wave erosion and other mechanical processes can damage this continuous prostrate cover and divide the platform into ridges (Golubic 1983 & 1985, Logan 1961). Sheets can therefore be classified in three subfacies: continuous, ridge-rill and amoeboid.

2.4.1.1 Continuous
Continuous sheets extensive are stratiform mats covering often tens to hundreds of square meters in the intertidal zone and are mainly primarily comprised of pustular-mats, however continuous sheet mats of smooth or tufted mat are also common (Fig. 2.3).
Figure 2.2: Facies and sub-facies divisions of various structures in Hamelin Pool.
Figure 2.3: Sheets: Continuous. A displays continuous sheet mat on the eastern margin of Hamelin Pool made from tufted mat. B – D are examples of continuous sheet mats from the south and southeastern margins of Hamelin Pool made from pustular-mat, located in the upper intertidal zone.

Continuous mat depth has been measured that exhibits sub-centimeter to over a half-meter depth. Diagenetic structures are also formed on continuous structures when long durations of desiccation are endured, such as polygonal cracks or gas-filled cavities.

2.4.1.2 Ridge-Rill
Ridge-rill sheets are stratiform sheets that have eroded elongate grooves eroded in the direction of prevailing wave translation (Fig. 2.4). Ridges are mainly composed of smooth or pustular-mat, and rills are filled with rippled mobile sediments, often prohibiting further colonization of microbial mat. Relief has been measured up to 20 cm. Ridge-rill mats are often formed at the seaward edge of continuous mats, where energy is
higher. Water energy carves out a groove, or is a result of water drainage concentrating the flow. Sediments accumulate in the grooves and microbial mats continue to accrete on the topographic highs.

Figure 2.4: Sheets: Ridge-Rill. A – C display sheet mats with ridge-rill morphology along the southern margin at the seaward edge of continuous sheet mat facies. Ridge-rill sheet mats in these images are all made from pustular-mat, located in the upper intertidal zone.

2.4.1.3 Amoeboid
Amoeboid sheets are microbial stratiform sheet mats formed on top of flat-topped or eroded relict stromatolite heads or in high-energy tidal flats (Fig. 2.5). Probe depth has indicated amoeboid sheets do not typically have a relief of more than 10 cm, although the structures amoeboid sheets colonize often exhibit a relief of nearly 20 cm.

Figure 2.5: Sheets: Amoeboid. A – C display sheet mats with amoeboid morphology all with pustular surface mat. Amoeboid sheet mats are found dominantly along the southwestern margin (A), and along the southeastern margin (B – C) of Hamelin Pool, in the upper intertidal zone.

2.4.2 Discrete Microbial Buildups
Discrete microbial buildups are lithified structures with relief (Playford et al. 2013). Colonized by smooth-mat, pustular-mat and colloform/gel-mat, discrete microbial buildups can have un laminated, laminated and heterogeneous internal fabrics. The main
factors shaping the morphology of the microbial buildups are the direction of wave translation, prevailing wind direction, and the nature of the substrate (Playford 1980). The main morphological classifications of discrete microbial buildups in Hamelin Pool include: columnar and merged columnar, elongate, elongate-nested, composite or segmented, sinuous, elongate-clustered, seif and tabular (Fig. 2.16).

2.4.2.1 Individual and Merged Columnar

Individual and merged structures can vary in sizes from less than 10cm from the seafloor up to nearly 60cm (observed) (Fig. 2.6). The average height of the structures is between 30 and 40cm. The aspect ratio of these structures is about one (close to circular). When stromatolites grow too close together, the individual heads are often merged into larger bioherms or reefs. The microbial mat colonizing the surface of the structure becomes continuous covering both structures and unifying them into one. The surface mat will subsequently lithify. Individual and merged-columnar structures are found in all tidal ranges from the stranded structures in the supratidal to intertidal and subtidal zones around the margin of the entire Pool. Surface mats are variable between pustular, smooth and colloform/gel dependent upon tidal-zone location. Intertidal to shallow subtidal zone structures may exhibit a flat, tabular surface as a result of accommodation space (Andres and Reid 2006). What is common about all the individual heads collected with their “base” shows that each column or dome is accreted upon a cobble (Fig. 2.7). This topographic high from the sediment-water interface provides a hard surface as a base for stromatolite growth. Microbial mats tend to colonize on hard surfaces. Forming on a hard surface elevated from the constantly migrating sand ripples allow structures to nucleate.
2.4.2.2 Elongate

Stromatolites generally exhibit relief of 20-30 cm above the seafloor, are between 15-30 cm wide and have been measured to over a meter in length (Fig. 2.8). The elliptical
shapes of elongate heads have a larger aspect ratio than individual columnar structures. The long axis is typically angled perpendicular to shore, or in the direction of wave translation. Surface mats are variable between pustular, smooth and colloform/gel and they are typically found in the intertidal and subtidal zones. Elongate heads sampled were either growing on a pebble, or the surface on which it grew was not able to be collected with the stromatolite. Elongate stromatolites exhibiting a narrow base generally form on a cobble, whereas stromatolites with a broader base appear to form directly on antecedent topography/hardground.

Figure 2.8: Discrete Microbial Buildups: Elongate. Elongated stromatolites in (A) are located on the southeastern margin of Hamelin Pool and covered with pustular surface mat; (B) are located on the southwestern margin of Hamelin Pool and are covered with smooth surface mat; (C) are forming in a band and located along the northeastern margin of Hamelin Pool and are not covered in an active microbial surface mat but instead dominated by macroalgae.

2.4.2.3 Elongate-nested

Stromatolites range from 15 to 40 cm in height and can be up to several meters long (Fig. 2.9) Elongations are always perpendicular to shore or in the direction of wave translation. They are found in abundance to the south and southeast of headlands in the subtidal zone. Only one of these stromatolites has been sampled and the fabric was uniform perhaps indicating that these structures are all recent in growth. Fluid hydraulics is the assumed driving force for morphology. Stromatolites grow on a microbial pavement or hardground that has been eroded into undulating or ridge-rill morphology. The channel formed would concentrate flow and enhance the ridge-rill morphology, further
influencing fluid hydraulics. Sediments are redistributed in the rills promoting microbial mats accumulate and accrete on the highs. Elongate-Nested stromatolites continue to “self generate” or “self sculpt” as they accrete. Examination of the stromatolite fabric displays constructional rather than erosional lamination.

Figure 2.9: Discrete Microbial Buildups: Elongate-nested. Elongated-nested stromatolites are dominantly located on the western margin of Hamelin Pool to the south-southeast of promontories. Structures begin as small elongate-nested mounds (A) and can accrete to have a relief of 30-40 cm (B-D). Depending on location in the tidal zone, surface mat change from pustular in the upper intertidal zone, smooth in the intertidal zone and colloform or gel in the subtidal zone.

2.4.2.4 Composite/Segmented
Segmented stromatolites average 30 to 40 cm in relief (Fig. 2.10). Although the entire stromatolite has an aspect ratio of near one, it is often composed of smaller elongated lobes with larger aspect ratios. The long axes of the lobes are oriented perpendicular to shore. Composite stromatolites are found in the same areas as segmented forms and
often have lobes on the larger stromatolites, but sometimes they exhibit knobbly surfaces. Some composite stromatolites can be massive, over a meter in height. Composite stromatolites were observed in the subtidal deep waters along the eastern margin and in the northwest. They are found in up to four meters water depth and blanketed with *Acetabularia* sp. and other macroalgae. Based on current known growth-rate prediction models (Logan et al. 1974 Playford 1980, Chivas and Polach 1990, Jahnert and Collins 2012 and Giusfredi 2014), it seems likely that massive composite structures accreted on large boulders, possibly brought in by a tsunami, although no

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*Figure 2.10: Discrete Microbial Buildups: Composite/Segmented. Composite/Segmented stromatolites occur in the subtidal zone and are often fringed with macroalgae. Massive composite stromatolites (>1 m in relief) (A & D), along with vast fields of smaller composite strictures (C) are generally centrally located along the eastern margin in 4 m water depth. Segmental stromatolites (B) have lobes with elongation in the direction of wave translation. Composite/Segmented stromatolites are also found in the subtidal zone in the west and also in the northwest but not in the abundance as the eastern margin.*
samples have been collected. Smaller composite and segmented structures were found accreting onto orthoquartzite cobbles. Segmented structures appear to be a result of a dynamic feedback loop of fluid hydraulics and sediment accumulation within the grooves of the lobes.

2.4.2.5 Sinuous

Sinuous structures are found in the nearshore environment in the supratidal or upper intertidal zone areas (Fig. 2.11). Dimensions average around 10 cm in width, with around 5-10 cm relief and can be over a meter in length. These narrow snake-like

![Figure 2.11: Discrete Microbial Buildups: Sinuous. Sinuous stromatolites occur in the upper intertidal zone. Figure (A) displays low-relief sinuous stromatolite structures beginning to develop relief from the surrounding flat. Figure (B) displays a sinuous stromatolite covered with pustular-mat. Figure (C & D) display sinuous stromatolites in the upper intertidal zone covered with smooth-mat. Sinuous stromatolites are found all around the margin in embayments and bights where the surface gradient is low.](image)
stromatolites come in a variety of multidirectional narrow buildups. In the upper intertidal zone, structures are covered with smooth-mat and/or pustular-mat. Sinuous stromatolites are modern and are growing on structural highs of a possible older system. Relict stromatolites are preferentially cemented around the margins and in breccia fields of old spalled heads, the center of the structure is eroded away, yet the cemented edges remain. These stromatolites are often colonized by new growth in strange shapes, or remain without microbial-mat covering in the supratidal zone.

2.4.2.6 **Elongate-clustered**
Elongate-clustered stromatolites often form in bands in the intertidal zone most commonly in embayments and bights (Fig. 2.12). They are typically 10-20 cm in height and are often connected and weakly lithified, with abundance covering kilometers. Elongate-clustered stromatolites have been recorded with both pustular and smooth-mat. Based on the interconnected patterns, it is possible that elongate-clustered stromatolites begin to accrete on topographic highs and biologically self-sculpt, providing ecosystems with resiliency to current related disturbances and environmental changes. Microbial communities may space themselves semi-regularly to help promote nutrient cycling (Rietkerk and van de Koppel 2008, Schlager and Purkis 2015).

Figure 2.12: Discrete Microbial Buildups: Elongate-clustered. Elongate-clustered stromatolites occur in the upper intertidal zone, usually covered in pustular-mats. Elongate-clustered stromatolites are found in areas where the shelf has a low gradient.
2.4.2.7 Seif

Seif structures are 20-30 cm in height and can be 1-3 m wide (Fig. 2.13). Seif structures are only found on the west side of the Pool along the shore-parallel, narrow shelf. These structures form in bands that can extend for tens of meters and often back step and have “tuning-fork” junctions opening to the south (Playford et al. 2013). The bands are generally several meters apart, separated by a grainstone, dominated by micritic grains. The bands are oriented in a north/south direction, but have lobes on the shoreward facing side that are in the direction of wave translation. Seif stromatolite structures are found

![Figure 2.13: Discrete Microbial Buildups: Seif. In the upper intertidal zone, seif stromatolites are covered by a crusty pustular-mat (A-D) and are arranged in N-S linear bands. Seif stromatolites lower in the tidal zone are covered by a crusty smooth-mat. Although the stromatolites are arranged in linear bands, individual lobes on the the structures are in the direction of wave translation.](image-url)
from the upper intertidal zone to the subtidal zone. The more built-up stromatolites are covered in pustular-mat whereas the deeper structures are covered in crusty smooth-mat. Seif stromatolites are attributed to strong winds and Langmuir circulation (Fig. 2.14), where helical water vortices meet at visible wind-rows, piling sediment between stromatolites (Playford 1980).

There is a seasonal cycle in water level occurring in Hamelin Pool. Lower water levels are common in the Australian summer, whereas higher water levels are common in Australian winter. During the summer, winds are dominated by the southerlies and blow over 25km/hr. Wind abrasion and shallow waters may perpetuate the N/S banding of the structures, pushing water through the channels between the bands. Additionally, the observed spacing and backstepping of the seif bands may indicate formation on the crests of an old Pleistocene dune system.

Figure 2.14: Illustration of seif stromatolites (Playford et al. 2013) growth controlled by strong prevailing southerly winds inducing paired helical vortices (Langmuir circulation).

2.4.2.8 Tabular
Tabular stromatolites are the final discrete microbial buildup designation that generally possess 30-40 cm relief off the sea floor and resemble flat-topped table-like structures
The tabular stromatolites can be covered by all mat types, pustular, smooth and colloform/gel and can be in intertidal and subtidal zone environments. They often appear as continuous tables for tens of meters parallel to the shore. Intertidal zone to shallow subtidal zone structures may exhibit the flat, tabular surface as a result of accommodation space. It may be difficult to determine if they are formed from merged heads, or are erosional features.

Figure 2.15: Discrete Microbial Buildups: Tabular. Tabular stromatolites occur throughout the tidal zone. Figure (A) displays tabular stromatolites covered with mixed pustular and smooth-mat composed definitively of individual structures, merged together to make expansive flat-topped tables. These particular structures are found along the northwestern margin of Hamelin Pool. Figure (B) displays flat-topped tabular structures covered in gel-mat, found on the western margin in the subtidal zone. Figures (C & D) are stromatolites found along the eastern margin in the subtidal zone, covered with smooth-mat.
Figure 2.16: Discrete buildup variations in Hamelin Pool. First column is the name of the buildup, second column is an aerial image of the structure (orthorectified by Ved Chirayath; obliques by Gumpei Izuno). Third column is a bicolor cartoon of the microbial build-up shapes. Fourth column is an underwater/shoreline photograph depending on position in the tidal zone and tidal height at time of picture.
2.4.3 *Pavements*

Subtidal zone pavements are lithified seafloor surfaces of synsedimentary cemented exposed carbonate layers (Wilson and Palmer 1992) found between one and six meters in depth in Hamelin Pool, and are volumetrically significant. Various forms of pavement can be found there, including hardgrounds having intergranular cements or microbially induced cementation by presence of microbial mats. Pavements are often colonized on the underside by serpulids and other encrusting marine organisms.

Boring organisms, such as *Solentia* sp. induce a biological micrite that can act as a critical element in fusing grains together at point contacts and stabilizing sediments. Pavements exhibit the same color as surrounding sediments, but often appear darker in color due to colonization of macroalgae. Pavements provide optimal places for *Sargassum* sp. to colonize and are often widespread.

*Fragum erugatum* is a characteristic element of many pavement deposits throughout the Pool. Hamelin Pool pavements can be found in various forms: low-relief microbial, undulose, transitional, tabular and blocky. Low-relief microbial and undulose pavements have notable microbial influence and are often colonized by microbial mats, and abundant macroalgae such as *Acetabularia* sp. Tabular and blocky pavements are not colonized by microbial mats but are connected by grain-contact cements.

2.4.3.1 *Low-relief microbial pavement*

Low-relief microbial pavements are characterized by small microbially induced structures with up to 20 cm relief above the sediment-water interface but up to 20 cm (Fig. 2.17). Low-relief microbial buildups cover vast expanses of nearshore, subtidal zones
and accrete with the assistance of microbial mats. Sediments fill in low-relief areas and the stromatolites continue to preferentially cement on topographic highs.

Figure 2.17: Pavement: Low-relief microbial. Figures (A-D) display the variability in subtidal zone low-relief microbial buildup pavements influenced by microbial mat. Regional location in the Pool may influence the type of microbial mat covering the surface of the structure (smooth-mat, colloform-mat, gel-mat or macro-algal cover).

Figure 2.18: Pavement: Undulose. Figures (A-C) display the undulose morphology of subtidal zone pavements. Undulose pavements are similar to low-relief microbial buildups but forming in longitudinal ridges. Regional location in the Pool may influence the type of microbial mat covering the surface of the structure (smooth-mat, colloform-mat, gel-mat or macro-algal cover).
2.4.3.2  Undulose pavement
Undulose pavements have ridge-rill morphology and are found in the upper subtidal zone (Fig. 2.18). Ridges are influenced by microbial communities, often colonized by patchy smooth-mat and blanketed by Acetabularia sp. Rills are eroded elongate grooves in the direction of wave translation and filled with sediments. Relief has been measured at up to 10 cm. Once the ridge-rill topography begins to take shape on a pavement, the mat continues to cover and stabilize the accreting slopes. Mobile sediments often prohibit further colonization of microbial mat. Pavement ridges act as obstacles to currents and cause eddies that deepen the areas surrounding rills. Fluid hydraulics continue to enhance pavement morphology. Eventually, the undulose pavement accretes high enough that the structures become discrete and continue to “self generate” or “self sculpt” as they accrete forming elongate or elongate-nested stromatolites.

2.4.3.3  Transitional pavement
Transitional pavements are contained wholly in the subtidal zone and are defined as tabular pavement that is accreting small microbially induced sedimentary structures, as a result of interspersed microbial mat growth (Fig. 2.19) Transitional pavement in Hamelin Pool is often in association with Acetabularia sp. and larger macroalgae.

Figure 2.19: Pavement: Transitional. Figures (A-C) display the morphology variations in transitional pavements found in the subtidal zone. Regional location in the Pool may influence the type of microbial mat covering the surface of the structure (smooth-mat, colloform-mat, gel-mat or macro-algal cover).
2.4.3.4 Tabular pavement
Tabular pavements are subtidal, flat substrate lithified at the sediment-water interface (Fig 2.20). They often contain Fragum sp., peloids, ooids and Foraminifera sp. cemented at grain contacts by biologically induced micrite often formed by boring organisms such as Solentia sp. Tabular pavements can be covered by a thin layer of sediment, blanketed by Acetabularia sp. or colonized by Sargassum sp.

![Image A](image1.jpg)
![Image B](image2.jpg)
![Image C](image3.jpg)
![Image D](image4.jpg)

**Figure 2.20: Pavement: Tabular.** Tabular Pavement is often colonized by a thin blanket of Acetabularia sp. or Sargassum sp. macro-algae (A-B). Image (C) exhibits a thin tabular pavement composed almost entirely of cemented coquina, forming a crustal layer over underlying sediments. Image (D) exhibits the often layered structure of tabular pavement with the surface covered in Acetabularia sp. and diatoms.

2.4.3.5 Blocky pavement
Blocky pavements are a subtidal substrate that is comprised of broken or reworked tabular pavement (Jahnert and Collins 2011, 2012) (Fig. 2.21). Sargassum sp. may
colonize block margins, and serpulids often inhabit the underside, leaving carbonate tubes.

Southwest of Nilemah Province NW-SE trending ridges of topographic highs form kilometer subtidal ribbons of blocky pavement extending from the Yaringa Promontory (Fig. 2.22). Rigorous ground-truthing of dark areas on the aerial image revealed eroded and reworked blocks of pavement from underlying dune crests. Internal composition of blocky pavement collected from this area should be investigated.

Figure 2.21: Pavement: Blocky. Images (A-D) are examples of blocky pavement in the subtidal zone. Blocky pavement is a reworked tabular pavement often colonized by a thin blanket of Acetabularia sp. or Sargassum sp. macro-algae (A-C).

2.4.4 Sediments
The dominant components that make up Hamelin Pool sediments include: quartz, peloids, irregular micritic grains, Foraminifera sp. tests, mollusk shells, ooids, bivalve shells,
specifically *Fragum erugatum*, serpulid worm tubes and *Acetabularia* sp. stalks. Many of these components are often covered in a superficial carbonate coating (Giusfredi 2014; Fig. 1.7). Various combinations of sediment components can be combined to form sediments including packstone, grainstone, floatstone and rudstone.

![Satellite image of Hutchison Embayment and adjacent sedimentary deposits, appearing dark in aerial imagery as a result of heavy macroalgal growth on blocky pavement. RapidEye 2014.](image)

**Figure 2.22:** Satellite image of Hutchison Embayment and adjacent sedimentary deposits, appearing dark in aerial imagery as a result of heavy macroalgal growth on blocky pavement. RapidEye 2014.

#### 2.4.4.1 Packstone

Packstone is composed of fine sediments mainly including small peloids, eroded quartz grains, and diatomaceous or carbonate ooze components.

#### 2.4.4.2 Grainstone

Grainstone lacks mud and is grain supported (Fig. 2.23). Most sediments that comprise
Figure 2.23: Sediments: Grainstone. Images (A-C) are examples of rippled grainstone sediments throughout the Pool. (A) has a large quartz component and is located in the northwest. (B & C) have a larger peloid and/or skeletal component, located in the west, near the seaward edge of Promontories.

Figure 2.24: Sediments: Floatstone. Images (A-D) are floatstone composed of Fragum erugatum in a skeletal to peloidal grainstone matrix. (A) is floatstone with discontinuous microbial mat at the sediment-water interface. (B) is floatstone with mobile flocculent diatom and macroalgal fluff at the sediment surface. (C) is floatstone fine grainstone component on the crest and the Fragum dominating troughs. (D) is floatstone sampled from the embayment with a large percentage of organic.

grainstone include detrital quartz, peloids, irregular micritic grains, ooids, and

*Foraminifera* tests.
2.4.4.3 Floatstone
Floatstone contains over 10% >2 mm *Fragum erugatum* bivalve shells but is matrix supported by grainstone (Fig. 2.24).

2.4.4.4 Rudstone
Rudstone in Hamelin Pool is classified as coarse-grained sediments supported by grains >2 mm (Fig. 2.25). *Fragum erugatum* shells are the main sediment component of grains >2 mm, usually abundant in areas of live *Fragum*.

![Figure 2.25: Sediments: Rudstone. Images (A-D) display rudstone comprised of Fragum erugatum bivalves. Images (A,B & D) are areas of live Fragum erugatum beds. Image (C) is in the vicinity of live beds but no longer contains many live Fragum.](image)

2.4.5 Beachrock
Beachrock is a lithified, intertidal deposit of cemented grains overlying unconsolidated sand (Scoffin and Stoddart 1987, Playford et al. 2013) (Fig. 2.26). Hamelin Pool
beachrock is primarily cemented rudstone facies composed of *Fragum erugatum* formed as a result of physiochemical precipitation of cements from seawater associated with high temperatures, calcium-carbonate saturation, and high rates of evaporation (Ginsburg 1953, Stoddart and Cann 1965). An alternate argument for beachrock formation is saturated groundwater input and mixing in isolated areas around the margin (Schmalz 1971) or precipitation of micrite, connecting grains at point contacts through production of calcium carbonate as a byproduct of microbial activity (Taylor and Illing 1969, Krumbein 1979, Strasser et al. 1989). Beachrock forms for tens of meters and is discontinuous along the shorelines of the Pool, but in some areas it is several layers thick, each layer being around 10 cm in thickness.

![Figure 2.26: Beachrock. Images (A-C) display varying beachrock deposits around the margin. Image (A) is located in the eastern margin of Hamelin Pool in the vicinity of Carbla Point. Images (B & C) occur on the western margin of Hamelin Pool.](image)

### 2.4.6 Boulders

Boulders in Hamelin Pool are a mappable unit and refer to allochthoanous blocks in the style of Wentworth (1922) and are >10.1 inches (256 mm) across (Fig. 2.27). Hamelin boulders are often encrusted with mussels, sponges, and serpulids or used as nucleating sites for stromatolite and macroalgal growth. The origin of boulders in Hamelin Pool and internal composition remains largely unknown. Sampled blocks have revealed orthoquartzite, conglomerate, limestone, and chert mineralogies. Boulders with little to no microbial accretion will be included in the classification.
Figure 2.27: Boulders. Images (A-C) display varying rock, boulder and rubble deposits around the margin of Hamelin Pool. Image (A) is a field of boulders in the north west displaying a field of rubble with surfaces colonized by a thin white colored microbial mat. Image (B) is a pile of flat boulders colonized by macroalgae on the western margin. Image (C) is showing allochthonous boulders in a pile in the north near the Faure Sill covered by masses of macroalgae and colonized by sponges.

2.4.7 Breccia

Breccia is an upper-intertidal to supratidal zone facies division. In the upper intertidal zone fields of breccia are often colonized by microbial mat (Fig. 2.28). Breccia forms

Figure 2.28: Breccia. Images (A-D) all display breccia facies of lithified supratidal pavements of relict spalled stromatolite heads, often leaving eroded ridge-and-ring patterns (D).
lithified pavements of relict spalled stromatolite heads, leaving eroded ridge-and-ring patterns. Breccia is created by desiccation, cementation and reworking of older carbonate deposits stranded from a time of higher sea level (Logan et al. 1974).

2.5 Discussion
Facies identification based on external morphology and not internal structure is a new and different way of investigating stromatolites and associated facies in Hamelin Pool. Previous studies have used stromatolite classifications based on surface mat. Removing the type of microbial mat responsible for creating the stromatolite has allowed for broader facies designations that can be broken down into smaller subfacies that define type. Although previous research provided a baseline for the study, the majority of publications have been restricted to the east and southeast margins of Hamelin Pool (Logan et al. 1974, Hoffman 1976, Playford and Cockban 1976, Bauld, 1984, Golubic 1985, Burne and Moore 1987,

Playford 1979, 1980 & 1990, Meischner 1992, Reid et al. 2003, Jahnert and Collins 2011, 2012 & 2013, Playford et al. 2013, Collins and Jahnert 2014 and others). Our investigation expands the scope of previous investigations, extending beyond the classic locations of Flagpole Landing and Carbla Point, exploring the entire margin and the basin. A surprising amount of heterogeneity was uncovered regarding the stromatolites and associated facies using this wholistic approach. This study is the most extensive, indiscriminate and comprehensive ground truthed study of Hamelin Pool to date, revealing many new stromatolite morphologies. Based on knowledge obtained from this study, new facies mapping units were defined and described.
Facies designations include broad, mappable categories including those with a microbial mat component: discrete microbial buildups, sheets and some subtidal pavements. Facies designations without microbial mat influence include: hardground pavements, allochthanoous boulders, beachrock, breccia, and sediments.

Using morphological classifications of stromatolites as discrete microbial buildups and separating them from microbial-mat types is a new methodology that has not been previously applied to Hamelin Pool investigations. Although internal fabric is a record of previous microbial surface mat, internal structures of stromatolites possess unknown heterogeneous fabrics. Similar morphologies can also exhibit different surface mats. Therefore, in order to better understand the structure and arrangement of the modern environment, it is critical to separate stromatolite macro-morphology from internal structure and to classify structures using morphology. The main factors shaping the macro-morphology of microbial buildups are extrinsic environmental factors: wind (wave-generating), direction of wave translation, currents, prevailing wind direction, location in the tidal zone/accommodation space and nature of the substrate (Playford 1980, Andres and Reid 2006, Playford et al. 2013).

Hydrodynamics includes not only the direction of wave translation that helps sculpt the macro-morphology, but also the intensity of the current, forcing grain saltation abrading and eroding the sides of the stromatolite structures. Calmer areas such as embayments, bights or areas where waves are dissipated by a break off-shore appear to allow for different structure types than in areas with higher energy.
Accomodation space appears to limit the processes needed for stromatolite building microbial communities to accrete (Andres and Reid 2006). In some cases, these processes result in flat-topped stromatolites (for microbial mat communities that trap and bind available sediment). Stromatolites colonized by microbial communities that do not require sediment grains for accretion such as *Entophysalis* sp. forming micritic cauliflower structures in the splash zone, are able to grow higher, but are still limited. Accommodation space is probably the largest contributing factor to stromatolite height.

The nature of the substrate has a large impact on the type of macro-morphology accreted. Stromatolites can accrete on top of cobbles or boulders (often allochthanous) and also on hardgrounds. Slope gradient also impacts growth.

Understanding environmental parameters and additional mechanical factors that influence growth forms will help improve prediction models for what to expect in a microbial carbonate environment. Low-energy settings produce continuous stratiform sheets. In areas of increased energy and drainage, sheets begin to divide into discontinuous features such as ridge-rill and amoeboid. Discrete stromatolites accrete on pavements using environmentally controlled morphologies that enhance stromatolite growth. If ridge-rill morphology is carved out of a pavement and microbial mat begins to accrete on the topographic highs, the mat begins to stabilize the slope and concentrate the sediments in the rills. The stromatolite builds up with carbonate precipitation and trapping and binding. The strong, lithified structures concentrate currents in the rills and cause eddies that undercut the structures, which in turn can cause a narrowing at the base forming columnar structures (Golubic 1985). Columns frequently grow close together and are connected or reconnected by surface mat.
Identifying structure types, microbial buildups, sediments and all associated facies will provide definitive mapping units around the Pool. Variations of any of these factors can produce different types of structures. This identification does not mix surface-mat type with stromatolite macro-morphology and offers better insight into different environments throughout the pool. The newly defined facies and sub-facies types will allow for creation of new maps where more information can be inferred about the stromatolite reef system itself, also appears to modify macro-morphologies as a result of changing wave energy and flow feedback loops (Andres and Reid 2006).

2.6 Conclusions
Seven main facies divisions have been identified in Hamelin Pool including: sheets, stromatolites as discrete microbial buildups, pavements, sediments, beachrock, boulders and breccia. The approach of identifying and defining different facies types based on morphologies provide the basis for understanding the physical environments acting on stromatolite growth. Facies types and morphologies have great application to astrobiological, paleo-environmental insight into ancient fossil outcrops and sub-surface petroleum reservoir interpretations.
Chapter 3  FACIES MAP, DIGITAL ELEVATION MODEL AND GIS DATABASE

3.1  Overview

The allure of research in Hamelin Pool is a result of the most prolific, actively accreting stromatolite system it contains. Stromatolites are intriguing because they have their roots in the Precambrian and are the first evidence of life on Earth, having endured for billions of years. In addition to being a natural wonder, stromatolites also have various applications to understanding early life on Earth, paleo-environmental interpretations, sub-surface petroleum reservoirs and possible life forms on other planets. Hamelin Pool is an embayment covering around 1300 square kilometers, and stromatolites only cover a narrow shore-parallel band 135 km long. Mapping associated facies along with the stromatolites (as described in Chapter 2) provides insight into this entire system.

Hamelin Pool was bounded by sheep stations that produced bountiful amounts of wool closer to the turn of the twentieth century. During that time, Joe Spaven’s lighter, Will Succeed sailed into Hamelin Pool through the main channel in Faure Sill. The Will Succeed was moored near the southern region of Hamelin Pool, where camels hauled bales of wool from shore, for loading onto the lighter (Playford et al. 2013). Eventually stations on the western side of Hamelin Pool closed down, and there was no need for improved maps for navigational purposes outside the needs of the science community.

As a result, locating existing data to begin this research campaign was difficult. Detailed maps of Hamelin Pool were unknown or inaccessible, and the knowledge base was limited. Previous research and ground-truthing data available were generally restricted to the east and southeast margins of Hamelin Pool, with nominal research conducted on the southwest margin (Logan et al. 1974, Hoffman 1976, Playford et al. 1976, Bauld, 1984,
Golubic 1985, Burne and Moore 1987, Playford 1979, 1980 & 1990, Meischner 1992, Reid et al. 2003, Jahnert and Collins 2011, 2012 & 2013, Playford et al. 2013, Collins and Jahnert 2014 and others). As such, the microbial deposits in Hamelin Pool and the associated facies were not well known outside the “classic” localities of Flagpole Landing (SE), Carbla Point (E) and Booldah Well (SW).

3.1.1 Bathymetry Maps
The first known bathymetry map of Hamelin Pool was published by Logan et al. (1974) and displayed a single 20 ft. isoline parallel to the margin (Fig. 3.1A). Another map, published by Burne and Veitch (1990) (Fig. 3.1B) was provided to the Department of Environment and Conservation (DEC), now the Department of Parks and Wildlife (DPaw) and the Geological Survey of Western Australia (GSWA). This bathymetric map and accompanying facies map surfaced in 2012, and was emailed as black and white photographs. Slowly, the colored map files were made available for our study. The Burne and Veitch (1990) bathymetry model was an improvement from the single isoline bathymetry model, but methods of map production were not described.

A high-resolution bathymetry model was published by Bierwirth et al. (1993) to test a new approach using Landsat satellite imagery and spectral signatures. Hamelin Pool was elected as an optimal study location for depth analysis due to the following: clear, shallow waters, reported availability of detailed bathymetry
Figure 3.1: Previous Hamelin Pool bathymetry models. (A) First known bathymetry model displaying one isoline bordering the Hamelin margin (Logan et al. 1974). (B) Improved bathymetry map, unknown data collection methods (Burne and Veitch 1990). (C) Model generated through combination of depth data and satellite imagery (Bierwirth et al. 1993). (D) Map produced by Jahnert and Collins (2012) depicting depth through color gradation and isolines.
data, and previously described bottom and facies types described by Logan and Cebulski (1970), Hagan and Logan (1974) and Burne and Hunt (1990) (Bierwirth et al. 1993) (Fig. 3.1C). The data used for the map included Landsat 5 TM (WRS 115-076; 30 August 1986) and hydrographic soundings provided by the Australian Survey Office restored to (Australian Height Datum) AHD. A bathymetry and substrate reflectance model to determine changes in bottom type was derived by “unmixing” the exponential influence of depth (Bierwirth et al. 1993). Although the model improved upon previously published maps, fundamental problems existed. For example, dark substrates, such as the organic rich sediments in Nilemah Embayment or those north of Snake Promontory were resolved to be much deeper as a result of spectral reflectance values.

Jahnert and Collins (2012) published a bathymetry model as a 3D view based on data received from the Department of Parks and Wildlife (DPaW) (formerly the Department of Environment and Conservation (DEC) (Fig. 3.1D). Color gradations, shading and isolines give a sense of Hamelin Pool depth and physiography, but again the method of model creation, source and type of depth data were not provided. Therefore, for the purposes of this research, it was critical to develop a high-resolution digital elevation model (DEM), along with methodology and data depository.

3.1.2 Facies Maps
The first facies classification map of Hamelin Pool was published by Burne and Veitch (1990) and appeared at the same time as the bathymetry map. The facies
Figure 3.2: Hamelin Pool W.A. Sea-bed Classification Map (Burne and Veitch 1990). The map displays interpreted facies including: stromatolites, shelf deposits, supratidal flats, sandy intertidal flats, slope deposits, grainstone and crusts, basin sediments, subtidal channel deposits, intertidal terrigenous sands, intertidal carbonate sands, organic ooze, carbonate ooze, ooid sands, and land.

The map displayed Hamelin Pool sea bed-classifications and depth contours (Fig. 3.2). Bottom type classifications included: stromatolites, supratidal flats, sandy intertidal flats, slope deposits, grainstone and crusts, basin sediments, subtidal channel deposits,
intertidal terrigenous sands, intertidal carbonate sands, organic ooze, carbonate ooze, ooid sands and land. The Burne and Veitch (1990) map was the first published map attempting to identify existing facies and establish their distribution and abundance in Hamelin Pool. However, notable inconsistencies were exhibited, such as the lack of stromatolitic structures at the iconic location of Carbla Point. Additionally, when the map was presented, accompanying text was not included.

Bierwirth et al. (1993) were the next to publish a substrate classification map. Satellite imagery included Landsat 5 TM (WRS 115-076; 30 August 1986), hydrographic soundings, previously described bottom and facies types by Logan and Cebulski (1970), Hagan and Logan (1974) and Burne and Hunt (1990). A substrate reflectance model was created by “unmixing” the exponential influence of depth by adding mathematical constraints (Fig. 3.3). Although the red, green and blue representations display facies changes and variations, actual facies types are only inferred from previous knowledge. Color was used to delineate features such as sea grass distribution in the dark, deep Faure Sill channels, microbial mats in the intertidal zone or upper subtidal zones where reflectance is high and also areas of sand that transition multiple depths (Bierwirth et al. 1993).

The next Hamelin Pool sea bed classification map was produced by Jahnert and Collins (2011). Methodology included remote sensing, underwater video, swath mapping and ground truthing. Data collection took place between 2008 and 2011.
Figure 3.3: Substrate classification and bathymetry maps (Bierwirth et al. 1993). Maps were derived from Landsat 5 TM. A. Landsat 5 TM image (bands 1, 2 and 3) with land blocked out in black. B. Residual image after depth removal of algorithm-derived substrate reflectance bands (1, 2 and 3). C. Substrate and depth model combined. Depth is shown as hillshade contours.

The publication documented large expanses of previously unrecorded subtidal deposits, and presented georeferenced maps recording the extent and variation of stromatolites. The map divided Hamelin Pool into seven distinct zones progressing from shore: the Holocene limit, supratidal breccia and films, intertidal mats and heads, subtidal buildups, microbial pavement and basinal sediments including bivalve shells and mud. The seagrass carbonate bank was also included (Fig. 1.8b). The classification system delineated prevalent facies type zones and identified vast subtidal microbial deposits that were virtually unknown, up until that time.

Whereas the previous Burne and Veitch (1990) map used stromatolites as the overarching facies type, Jahnert and Collins (2011) subdivided zones of stromatolites into distinct subfacies. The new classification scheme included pustular microbial deposits, smooth...
microbial deposits, colloform microbial deposits, cerebroid microbial deposits and microbial pavement. Although the new schema included similar terminology to Logan et al. (1974), Playford (1990) and others, the term “mat” was noticeably removed from the facies designations (e.g. pustular stromatolites rather than pustular-mat stromatolites).

Jahnert and Collins (2011) also included two smaller areas of detailed mapping encompassing the iconic locations of Carbla Point and Flagpole Landing. Designated focus areas featured a complicated array of high detail facies boundaries, primarily defined by tonal variations from high-resolution aerial orthophotos, provided by DPaW.

In a follow-up 2012 publication, Jahnert and Collins described microbial carbonate morphology in association with fabric. They state the structure of various build-ups was reported to be the result of reflections of sediment availability, bivalve skeleton supply, substrate morphology and depth, wave activity, tidal run off and sea level. Internal stromatolite fabrics are a record of the microbial surface mat. Different microbial mat types are found in different locations within the tidal zone, resulting in an intrinsic relationship between internal fabric and water depth. Sampled structures therefore often exhibit a shallowing upward succession of fabric types as a result of falling sea level.

The 2012 publication produced an extremely detailed facies map of Hamelin Pool, recording the distribution of the different structure types around the margins. This facies map used surface mat as the diagnostic facies division, corresponding to depth zones (Fig. 3.4) Structure types, identified by surface maps were quantified and area of microbial deposits was reported. Methodology included coastal and marine ground truth traverses, video transects, multibeam surveys, aerial photography, samples and interpretation of orthophotos. Although the map figure caption notes ground truthed data is lacking in the
Figure 3.4: High-resolution sedimentary and organo-substrate map of Hamelin Pool (Jahnert and Collins 2012). Ground truthing was concentrated on southeast margin.
Classification schemes of Jahnert and Collins (2012) (Fig. 3.5) described substrates and sediments within four main zones: hinterland, supratidal, intertidal and subtidal. This map was a further advance in identification and documentation of subtidal microbial deposits in Hamelin Pool, and presents a visual representation of the distribution of these deposits.

During the first field campaign of the present study in 2012, the Jahnert and Collins paper was published. As a result of the paper, we were able to take the detailed map into the central basin, it should be noted that all ground truthed data are limited and concentrated on the eastern margin, near classic localities.
field and ground truth assigned facies boundaries. Unfortunately, most areas ground-truthed produced non-unique solutions such as diatom mat covering soft sediments mapped as pavement. Additionally, facies boundaries and facies identifications within their own classification scheme were grossly invalid along the western margin when ground truthed. Therefore we have deemed the Jahnert and Collins (2012) invalid.

Ground truthing the Jahnert and Collins (2012) map proved to be invaluable in planning field research. Our initial proposed methodologies for Hamelin Pool data collection and map creation were nearly identical to those used by Jahnert and Collins (2011, 2012) including: coastal and marine ground truth traverses, video transects, aerial photography and samples used to help interpret and delineate facies boundaries using aerial orthophoto tonal variations. The fundamental problems regarding identifying incorrect facies and/or facies boundaries discovered while ground truthing Jahnert and Collins (2012) maps included:

1. Microbial surface mat is not a reliable indicator of type of structure or morphology.

2. Flocculent diatom mat is an abundant feature in the subtidal at the sediment/water interface, often giving a darker appearance on aerial orthophotos which is often mismapped as a facies type i.e.: pavement.

3. The classic zonation that is present along the east and south-east margins of Hamelin Pool near the iconic localities of Flagpole Landing and Carbla Point cannot be extrapolated along the margin of the Pool.
4. Some structures with extensive trapped and bound sediments in the microbial surface mats are sometimes not able to be resolved from aerial photos as they blend with the surrounding sediments.

In addition to the problems encountered while mapping based on minimal ground truthing and delineating facies boundaries by tonal variations visible in aerial orthophotos, mapping by mat types is only indicative of the depth of the structure. Mapping structures based on morphology provides a more revealing and diagnostic facies map that facilitates interpretation of the surrounding environment. Therefore, removing biological communities from geological facies type is prudent. This chapter presents a new map, based upon described facies and sub-facies from chapter 2.

The results of this study determine the distribution and extent of microbial deposits and surrounding facies in Hamelin Pool mapped independently from microbial mat surface community. Interrogation of structural morphology, together with distribution and environmental parameters (chapter 4) will help clarify previous gaps in knowledge regarding controls on microbial growth. Results will facilitate a more comprehensive understanding of ancient systems, as fossil systems have great morphological diversity, abundance and distribution (Hoffman 1974, Walter 1983, Grey 1984 and 1994, Bunting 1986, Schopf et al. 2007, Flannery and Walter 2011). Additionally, mapping the extent of existing structures in Hamelin Pool will provide a valuable tool for analysis and management a UNESCO World Heritage site and Western Australia’s only marine reserve.

Maps of microbial mat type distribution are beyond the scope of this dissertation.
3.1.3 Research Objectives
Methods are often unavailable with published bathymetry models. Therefore map production processes and hydrographic sounding data are unknown. Published maps from recent publications (Bierworth et al. 1993 and presumably Jahnert and Collins 2012), have been determined by combining the sounding data with pixel color. Substrate color has often affected the algorithm computations providing false depth data. The first objective of this chapter was development of a high-resolution bathymetry model using a substrate independent algorithm paired with high-resolution soundings. Results will assist interpretation of Hamelin Pool physiography to be correlated with stromatolite and associated facies distribution.

The second research objective includes integration of new mapping classifications as described in Chapter 2, with extensive ground truth and remotely sensed data to accurately describe the features in Hamelin Pool. New definitions provide clear, concise mapping units, independent of microbial surface mat classifications. Facies categories include structures that are both influenced and/or induced by microbial mats as well as those independent of microbial mat. The purpose of this investigation is to capture and identify the heterogeneity of all microbial deposits (sheets, discrete microbial buildups and pavements) around the margin of the pool and investigate associated facies including sediments, breccia, boulders and beachrock.

Ultimately, data collected will be collated into a single GIS database that will become in time, publicly accessible. The existing data set is the largest, and most comprehensive dataset for Hamelin Pool.
3.1.4 Materials and Methods
This study employed use of multiple high-resolution satellite images and GIS tools to map and quantify microbial buildups and associated lithofacies to create facies maps. Existing imagery used for Hamelin Pool included DigitalGlobe Worldview-2 (0.46 m resolution; 8 spectral bands), Landsat 7 (28.5 m resolution, 8 spectral bands) and Landsat 8 (30 m resolution, 11 spectral bands). High-resolution aerial orthophotos captured in 2007 with 60% overlap on film, scanned at 1950dpi and mosaicked to provide a resolution of 50cm, were provided by the Geological Survey of Western Australia as an RGB base map. Geobodies, such as microbial reefs, tidal flats, ooid shoals, and coquina ridges were mapped using GIS tools such as ESRI ArcGIS with 3D Analyst and Spatial Analyst Extensions, and Global Mapper. Single beam sonar soundings were collected using a high precision survey grade single beam echo sounder (Ohmex SonarMite v3 EchoSounder - Legacy) coupled directly to a Trimble rover during the 2013 field campaign. The rover was hard-mounted on a boat at a fixed height above the water surface with the transducer mounted directly to the rover pole. Depths were subtracted from the measured water surface elevations giving an absolute elevation at each sample point. The nominal zero elevation was established using RTK survey and post processed correlate with the Hamelin Pool benchmark north of Flagpole Landing (A906; 4.253 m below Australian Height Datum). The Trimble R10 GNSS receiver has a built in tilt sensor that enabled real-time tracking of the rover pole tilt to help eliminate errors resulting from excessive tilt due to wind driven swells. Water surface elevations were checked with random sampling throughout bathymetric data collection to exclude data outliers.
Sonar data were combined with Landsat 8 (30 m resolution, Band 1, Coastal/Aerosol – 0.433-0.453 µm, Band 3, Green – 0.525-0.600 µm, Band 4, Red – 0.630-0.680 µm and Band 5, Near-IR – 0.845-0.885 µm) using ENVI’s SPEAR Relative Water Depth tool to create the highest resolution bathymetry map of Hamelin Pool, to date. The SPEAR Relative Depth tool uses the Stumpf and Holderied (2003) bottom albedo-independent bathymetry algorithm. The rendering was calibrated to absolute depth using the Log Ratio Transform and an imported ascii file of absolute elevations collected from the single beam sonar survey. The Log Ratio Transform method aids in decorrelating water depth from bottom albedo. Single beam sonar ground truth points follow a pattern. The coastal band was used in the bathymetry mapping as it is the shortest wavelength and therefore not absorbed as quickly in deeper waters. If light-waves are absorbed by the water, depth cannot be appropriately calculated as wavelengths are not reflected back to the sensor.

Oblique aerial photographs provided by Gumpei Izuno were captured roughly every hundred meters using a digital camera from the side of a fixed wing aircraft. Photos were georeferenced using ArcGIS to aid in mapping and determination of facies boundaries.

Nearly 60km of shoreline images were captured at low tide at an interval of about 10m using a Canon Powershot D20 with an internal true GPS. Photos were loaded into Picasa to reference their location on the shoreline. In addition, over 20Gb of underwater georeferenced photography was captured to aid in lower intertidal zone and subtidal zone identification of structures.
Towed video was used for ground truthing in 2012. GoPro Hero2 HD camera in a modified underwater housing and larger hydrodynamic casing was mounted to the starboard aft of the boat. Waterproof AV cables were connected to an onboard action TV so video could be not only be recorded, but also viewed in real-time.

Rigorous ground truthing was completed over the course of the three field seasons. The 2012 field season focused on predetermined transects, mainly extending from the headlands. Underwater video was towed and ground truth spot dives were made at changes in tonal variations from aerial orthophotos. Use of underwater video proved difficult for identification of subtidal pavement boundaries; thus continued campaigns focused primarily on in-water identifications. The 2013 field season focused largely along the margins of the pool extending from the shore to the shallow subtidal zone whereas the 2014 field campaign focused on the areas not covered in 2013. Offshore areas were also investigated, explored using manta tow with spot dives (Fig. 1.9).

All data were compiled into a comprehensive portable Hamelin Pool data system to be initially accessible to sponsors and ultimately to the public. The GIS dataset will contain all collated data from 2012, 2013 and 2014 field seasons.

3.2 Results
3.2.1 Hamelin Pool Bathymetry Map Results
The highest resolution digital elevation (DEM) model to date (Fig. 3.6) was generated based on the Stumpf and Holderied (2003) bottom albedo-independent bathymetry algorithm, resulting in an $R^2$ value of 0.698 (Fig. 3.7). Maximum depths in Hamelin Pool recorded by hydrographic survey are around 11 meters. The derived bathymetry model is more accurate in shallow waters than in the deeper waters, where the model begins to
Figure 3.6: Derived Bathymetry Model. The bathymetry model was derived from Landsat 8 image (bands 1, 3, 4, and 5) using the Stumpf and Holderied (2003) bottom albedo-independent bathymetry algorithm. Four Promontories are located on the western margin including (from north to south) Petit, Anchorage, Snake and Nilemah.
lose accuracy up to 1.3 meters. Measurement errors and type of fit were calibrated using
the third degree polynomial. This resulted in the best-fit model, which minimized the
variance of the unbiased estimators of the coefficients.

The derived model greatly improves upon the regional bathymetric setting and is
g geomorphically realistic, portraying the distinctly different underwater features along the
costline of Hamelin Pool. The model reveals the large-scale complexity and variability
around the margin of the embayment including the distinct asymmetry of the sublittoral
platform. Smaller scale physiography depicts former regional and local tectonics, current
movements and flows, shelf vs. ramp topography, all of which affect stromatolite growth.

The western margin of the Pool is dominated by four main promontories: Petit,
Anchorage, Snake and Nilemah (Fig. 3.6). Historical literature (Hagan and Logan 1974)
also makes note of a minor fifth bank, Nanga Promontory, which is present, but
negligible in the current model.
Geographically, the Pool can begin to be separated by regionally similar physiography. Moving anti-clockwise around the margin of the Pool the independent areas can be described as such:

- The northwest margin has one broad promontory (Petit Promontory). North of Petit Promontory, the intertidal zone is narrow and descends rapidly into the subtidal zone. South of Petit Promontory and north of Anchorage Promontory (the next promontory to the south) is a small bight. This bight has a narrow intertidal zone, and the sublittoral platform slopes and slopes into the basin in the first 500 meters from shore (Fig. 3.8a). The overall gradient of the bight is ~0.45% (~0.25° slope).

- South of Petit Promontory along the margin, three more Promontories mimic the headlands. Transects extending from the headlands across the promontories have low-grade ramps at 0.136% (~0.078° slope), paired with a sharply descending 70% gradient (35° slope) drop off at the bank margin into the basin to 6 – 7 meter water depth (Fig. 3.8b).

- Transects extending the southern headland better suit the published description of headlands modeled on the eastern margin (Fig. 3.8d). The gradient is a 0.33% (0.191° slope).

- Bights south of Anchorage Promontory, Snake Promontory and Nilemah Promontory have large intertidal zones with gentle ramps into the basin (similar to Fig. 3.8a).
• The southwest margin is a shore parallel narrow shelf up to 1.5 km wide with a broad intertidal zone and low 0.083% graded shelf (~0.05° slope) that drops swiftly into the embayment plain at a very sharp transition boundary with a 4% gradient (2.29° slope) (Fig. 3.8e).

• The southern region of Hamelin Pool, Nilemah Embayment, is a broad supratidal flat displaying a broad, gently sloping ramp with a 0.067% gradient (0.038° slope) into the basin (Fig. 3.9f).

• The southeast margin is dominated by a broad intertidal zone that mimics the headland as a large shallow subtidal platform before descending into the basin. This ramp geomorphology exhibits a 0.2% gradient (0.115° slope) (Fig. 3.9g)

• On the eastern margin, the intertidal zone becomes a narrow strip along the coastline. This zone transitions quickly into the subtidal zone onto a shore parallel narrow platform at a 0.467% gradient (0.268° slope) of about 4-5 meters water depth before transitioning to the basin (Fig. 3.9h). (The calculated gradient is one order of magnitude more gradual than the reported gradient of Jahnert and Collins (2012). This can be rationalized as gradients calculated by Jahnert and Collins (2012) were from multibeam survey data, which were unable to measure to shore as a result of depth limitations. If the first gradually sloped 500 meters of shoreward end of the transect are removed, the gradient becomes the same as reported by Jahnert and Collins (2012).

• Between Kopke and Yaringa Promontories the northeastern margin is dominated by broad supratidal flats and gently sloping ramps extending nearly 6 km from
Figure 3.8: Transects representing different shelf physiographies on the western margin. Transects display the first 1500 meters from shore (with the exception of b) on the western margin of Hamelin Pool. See transect locations in Fig. 3.6 (a) displays a transect extending a bight in the northwest. (b) extends a promontory on the western margin (but is extended to 2300 meters from shore to capture the drop into the basin). (d) displays a transect extending to the southeast of a headland. (e) displays the narrow shore-parallel shelf extending from the southwest margin.
Figure 3.9: Transects representing different shelf physiographies on the eastern and southern margins of Hamelin Pool. Transects represent different shelf physiographies within the first 1500 meters from shore. See transect locations in Fig. 3.6 (i) displays a transect extending a bight in the Northeast. (h) extends from a headland on the eastern margin. (g) displays a transect extending a ramp extending from the eastern margin. (f) displays a transect extending the from the shore in Nilemah embayment from south to north.
shore in some areas at a 0.067% gradient (0.038° slope) (Fig. 3.9i) before joining the embayment plain at 6 – 8 meters depth.

Interrogation of bathymetry data, and recognition of margin physiography has revealed that Hamelin Pool has an identifiable and variable tidal zone and sublittoral platform, with a wide array of an encompasses the sublittoral platform (between 1 to 5-6 meters). Zone 3 includes the embayment plain (greater than 5-6 meters). Using the three divisions in Hamelin Pool based on bathymetry may help offer insight to location of various structures.

3.2.2 Hamelin Pool Facies Map Results
Facies and subfacies of Hamelin Pool were mapped in great detail (Fig 3.10; Legend Fig. 3.11) using the new classification system (Fig 2.2) for Hamelin Pool. Mapped structures based on morphology, included: weakly lithified sheets, a variety of discrete microbial buildups (Fig 2.16), associated pavements, sediments breccia, boulders and beachrock mapped in detail based on extensive ground truth observations throughout the Pool (Fig 1.9). Structure locations around the margin of the Pool mapped with the new facies classification system displayed a previously unrecognized heterogeneity and distribution.

Total area and percentage of facies types (Table 3.1) display only a small amount of microbial deposits and pavements in relation to the vast area of Hamelin Pool.

3.2.2.1 Sheets
Sheet mats make up only 2.77% of facies area in Hamelin Pool, covering 40.99 sq. km in area (Table 3.1 & Table 3.2). Continuous sheets are the dominant sub-facies type within sheet mats and make up 95.68% of all weakly lithified stratiform sheets comprising only 2.61% of entire Hamelin Pool facies. Continuous sheets are found commonly in bights
Figure 3.10: High-resolution facies map of Hamelin Pool.
Figure 3.11: Legend of Hamelin Pool facies and sub-facies divisions. Colors identify the facies boundaries of the Hamelin Pool facies map (Fig. 3.10).

Table 3.1: Total area and percentage of facies types mapped in Hamelin Pool. Total area is measured at 1300 sq. km, including Hamelin Coquina deposits around the margin and bisecting the Faure Sill.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Total sq. km</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheet</td>
<td>40.99</td>
<td>2.77</td>
</tr>
<tr>
<td>Discrete Microbial Buildups</td>
<td>22.44</td>
<td>1.52</td>
</tr>
<tr>
<td>Pavement</td>
<td>138.85</td>
<td>9.38</td>
</tr>
<tr>
<td>Sediment</td>
<td>1274.99</td>
<td>86.10</td>
</tr>
<tr>
<td>Beachrock</td>
<td>0.091</td>
<td>0.01</td>
</tr>
<tr>
<td>Boulders</td>
<td>0.148</td>
<td>0.01</td>
</tr>
<tr>
<td>Breccia</td>
<td>3.321</td>
<td>0.22</td>
</tr>
</tbody>
</table>
Table 3.2: Total area and percentage sheets mapped in Hamelin Pool. % Facies indicates the area percentage of the total facies (ie: sheets). % Total Pool is the area percentage of that sub-facies type out all components mapped in Hamelin Pool.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Sub-Facies</th>
<th>Total sq. km</th>
<th>% Facies</th>
<th>% Total Pool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheet</td>
<td>Continuous</td>
<td>39.22</td>
<td>95.68</td>
<td>2.61</td>
</tr>
<tr>
<td></td>
<td>Ridge-Rill</td>
<td>0.30</td>
<td>0.74</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>Amoeboid</td>
<td>1.47</td>
<td>3.58</td>
<td>0.10</td>
</tr>
</tbody>
</table>

around the margin of the Pool, but the most dominant accumulations are found in Nilemah embayment and also in Hutchison Embayment. Ridge-rill and amoeboid sheet mats are minor components and typically form at the seaward end of continuous sheet mats dominantly in the southwest and southeast.

3.2.2.2 Discrete Microbial Buildups
Hamelin Pool contains the most abundant and diverse assemblage of modern marine stromatolites (Table 3.1 & Table 3.3). These discrete microbial buildups comprise only 22.44 sq. km of Hamelin Pool, or 1.52% of the entire area. When calculated at an average of four stromatolites per square meter, an estimation of total stromatolites in Hamelin Pool exceeds 100,000,000. Individual and merged columnar buildups are the most abundant stromatolite sub-facies type in Hamelin Pool comprising 34.76% of total stromatolite facies but only making 0.6% of the entire area of Hamelin Pool. Individual and merged columnar stromatolites are found in all locations around Hamelin Pool, in bights, embayments, off headlands and at the base of promontories. Individual columns, which make up an even smaller percentage, are typically the most common and widely known stromatolite structures.
Elongate-clustered stromatolites are the second most abundant discrete microbial buildups type found in Hamelin Pool making up 27.62% of the facies designation and 0.48% of designated facies in the Pool. Elongate-clustered stromatolites are located in Nilenah embayment as well as in the northeastern bight.

Elongate-nested discrete microbial buildups are the third most abundant structures, comprising 13.73% of total stromatolite facies, but only 0.24% of total area within the Pool. Elongate-nested structures are found primarily on the west side of the Pool in large fields south and south east of headlands and their associated promontories. Elongate-nested structures are also located on the eastern margin south of headlands, but are much smaller and not as well-developed.

Elongate structures, a smaller component of discrete microbial buildups, making up only 6.69% of total discrete microbial buildups and covering only 0.12% of the total Hamelin Pool area. Elongate structures are located mainly in the central location of bights, always trending perpendicular to shore. They are common in the northeast, as well as in the southeast with additional structures located on the western margin.

Segmented / Composite are another small constituent of Hamelin Pool discrete microbial buildups, composing 6.53% of total stromatolite structures and only 0.11% total area of the Pool. Segmented and composite structures (often massive) are typically found in the subtidal zone in about 2-4 meters water depth around the margin. They are most common along the eastern margin, in the deeper areas off the western margin, but are also common in the northwestern bight, where the intertidal zone is narrow and drops quickly to that depth range.
Seif stromatolites are a small facies component and dominate the southwestern shelf, but are not found in many other locations throughout Hamelin Pool. Seif stromatolites make up only 6.19% of the total discrete microbial facies type, comprising only 0.11% of the entire Pool.

Table 3.3: Total area and percentage of discrete microbial buildups mapped in Hamelin Pool. % Facies indicates the area percentage of the total facies (ie: discrete microbial buildups). % Total Pool is the area percentage of that sub-facies type out all components mapped in Hamelin Pool.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Sub-Facies</th>
<th>Total sq. km</th>
<th>% Facies</th>
<th>% Total Pool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discrete Microbial</td>
<td>Individual / Merged</td>
<td>7.80</td>
<td>34.76</td>
<td>0.60</td>
</tr>
<tr>
<td>Buildups</td>
<td>Elongate</td>
<td>1.50</td>
<td>6.69</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>Elongate Nested</td>
<td>3.08</td>
<td>13.73</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>Elongate Clusted</td>
<td>6.20</td>
<td>27.62</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>Seif</td>
<td>1.39</td>
<td>6.19</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>Segemented / Composite</td>
<td>1.47</td>
<td>6.53</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>Tabular</td>
<td>1.01</td>
<td>4.49</td>
<td>0.08</td>
</tr>
</tbody>
</table>

The smallest discrete microbial buildup subfacies is tabular buildups. These flat-topped deposits make up only 4.49% of the facies type, covering only 0.08% of Hamelin Pool area. Tabular stromatolites are found in the northwest of Hamelin Pool, on the western margin, but most frequently along the eastern margin.

3.2.2.3 Pavement
Subtidal Pavements found in Hamelin Pool make up the largest facies division second to sediments (Table 3.1 & Table 3.4). Pavements cover 138.85 sq. km of Hamelin Pool, making up 9.38% of the area enclosed in the embayment. Sub facies divisions included: tabular pavement, which was mapped as the same facies unit as blocky pavement; low-relief microbial pavement, mapped in the same unit as undulose pavement, as both are
subtidal pavements covered with microbial mats and accreting; transitional pavement is a combination of the two. Tabular and blocky pavement cover over 100 sq. km of Hamelin Pool, making up 95.68% of the pavement facies type, and 7.01% of the entire area, and occurs all around the pool, but is minimal in the northwest. Low-relief microbial/undulose pavement makes up 15.54% of the facies and is often found as the subtidal pavement shoreward of the tabular pavement. Transitional pavement makes up only 9.66% of the pavement facies division and 0.91% of the total Hamelin Pool Facies.

Table 3.4: Total area and percentage of pavement mapped in Hamelin Pool. % Facies indicates the area percentage of the total facies (ie: pavement). % Total Pool is the area percentage of that sub-facies type out all components mapped in Hamelin Pool.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Sub-Facies</th>
<th>Total sq. km</th>
<th>% Facies</th>
<th>% Total Pool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pavement</td>
<td>Tabular/Blocky</td>
<td>103.85</td>
<td>95.68</td>
<td>7.01</td>
</tr>
<tr>
<td></td>
<td>Transitional</td>
<td>13.42</td>
<td>9.66</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>LRM / Undulose</td>
<td>21.58</td>
<td>15.54</td>
<td>1.46</td>
</tr>
</tbody>
</table>

3.2.2.4 Sediments
Sediments are the main facies component throughout the Pool making up over 86% of facies (Table 3.1 & Table 3.5). Floatstone is the most abundant sediment type in Hamelin Pool comprising 48.61% of all sediments and 41.85% of the entire Hamelin Pool embayment. It is the most common facies type and occurs throughout the Pool, but is less common in Nilemah Embayment, as well as near the Faure Sill. Grainstone is the second most abundant sediment type, comprising 34.39% of all sediments and 29.61% of the entire Hamelin Pool embayment. Grainstone is found at the Faure Sill in the northern region of Hamelin Pool. Grainstone is also common to the north of promontories on the western margin, in the embayment plain, and in the northeastern bight. Packstone is the
next most abundant sediment in the pool composing 9.41% of all sediments and 8.10% of the entire Hamelin Pool embayment. Packstone is common in Nilemeh embayment and to the north of Snake Bank and in the northeasterly bight. The smallest sediment component in the Pool is coquina rudstone. Rudstone makes up 7.60% of all sediments and 6.54% of the entire Hamelin Pool embayment. Cemented Hamelin Coquina is found around the margins of the Pool. Live *Fragum erugatum* are found in small beds in sporadic locations along the western margins and often out on the promontories in thin surface beds. Along the eastern margin, live fragum beds are abundant. Rudstone is also located in Hutchison Embayment. Rudstone in Hutchison

*Table 3.5: Total area and percentage sediment types mapped in Hamelin Pool. % Facies indicates the area percentage of the total facies (i.e., sediments). % Total Pool is the area percentage of that sub-facies type out all components mapped in Hamelin Pool.*

<table>
<thead>
<tr>
<th>Facies</th>
<th>Sub-Facies</th>
<th>Total sq. km</th>
<th>% Facies</th>
<th>% Total Pool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediments</td>
<td>Rudstone</td>
<td>96.84</td>
<td>7.60</td>
<td>6.54</td>
</tr>
<tr>
<td>Floatstone</td>
<td>619.74</td>
<td>48.61</td>
<td>41.85</td>
<td></td>
</tr>
<tr>
<td>Grainstone</td>
<td>438.47</td>
<td>34.39</td>
<td>29.61</td>
<td></td>
</tr>
<tr>
<td>Packstone</td>
<td>119.93</td>
<td>9.41</td>
<td>8.10</td>
<td></td>
</tr>
</tbody>
</table>

Embayment contains rare *Fragum erugatum*, but is instead by large cornflake like micritic flakes.

3.2.2.5 Beachrock

Beachrock is not a common constituent in Hamelin Pool, but is present along the margin, covering only about 0.09 sq km of Hamelin Pool, less than 0.01% of the total Pool area (Table 3.1 & 3.6). Beachrock is most commonly found centrally, along the eastern margin and also in the northwest. Coquina beachrock could also be included as a
rudstone facies, as it is composed predominantly *Fragum erugatum* shells. It is important to identify the location of prevalent beachrock as a possible indicator of fresh water.

3.2.2.6 Boulders

Boulders are also a small component in Hamelin Pool, covering only 0.15 sq. km, less than 0.01% of the total area (Table 3.1 & 3.6). Boulders are often allochthanoous blocks that are brought in by possible storm, cyclone, or tsunami activity. These blocks often form the base for stromatolite nucleation. The most common localities for boulders are near the Faure Sill on both east and west sides of the Pool. Additionally, deposits are abundant in the northeast and east.

Table 3.6: Total area and percentage of individual facies types that do not have sub-facies types. % Facies indicates the area percentage of the total facies – ie: 100% of individual facies. % Total Pool is the area percentage measured against all components mapped in Hamelin Pool.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Sub-Facies</th>
<th>Total sq. km</th>
<th>% Facies</th>
<th>% Total Pool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beachrock</td>
<td></td>
<td>0.09</td>
<td>100.00</td>
<td>0.01</td>
</tr>
<tr>
<td>Boulders</td>
<td></td>
<td>0.15</td>
<td>100.00</td>
<td>0.01</td>
</tr>
<tr>
<td>Breccia</td>
<td></td>
<td>3.32</td>
<td>100.00</td>
<td>0.22</td>
</tr>
</tbody>
</table>

3.2.2.7 Breccia

Breccia covers a total of 3.32 sq. km, making up 0.22% of Hamelin Pool area (Table 3.1 & 3.6). Breccia fields are uncommon in the northwest, but become more common moving south along the western margin. Breccia fields are also found along the fringing margins of Nilemah embayment, along the eastern margin and are prolific along the northeastern margin. In the time from the last sea level highstand 6800 years BP, a change in relative sea level exposed many sheet mats and structures around the margin of
the pool which later spalled and eroded into the breccia facies. Therefore these structures are most commonly found in bights.

Simplifying the facies model into the main facies divisions: sheets, discrete microbial buildups, pavements and sediments provides a straightforward model of facies locations around the margin (Fig. 3.12) Results from this summary visually demonstrate the small area in the pool dominated by discrete microbial buildups. Although the shore parallel band of stromatolite facies comprises less than 2% of the total area in Hamelin Pool (Table 3.1), Hamelin Pool remains the largest assemblage of modern stromatolites in existence. The narrow facies belt along the margin of the large embayment may help interpret ancient systems, especially those on the margin of elongated rifts that offer similar physiography of the Pool. As a result of the large embayments, Nilemah and Hutchison, sheet mats cover more area (<3%; Figure 3.1) than discrete microbial buildups, however are confined to smaller bights around the remainder of the margin. Pavements, also induced by microbes, cover a markedly higher area (>10%; Table 3.1). Sediment facies make up the largest area percentage (>86%; Table 3.1) of Hamelin Pool. Composition of sediments may be one of the most important factors aiding in interpretation of similar systems.

3.3 Discussion

Production of the high-resolution bathymetry model in this chapter exposed the underwater terrain in Hamelin Pool, which in turn provides new insight to stromatolite distribution. Previous research has helped resolve the location of the tidal zone (Logan et al. 1974, Burne and Johnson 2012, Playford et al. 2013) and facilitated the division of the
Figure 3.12: Simplified Facies Model. High-resolution Facies model simplified into four main components: Discrete Microbial Buildups include: individual and merged columnar, elongate, elongate-nested, elongate-clustered, segmented/composite, seif and tabular structures. Pavement includes: low-relief microbial/undulose, transitional and tabular/blocky. Sheets include continuous, ridge-rill and continuous. Sediments include: packstone, grainstone, floatstone and rudstone. Additionally boulders, beachrock and breccia (breccia is cemented grainstone) were included in the sediment division.
bathymetry model into three simple zones (Fig. 3.13). Along the shoreline, zone 1 (not to be confused with Burne and Johnson’s (2012) microbial community zones 1-3, which would all fall into the currently described zone 1 domain) extends to a depth of 1 m. This zone includes the entire tidal zone from the remainder of the Pool, including the supratidal zone that is affected by extreme high tides, the intertidal zone and the shallow subtidal zone, which are affected by abnormal low tides. Comparison between the bathymetry map and the facies map indicates this is the most common area for stromatolite growth. Zone 2 encompasses the sublittoral platform (up to 5-6 meters) and is dominated by sparse buildups and pavement. Zone 3 includes the embayment plain (up to 11 meters). The basin floor is devoid of stromatolite growth and other structures, aside from the random block deposited by storms or other high-energy events. Instead, abundant seagrass beds are found in the north and an organic rich southern embayment.

Structures are prevalent all around the margin in various sizes and shapes, dominating zone 1. The varying underwater terrain and physical geometries are believed to reflect the underlying geologic controls. Physiography also has a large impact on how wave energy is dissipated, which would affect the shoreline and accreting structures. The elongation of Hamelin Pool is controlled by a N-S oriented fault system while the promontories visible on the western margin are a result of a NE-SW fault system (Jahnert and Collins 2012 and 2013). The western margin is flanked by the Nanga Peninsula, covered by red, iron rich transverse and parabolic sand dunes (Playford et al. 2013). Erosion truncates dune ends of the Peron Sandstone where sediment is rich in quartz. At the base of some sandstone deposits, boulders have been dislodged from the bluffs
Figure 3.13: Bathymetry Zones. Generalized map depicting the (1) derived tidal zone (supratidal, intertidal and shallow subtidal), (2) the sublittoral platform and the basinal embayment plain (3). Promontories along the western margin are also identified: (a) Petit, (b) Anchorage, (c) Snake, (d) Nilemah. Nilemah embayment is also labeled (e).
resulting in rocky substrates in the intertidal zone (Logan and Cebulski 1970). The gentle sloping of the western bights, southern and eastern embayments result from lower sea levels during the last glacial. Because sea level was much lower, wind blew exposed marine skeletons and other sediments into dunes onto marginal anticlines. The eastern margin is composed of flat Cretaceous and Pleistocene limestone beds that are eroded into platforms (Logan and Cebulski 1970), contributing to the ramp geomorphology. In the northeast, sediments are often comprised of small lithoclasts that originated from the surrounding eolianite (Logan and Cebulski 1970). Littoral currents and tidal scour are important energy factors (Logan and Cebulski 1970, Logan et al. 1974), which move across the terrain and help shape the structures.

Examining how the underlying geomorphology can affect the energy regime and water movement in Hamelin Pool may help provide answers to structure morphology in the long-lived stromatolite argument involving nature (biology) vs. nurture (environment) (Ginsburg 1991). An example of this concept can be witnessed in embayments with low gradients, low energy (Logan and Cebulski 1970), and well-defined tidal zonations (Logan et al. 1974). Both the large bight in the northeast and large Nilemah Embayment in the south share the same low gradients (0.067% gradient). In bights, wave action is dampened by adjacent headlands and refracted when crossing over the shelf so that wave energy is perpendicular to shore. The Nilemah Embayment is sheltered on three sides and protected from southerly winds. As a result of the protected environments and low gradient ramps, wave energy is dissipated. Both of these regions share the same main facies types: continuous sheets and elongate-clustered stromatolites, with elongations perpendicular to shore. These structures are more apt to have a strong biological
influence than physical energy. This hypothesis will be examined in the following chapters with field monitoring data.

Other areas of the Pool display different geomorphology, also resulting in different structures. In the southeast, the low-grade ramp is reported to have a drag effect on incoming waves, causing the wave height to change as it nears shore. Because the wavelength shortens and the frequency of the wave remains the same, the shallow water will result in breaking waves and causing turbulent flows that will have an effect on structure morphology (Logan and Cebulski 1970). The southeastern margin exhibits common individual and merged columnar structures, indicating that the turbulent flow may result in this structure type.

As observed in Fig. 3.9h, headlands on the eastern margin show gradients consistent with previous research, with smooth, irregular or steep gradients typically impacted with high energy and fronted by “deep” water (Logan and Cebulski 1970, Logan et al. 1974) Headlands on the eastern margin are eroded Pleistocene dune rocks and/or Cretaceous limestone (Logan et al. 1974). Carbla Point, the iconic headland on the eastern margin exhibits the described steeper gradient, with resulting high energy impacting the coastline. As a result of intense energy and wave stress resulting from physical processes, stromatolite morphologies are influenced (Hoffman 1976). Similar to the southeast, the Carbla Point headland is dominated by individual and merged columns, often with thin basal necks. Strong wave energy also contributes to suspension and resuspension of grains and other bioclasts that are subsequently trapped and bound, facilitating structure accretion. Structures in this environment have been recorded to reach heights of up to 1.5 meters. Therefore, as witnessed in both the east and southeast margin of the Pool, high-
energy environments and the resulting turbulent flows on may have more of an effect on structure morphology than the biological component.

Headlands on the western margin (Fig 3.8b-c) display different gradients than eastern headlands, typically mimicked by large broad promontories. Western Promontories have gradual slope gradients before dropping sharply to meet the embayment plain. Stromatolitic buildups are not found growing on promontories long distances from shore, albeit depth and substrate are suitable. Steep gradients at the promontory margins, are impacted by high energy which is evidenced by the tabular pavement broken into blocks.

Similar to the boundary edge of promontories, the southwestern margin also has steep marginal slopes where wave energy is expended at the shelf break. Blocky pavement is found along the margins here as a result of the wave power and reworking. Blocky pavement is therefore a common feature along the western side. Blocky pavement is present on the eastern margin, but not to the extent of the west.

The most detailed exploration of the Pool to date has resulted in recognition of a complex arrangement of facies types varying drastically around the margin displaying incredible macro-morphological forms, shapes, scales and diversity. Different facies associations appear to be influenced by shelf physiography, associated energies and available substrate.

3.4 Conclusions

Four different maps were generated and presented in this chapter: a high-resolution bathymetry map, a simplified bathymetry map, a high-resolution facies map and a simplified facies map.
The high-resolution bathymetry model advances previously generated models as due to the increased resolution satellite imagery and availability of high-density depth soundings. Additionally, these depth data were processed in combination with an algorithm that largely eliminates substrate effects. Previously unobserved/undocumented geomorphologies around the margin were illuminated with the current model. Regional-scale physiographic similarities and differences were exposed, facilitating a better understanding of the interaction of microbial buildups and their associated facies with the environment (ie: shelf vs. ramp, headland vs. bight, grade of slope into the basin, the location relative to the Faure Sill, etc.). This bathymetry model allowed for the production of the generalized bathymetry distinguishing three main zones: (1) tidal, (2) sublittoral platform and (3) basin, establishing potential real-estate for microbial structure development.

The high-resolution facies map eliminated mapping based on structures classified by microbial surface mat, but instead focused the distribution of different morphological structures. Our classification regime advances previous models, not only by classifying facies types in a novel way, but also in integrating the most comprehensive ground truth survey of Hamelin Pool to date. Results add a new level of accuracy in identification and distribution of various facies in Hamelin Pool. The high-resolution facies model facilitated consolidation of multiple sub-facies delineations into the five main facies divisions: sheets, discrete microbial buildups, pavement, sediments and other (breccia, beachrock and boulders). The simplified facies map helps provide insight to ancient environments in regards to facies abundance. The narrow facies band of discrete microbial buildups is likely related to biology (nature), whereas the morphological
delineated subfacies may provide more insight to physical parameters and location (nurture).

At the onset of this research, stromatolite investigation was paramount. At the conclusion of the mapping investigation, interesting results showed that stromatolites comprised less than 2% of Hamelin Pool facies. Stratiform sheets and subtidal pavements made up a larger area percentage than stromatolites, but most notable is the sediment facies, making up over 86% of Hamelin Pool facies (Fig. 3.14).

![Facies percentages in Hamelin Pool](image)

Figure 3.14: Facies percentages in Hamelin Pool.

The new maps, when used in connection with each other reveals further insight regarding spatial distribution of microbial deposits located around the margins of Hamelin Pool. Understanding the general physiography of the Pool and the location and type of structures present raises new questions regarding the intrinsic vs. extrinsic controls on stromatolite development, particularly involving the local environmental pressures.
Chapter 4  
ENVIRONMENTAL PRESSURES IN HAMELIN POOL

4.1  Overview

Environmental pressures are fundamental in understanding modern stromatolite growth. Seawater chemistry affects which microbial community is best suited/tolerant to a particular environment, microbial metabolism, as well as seawater carbonate saturation state (Riding 2000). High salinity levels exclude eukaryotes, resulting in reduction of grazing animals (Garrett 1970, Walter and Heys 1985), and/or competition for space (Fischer 1965).

The favorable theory for stromatolite accretion is a complex interaction of biological, chemical, hydrodynamic, and sedimentological factors (Bosak et al. 2013a and 2013b). Changes in the Earth’s atmosphere, changes in ocean chemistry including carbonate saturation state and availability of free-oxygen (Grotzinger 1990), along with evolution of species have affected stromatolite growth through time, resulting in their decline (Fischer 1965, Garrett 1970, Walter and Heys 1985, Feldmann and McKenzie 1998). Because stromatolites are uncommon today, it is assumed that all conditions must be met to initiate structure growth. Prolific stromatolite development in Hamelin Pool is perhaps a result of the extreme physical and chemical conditions that have persisted for the last 2700 years (Chivas et al. 1990).

In order to better understand the modern Hamelin Pool system, it is critical to capture the environmental pressures permitting stromatolite growth. The assemblage in Hamelin Pool is relatively recent, containing stromatolites with ages dating back only a few thousand years.
The evolution of the Hamelin Pool basin set the stage with conditions conducive to stromatolite accretion. Around four thousand years ago, sea level stood roughly two meters higher than present (Logan et al. 1974, Burne 1990). Abundant sea grass banks were thriving at the mouth of the current Hamelin Pool embayment and began to facilitate growth of the Faure Sill. Water exchange became restricted over the sill and over time sea level began to fall, further restricting flow. Several small channels transect
the Faure Sill, but the majority of flow happens through Will Succeed Channel, the deepest and largest conduit, allowing for the bulk of water exchange between the two bodies (Logan and Cebulski 1970) (Fig 4.1). Minimal recharge paired with evaporation rates one order of magnitude greater than precipitation rates (Historical data presented in Table 4.1), result in a highly saline, evaporative body of water (Logan and Cebulski 1970). Salinity gradients, temperature gradients, desiccation gradients (tide influence) and other characteristics of the Hamelin Pool hydrologic system including waves, currents and water chemistry exert control and influence the distribution of the microbial assemblages and associated facies in Hamelin Pool (Logan and Cebulski 1970, Logan et al. 1974, Golubic and Hofmann 1976, 1985, Playford 1990, Jahnert and Collins 2011, 2012, Burne and Johnson 2012, Playford et al. 2013 and Collins and Jahnert 2014).

Table 4.1: Historical Environmental Records. Average temperature, rainfall and evaporation data compiled over 45 years of recordings by the Royal Australian Air Force, 1943 (Logan and Cebulski 1970).

<table>
<thead>
<tr>
<th>Location</th>
<th>Month</th>
<th>Average max. temp. (°C)</th>
<th>Average min. temp. (°C)</th>
<th>Rainfall (cm)</th>
<th>Evaporation (cm)</th>
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<td>36.67</td>
<td>20.22</td>
<td>0.66</td>
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<td>February</td>
<td>36.28</td>
<td>20.72</td>
<td>1.27</td>
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<tr>
<td></td>
<td>March</td>
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<td>19.61</td>
<td>1.45</td>
<td>25.40</td>
</tr>
<tr>
<td></td>
<td>April</td>
<td>30.50</td>
<td>16.83</td>
<td>0.99</td>
<td>17.78</td>
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<tr>
<td></td>
<td>May</td>
<td>25.00</td>
<td>12.94</td>
<td>3.15</td>
<td>10.16</td>
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<tr>
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<tr>
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<td>0.36</td>
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<td>14.67</td>
<td>20.07</td>
<td>218.44</td>
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</tbody>
</table>

4.1.1 Salinity

High salinity concentrations in Hamelin Pool help to limit eukaryotic organisms that would prohibit growth of stromatolite building microbial communities (Fisher 1965,
Salinity in Shark Bay increases as one moves farther from the Indian Ocean and can be categorized into three different zones. Where the Indian Ocean meets Shark Bay, water remains of oceanic salinity (35-40‰), then progresses to metahaline salinity (40-55‰) moving south down Disappointment Reach and develops into a hypersaline (50-70‰) body of water after crossing the Faure Sill. The Faure Sill, formed around 4000 years ago, is the semi-restrictive barrier creating the salocline between Hamelin Pool and Disappointment Reach (Logan et al. 1974).

Another mechanism of altering Hamelin Pool salinity is the input of water other than recharge from over the sill. This includes the rainwater and/or groundwater input. Due to the subtropical arid to semi-arid climate, most precipitation occurs in the Pool during the winter months (May, June and July) and is sporadic and highly localized across the Shark Bay area (Logan and Cebulski 1970; table 4.1). Periods of heavy rainfall can occur during the summer months (December through March) when associated with cyclones (Logan and Cebulski 1970). Continental groundwater can appear as freshwater lenses within Pleistocene sands and coquina beach ridges. Artesian water can discharge from boreholes drilled into the aquifer system underlying near-surface sands. Marine brines formed from continued evaporation can also be discharged as groundwater (Burne et al. 1982).

4.1.2 Temperature
Historically reported temperatures of Hamelin Pool cover a broad range, between 15°C to 30°C. This wide range is an additional factor contributing to the exclusion of eukaryotes. Summer water temperatures range between 26 - 30°C and winter temperatures typically
range between 15 - 20°C (Burne and Hunt 1990, Logan et al. 1974). Logan and Cebulski (1970) and Burling et al. (1997) reported that the circulation pattern in Hamelin Pool is such that there is no vertical thermal stratification of the water column. It remains unclear if temperature is variable around the margin or between the sublittoral platform and the basin. As to date no data temperature data has been reported from the basin.

4.1.3 Tide
Tide is a major factor controlling water movement (Logan and Cebulski 1970). Hamelin Pool has a semidiurnal tide with tidal movement dampened by the Faure Sill, which attenuates 60-75% of the energy (Burling et al. 2003). The zonation of microbial mats, stromatolites and other microbial buildups found in Hamelin Pool have generally been related to frequency of inundation and exposure/desiccation within the tidal zone (e.g. Logan 1961, Logan et al. 1974, Golubic and Hofmann 1976, Golubic 1985, Playford 1990, Jahnert and Collins 2011, 2012, Burne and Johnson 2012, Playford et al. 2013).

Historical tidal records have been collected from two locations, both along the southeastern margin of Hamelin Pool. The first tides were collected between June 1979 to August 1980 (15 months/416 days) by the Western Australian Department of Marine and Harbours at 15-minute intervals (Playford 1990, Playford et al. 2013). The second set of historical data were recorded and collected between October 1983 and April 1985 (18 months/unknown days) by the Baas Becking Geobiological Laboratory at two-hour intervals (Burne and Johnson 2012). Based upon these records, the accepted range of the Hamelin Pool tidal zone was established as 93 cm above and 66 cm below mean sea level (Playford et al. 2013). The supratidal zone is classified as the area above mean high water level to highest high tide mark, extending from 25 cm to 93 cm above mean sea level.
The intertidal zone is the area between mean high water and mean low water, between 25 cm above and 20 cm below mean sea level. Shallow subtidal zone is classified below mean low water level and lowest tide level or 20 cm to 66 cm below mean sea level (Playford et al. 2013).

By definition, tide typically refers to the periodic rise and fall of the sea, produced by gravitational forces of the moon and sun. However, Hamelin Pool is a shallow, restricted marine embayment, with strong meteorological influences. Often, the meteorological pressures may overpower the astronomical influence, and therefore must be examined in the tidal signal. Tidal oscillation is strongly influenced by the southerlies, which are strongest in summer and can inhibit flood waters and suppress normal tidal oscillation (Read 1974, Playford 1990, Playford et al. 2013). Burne and Johnson (2012) noted the meteorological and astronomical signals, but also separated the tide into two additional components: the seasonal and short term irregular (11 day cycles).

The daily tide in Hamelin Pool, based on an irregular oscillating mean, is reported to be around 60 cm (Logan and Cebulski 1970). The shifting mean is a result of seasonal effects where mean position is 50 cm higher during winter months as a result of higher water levels due to light southerly winds, higher precipitation rates paired with lower evaporation rates. Levels can also be affected by occasional abnormally high or low tides, northerly winds, cyclones or low-pressure systems. As a result, overall tidal range is much larger over the course of the year (Hagan and Logan 1974, Burne and Johnson 2012, Playford et al. 2013).
4.1.4 **Currents & Winds**  
It is well accepted that stromatolite morphologies come in a variety of shapes and forms as a result of the physical environment, namely water movement producing shear and abrasion (from moving sediments) forces (Logan 1961, Gebelein 1969, Logan et al. 1974, Hofmann 1973 and 1976, Hoffman 1976, Walter 1976, Ginsburg 1991, Andres & Reid 2006, Eckman et al. 2008 etc.). Logan and Cebulski (1970) reported that tidal currents and wind driven longshore drift promoted the regional circulation within Hamelin Pool, however when current flow within Shark Bay was diagramed, general information for Hamelin Pool was not included. To date, general direction of currents with the embayment are still unknown, however it is clear that winds have a large effect on water circulation.

The wind-wave system in Hamelin Pool is the result of local winds blowing over the surface of the water. Waves are influenced by the wind speed, fetch, width of the fetch, wind duration and water depth (Young 1999). The wind influence in Hamelin Pool creates a large amount of random wave-action in regards to wave height, wave-length, wave period, duration and direction. However, waves are typically refracted when crossing onto the sublittoral platform, turning them perpendicular to shore (Logan and Cebulski 1970), regardless of wind.

In long term tidal monitoring and coincident wind records, the effect of wind on sea level and water movement can be observed (Burne and Johnson 2012). Summer month winds are predominantly from the south, and strongest between October and March averaging between 18-28 km/hr with a maximum-recorded velocity of 45 km/hr. Prevailing southerlies help push the water body north, which in combination with high atmospheric
pressure, low rainfall and high evaporation rates result in overall lower Hamelin Pool water levels in summer than in winter (Playford et al. 2013). Long durations of strong southerlies in summer months can dampen the normal tidal cycle, reducing water exchange across the Faure Sill. Although southerlies also dominate in winter months, the strength and duration is much lower than in the summer months and only average between 9-15 km/hr often resulting in higher water levels in the south (Logan and Cebulski 1970).

The tradewinds also influence water level in Hamelin Pool bringing strong sea breeze system typically in the afternoons (Logan and Cebulski 1970), piling water on the eastern margin.

Cyclonic winds 80 – 120 km/hr can occur on average every 6 years gusting to maximum velocities of 180 – 200 km/hr and often lasting for a duration of up to 12 hours. Cyclonic events are accompanied with heavy rains (Read 1974) and have the capability to substantially rework, reshape and/or remove beaches, intertidal zone sands and/or structures. These episodes can cause long periods of abnormal microbial mat exposure and/or inundation (Burne and Johnson 2012, Playford et al. 2013).

The Bureau of Meteorology began recording storm activity in Shark Bay in 1906. Historically, cyclones approach from the north and the northeast and have caused significant changes to the sublittoral platform as a result of reworking from wave action and flooding (Logan et al. 1974). As a consequence of the disturbance events, many larger sediment grains are moved into the deeper parts of the embayment plain (Jahnert and Collins 2012), which may also get churned and mixed into the water column.
Hamelin Pool has dark, organic rich, basinal sediments in the southern region and following cyclone events, water has been reported the water becomes a dark, murky shade of gray to black from re-suspended bottom sediment (Mack, R., Personal comm. DPaW, 2012).

In addition to cyclonic events, Hamelin Pool has also been impacted and shaped by tsunamis (Playford et al. 2013). Tsunamis are a natural catastrophic phenomenon caused by large underwater earthquakes, submarine landslides, underwater volcanic eruptions and asteroid impacts that cause mass water movement, impacting shorelines. Sedimentological units are often displaced by these catastrophic waves. Evidence in Shark Bay includes boulders up to 700 tons torn from coastal cliffs and carried up to 400 m inland and 15 m above sea level (Scheffers et al. 2008, Playford et al. 2013). Bryant et al. (2007) recorded stories passed down from the traditional owners observing large waves overtaking the coastline and wiping out entire tribes as recent as the 17th century. Deposition of the oldest and largest (nearly 9 meters above sea level) dune at Flagpole Landing is attributed to a mega-tsunami that occurred less than 3,000 years ago (Playford et al. 2013).

In addition to physical factors, water chemistry plays an important role in cementation and lithification of microbial buildups. Recent surveys conducted by Jahnert and Collins (2012) show that pH (7.5 – 8.6) and Ca$^{2+}$ ion availability (500 – 1080 mg/l) are both high, supporting high rates of cementation. Additional samples are needed to capture water chemistry along the margin of the Pool.
Although environmental data has been collected in several intervals since the inception of research in Hamelin Pool, it is often unclear how and where the data was collected and many questions remain unanswered, for instance:

1. Salinity has never been logged over a continuous period in Hamelin Pool. Existing records were collected from point measurements and distribution is unclear.

2. It is unknown if temperature in Hamelin Pool has been logged on a continuous basis as methods and locations are unclear. Long-term temperature variation, regional differences and vertical temperature stratification in the water column are unknown.

3. Water level has been investigated in the southeast region of Hamelin Pool. As it has been reported that the meteorological tide influence is larger than the astronomical tidal influence, regional water levels should be examined. Short term events and seasonal weather influences may have different effects on water levels during different times of the year, in turn regionally affecting microbial mat aerial exposure episodes.

4. To date, general direction of currents within the Hamelin Pool embayment, remain unknown.

5. Although Baas Becking geobiological laboratory carried out a large study on the water chemistry of Hamelin Pool, collection sites were limited to the southern region of Hamelin Pool and were not able to capture Pool variability. Additionally, more information is needed regarding carbonate saturation state of Hamelin Pool and available Ca²⁺ ions. This information will advance our
understanding of stromatolite and pavement precipitation of calcium carbonate cements.

4.2 Research Objective
In order to better understand the environmental parameters affecting the growth of the modern Hamelin Pool system, a series of loggers and in situ measurements are needed to address the gaps in knowledge. Continuous salinity and temperature logging are needed to observe annual variability and capture horizontal and vertical temperature stratification of Hamelin Pool waters, and how they influence microbial communities. Environmental parameters including tide (both meteorological and astronomical), currents and wind should provide insight to understanding structure morphologies. The effect of local winds, pressure systems and abnormal disturbance events may contribute to erosional forces by lifting and moving sediments in the water column.

Another factor to consider in long term monitoring of Hamelin Pool is in relation to the effect of sea level rise and the impact it may have on the modern microbial system. If sea level continues to rise, this contemporary system may be eradicated. Indeed, this may be the most critical time to monitor stromatolites. We must develop a baseline for understanding what factors affect and contribute to stromatolite growth. Monitoring changing environmental pressures in the coming decades can provide a measure of how these factors influence and impact the system. Therefore, this research objective to capture the heterogeneity of salinity, tides, temperature and currents around the margin of the Pool is critical for understanding the system.
4.3 Materials & Methods

4.3.1 Picket Installation

Sixteen star-pickets were installed for logger attachment and deployment in multiple locations around the margins of Hamelin Pool in an attempt to capture the regional variability of environmental parameters (Fig 4.2). Pickets were set in in the basin (5 – 8.5 m depth) and on the sublittoral platform (2 m depth). Eleven pickets were established at the marine end of predetermined transects chosen with the assistance of Dr. Playford in 2012.

Absolute elevation of tidal loggers was determined using high precision survey grade single beam sonar (Ohmex SonarMite v3 EchoSounder - Legacy) coupled directly to a Trimble rover. The rover was hard mounted on a boat at a fixed height above the water surface with the transducer mounted directly to the rover pole. Depths were subtracted from the measured water surface elevations giving an absolute elevation at each sample point. The nominal zero elevation was established using RTK survey and post processed to correlate with the Hamelin Pool benchmark north of Flagpole Landing (A906; 4.253 m below Australian Height Datum).

4.3.2 Salinity Loggers

Salinity data were collected using AquiStar CT2x submersible smart sensors capable of collecting a wide range of conductivity measurements (10,000 to 100,000 μSiemans/cm). Logging was continuous except during biannual collection (downloading, cleaning and redeployment of loggers). Salinity loggers were attached to the pickets at ~2-3 m depth and set to record at 30 minute intervals from 8 March 2013 to 9 November 2014 (609 days).
4.3.3  **Temperature Loggers**
Onset HOBO TidbiT v2 Water Temperature Data Loggers (UTBI-001) were attached to the star pickets and set to record temperature at 30-minute intervals from 6 April 2012 to 9 Nov 2014 (944 days). Logging was continuous except during biannual collection (downloading and redeployment of loggers). Five additional key locations were selected in 2013 on the sublittoral platform that included the northwest, west, south, east, and northeast. Temperature loggers were attached to pickets at ~2-3 m depth and set to record at 30 minute intervals from 8 March 2013 to 9 November 2014 (609 days).

4.3.4  **Pressure Loggers**
Tidal data were collected using Solinst Model 3001 Levelogger Junior Edge and calibrated against local Hamelin Pool barometric pressure. Temperature loggers were attached to the shallower pickets at ~2-3 m depth and set to record at 30 minute intervals from 8 March 2013 to 9 November 2014 (609 days). Logging was continuous except during biannual collection (downloading, cleaning and redeployment of loggers) and in the case of logger failure.

4.3.5  **Current Meters**
Current meters, built and provided by the Marine Geophysics Laboratory at James Cook University (JCU), were also deployed on the sublittoral platform ~2-3 meter water depth. Current meters collected data at 4-minute intervals from 5 March to 24 April 2013 (50 days) and from 13 March – 25 April 2014 (43 days). Data were processed by Rachael McDonald at James Cook University (JCU), Townsville, Queensland, Australia. Data were corrected by Thomas Stevens.
Figure 4.2: Hamelin Pool Logger Locations. Map of Hamelin Pool displaying the logging regime for the 2012, 2013 and 2014 field seasons including temperature, level (pressure/tide) and salinity loggers along with current meters that were deployed during the regular field seasons in 2013 and 2014. Loggers on the sublittoral platform in ~2-3 m water are highlighted in green.

4.3.6 Data Processing

Environmental logging data were processed using Excel and/or Matlab. Maximum, minimum, range and mean were calculated for all logged locations. For process and
evaluation, data were filtered to 1-hour intervals. Harmonic analysis was completed for tidal data. Tides were broken down into different harmonic constituents specific to location, associated with the gravitational effects of celestial bodies. Combining amplitude effects of the largest harmonic constituents can construct a close approximation for the predicted tidal curve in that location. Tidal data were processed using the same constituents identified by Burling et al. (2003) (M₂, S₂, K₂, and O₁), and interrogated using exploratory methods to extract periodicities (sensu Burne and Johnson 2012). This method identified the astronomical and seasonal periodicitites of Hamelin Pool water elevation. Periodic frequencies were fit to the collected data using the “least-square fit” method. Modeled data were removed to reveal the meteorological tidal component (sensu Burne and Johnson 2012 and Playford et. al 2013).

Table 4.2: Location and environmental setting of “CM” star pickets containing temperature, pressure and salinity loggers. Current meters were also deployed at “CM” locations. Sediments are described using the Dunham classification.

<table>
<thead>
<tr>
<th>Map Location</th>
<th>Waypoint</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Zone</th>
<th>Depth (m)</th>
<th>Sediment Name</th>
<th>Sediment Color</th>
<th>Abundant</th>
<th>Common</th>
<th>Rare</th>
<th>Bottom Type</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 T1_CM</td>
<td>-26.04753</td>
<td>113.91936</td>
<td>Sublittoral Shelf</td>
<td>2.77</td>
<td>Skeletal Floatstone in a granitostone matrix</td>
<td>tan</td>
<td>quartz, peloids</td>
<td>Fragum erugatum</td>
<td>Xholia</td>
<td>Sediment</td>
<td>ripples at 40&quot;</td>
<td></td>
</tr>
<tr>
<td>5 T3_CM</td>
<td>-26.21359</td>
<td>113.99294</td>
<td>Sublittoral Shelf</td>
<td>2.97</td>
<td>Fragum Floatstone in a coarse skeletal granitostone matrix</td>
<td>very light grey-brown</td>
<td>Fragum erugatum, Acutilabularia sp., staks, benthic forams</td>
<td>Foraminifera, sponge tubes, quartz, limpa</td>
<td>Black gravel</td>
<td>Tabular Pavement</td>
<td>Ripple</td>
<td></td>
</tr>
<tr>
<td>9 T6_ME</td>
<td>-26.4982</td>
<td>114.08538</td>
<td>Sublittoral Shelf</td>
<td>2.95</td>
<td>Fragum Rudstone in a fine skeletal granitostone matrix</td>
<td>grey</td>
<td>Fragum erugatum</td>
<td>Acutilabularia sp., sponge tubes, tiny gastropods</td>
<td>Forams</td>
<td>Sediment</td>
<td>Very soft, pocket drives in deeply &amp; easily</td>
<td></td>
</tr>
<tr>
<td>11 T9a_CM</td>
<td>-26.26523</td>
<td>114.21578</td>
<td>Sublittoral Shelf</td>
<td>2.76</td>
<td>Fragum Rudstone in a skeletal granitostone matrix</td>
<td>grey</td>
<td>Fragum erugatum, Acutilabularia sp., staks, benthic forams</td>
<td>Black gravels</td>
<td>Tine railed gastropods</td>
<td>Sediment</td>
<td>Ripple, probe can be inserted 5-6 cm</td>
<td></td>
</tr>
<tr>
<td>16 T11_CM</td>
<td>-26.68072</td>
<td>114.20044</td>
<td>Sublittoral Shelf</td>
<td>2.35</td>
<td>Fragum Floatstone in a fine grained skeletal matrix</td>
<td>light grey</td>
<td>Fragum erugatum, peloids</td>
<td>Acutilabularia sp.</td>
<td>Tine railed gastropods</td>
<td>Sediment</td>
<td>Ripples</td>
<td></td>
</tr>
</tbody>
</table>
### Table 4.3: Location and environmental setting of "ME" star pickets containing temperature loggers. Sediments were described using the Dunham classification. Star pickets at T11_ME and T11_ME were not recovered and therefore not included in the table.

<table>
<thead>
<tr>
<th>Map Location</th>
<th>Location</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Zone</th>
<th>Depth (m)</th>
<th>Sediment Type</th>
<th>Color</th>
<th>Abundant</th>
<th>Common</th>
<th>Rare</th>
<th>Bottom type</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1_ME</td>
<td>-26.0439</td>
<td>113.92872</td>
<td>Embayment Plain</td>
<td>8.5</td>
<td>Fragum floatstone in a fine grained skeletal matrix</td>
<td>very dark</td>
<td>Fragum erugatum</td>
<td>Acetabularia stalks, forams, quartz, benthic forams</td>
<td>mussel fragments</td>
<td>very soft, picket drives in deeply &amp; easily</td>
<td>surface covered with floccules</td>
<td></td>
</tr>
<tr>
<td>T3_ME</td>
<td>-26.20816</td>
<td>114.02254</td>
<td>Embayment Plain</td>
<td>7.0</td>
<td>Fragum floatstone in a coarse skeletal grainstone matrix</td>
<td>light grey</td>
<td>Fragum erugatum, tiny coiled gastropods, skeletal fragments, black carbonate grains</td>
<td>Acetabularia Stalks</td>
<td>Serpulids, mussel fragments</td>
<td>very soft, picket drives in deeply &amp; easily</td>
<td>surface covered with floccules</td>
<td></td>
</tr>
<tr>
<td>T4_ME</td>
<td>-26.34161</td>
<td>114.00436</td>
<td>Embayment Plain</td>
<td>7.0</td>
<td>Fragum rudstone in a very fine to fine skeletal matrix</td>
<td>dark grey</td>
<td>Fragum erugatum, tiny coiled gastropods, black carbonate grains</td>
<td>Acetabularia Stalks</td>
<td>Serpulids</td>
<td>very soft, picket drives in deeply &amp; easily</td>
<td>surface covered with floccules</td>
<td></td>
</tr>
<tr>
<td>T5_ME</td>
<td>-26.4049</td>
<td>114.06389</td>
<td>Embayment Plain</td>
<td>5.5</td>
<td>Fragum rudstone in a very fine to fine skeletal grainstone matrix</td>
<td>very dark grey</td>
<td>Fragum erugatum, tiny coiled gastropods, Acetabularia stalks</td>
<td>Serpulids</td>
<td>Mussel fragments</td>
<td>very soft, picket drives in deeply &amp; easily</td>
<td>surface covered with floccules</td>
<td></td>
</tr>
<tr>
<td>T7a_ME</td>
<td>-26.38274</td>
<td>114.34532</td>
<td>Embayment Plain</td>
<td>5.0</td>
<td>Fragum rudstone in a coarse skeletal grainstone matrix</td>
<td>light grey</td>
<td>Fragum erugatum, Acetabularia stalks, serpulids</td>
<td>Tiny coiled gastropods, benthic forams, quartz, black carbonate grains</td>
<td>very soft, picket drives in deeply &amp; easily</td>
<td>surface covered with floccules</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T8_ME</td>
<td>-26.33017</td>
<td>114.36309</td>
<td>Embayment Plain</td>
<td>8.0</td>
<td>Fragum floatstone in a coarse skeletal grainstone matrix</td>
<td>black</td>
<td>Fragum erugatum, Acetabularia stalks</td>
<td>Tiny coiled gastropods, forams, serpulids</td>
<td>Very soft, picket drives in deeply &amp; easily</td>
<td>Surface covered with floccules</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T9a_ME</td>
<td>-26.26497</td>
<td>114.19306</td>
<td>Sublittoral platform transition to Embayment Plain</td>
<td>4.5</td>
<td>Fragum rudstone in coarse skeletal grainstone matrix</td>
<td>light grey</td>
<td>Fragum erugatum, Acetabularia Stalks, cemented clasts</td>
<td>Acetabularia stalks, Acetabularia, lumps, benthic forams</td>
<td>Thin layer of pavement with soft underneath</td>
<td>Pavement and microalgae covered with floccules</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T10_ME</td>
<td>-26.1864</td>
<td>114.14567</td>
<td>Embayment Plain</td>
<td>6.5</td>
<td>Fragum rudstone in a coarse skeletal grainstone matrix</td>
<td>Very light grey</td>
<td>Fragum erugatum, Acetabularia stalks, aggregate clumps</td>
<td>Serpulids, tiny coiled gastropods, benthic forams, quartz</td>
<td>Very soft, picket drives in deeply &amp; easily</td>
<td>Surface covered with floccules</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T11_ME</td>
<td>-26.09334</td>
<td>114.14616</td>
<td>Embayment Plain</td>
<td>8.0</td>
<td>Fragum floatstone in a skeletal grainstone matrix</td>
<td>very light grey</td>
<td>Fragum erugatum, Acetabularia stalks, benthic forams</td>
<td>Tiny coiled gastropods, forams</td>
<td>Very soft, picket drives in deeply &amp; easily</td>
<td>Surface covered with floccules</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.4 Results
4.4.1 Description of Logger Sites
Logger sites were denoted “CM” (current meter location) or “ME” (marine end of transect location) (Fig. 4.2; “CM” locations highlighted in green). Environmental setting and sediment type was classified at all star picket locations (Table 4.2 – “CM” locations; Table 4.3 – “ME” locations). Star pickets installed at, or just after the transition into the basin, held temperature loggers for the duration of research. Star pickets were installed as presented in the tables with location descriptions.

4.4.2 Salinity
Salinity loggers revealed an annually sinuous curve with elevated salinity levels in Austral winter months (April - August). Lower salinity values were present in Austral summer months (October – March) (Fig. 4.3). Isolated incidences of low salinity were recorded at T1_CM (Fig. 4.2; location 1), T9a_CM (Fig. 4.2; location 13) and T11_CM (Fig. 4.2; location 16). Local rainfall does not coincide with observed drops in salinity levels. Highest overall salinity values were recorded in Nilemah Embayment (T6_CM, Fig. 4.2; location 9) with the 91.49‰ as the maximum reading (Table 4.4). The minimum salinity reading was recorded off Carbla Point (T9a_CM, Fig. 4.2; location 13) at 15.66‰. Average salinity levels for Hamelin Pool were in the hypersaline range. Lowest salinities were recorded near the Faure Sill, averaging 62.96‰ on the northwest margin (T1_CM, Fig. 4.2; location 1), and 65.55‰ on the northeast margin (T11_CM, Fig. 4.2; location 16). Average salinities increased moving further south into the embayment with the highest average salinities recorded at T6_CM (Fig. 4.2; location 9) (averaging 71.21‰). The largest salinity range was recorded off Carbla Point and the smallest range was recorded in Nilemah Embayment (Fig. 4.4).
4.4.3 Temperature

Temperature data were collected at all star picket locations both in the embayment plain and on the sublittoral platform. Additionally, air temperature data were collected in the shade at Hamelin Station using the same model data logger and compared with water values. Water temperature closely follows air temperature (Fig. 4.5). Warmest average water temperatures occur between November – April, while coldest average water temperatures occur between May and October.

The overall average temperature of Hamelin Pool loggers combined from all logging sites is fairly consistent between 22-23°C. The largest temperature range of nearly 22°C occurs in the south, Nilemah Embayment (T6_CM, Fig. 4.2; location 9) with the minimum recorded temperature of 11.15°C and maximum recorded temperature of 31.26°C (Table 4.5). Larger ranges were recorded on the sublittoral platform than in the
basin. The eastern side of the Pool exhibits higher maximum temperatures than the western side of the Pool. Smaller temperature ranges were also recorded from the basin on the eastern margin (Fig. 4.6b).

Table 4.4: (on right) Salinity Range. Maximum, minimum, range and average salinity measured in ppt between loggers at “CM” star pickets.

<table>
<thead>
<tr>
<th></th>
<th>Maximum</th>
<th>Minimum</th>
<th>Range</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1_CM</td>
<td>75.82%</td>
<td>30.37%</td>
<td>45.45%</td>
<td>62.96%</td>
</tr>
<tr>
<td>T3_CM</td>
<td>80.08%</td>
<td>27.17%</td>
<td>52.91%</td>
<td>71.21%</td>
</tr>
<tr>
<td>T6_CM</td>
<td>91.49%</td>
<td>45.28%</td>
<td>46.21%</td>
<td>66.12%</td>
</tr>
<tr>
<td>T9a_CM</td>
<td>86.63%</td>
<td>15.66%</td>
<td>70.97%</td>
<td>66.12%</td>
</tr>
<tr>
<td>T11_CM</td>
<td>80.74%</td>
<td>39.91%</td>
<td>40.83%</td>
<td>65.55%</td>
</tr>
</tbody>
</table>

Figure 4.4: (on left) Salinity Range. Visual representation of table 4.3. Salinity range between loggers at “CM” star pickets. Yellow line on each bar represents average temperature.
Figure 4.5: Air temperature compared with averaged water temperature. Water temperature was averaged from all logger locations (blue line) and overlain on air temperature (green line).

In measuring the deviation from the mean temperature, data shows shallow water loggers display much higher deviation from the mean (Fig. 4.6a; a1 and a2). During the winter months, the sublittoral sites can become more than 2°C cooler than mean water temperature (Fig. 4.6a; a2). During summer months, the sublittoral sites can become more than 5°C warmer than mean water temperature (Fig. 4.6; a2). The largest temperature range was recorded in the south at T6_CM (Fig. 4.2; location 9) in the Nilemah Embayment.
Figure 4.6: Figure (a) displays temperature at each logging location measured as deviation from mean water temperature. (a1) presents temperature data collected in deeper waters of the embayment plain ("ME" loggers) (a2) presents temperature data collected in shallower waters of the sublittoral platform ("CM" loggers). Figure (b) is the visual representation of table 4.4 displaying the maximum, minimum and range of temperatures. Average temperature is around 22°C across the entire Pool.
Table 4.5: Hamelin Pool Temperature. Maximum, minimum, range and average temperature measured in degrees centigrade at all loggers in Hamelin Pool and the air temperature logger, recording data at Hamelin Station.

<table>
<thead>
<tr>
<th>Map Location</th>
<th>Location</th>
<th>Maximum (°C)</th>
<th>Minimum (°C)</th>
<th>Range (°C)</th>
<th>Average (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>T1_CM</td>
<td>31.46</td>
<td>14.17</td>
<td>17.29</td>
<td>22.04</td>
</tr>
<tr>
<td>2</td>
<td>T1_ME</td>
<td>29.89</td>
<td>14.63</td>
<td>15.27</td>
<td>21.86</td>
</tr>
<tr>
<td>4</td>
<td>T2b_ME</td>
<td>31.18</td>
<td>14.00</td>
<td>17.18</td>
<td>22.04</td>
</tr>
<tr>
<td>5</td>
<td>T3_CM</td>
<td>30.75</td>
<td>15.06</td>
<td>15.69</td>
<td>21.99</td>
</tr>
<tr>
<td>6</td>
<td>T3_ME</td>
<td>30.57</td>
<td>15.61</td>
<td>14.97</td>
<td>22.97</td>
</tr>
<tr>
<td>7</td>
<td>T4_ME</td>
<td>30.65</td>
<td>14.84</td>
<td>15.81</td>
<td>22.54</td>
</tr>
<tr>
<td>8</td>
<td>T5_ME</td>
<td>31.00</td>
<td>14.36</td>
<td>16.64</td>
<td>22.11</td>
</tr>
<tr>
<td>9</td>
<td>T6_CM</td>
<td>32.98</td>
<td>11.15</td>
<td>21.82</td>
<td>22.13</td>
</tr>
<tr>
<td>10</td>
<td>T7a_ME</td>
<td>31.26</td>
<td>13.69</td>
<td>17.57</td>
<td>22.27</td>
</tr>
<tr>
<td>11</td>
<td>T8_ME</td>
<td>31.56</td>
<td>14.53</td>
<td>17.03</td>
<td>22.15</td>
</tr>
<tr>
<td>13</td>
<td>T9a_CM</td>
<td>31.97</td>
<td>14.07</td>
<td>17.90</td>
<td>22.17</td>
</tr>
<tr>
<td>12</td>
<td>T9a_ME</td>
<td>31.10</td>
<td>14.75</td>
<td>16.36</td>
<td>22.39</td>
</tr>
<tr>
<td>14</td>
<td>T10_ME</td>
<td>32.10</td>
<td>14.58</td>
<td>17.52</td>
<td>22.31</td>
</tr>
<tr>
<td>16</td>
<td>T11_CM</td>
<td>31.97</td>
<td>13.91</td>
<td>18.06</td>
<td>22.47</td>
</tr>
<tr>
<td>N/A</td>
<td>Air</td>
<td>50.51</td>
<td>6.70</td>
<td>43.81</td>
<td>23.81</td>
</tr>
</tbody>
</table>

4.4.4 Tide

Tidal data were captured at 30-minute intervals from March 2013 until March 2014 (Fig. 4.8a; Fig. 4.9a, Fig. 4.10a, Fig. 4.11a). Between March 2014 and 9 November 2014 (a combined total of 609 days), loggers recorded data at lower-resolution 1-hour intervals due to limited logger internal memory and logger collection date uncertainty. Loss of critical data occurred when filtering the data-set. Examination of the 30-minute interval
data, revealed larger tidal ranges on the eastern side of the Pool than on the western margin. Data were resampled to accommodate the 1-hour time interval in order to analyze a longer period, as the time of logger retrieval was unknown. Smallest tidal range was recorded in the northwest, but logging duration was also the shortest due to logger failure (Table 4.6).

Table 4.6: Recorded Hamelin Pool Tides. Tidal measurement in Hamelin Pool between March 12, 2013 and November 7, 2014. Minimum, maximum, range and mean sea level above or below 0 meters, relative to Australian Height Datum (AHD) tied to Benchmark A 906.

<table>
<thead>
<tr>
<th>Map Location</th>
<th>Location</th>
<th>Measurement 30-minute interval (m)</th>
<th>1-hour interval (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>T1_CM</td>
<td>Min -0.79</td>
<td>-0.77</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max 0.86</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Range 1.65</td>
<td>1.63</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average -0.04</td>
<td>-0.04</td>
</tr>
<tr>
<td>5</td>
<td>T3_CM</td>
<td>Min -0.58</td>
<td>-0.56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max 1.29</td>
<td>1.29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Range 1.87</td>
<td>1.85</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average 0.28</td>
<td>0.26</td>
</tr>
<tr>
<td>13</td>
<td>T9a_CM</td>
<td>Min -0.60</td>
<td>-0.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max 1.44</td>
<td>1.32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Range 2.04</td>
<td>1.92</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average 0.26</td>
<td>0.22</td>
</tr>
<tr>
<td>16</td>
<td>T11_CM</td>
<td>Min -0.80</td>
<td>-0.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max 1.23</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Range 2.03</td>
<td>1.76</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average 0.04</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Mean sea level is near 0 meters just south of the sill at sites T1_CM (Fig. 4.2; location 1) in the northwest and T11_CM (Fig. 4.2; location 16) in the northeast. Loggers located midway, T3_CM (Fig. 4.2; location 6) in the west and T9a_CM (Fig. 4.2; location 13) in the east, mean sea level is 22 cm and 26 cm, respectively (Fig. 4.7). Variance calculations (Table 4.7) in Hamelin Pool show that 75-80% of the sea surface height variability is not a result of the four major tidal components modeled (M2, S2, K1 and O1).
Figure 4.7: Visual representation of tidal range (table 4.5) at 1-hour interval collection between March 12, 2013 and November 7, 2014, displaying the maximum, minimum and range and average tidal height. Mean sea level is slightly lower in the north.

Burling et al. (2003), reported on the basic harmonic constituents $M_2$, $S_2$, $K_1$ and $O_1$ (diurnal; semi-diurnal) to model the tide in Hamelin Pool. Values calculated in Hamelin Pool were similar, but elevated to those reported, perhaps as a result of bathymetry effects due to logger location (Table 4.8). The modeled astronomical signal represents 20% of the entire signal.

Table 4.7: Calculation of variance to show how well modeled tidal constituents mathematically fit the data as the ratio between the model variability and the data variability.

<table>
<thead>
<tr>
<th>Logger</th>
<th>T1_CM</th>
<th>T3_CM</th>
<th>T9a_CM</th>
<th>T11_CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Map Location</td>
<td>1</td>
<td>5</td>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td>Variance</td>
<td>19.0%</td>
<td>25.1%</td>
<td>26.3%</td>
<td>18.9%</td>
</tr>
</tbody>
</table>
Table 4.8: Tidal constituents for harmonic analysis in Hamelin Pool. The most influential astronomical tide components in Hamelin Pool as reported by Burling et al. 2003 included $M_2$, $S_2$, $K_1$, and $O_1$. Table displays collected values vs. previously published values.

<table>
<thead>
<tr>
<th>Logger</th>
<th>$M_2$</th>
<th>$S_2$</th>
<th>$K_1$</th>
<th>$O_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>10.93</td>
<td>3.92</td>
<td>9.49</td>
<td>6.26</td>
</tr>
<tr>
<td>T3</td>
<td>13.67</td>
<td>4.78</td>
<td>10.56</td>
<td>6.48</td>
</tr>
<tr>
<td>T9</td>
<td>15.01</td>
<td>5.56</td>
<td>10.83</td>
<td>6.61</td>
</tr>
<tr>
<td>T11</td>
<td>12.38</td>
<td>4.76</td>
<td>10.08</td>
<td>6.32</td>
</tr>
<tr>
<td>Burling et al. 2003</td>
<td>11.2</td>
<td>3.5</td>
<td>8.6</td>
<td>5.9</td>
</tr>
</tbody>
</table>

Near the Faure Sill, water levels averaged around 5 cm higher in the wet season (May - July) than in the dry season (March – November). Midway along the margin on both the east and west side of the Pool, water levels were around 10cm higher in the wet season than in the dry season (Table 4.9). This seasonal cycle was also removed from the tidal signal (Fig. 4.8b; Fig 4.9b, Fig. 4.10b, Fig. 4.11b). The seasonal component comprises only about 19% of the entire tide signal.

Table 4.9: Seasonal difference in mean sea level. Measurements captured between March 12, 2013 and November 7, 2014 relative to Australian Height Datum (AHD) tied to Benchmark A 906. T1_CM experienced logger failure for the majority of dry season (December-March) therefore data collection are not considered in the comparison. Mean sea level is higher during the wet season (May-July) than in the dry season.

<table>
<thead>
<tr>
<th>Duration</th>
<th>T1_CM (m)</th>
<th>T3_CM (m)</th>
<th>T9a_CM (m)</th>
<th>T11_CM (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>May - July</td>
<td>0.07</td>
<td>0.34</td>
<td>0.31</td>
<td>0.07</td>
</tr>
<tr>
<td>December - March</td>
<td>-0.03</td>
<td>0.23</td>
<td>0.21</td>
<td>0.03</td>
</tr>
</tbody>
</table>

The residual signal, remaining after both astronomical and seasonal components were removed represents the resultant meteorological component (Fig. 4.8c; Fig 4.9c, Fig. 4.10c, Fig. 4.11c). Meteorological tide is a local weather signal (ie: wind and various
pressure systems – low pressure systems have been correlated with rise in sea level on the south western coast of Australia (Hodgkin and Di Lolo 1958), and comprises nearly 60% of the tidal signal. Data from logger T1_CM captured the meteorological tide in northwest region of the pool indicating a 1.384 m range in water level. This location showed the smallest meteorological effects. Logger T3_CM, located on Snake Bank on the western margin reported meteorological tidal range to span 1.608 m. The eastern margin logger locations, T11_CM in the northeast, and T9a_CM mid-eastern margin, off Carbla Point, displayed the largest meteorological tidal range of 1.676 and 1.671 meters, respectively.

Additionally, Hamelin Pool tides can be classified as a mix of diurnal and semi-diurnal tides (Eq. 4.1). Form factor was reported as 1.06 in the northwest (T1_CM), 0.92 in the west (T3_CM), 0.85 in the east (T9a_CM) and 0.96 in the northeast (T11_CM). As the form factor is close to 1, Hamelin Pool behaves as a mixed diurnal and semi-diurnal system.

\[
\left[ \frac{(K1 + O1)}{(M2 + S2)} \right]
\]

Eq. 4.1: Form factor equation. Equation used to calculate form factor, a non-dimensional number to express the characteristic of the tidal regime as diurnal or semi-diurnal. The higher the form factor, the more diurnal the tide. The lower the form factor, the more semi-diurnal the tide.

4.4.5 Current

Current meters were not calibrated correctly for direction and thus, directional data were not used in this study. Velocity data were collected and are accurate within 0.02 meters/second. Velocities were plotted for each individual current meter for the time period of March 7, 2013 – April 24, 2013 (Fig. 4.12 A-E). Velocities plotted in
Figure 4.8: Harmonic analysis of logger T1_CM (Fig. 4.2; location 1) tidal cycles in Hamelin Pool. (a) is the original signal (raw), (b) displays the modeled tide from known constituents ($M_2$, $S_2$, $K_1$, and $O_1$) in gray, overlain by the seasonal sinusoidal curve shown in black. (c) displays the modeled tidal signal and seasonal signal were removed from the raw logged data to display the residual fluctuation caused by local effects. Data is truncated due to logger failure.
Figure 4.9: Harmonic analysis of logger T3_CM (Fig. 4.2; location 5) tidal cycles in Hamelin Pool. (a) is the original signal (raw), (b) displays the modeled tide from known constituents (M₂, S₂, K₁, and O₁) in gray, overlain by the seasonal sinusoidal curve shown in black. (c) displays the modeled tidal signal and seasonal signal were removed from the raw logged data to display the residual fluctuation caused by local effects.
Figure 4.10: Harmonic analysis of logger T9a_CM (Fig. 4.2; location 13) tidal cycles in Hamelin Pool. (a) is the original signal (raw), (b) displays the modeled tide from known constituents ($M_2$, $S_2$, $K_1$, and $O_1$) in gray, overlain by the seasonal sinusoidal curve shown in black. (c) displays the modeled tidal signal and seasonal signal were removed from the raw logged data to display the residual fluctuation caused by local effects.
Figure 4.11: Harmonic analysis of logger T11_CM (Fig. 4.2; location 16) tidal cycles in Hamelin Pool. (a) is the original signal (raw), (b) displays the modeled tide from known constituents ($M_2$, $S_2$, $K_1$ and $O_1$) in gray, overlain by the seasonal sinusoidal curve shown in black. (c) modeled tidal signal and seasonal signal were removed from the raw logged data to display the residual fluctuation caused by local effects.

ascending order (Fig. 4.12 F) allowed for a best-fit line to characterize localized normal range current flow velocities. From these calculations abnormal disturbance events could be calculated (Table 4.10), and are highlighted in yellow in Fig. 4.12 (A-E). The eastern margin of Hamelin Pool shared a similar range of normal current between 0-0.28 m/s. The western margin also shared a similar range at 0-0.27 m/s in the northwest and 0-0.25 m/s about midway on the western margin. The southern embayment had a normal current range that was considerably calmer than elsewhere in the Pool with a range of
Figure 4.12: Current meter velocities recorded between March 7, 2013 – April 24, 2013. A-E show the current velocities in m/s with sampling increments every 4 minutes. The yellow bands highlight the irregular disturbance events calculated from departure of the best fit line of the velocities plotted in ascending speed in F.
Table 4.10: Minimum and maximum current measurements. Site-specific disturbance thresholds were calculated from best fit lines in Fig. 4.12F. % Time of abnormal disturbance events for the time of recordings is listed in yellow.

<table>
<thead>
<tr>
<th>Logger</th>
<th>T1_CM</th>
<th>T3_CM</th>
<th>T6_CM</th>
<th>T9_CM</th>
<th>T11_CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Map Location</td>
<td>1</td>
<td>5</td>
<td>9</td>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td>Min (m/s)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Max (m/s)</td>
<td>0.63</td>
<td>0.73</td>
<td>0.57</td>
<td>0.60</td>
<td>0.74</td>
</tr>
<tr>
<td>Average (m/s)</td>
<td>0.15</td>
<td>0.13</td>
<td>0.07</td>
<td>0.12</td>
<td>0.14</td>
</tr>
<tr>
<td>Disturbance Threshold (m/s)</td>
<td>0.27</td>
<td>0.25</td>
<td>0.14</td>
<td>0.28</td>
<td>0.28</td>
</tr>
<tr>
<td>% Abnormal</td>
<td>12.8</td>
<td>8.3</td>
<td>11.2</td>
<td>6.8</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Only 0-0.14 m/s. Abnormal disturbance events composed 9% of the current velocity signal. During strong disturbance events, current velocities reached a maximum of 0.74 m/s.

4.5 Discussion

Historical data have suggested that all facets of stromatolite growth including structure building microbial communities, geometries of internal fabrics and gross structure morphology are considered to be a result of complex interaction between biological, chemical, hydrodynamic, and sedimentological factors (e.g. summary by Bosak et al. 2013a and 2013b). The hypersaline embayment features variable energy, wide ranges in annual temperatures, and a shallow low grading sublittoral ramp where tidal range provides harsh periods of exposure (Logan et al. 1974, Golubic and Hofmann 1976, Golubic 1985, Playford 1990, Jahnert and Collins 2011, 2012, Burne and Johnson 2012, Playford et al. 2013 and Collins and Jahnert 2014). These components often provide environments unsuitable for higher life that could graze upon microbial mats (Garrett
1970, Walter and Heys 1985), and/or compete for space (Fischer 1965), thereby promoting growth of stromatolite building microbial mat communities.

4.5.1 Salinity
Previous research recorded salinity in Hamelin Pool as hypersaline (50- >70‰). Historical salinity readings were taken as point source readings and not recorded continuously over long periods of time. Salinity recordings of this study, averaged between ~63-71‰ which is well within the previously reported hypersaline water classification. Hypersaline waters in Hamelin Pool are extremely important in stromatolite growth. Microbial communities and microbial mats located in areas with salinities less than 53‰ show reported reductions to thin films by grazing organisms (Logan et al. 1974). South of the Faure Sill, stromatolite growth is scare and in many places absent. However, Amphibolis Antarctica, a seagrass that thrives in salinities between 40-50‰ (Walker 1991) is in abundance. Seagrass beds throughout Shark Bay are extremely important areas because they support large populations of dugongs, encrusters, scaphopods and coralline algae (Kendrick et al. 1988), all of which have been observed in this area of Hamelin Pool. Normal oceanic salinities facilitate species diversity, which would result in microbial mat predation.

In addition to excluding many predatory species, hypersaline waters also help in cementation of microbial structures as they are typically near the aragonite-precipitation threshold (Logan et al. 1974). Penecontemporaneous cements and lithification are promoted in the cementation of trapped and bound grains into layers and also in building the frameworks of microbial buildups. This early preservation of the structure may help prevent erosion during local disturbance events.
Continuous monitoring showed a wide range of salinities with the maximum salinity readings in Nilemah Embayment of over 90‰. Continuous logging also provided insight to disturbance events where episodes of low salinity were experienced in the Pool, especially along the eastern margin. Episodic drops in salinity have not been previously captured in individual point source readings. Recorded low salinity anomalies cannot be correlated with local rainfall events. Lacustrine microbialites often form in conjunction with groundwater discharge so it is plausible that Hamelin Pool stromatolites may have similar associations (Burne 1986). Areas of ground water around Hamelin Pool’s coastline have been previously identified (Table 4.11).

The known aquifer in the Shark Bay area is 100-500 m below sea level. Salinity is 3-6‰ and temperature has been recorded up to 50°C. The aquifer is confined in the Birdsong Sandstone, and not expected to discharge into Hamelin Pool (Payne et al. 1987). Additional sources of groundwater could be evaporated highly saline waters (Ferguson et al. 1981), freshwater seeps from unconfined aquifers containing a meteoric component derived from immediate recharge and run-off (unconfined aquifers have been recorded in the Tamala Limestone and in the Peron Sandstone) or from local rivers (Plumb et al. 1986).

The Gascoyne and Wooramel rivers are seasonal but surface and subsurface flows from these rivers are not considered to have significant discharge into Hamelin Pool (Logan and Cebulski 1970). Historical characterization of ground water to determine chemical signature and probable origin was completed by the Baas Becking team (Table 4.11). Due to the reduction in salinity concentration, it is probable that ground waters are a result of meteoric influence and local recharge than from evaporated hypersaline ground
Figure 4.13: Cross section of Holocene and Pleistocene deposits along the margin of Hamelin Pool depicting the stratigraphic Late Pleistocene marine layer that is minimally permeable and may act as a horizon to facilitate groundwater flow into Hamelin Pool. (modified from Ferguson et al. 1984)

Table 4.11: Chemical parameters and probable origins of groundwater survey samples from Hamelin Pool. Historical data collected by the Baas Becking research group (Burne et al. 1982)

<table>
<thead>
<tr>
<th>Location</th>
<th>Origin (probable)</th>
<th>Salinity %</th>
<th>pH</th>
<th>Alkalinity</th>
<th>Ca/Cl</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well in CQ beach ridge (Booldah Well)</td>
<td>Meteoric</td>
<td>11</td>
<td>8.49</td>
<td>5.9</td>
<td>7.8</td>
</tr>
<tr>
<td>Borehole Hamelin Station</td>
<td>Artesian</td>
<td>5</td>
<td>6.70</td>
<td>4.1</td>
<td>6.1</td>
</tr>
<tr>
<td>Hamelin Pool Nearshore surface water</td>
<td>Marine</td>
<td>78</td>
<td>8.06</td>
<td>3.0</td>
<td>2.1</td>
</tr>
<tr>
<td>Saline water beneath CQ dunes Nilemah</td>
<td>Meteoric component</td>
<td>33</td>
<td>7.58</td>
<td>2.9</td>
<td>2.8</td>
</tr>
<tr>
<td>Water from base of dunes at playford site</td>
<td>Meteoric component</td>
<td>30</td>
<td>7.81</td>
<td>2.2</td>
<td>2.7</td>
</tr>
<tr>
<td>Water from high discharge area – Flapole</td>
<td>Meteoric and artesian</td>
<td>30</td>
<td>7.62</td>
<td>3.2</td>
<td>3.2</td>
</tr>
</tbody>
</table>

It is possible that groundwater may travel along the minimally permeable Pleistocene horizon of calcrete and clay (Fig. 4.13), as a freshwater lens above the saltwater wedge (Plumb et al. 1985). There have been recorded fresh water springs near
Monkey Mia and also near Flagpole Landing. Groundwater discharge has been observed at Flagpole landing at the base of the coquina dunes. This discharge causes fresh water to pool at the surface of the supratidal sediments. This alone may suggest that water is charged from an artesian source (Ferguson et al. 1981). Stories from station owners tell of goats swimming out into Hamelin Pool, perhaps in search of fresh water. The amount and source of “fresh” water discharge into Hamelin Pool, however remains unknown (CALM 1998).

Groundwater discharge into Hamelin Pool may be important in promoting stromatolite growth and accretion. Small fluctuations in water chemistry and evaporation of porewaters in interstices, can promote cryptocrystalline and aragonite growth (Logan et al. 1974). If stromatolite growth is similar to the lacustrine environments of south Western Australia lakes, ground water may provide calcium rich waters needed for cementation, early lithification and grain production (Burne and Moore 1987).

4.5.2 Temperature
Most organisms are adapted to a fairly narrow temperature range and only a few are adapted to deal with such a large temperature range as recorded in Hamelin Pool (11-33°C). It must be noted that the Onset HOBO temperature loggers an encased in a clear plastic and therefore may record enhanced temperature readings as a result of sunlight in shallow waters. Further investigation is necessary however, as data fall within expected values. Highest temperature ranges were recorded in the southern embayment, indicating that the environment becomes more restrictive farther south from the Sill. Additionally, there was a seasonal cycle of warmer water in the summer and colder water in the winter that agreed with historical records (Burne and Hunt 1990, Logan et al. 1974). As
historically reported, vertical thermal stratification within the water column was not prevalent (Logan and Cebulski 1970 and Burling et al. 1997). However, our data suggests regional changes and differences between temperatures recorded on the sublittoral platform and in the basin.

Water temperature is a critical factor when considering habitat. Aquatic organisms have a certain temperature required for survival and for thriving. If the range of temperature exceeds or drops below an organisms required range, survival is often compromised. Organisms are typically physiologically affected by water temperature in regards to growth, reproduction, metabolism, mobility, respiration and other factors. Therefore, water temperature regulates what organisms are capable of thriving (Hoegh-Guldberg 1999). The average temperature range of the Indian Ocean that provides Hamelin Pool recharge waters varies only 4-7°C annually (Lamb 1973). For example, coral species can tolerate a narrow temperature range and therefore thrive in the bordering waters of the Indian Ocean, where wide temperature variance is not experienced (Hoegh-Guldberg 1999). The largest range in Hamelin Pool temperature was recorded in Nilemah Embayment at 21.8°C, which is 3-5 times the temperature range of the bordering Indian Ocean, restricting species diversity as a result of the harsh environment.

Fluctuating temperatures influence density, conductivity, pH and alkalinity. Solubility of oxygen and carbon dioxide are decreased with increasing water temperature and elevated temperatures increase the likelihood for anoxic of hypoxic conditions due to bacterial respiration (Luoma 1983).
4.5.3 **Tide**

The seasonal component of water level in Hamelin Pool is responsible for an average of 10 - 20% of the tidal signal. Higher water levels in the winter months and lower water levels in the summer months are a result of low precipitation, soaring air temperatures leading to high levels of evaporation, prevailing southerly winds and high atmospheric pressures (Burne and Johnson 2012, Playford et al. 2013).


This study extracted the astronomical, seasonal and resulting meteorological component to sea level elevation in Hamelin Pool to better evaluate which tidal component influences the exposure index. Burne and Johnson (2012) extracted an additional 11-day short-term irregular cycle, which was not observed in our exploratory analysis.

As a result of the multiple modeled components affecting Hamelin Pool water level, the overall sinusoidal tidal range is much larger over the course of the year (Hagan and Logan 1974, Burne and Johnson 2012), than exhibited in a daily tidal period. Burling et al. (2003) reports a tidal transition in Hamelin Pool where the north is dominated by semi-diurnal tides changing to diurnal tides in the south. In calculating the form factor (Eq. 4.1), historical data shows a value of 0.99 meaning that diurnal and semi-diurnal forces affect the Pool equally (Burling et a. 2003). Our analysis agrees with Burling et al. (2003) that the system is a mixed diurnal to semidiurnal system. Geographic location of loggers expose higher diurnal effects in the north (T1 - 1.06; T11 – 0.96) trending
stronger semi-diurnal influence in the south (mid-Pool loggers: T3 – 0.92; T9 – 0.85). This may be an over interpretation of data, as meteorological effects overpower the astronomical signal.

In addition to exposure, water level may have a large effect of the location and prevalence of stromatolites in Hamelin Pool. Higher levels of water in the winter months may prevent ground water intrusion into the Pool due to the added pressure of the higher water column. However, further research is needed to confirm this hypothesis.

4.5.4 Current
Current velocities range from 0 to 74 cm/second. Stronger current velocities were evident near the Sill and dampened in the embayment, as it is largely protected from southerly winds. Hamelin Pool current velocities and direction of water movement are closely related to local winds. Winds blowing along a body of water cause friction; coupling wind and water surface to push the water. Water in turn moves and piles up in the direction the wind is blowing, often creating current velocities up to 5% of wind speed (Mangor 2004).

Wind also drives longshore drift and can dampen the tidal cycle. Prevailing southerly winds, waves and littoral currents result in net northward movement of sediment (Read 1974). This often brings strong currents on the on the broad eastern ramp that are enhanced on summer afternoons when the sea breeze shifts the wind direction from the west. Waves are typically refracted upon crossing the sublittoral platform and turned normal to shore (Logan and Cebulski 1970), influencing the morphology of many microbial buildups, often causing an elongation perpendicular to shore.
Strong winds with velocities over 40 km/h occur often in the summer season and cause extensive microbial mat exposures (Jahnert and Collins 2012), drawing water away from the southern shoreline, indicating a large influence from local weather. Current meters deployed in the 2013 field season showed high water velocities up to 74 cm/sec as a result of the shallow waters. Loggers should be deployed for longer periods to capture heightened water velocities experienced during storm events. It has been reported that storms are capable of eroding years of growth of weakly lithified stromatolites and microbial mat (Playford 1990).

Based on months of field reconnaissance, it is clear that stromatolitic structures may be affected by large storm energy or strong water velocities. This was evidenced by overturned stromatolites, particularly those with narrow bases that nucleated upon small cobbles or pebbles. Structures not securely cemented to the surface, but perhaps only nestled in the unlithified sediments, nucleated atop a pebble, have a higher chance of overturning.

Sediment movement caused by strong currents may also effectively cover, uncover and/or erode microbial buildups by abrasion. In areas where depth is less than half the wavelength of a wave, particularly where stromatolites are actively accreting, sediment winnowing occurs. Fine-grained materials are entrained in the water column in nearshore environments. Coarser sediments are left behind and often pile up at the base of microbial buildups while the fines in suspension get trapped and bound into microbial mats or carried to lower energy areas where they are settle (Logan and Cebulski 1970). Further investigation of grain size fractions of trapped and bound sediments is merited to examine selectivity based grain availability based upon suspension in the water column.
In addition to unique weather disturbances like cyclones, Hamelin Pool has also experienced the catastrophic wave force from tsunamis (Playford et al. 2013). Tsunami forces may have resulted in the creation of massive composite stromatolites located in the subtidal zone off Carbla Point and neighboring coastlines. Stromatolites sampled and slabbed from this area often uncover microbial buildups nucleating on a large block of orthoquartzite or a conglomerate material. In some samples, the nucleation block makes up a larger percentage than the microbial deposit. There is a large out-of-place block of quartz sandstone eolianite off Carbla Point that overlies stromatolite structures. Another boulder of the same type was deposited in the shallow subtidal zone and is a major navigational hazard. Carbla oolite has been eroded in many areas on high-energy shores and in some places removed entirely (Logan and Cebulski 1970). It is probable that a wave generated by a tsunami would be capable of removing and displacing blocks of that size, with possible redeposition on the nearshore sublittoral platform. These large structures provide nucleation sites for stromatolite growth. This concept will be explored more in depth in the following chapter.

Wind, currents and wave action in Hamelin Pool are part of the extrinsic factors influencing stromatolite growth, most likely excluding higher organisms. Stromatolite formation and macro-morphology is indeed a dynamic balance between rate of accretion and erosional forces (Chivas et al. 1990), where the rate of accretion must be larger than the rate of erosion for preservation potential (Andres and Reid 2006).

In order to better understand the active stromatolite building microbial system, it will be critical to better understand and investigate the percentage of microbial mats in Hamelin
Pool and the corresponding thresholds of salinity, temperature and desiccation gradients combined with the additional characteristics of the Hamelin Pool hydrologic system.

4.6 Conclusions
The favorable theory for stromatolite accretion in modern environments is a complex interaction of biological, chemical, hydrodynamic, and sedimentological factors (Bosak et al. 2013a and 2013b). Because stromatolites are uncommon today, it is assumed that a certain combination of intrinsic and extrinsic conditions must be met to initiate stromatolite formation and preserve structures (Andres and Reid 2006, Andres et al. 2009).

Extreme environmental parameters in Hamelin Pool may exclude eukaryotes, allowing for extensive development of stromatolite building microbial communities. If supersaturated ground water with respect to calcium carbonate is intruding along the margins, it may also encourage early lithification and preservation.

Salinities are sinuous over the course of the year with higher salinities in the winter months and lower salinities in the southern months. This data is counter-intuitive as water levels are higher in the winter than in the summer and high levels of evaporation due to extreme temperatures in the southern months and high levels of evaporation. It is possible that a lens of highly saturated water surrounds Hamelin Pool. During times of high water levels, the additional pressure is stronger than the ground water head, and intrusion of ground water is minimal. In the summer, during times of lower salinity and lower water levels, the additional water pressure is removed and the ground water head is strong enough to push ground water into the Pool around the margin.
High summer water temperatures of Hamelin Pool would encourage carbonate precipitation of highly saturated ground water. Evidence of “fresh” water can be observed and/or recorded in a number of ways including:

1. All continuous conductivity loggers recorded higher salinity values during winter months.

2. Four of the five salinity loggers recorded episodic “fresh” water signals.

3. Isolated recordings collected by YSI (miniature CTD) captured salinity readings less than oceanic salinity (< 35‰).

4. Pycnoclines can be observed while swimming.

5. Beachrock is prevalent along the margin of Hamelin Pool.

6. Sea snake populations are thriving and require fresh drinking water for survival (D’Anastasi personal comm. 2013, Parke et al. 2014).

7. Holes created by kangaroos for drinking water are present along the margin of the Pool (Playford et al. 2013).

8. Goats have been observed swimming out into the Pool for unknown reasons -- suspected of searching for fresh water lenses on the surface (Wake, B., Hamelin Station, personal comm. 2013).

9. Fresh water has been previously collected from the surface of Hamelin Pool for drinking (Wake, B., Hamelin Station, personal comm. 2013).

All observations support the presence of fresh water intrusions. However, the aspect of fresh water intrusion and chemical composition of water warrants further research.
Similar environmental conditions (ie: salinity, temperature, wind and tide) affect although Logan (1961) stated that stromatolites were growing in L’Haridon Bight, the small embayment adjacent to Hamelin Pool, this report has yet to be confirmed. Aside from Logan, the only reports of microbial activity in L’Haridon Bight include colonization by abundant microbial sheet mats. It seems that early lithification is essential for accretion and preservation of stromatolites (Andres and Reid 2006). If highly saturated ground water intrusion has a large affect on stromatolite accretion, it may be a result of the geographic location of L’Haridon Bight on the peninsula between Hamelin Pool and Henri Freycinet Harbour, where the pressure of the system is not high enough to push the ground water up the anticline. Further research is required to substantiate this claim.

The modern environment is key to understanding certain aspects of environmental conditions of early Earth when higher organisms had not yet evolved. The vulnerability of stromatolites is that they grow very slowly and the Hamelin Pool system may be deteriorating as a result of currently rising sea level and human induced eutrophication through runoff. If the equilibrium of the system is disrupted, it could be driven to extinction. Therefore, it is critical to continue long-term monitoring to better understand why such a diverse assemblage of stromatolites is able to flourish in Hamelin Pool.

Understanding the various environmental pressures in Hamelin Pool is important to interpret the ecological habitat of stromatolite building microbial mats. Although the widely accepted reason for thriving growth is the effect of physical and chemical conditions in Hamelin Pool, this study collected continuous data, increasing the resolution of environmental parameters. Salinity measurements were higher in the
southern embayment than near the Faure Sill and large “fresh” water disturbance periods were observed on the eastern margin. Water temperature closely mirrors air temperature and has a range of over 20°C annually in Nilemah Embayment. Tides are annually sinuous with higher water levels in the winter months. Currents exhibit stronger velocities near the sill and weaker velocities in the embayment. Prevailing southerly winds pile water in the north causing mean water height to be over 20 cm higher near the Faure Sill. Environmental parameters observed and recorded in Hamelin Pool prove to be surprisingly heterogeneous along the margin of the Pool. Data will be integrated in the following chapter for improved interpretation of heterogeneity of stromatolites, associated facies and sediment bodies along the margin of Hamelin Pool.

This study illuminates the fact that much is still unknown regarding the contemporary system and more research is needed to better understand the modern microbial system. Carbonate saturation state of sea-water is perhaps highly relevant to the modern system, which could be interpreted to reflect abundance of stromatolites throughout the rock record, making modern microbial carbonates an important analog for historical seawater carbonate chemistry (Fischer 1965, Grotzinger 1990, Riding and Liang 2005).
Chapter 5  STROMATOLITE PROVINCES OF HAMELIN POOL

5.1 Overview
Previous chapters have established morphological variability of discrete microbial buildups, distribution of structures and associated facies, physiological variability and environmental parameters in Hamelin Pool. This chapter will focus on integration and interpretation of previous findings.

Our mapping approach contrasted with previous methods, emphasizing on morphology-based stromatolite classifications. Comprehensive ground-truthing extended well outside the main iconic locations of Carbla Point and Flagpole Landing, where field observations were collected from earlier studies (e.g. (Logan et al. 1974, Hoffman 1976, Playford et al. 1976, Bauld, 1984, Golubic 1985, Burne and Moore 1987, Playford 1979, 1980 & 1990, Meischner 1992, Reid et al. 2003, Jahnert and Collins 2011, 2012 & 2013, Playford et al. 2013, Collins and Jahnert 2014 and others). Beyond the sites of previous study, we found a unique geographic distribution of morphologically distinct stromatolite structures. Clear differences were evident in features such as the extent of stromatolite cover, degree of stromatolite elongation, and the extent of meter-scale reef structures, amongst others. This geographic zonation allowed the differentiation of eight “Stromatolite Provinces”, each with distinct patterns of stromatolite morphology and unique shelf physiography.

5.2 Eight Stromatolite Provinces of Hamelin Pool
Mapping revealed a unique geographic distribution of morphologically distinct stromatolite structures, many of which are previously undocumented. Various facies associations (weakly lithified to non-lithified sheets, discrete microbial buildups, sediment types, pavements,), paired with shelf physiography and environmental parameters (temperature, salinity, tide and current), allow subdivision of Hamelin into
eight independent provinces: Faure, Nanga, Spaven, Booldah, Nilemah, Flagpole, Carbla and Hutchison (beginning in the NW and moving anti-clockwise around the margin) (Fig. 5.1).

Figure 5.1: Map of Hamelin Pool displaying Eight Province boundaries. Each Province has a unique geographic distribution of morphologically distinct buildups, physiography, environmental conditions, sediment types, pavements and microbial mat zonations, with each region around the margin delineating a package with defining characteristics.
5.2.1 Faure Province

Faure Province (Fig. 5.1) is located in the Northern end of Hamelin Pool, and includes the east and west margins. Aptly named for the large influence of water exchange through the channels in the Faure Sill, Faure Province is dominated by ribbon “reefs” composed mainly of rock rubble and eroded microbial deposits, all blanketed with macroalgae. Additionally, the Faure Province showcases an abundance of low-relief microbial pavement often colonized by mussel beds, coquina beach rock, allochthonous boulders, terraced sea floor structures, healthy sea-grass beds, and abundant marine species diversity (Fig. 5.2).

Structures comprise a total area of 20.08 km² in Faure Province. Pavement is the largest facies type in Faure Province and covers a total of 15.4 km² (89% of total facies). Pavement in the Faure Province is typically tabular or blocky (51%) or low-relief microbial (46%). Transitional buildups make up only 3% of pavement. Sheet mats colonize 1.31 km² (8% of total recorded structures) but are only found on the eastern margin of the Faure Province in a region restricted by longshore current, creating a semi-barred embayment. Discrete microbial buildups make up 0.27 km² (or 2% of total recorded structures). Individual and merged columnar structures make up 100% of microbial buildups. Bands of relict reefs make up 0.12 km² of this sub-facies classification. Other facies types including boulders and beachrock comprise less than 1% of structures in Faure Province. Beachrock is only found on the western margin, dominating nearly the entire shoreline. Sediments are mainly fine-grained, well-sorted quartz on the western margin, trending to floatstone away from the sill. The eastern
margin is also comprised of fine grainstone, but has more common carbonate components such as peloids and skeletal fragments.

On the western margin, the shelf forms a narrow gently sloping ramp with a very narrow intertidal zone. On the eastern margin, the shelf forms a broader gently sloping ramp with a wider intertidal zone (Fig. 3.6). A representative transect (Fig. 5.3) was derived from Faure Province West. The tidal zone (Zone 1) features thin, fragile crust nearshore, often covered by a slight, semi-cohesive flocculent, white mat. Further seaward, low-relief microbial pavement with low-relief microbial buildups is found, blanketed in macroalgae along with common ribbons of eroded microbial structures and rubble. On aerial images, these structures appear as dark black bands, a result of the abundant macroalgae and Acetabularia sp. colonization on the structures. Ribbons are often interrupted, but are always shore parallel. The shallow subtidal and sublittoral platform (Zone 2) showcases an abundance of undulose and low-relief microbial pavement that is well-lithified substrate with semi-lithified surface mat. Sediment type in this area is quartz-dominated grainstone. The distal end of the transect (Zone 3) boasts vast expanses of healthy seagrass Amphibolis antarctica that may help in baffling fine grains entering Hamelin Pool over the Faure Sill.

Salinity measurements taken from the northern end of Hamelin Pool, on both the east and west margin, show the lowest salinity readings (Table 4.4; Fig. 4.4). The Faure Sill acts as the saloclone from the rest of Shark Bay as a semi-restrictive barrier altering the salinity gradient. Stromatolite-building microbial mat communities are able to thrive in Hamelin Pool partly as a result of the hypersaline waters that exclude
Figure 5.2: Facies map of Faure Province (West) in Hamelin Pool. Faure Province dominated by rock rubble ribbon “reefs”, eroded stromatolites, coquina beach rock, low-relief microbial pavement often colonized by mussel beds, terraced sea floor structures, healthy sea-grass beds and abundant marine species diversity. Scarce microbial buildups form a narrow facies band paralleling the coastline, and the sediment is grainstone dominated by quartz.
Figure 5.3: Idealized transect illustration of Faure Province (West) displaying the most abundant facies types in Zone 1 (tidal zone), Zone 2 (sublittoral platform) and Zone 3 (basin/embayment plain). All zones are correlated by color (after Fig. 3.13). Synthetic transect location is shown in white on the location map.
colonization of more complex organisms that may graze on, or are better competitors. Microbial communities and microbial mats located in areas with salinities less than 53‰ show reported reductions to thin films by grazing organisms (Logan et al. 1974). Indeed, just south of the Faure Sill, stromatolite growth is scarce and in many places absent. However, *Amphibolis antarctica*, a seagrass that thrives in salinities between 40-50‰ (Walker 1991), along with active mussel beds, sponges and macroalgae are in abundance.

Faure Province may have once been a mecca for stromatolite growth, as there are many relict structures now covered in macroalgae. However, in order to confirm this, structures would need to be sampled and internal fabrics should be examined. Low-relief microbial pavement, is however a prolific component of Faure Province on both east and west margins of the Pool indicating that conditions still exist today for microbial accretion and lithification.

5.2.2 *Nanga Province*

Nanga Province can be described as a bight located along the northwest margin of Hamelin Pool, with a narrow intertidal zone that slopes rapidly into the basin. Nanga Province shares a northern border with the Faure Province, bisecting Petit Promontory (Fig 5.1). The southern boundary extends from Spaven Point, intersecting Anchorage Promontory. This province, named for the Nanga Peninsula responsible for the western margin of Hamelin Pool, has thin, shore parallel facies belts in the central bight that broaden as they approach the Points (Fisherman’s and Spaven), comprising the Promontories (Fig. 5.4).

Structures comprise a total area of 24.02 km² in Nanga Province, most of which is pavement, covering a total of 22.63 km² (94% of total recorded structures) (Fig 5.4).
Low-relief microbial pavement is concentrated on Petit Promontory, near the northern boundary of the Province and is often colonized by living mussel beds. Tabular and blocky pavement is the more common facies type and dominates the southern region of the Province and Spaven Promontory. Nanga Province is the only Province in Hamelin Pool without sheet mats. Discrete microbial buildup facies cover 1.35 km² (or 6% of total recorded structures). The principal facies component that defines the Nanga Province are the nearshore merged heads amalgamating into massive tabular structures, constituting 32% of total microbial buildups. Segmented and composite structures make up 28% of discrete microbial buildups and are located on the seaward side of the tabular structures, in deeper water. These composite structures are mostly devoid of microbial mat and are fully colonized by macroalgae. Together, the tabular and composite stromatolite structures form a continuous shore parallel band of structures. A small region of elongate-nested structures (25% of discrete microbial buildups) are located just south of Fisherman’s Point, forming in shore parallel bands with structure elongation perpendicular to shore. Individual and merged columnar structures make up 15% of microbial buildups, nearly half of which are bands of relict reefs often colonized by macroalgae and/or a thin white microbial mat. Other facies types including boulders and beachrock comprise less than 1% of structures in Nanga Province. Sediments are mainly fine grained, well-sorted quartz grainstones. North of Spaven Point, the first locality of living *Fragum erugatum* beds is evident. On shore, nearing Spaven Point, floatstone facies trends into Hamelin Coquina.

Nanga Province is a small bight sandwiched between two Promontories, with a narrow tidal zone that grades swiftly into the basin, resulting in a narrow shore parallel area
Figure 5.4: Facies map of Nanga Province in Hamelin Pool. Nanga Province includes nearshore merged heads amalgamating into massive tabular structures in a shore-parallel facies belt. Other features include coquina beach rock and low-relief microbial pavement. Sediment is dominantly grainstone with abundant quartz grains eroded from the Peron Sandstone.
Figure 5.5: Idealized transect illustration of Nanga Province displaying the most abundant facies types in Zone 1 (tidal zone), Zone 2 (sublittoral platform) and Zone 3 (basin/embayment plain). All zones are correlated by color (after Fig. 3.13). Nanga Province has a narrow intertidal zone in the bight that slopes rapidly into the basin. Synthetic transect location is shown in white on the location map.
suitable for stromatolite growth. The representative transect of Nanga Province (Fig. 5.5) describes the seaward zonation of this bight. The shoreline is dominated by ribbons of coquina beach rock, followed by relict reef ribbons of individual and merged columns covered in macroalgae and low-relief microbial pavement in the tidal zone (Zone 1). The iconic tabular heads are located in the shallow subtidal zone and on the sublittoral platform (Zone 2). These heads are colonized by coccoid cyanobacterial smooth-mats, with macroalgae on the sides. Composite stromatolites form adjacent to these structures, in the deeper water. Tabular Pavement is also found on the sublittoral platform before dropping off into the basin (Zone 3). Basin sediments are composed of grainstone or floatstone dominated by quartz, eroded from the flanking Peron Sandstone.

Environmental parameters that affect the region include an average salinity of 63‰, the lowest average salinity recorded, averaged over long term monitoring (Table 4.4; Fig. 4.4). Lower average salinities may contribute to the abundance of macroalgal growth, in turn restricting growth of stromatolite building microbial communities. Nanga does have abundant nearshore structures, but not many seaward. Bathymetry could be a major factor in this Province influencing the deficiency, as the ramp reaches the basin within the first 700 meters of shore. Currents measured on Petit Promontory indicated that the northwestern region in Hamelin Pool has the highest average current velocities (0.15 m/s). Additionally, the abnormal disturbance threshold (0.27 m/s) was breached 12.8% of the time during the two months of data collection measured in in 2013 (Table 4.10; Fig 4.12A). High energy, narrow intertidal range,
lower salinities and dominant siliciclastics are the distinctive drivers affecting stromatolite growth in the region.

5.2.3 Spaven Province
Spaven Province shares the northern boundary with the southern boundary of the Nanga Province, intersecting Anchorage Promontory, and includes Snake Promontory and Nilemah Promontory to the south. (Fig. 5.1).

The diagnostic feature of Spaven Province are fields of elongate-nested subtidal structures south of each of the three promontories in Spaven Province, which have never been previously reported. These structures are morphologically similar to 1.8 billion year old stromatolites in the Pethei formation of the Northwest Territories (Hoffman 1974) (Fig. 5.6). Although elongate-nested structures are found in other locations in the Pool, none are as well developed as in this Province. These signature stromatolites were first discovered while exploring south of Spaven Point, the namesake for Spaven Province.

Figure 5.6: Longitudinal stromatolites of Great Slave Lake in the Pethei Formation, Northern Territory, Canada, compared to morphologically similar Hamelin Pool stromatolites common in Spaven Province.

Structures comprise a total area of 58.97 km² in Spaven Province (Fig 5.7). Pavement is the most common facies type covering a total of 47.72 km² (84% of total recorded
structure area). Pavement is common in Spaven Province with tabular and blocky pavement comprising the bulk of all promontories. The seaward edge of the promontories drop rapidly into the basin down to 6-7 meters water depth. Currents flowing over steep promontory margins result in brecciation of tabular pavement. Promontory margins are therefore comprised mainly of blocky pavement. Near shore, low-relief microbial to undulose and transitional pavement, always with abundant *Acetabularia* sp., is often shoreward of tabular pavements. The base of Snake Promontory also has a large area of transitional pavement.

Discrete microbial buildups cover a total of 6.38 km$^2$ (11%) of Spaven Province. The signature feature of the Province, elongate-nested stromatolites are the most dominant stromatolite structure, comprising 43% of the discrete microbial buildup facies type. The spectacular developments of the signature elongate-nested stromatolites, form to the south of each of three promontories (Anchorage, Snake and Nilemah), or east to southeast of the prominent headlands, with direction of elongation normal to shore. These cigar shaped features are typically colonized by smooth surface mats. Individual and merged columnar stromatolites are the second most common stromatolite buildups comprising 26% of the facies division. These structures form in near shore environments and are often found as relict eroded ribbon reefs. 13% of the individual and merged columnar structures are bands of relict structures. Elongate-clustered stromatolites make their first appearance on the western margin in Spaven Province, as 16% of the facies. These structures were first observed seaward of the small cuspate bights in the larger bight between Anchorage Promontory and Snake Promontory. Additionally, smaller components of discrete microbial buildups in Spaven Province include: intertidally
forming elongate structures in bights with elongation normal to shore, subtidal tabular structures, segmented/composite structures, and seif structures.

Just south of Spaven Point, at the northern end of Spaven Province, is the first occurrence of sheet mats on the western margin, which dominate the shoreline of the bights. These weakly lithifying to non-lithifying stratiform sheets cover 2.97 km$^2$, or 5% of the total identified structures in Spaven Province.

Shores are comprised mainly of Holocene deposited coquina, and *Fragum erugatum* dominated rudstone to floatstone. Sediments are typically floatstone, with occasional live *Fragum erugatum* beds offshore, isolated areas of grainstone, and an area of packstone extending from the northern end of Snake Promontory.

Spaven Province has multiple shelf geomorphologies and a variable physiographic setting. As a result of these variations, wide arrays of facies types are present (Fig. 5.7). In fact, Spaven Province exhibits each of the seven described stromatolite morphologies. Spaven Province promontories and bights display cuspate features with low gradients and low energy, along the shoreline, resulting in abundant sheet mats. Promontory edges descend sharply into the embayment plain, resulting in abundant blocks of pavement. Low gradients with combined with shore normal currents result in stromatolites elongated perpendicular to shore, which are dominantly nested in Spaven Province.

The representative transect of Spaven Province (Fig. 5.8) depicts the seaward zonation of a transect extending from the southern edge of the headland, crossing the southern margin of a promontory before descending into the basin. The shoreline is dominated by large expanses of breccia, and in some cases, large platforms of pavement exhibiting octagonal
cracking. Although brecciated surfaces are abundant, many are located at higher elevations than the transect onset and therefore are only minimally illustrated. Structures in the tidal zone (Zone 1) include some breccia, followed by continuous sheet mats, which trend to individual and merged columns. Buildups are covered with pustular-mat trending to smooth-mat at lower elevations. Seaward of the individual and merged columns, the iconic elongate-nested structures become prominent. Elongate structures taper to low-relief structures moving seaward (Zone 2). The flanks of elongate structures are dominated by Acetabularia sp., and minor macroalgae. Directly before the sublittoral platform descends to the embayment plain, massive tabular structures become abundant, followed by massive composite structures thick with macroalage. The embayment plain (Zone 3) is commonly floatstone, dominated by peloids, quartz grains, Fragum erugatum bivalve shells and Foraminifera sp.

Environmental parameters affecting the region include a large tidal range (spanning 1.85 m – measured over 20 months) (Table 4.6; Fig. 4.7), temperature range of between 14.0°-31.2° (Table 4.5; Fig. 4.6b) paired with high average salinities (67.9‰) (Table 4.4; Fig. 4.4). Currents measured on Snake Promontory indicated average current velocities (0.13 m/s) slightly lower than Nanga Province to the north. The abnormal disturbance threshold (0.25 m/s) was lower, and was only breached 8.3% of the time, meaning general energy and disturbance events were low during the two months of data collection measured in 2013 (Table 4.10; Fig. 4.12C).

Additionally, local uplift along the western margin is probable. Stromatolite fields along the margin are sheared in half in many locations. Playford et al. (2013; Figures 294-297) describes the “stepped” emergence of stromatolites along the western margin, causing
Figure 5.7 Facies map of Spaven Province, located along the western margin of Hamelin Pool. Spaven Province is characterized by spectacular development of elongate-nested stromatolites, forming to the south of each of three promontories (Anchorage, Snake and Nilemah) that dominate shelf physiography. Additional common facies types include tabular stromatolites, individual and merged columns, minor elongate clusters in bights, stratiform sheets, breccia and floatstone.
Figure 5.8: Idealized transect illustration of Spaven Province displaying the most abundant facies types in Zone 1 (tidal zone), Zone 2 (sublittoral platform) and Zone 3 (basin/embayment plain). All zones are correlated by color (after Fig. 3.13). The depth transect extends from the southern edge of a headland, crossing the southern margin of a promontory before descending into the basin. Synthetic transect location is shown in white on the location map.
many stromatolites to be stranded in the supratidal zone. He attributes the stranding of structures to probable tectonic effects associated with the continually rising anticline. Polygonal jointing is also common near Spaven Point, comparable to polygonal jointing at Faure Island, where 14.5 m of uplift has been recorded, pointing to tectonic activity in Hamelin (Playford et al. 2013). Combined with variable shelf physiography providing multiple environments (i.e.: headlands, promontories, bights, shelves and ramps), Spaven Province boasts the highest amount of diversity for facies and sub-facies types including various stromatolite growth morphologies.

5.2.4 Booldah Province
Booldah Province is located along the southwestern margin of Hamelin Pool. The northern boundary of Booldah Province is just south of Nilemah Promontory. The southern boundary is just north of the Nilemah Embayment. Booldah Province is location to one of the well-known camel tracks cut through stromatolites to transport wool from local sheep stations to a lighter barge, stationed in the deeper waters off the shelf. Positioned close to Nilemah Homestead and station, just to the west of the camel track is an Aboriginal well known locally as Booldah, the namesake for the Booldah Province.

The defining features of Booldah Province are seif stromatolites. Seif stromatolites form N-S bands tens of meters in length, parallel to prevailing wind direction. Bands of seif stromatolites are composed of merged heads with scalloped lobes perpendicular to shore, in the direction of wave translation. The upper surfaces of seif stromatolites are covered by crusty pustular-mats, whereas flanks are composed of crusty smooth-mats. A second characteristic feature of the Booldah Province is the extensive development of subtidal
pavement covered with gelatinous mat producing abundant micritic precipitates. Low-relief microbial to undulose pavement in Booldah Province often has elongations at 130°. Troughs between undulations are filled with sediments of irregular micritic grainstone. Eroded gel mat is common in nearshore areas and micritic grains formed in the gel-mats are the major sediment component often comprising 60-70% of the sample (Fig. 5.9).

Structures comprise a total area of 25.50 km² in Booldah Province (Fig 5.10). Pavement is the most common facies type covering a total of 18.75 km² (73% of total recorded structure area). In addition to the undulating to low-relief gel covered pavement comprising 31% of pavement in Booldah Province, pavement on the seaward edge of the Booldah shelf is tabular. Dark areas on aerial orthophotos were investigated to reveal broken blocks of tabular pavement covered in abundant *Sargassum* sp., creating a habitat supporting abundant sea snake populations. Tabular and blocky pavement make up 69% of the total pavement.

Discrete microbial buildups cover a total area of 3.20 km² (13% of the total recorded structures). Although the iconic seif stromatolites make up 44% of discrete microbial buildups, elongate-clustered stromatolites, often found in the same area with the same mat-types as seif structures are actually more abundant, comprising 45% of the structures. Individual and merged columnar stromatolites make up 11% of discrete microbial buildups, colonized by pustular, smooth, or colloform/gel mats. Relict reef ribbons are also common, and covered with a thin veneer of pustular-mat and in some places hard cauliflower precipitates when located in the splash zone.
Facies belts parallel the shore comprised mainly of continuous stratiform sheet mats, colonizing 3.25 km² (13%) of Booldah Province, often overlying breccia fields.

Holocene deposited coquina beds make up the shoreline facies. Although *Fragum erugatum* are common sediment constituents, irregular micritic grains are the main component (Fig. 5.9).

Booldah Province is characterized as a narrow shelf up to 1.5 km wide. The shelf has a low grade to the edge of the sublittoral platform. The sublittoral platform drops abruptly into the basin at a very sharp transition boundary to deeper waters. The moderately

*Figure 5.9: Photo of sediment taken from the Booldah Province. Eroded gel-mat is common and contributes to the abundance of irregular micritic grains making up the bulk of Booldah Province sediment.*
Figure 5.10: Facies map of Booldah Province located along the south-western margin of Hamelin Pool, is characterized by a prominent pattern of seif stromatolites, forming north-south bands tens of meters in length, parallel to prevailing wind direction. The margin of the Province is a narrow, shallow shelf that drops abruptly into the basin.
Figure 5.11: Idealized transect illustration of Booldah Province displaying the most abundant facies types in Zone 1 (tidal zone), Zone 2 (sublittoral platform) and Zone 3 (basin/embayment plain). All zones are correlated by color (after Fig. 3.13). The depth transect perpendicular from shore, transecting the narrow shelf into the basin. Synthetic transect location is shown in white on the location map.
uniform shelf physiography results in similar facies associations and transitions along the entire margin (Fig. 5.10).

The representative transect of Booldah Province (Fig. 5.11) extends perpendicular to the shoreline, transecting the shelf. The shoreline is dominated by breccia fields transitioning to individual and merged columns that are often in a band of relict heads along the breccia edge. Seaward of the individual and merged columns, the iconic seif structures are prominent features found within the tidal zone (Zone 1). Seif structures taper to lower relief structures and then into low-relief undulose pavement, transitioning to tabular pavement (Zone 2). The shelf edge is mainly blocky pavement that drops abruptly to the basin. Only a few meters from the shelf edge, a sediment probe can be inserted over a meter and the sediments are floatstone rich in organics (Zone 3).

Temperature data were collected just off the shelf in the Booldah Province and a 22°C average temperature was recorded, matching the average in Hamelin Pool (Table 4.5; Fig. 4.6b). Salinity, tide and current data were not collected. Development of the seif stromatolites in Booldah Province, are related to the dominant southerly winds, shallow depth of the shelf, combined with Langmuir circulation (Playford et al. 2013). Additionally, the asymmetric shape and back-stepping of the seif bands, would suggest that the structures accrete on cemented crests of underlying beach ridges. The uniform, shallow hypersaline shelf may also contribute to the production of gel-mat, which carpets the subtidal zone.

5.2.5 Nilemah Province
Nilemah Province encompasses the southern region of the Pool, known as Nilemah Embayment, or Hamelin, spelled backwards (Fig. 5.1). Structures comprise a total area
of 25.93 km² in Nilemah Province (Fig 5.12). Weakly lithified to unlithified stratiform sheet mats comprise 8.53 km² or 33% of the area of total recorded structures. As a result, the key feature characterizing the Nilemah Province are extensive tidal flat deposits of unlithified to semi-lithified pustular sheet mats. Nearshore continuous sheet mat grades from desiccated mini-pustular to tufted mat mixed with soft pustular (wet more frequently) to soft pustular. This wedge-shaped deposit thickens seaward, trending from 8 cm nearshore to 44 cm at the distal end of the facies unit. Ridge-rill structures are also common with a 350 to 360° orientation, also covered in soft pustular microbial mat. Nearshore sheets of non-lithifying *Microcoleus* sp. mats are present, but not abundant.

Discrete microbial buildups cover 2.53 km² of the Nilemah Province, or 10% of total recorded structures. Elongate clusters are the most prevalent structure type in Nilemah Province. Structures are 1-3 meters long, covered in soft pustular-mat, and oriented at 350°. They vary from narrow structures (10cm) to up to a meter across and from 20 to 40 cm in height. Ephemeral pinnacle mats (Fig. 5.13) are also found interspersed on the surface of these structures. Individual and merged columns with up to 40 cm relief, are also prevalent in areas and are colonized by soft pustular or smooth-mat. Individual and merged columns make up a much smaller component of discrete microbial buildups found in Nilemah Province. Pavement covers a total area of 14.89 km², dominated by the tabular morphology (79%). Tabular pavement is mainly impenetrable with a probe. Some areas of pavement in the Nilemah Province is composed of 2-5 cm *Fragum* rudstone coquina and can be easily broken with a sediment probe. Black anoxic sediments are found underneath these layered coquina crust pavement structures. Low-relief microbial pavement to undulose pavement is also common, comprising 21% of
Figure 5.12: Facies map of Nilemah Province, comprising the southern Nilemah Embayment in Hamelin Pool. Nilemah Province is a low-grade tidal-flat environment colonized by extensive microbial mats building unlithified to weakly lithified stratiform sheet mats. Seaward is dominated by elongate-clustered structures, undulose and tabular pavement.
pavements. Undulose pavement is low-relief with elongation normal to shore at 350°, in the direction of wave translation. Sediment is generally rippled (35°) grainstone to floatstone with abundant *Fragum erugatum*, peloids and forams, often covered with flocculent diatom mat.

The geomorphology of the Nilemah Embayment/Nilemah Province is a broad supratidal flat that slopes gently (0.067% gradient) into the basin (Fig. 3.9f). The representative transect of Nilemah Province (Fig. 5.14) transects the tidal flat (Zone 1) from south to north along the low-grade ramp. The first kilometer is dominated by continuous sheet mat, trending into ridge-rill mat. Elongate clusters begin at the seaward end of the sheet.
Figure 5.14: Idealized transect illustration of Nilemah Province displaying the most abundant facies types in Zone 1 (tidal zone), Zone 2 (sublittoral platform) and Zone 3 (basin/embayment plain). All zones are correlated by color (after Fig. 3.13). The depth transect is perpendicular from shore from south to north, transecting 1500 meters of shallow tidal flat. Synthetic transect location is shown in white on the location map.
structures. The representative transect is terminated at 1500 m to for consistency throughout each Province. If the transect were to continue seaward, it would descend to a band of floatstone, followed by tabular pavement into a basin of black, organic rich anoxic sediments.

Environmental parameters affecting the region include one of the smaller salinity ranges (45.3 - 91.5‰), but also has the highest maximum salinity recorded (Table 4.4; Fig. 4.4). Average temperature range (11.2°C – 33.0°C) was the highest along with highest maximum temperature recorded in Hamelin Pool (Table 4.5; Fig. 4.6b). Although the tidal logger did not yield any data for Nilemah Province, the current data were anomalous from the four additional loggers in that they logged much lower speeds. Currents measured in Nilemah Embayment indicated the lowest average current velocities (0.07 m/s). The abnormal disturbance threshold was also the lowest in the Pool (0.14 m/s), but breached the level only 11.2% of the time. The strongest currents only reached 0.57 m/s signifying the region of lowest energy in Hamelin Pool during the two months of data collection measured in 2013 (Table 4.10; Fig. 4.12E). Sheet mats are prevalent in the Nilemah embayment because wave action is light as a result of the prevailing southerly winds that typically direct most wave action off shore (Brown and Woods 1974). In contrast, northerly storms can cause intense wave action and high water levels covering the intertidal and often supratidal zones. In these rare episodes, substrates are scoured and there is a net sediment movement from the sublittoral platform to the Nilemah embayment. Longshore drift and southerly winds eventually drive sediments back into the basin (Brown and Woods 1974). Common low energy also promotes the growth of elongate-clustered structures in the shallow subtidal zone. Nilemah Province is a unique
package with low energy, high temperatures, high salinities, and a tidal zone that spans kilometers, combining to make an extreme environment, promoting prolific growth of microbial mat communities.

5.2.6 Flagpole Province
Flagpole Landing has been a focal point for previous research in Hamelin Pool and is the location of the tourist boardwalk, hence the name Flagpole Province. This Province is located along the southeastern margin, where the well documented individual columns and merged columns are prevalent (Fig. 5.1).

In addition to the iconic stromatolite heads, an association of unique facies also exists (Fig. 5.15). Structures cover a total area of 41.11 km². The nearshore environment is extensive platforms with patches of breccia comprised of old spalled stromatolite heads broken into pieces, creating a fairly planar surface. This brecciated surface can often be colonized by sheet mat. Weakly-lithified to unlithified stratiform sheets cover 1.66 km² of Flagpole Province (or 4% total structures). Continuous stratiform sheets comprise 95% of sheet mats found in Flagpole Province. Nearshore continuous sheet mats are dominantly tufted mats established by filamentous cyanobacteria *Lyngbya* sp. Continuous pustular-mats continue to the seaward end of the breccia field or upper intertidal platform. In some areas of the Flagpole Province sheets become ridge-rill or amoeboid on the seaward end of the platform after the continuous sheet mats cease. Amoeboid sheet structures are dominated by pustular-mat and are generally over 10cm in thickness. In other areas, the continuous sheet mat terminates at the edge of the intertidal zone before an abrupt drop to deeper water (~1 m), often bordered by an eroded system
Figure 5.15: Facies map of Flagpole Province along the southeastern margin of Hamelin Pool. Individual and merged columnar stromatolites are the characteristic facies type in this region. Flagpole Province encompasses possesses two headlands and two large embayments with wide ramps. These stromatolites occur seaward of two main headlands and on a gradually sloping ramp that extends nearly 7 km in some areas. Other facies include continuous sheet mats, elongate clusters, elongate buildups, tabular, blocky, undulose and transitional pavement. Sediment is comprised of floatstone with common live Fragum erugatum beds in the subtidal zone.
Figure 5.16: Idealized transect illustration of Flagpole Province displaying the most abundant facies types in Zone 1 (tidal zone), Zone 2 (sublittoral platform) and Zone 3 (basin/embayment plain). All zones are correlated by color (after Fig. 3.13). The depth transect perpendicular from shore, tidal zone and the sublittoral platform over 1500m. Synthetic transect location is shown in white on the location map.
of individual and merged columns typically colonized by film mat or cauliflower structures.

Stromatolites cover 5.51 km$^2$ (13% of the total recorded structures) in the Flagpole Province. Individual and merged stromatolite structures comprise 69% of this figure presenting the classic seaward zonation of surface mats from film mat grading to pustular-mat, grading to smooth-mat, grading to colloform/gelatinous mats. Around the main headland, a large area of elongate heads are prevalent, 20-30cm in relief and up to one meter in length, with the elongation perpendicular to shore. Elongate-clustered stromatolites are also found (14% of discrete microbial buildups) in the bights with elongation perpendicular to shore with living pustular-mats colonizing the surface. Additional structures that are minor components in Flagpole Province include elongate stromatolites and also composite/segmented structures.

Pavement in Flagpole Province covers 32.72 km$^2$ (80%) and is dominantly tabular with patches of blocks (90%). Undulose to low-relief microbial pavement covers (2%) of the nearshore environment and transitional pavement (8%) is more common in the northern region of the Province. Headlands are mimicked by areas of tabular pavement but not nearly as extensive as the well-developed promontories in the west.

Sediment patches comprised of coarse grainstone to floatstone. Sediments are often colonized with a smooth, crusty mat or covered by flocculent diatom mat. Live *Fragum erugatum* beds are common in the subtidal zone.

Flagpole Province, in the southeast region of Hamelin Pool, has two headlands and two large embayments with wide ramps. Stromatolites occur seaward of two main headlands
and on a gradually sloping ramp that extends nearly 7 km in some areas. The representative transect of Flagpole Province (Fig. 5.16) depicts the seaward zonation of a transect trending from east to west with a narrow condensed facies band parallel to shore (Zone 1). Although the transition to the sublittoral platform (Zone 2) happens rapidly, the platform is a low-grade ramp to the basin. The upper intertidal zone is dominated by fields of breccia and continuous sheets trending to amoeboid sheets. Columnar stromatolites, primarily located in the lower intertidal and subtidal zones, are seaward of sheet mats. The sublittoral platform is also home to several individual and merged columnar structures, but is generally dominated by tabular pavement that is blocky in some areas. Although the representative transect terminates at 1500 m, continuation of the transect seaward would descend into a floatstone dominated basin with areas of patchy live *Fragum erugatum* rudstone facies (Zone 3).

Temperature data collected in two different areas in Flagpole Province revealed average temperature range (13.7°C – 31.6°C) is within a normal range when compared to most regions in the Pool, with a similar 22.2°C average (Table 4.5; Fig. 4.6b). Salinity, tide and current data were not collected.

Flagpole Province exhibits the most developed areas of individual and merged columnar stromatolites, so often presented when discussing Hamelin Pool stromatolites. Indeed, the iconic structures on the eastern margin of Hamelin Pool are easier to access than anywhere else in the Pool. The accessibility of this region contributes to the enduring misinterpretation of stromatolites in other areas of Hamelin Pool. Visitors to Hamelin Pool can view the classic columnar stromatolites at the boardwalk, located at Flagpole Landing. The majority of reported previous research examines and reviews structures
from this locality, a geographically limited portion of Hamelin Pool. Data regarding stromatolites in this region of Pool describe a stromatolite system with representative biological zones with recognition of pustular, smooth and colloform-mat stromatolites (Logan et al. 1974, Playford 1990). Although structures have been fairly accurately described in Flagpole Province, as a result of the geographic focus, the findings are not always applicable to other regions in Hamelin Pool, and have unfortunately often been extrapolated as such. Therefore, we find that previous maps (e.g. Jahnert and Collins 2011, 2012) that define facies units such as pustular, smooth and colloform stromatolites to be inaccurate as there is no simple correlation with surface mats.

5.2.7 Carbla Province
Carbla Province is located along the eastern margin, sharing a southern border with Flagpole Province that extends from Point Sweenymia (Fig. 5.1). The northern border is just south of Hutcheson Embayment. Carbla Province is named after the most iconic stromatolite locality in Hamelin Pool, Carbla Point. Carbla Point is not only heavily laden with microbial buildups, but the structures are extremely variable in shapes, sizes and mat types. Carbla Province does not share the amount of diversity contained at Carbla Point, but is dominated by massive buildups of tabular structures in the lower intertidal to shallow subtidal zone and composite / segmented structures in the subtidal zone.

Large microbial buildup diversity is exhibited in Carbla Province (Fig. 5.17). A narrow, shore-parallel band is home to discrete microbial buildups of Carbla Province covering 1.96 km², or 10% of total recorded facies within the Province. The dominant forms of
discrete buildups documented in Carbla Province include Individual and merged columnar (41%), composite/segmented (22%), tabular (20%), elongate structures (16%).

Classic Carbla stromatolite heads fall under the previous “classic” category of black film and red film stromatolites. These structures are considered relict and were stranded in the upper intertidal to supratidal zones by a relative fall in sea level. These structures are however often (even daily) inundated by seawater at high tide. When wet, they exhibit a bright green color (presumably due to a film mat of living Entophysalis sp.). In deeper water, where exposure is less frequent, black film heads are rimmed by living pustular or coated with cauliflower structures (Entophysalis sp.). Outside the vicinity of the Carbla Point headland, the classic structures are not dominate features. Instead, the heads are made up of mostly discrete columnar and merged heads covered in pustular-mat, grading to smooth coccoid dominated mats in deeper water. Many nearshore heads are also elongated with the long axis perpendicular to shore. Structure elevation controls the prevailing surface mat type.

Tabular structures composed of amalgamated stromatolites with extremely flat tops, coccoid dominated smooth-mats and macroalgae fringing the sides are found in the lower intertidal to subtidal zones in Carbla Province. Often tables exhibit fingers extending in the direction of wave translation, but can exist as amoeboid structures with no apparent direction. Gigantic tables can reach over 5 meters in length and over 2 meters in width, however relief does not typically exceed one meter. Tables situated higher in the intertidal zone are colonized by pustular-mat. Accomodation space is the probable cause for the flattening of the stromatolite surfaces into tabular stromatolite structures in Carbla Province.
In the subtidal zone, large domains containing composite/segmented heads. These structures are possibly equivalent to Jahnert and Collins (2011, 2012) cerebroid structures, however this remains unclear. Although heads are present as individual structures, these heads are typically separated into lobes with the entire structure covered in macroalgae (Fig. 5.15). Buildups generally range between 20-50cm in relief and are affixed to pavement crust, several centimeters thick. Structures are covered in *Acetabularia* sp. and other macroalgae. Sample collection of a segmented head revealed light green clay subsurface beneath the pavement. Bladed/segmented heads are also often elongated between 45 and 65° but are vastly distinct from the general elongated head classification. Structures can become massive in size, manifesting into composite structures including: buns domes, amoeboid, ridges, sometimes with large sand filled depressions in the center or most commonly with segmented lobes or colloform knobs adorning the top. Structures can reach up to 2 m in height. *Acetabularia* sp. and other green algae covers the entire surface. Amalgamation sutures are still visible through the green algae. Huge blocks of outcropping country rock covered by a thin (up to 5cm) veneer of microbial crust, may have implications regarding many massive structures.

Similar to Flagpole Province, breccia is a common facies type along the margin in the upper intertidal to supratidal zone areas, indicating a time when sea level was higher. As a result of sea level fall, structures and sheet mats became exposed for long periods of time consequently eroding and spalling into expansive breccia fields along the shoreline. Continuous sheets, colonizing 0.68 km² of Carbla Province (3% of mapped facies in Carbla Province) use these flat, eroded intertidal zone surfaces to colonize. Filamentous
Figure 5.17: Facies map of Carbla Province in Hamelin Pool. Carbla Province is dominated by massive buildups. Individual and Merged Columnar discrete microbial buildups occupy the shoreline, often stranded from a time of higher relative sea level. The subtidal zone has abundant tabular stromatolites, composite and segmented structures. The shore parallel belt of discrete microbial buildups closely hugs the shoreline. The subtidal zone has abundant living rudstone beds comprised of Fragum erugatum.
cyanobacteria *Lyngbya* sp. establish unlithified sheet mats that blanket shoreward areas. Coccoid cyanobacteria *Entophysalis* sp. form pustular-mats and cover seaward flats. Sheets terminate at the platform edge when located on headlands before dropping into subtidal zones uninhabitable by sheet mats.

Coquina beach rock (often tarnished black) is also present along much of the shoreline, which extends into the intertidal zone and is often brecciated.

Pavements are the most common facies type in Carbla Province, covering 17.15 km$^2$. Undulose pavement is also present with elongations normal to shore, covered in *Acetabularia* sp. and with sporadic low-relief microbial buildups. Seaward of the undulose pavement is tabular pavement, the most common pavement sub-facies. Tabular pavement makes up 72% of pavements, which are composed heavily of coquina shells.

Sediments are fine grainstone nearshore and are often dark in color, or composed mainly of peloids, ooids and forams. Grainstone coarsens moving away from shore. Floatstone is also present in areas with large skeletal fragments and *Fragum erugatum* components. In 4 – 5 m water depth, sediment type is mainly floatstone to rudstone as living *Fragum erugatum* beds are abundant.

The distinct physiography of the margin results in a narrow strip making up the intertidal zone, which descends rapidly into the subtidal zone to depths of 4-5 meters before transitioning into the basin. An idealized transect of the Carbla Province (Fig. 5.18) shows a unique zonation of facies. Depending on the grade of the shoreline, the typical feature can be breccia, breccia covered with sheet mat or beach rock. Columns and merged columns are common around
Figure 5.18: Idealized transect illustration of Carbla Province displaying the most abundant facies types in Zone 1 (tidal zone), Zone 2 (sublittoral platform) and Zone 3 (basin/embayment plain). All zones are correlated by color (after Fig. 3.13). Synthetic transect location is shown in white on the location map.
headlands in this Province. Nearshore intertidal to shallow subtidal zones (Zone 1) tabular structures are the dominant structure type, often becoming just one huge amalgamated tabular stromatolite dominated platform with complete coverage of the area. In bights, a band of sediments often follows these structures. Incredibly well cemented, high relief massive composite and segmented structures have accreted seaward of the sand band between 2-4 meters water depth. Smaller composite/segmented structures are found seaward that often have surfaces with vermiculated, coccoid dominated smooth-mats. These structures are weakly lithified and can be penetrated by probe, 5-10 cm. Seaward of the buildups, undulose pavement becomes the dominant facies type that thins to plates of lithified pavement, colonized by *Sargassum* sp. Tabular pavement is patchy, with intermittent sediments and occasional blocks of pavement (Zone 2). At five meters water depth, unconsolidated sediments can be probed to over a meter in depth, sediments are floatstone or rudstone where live *Fragum erugatum* beds are common (Zone 3).

Environmental parameters affecting the region include a large tidal range (spanning 2.04 m – measured over 20 months) with a mean water level of 0.24 cm (Table 4.6; Fig. 4.7). Average temperature range is of between 14.6°-32.0° (average 22.3° - consistent with the rest of Hamelin Pool) (Table 4.5; Fig. 4.6b). Salinity range is the most variable in Hamelin Pool (15.7‰ – 86.3‰), and has an average 66.1‰ (Table 4.4; Fig. 4.4). Currents measured in Carbla Province, collected off Carbla Point in 2 m water depth at 4-minute intervals, were on par with the rest of Pool outside the Nilemah Province at 0.12 m/s. The abnormal disturbance threshold was highest (0.28 m/s), but the Province only experienced stronger than normal currents only 6.8% of the time. The strongest currents
only reached 0.60 m/s during the two months of data collection measured in 2013 (Table 4.10; Fig. 4.12D).

A key word to describe Carbla Province is “massive” as intertidal and subtidal zone structures are abnormally large throughout the entire Province. The bathymetry profile in this province is perhaps key to massive structures. The nearshore shelf/intertidal zone quickly drops to a depth of a few meters. The depth provides accommodation space for large structures to accrete. A small structure, assumed to be a stromatolite, was sampled from Carbla Province for the Hamelin Pool stromatolite collection. Upon slabbing, a nucleus of a conglomerate material with a microbial crust was uncovered. It is my hypothesis that massive structures in the subtidal zone may be microbial buildup accreting atop allochthonous boulders positioned by a high energy weather event such as a tsunami or mega-tsunmai. Current growth models would not substantiate a structure of this size (up to 2 meters). Growth rates from previous publications would indicate that a structure of 1.5 meter would need to be growing at a rate of 0.75 mm/year (Jahnert and Collins 2012) to reach present height, which is faster than predicted by all studies except Logan et al. (1974). If these structures commenced growing only 2,000 years ago, it is more likely that the stromatolite is accreting on a very large nucleus. Using Playford’s (1980) estimate (as it was measured in situ), we can calculate that the block the stromatolite is nucleating on cannot be smaller that 50cm in relief off the seafloor. It could be possible that these boulders that provided the base for stromatolite growth came from large tsunami or storm deposits. Additionally, there is a large out-of-place block of eolianite off Carbla Point that appears to be overlying younger structures, along with another large rock reef deposited in the subtidal zone. Therefore, deposition of large
boulder size debris due to the direction of the storm and bathymetry profile could have a large impact on the massive structures in Carbla Province.

Table 5.1: Extrapolated time needed to accrete a 1.5 meter stromatolite. Growth rates derived from previous research.

<table>
<thead>
<tr>
<th>Publication</th>
<th>growth rate mm/yr</th>
<th>Methodology</th>
<th>Accretion time for 1.5 m structure (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Logan et al. (1974)</td>
<td>&lt; 1</td>
<td>unknown</td>
<td>&gt; 1,500</td>
</tr>
<tr>
<td>Playford (1980)</td>
<td>&gt; 0.5</td>
<td>in situ measurements</td>
<td>&gt; 3,000</td>
</tr>
<tr>
<td>Chivas and Polach (1990)</td>
<td>0.04 - 0.24</td>
<td>C-14 dating methods</td>
<td>6,250 - 37,500</td>
</tr>
<tr>
<td>Jahnert and Collins (2012)</td>
<td>0.1 - &lt; 0.5</td>
<td>C-14 dating methods</td>
<td>&lt; 3,000 - 15,000</td>
</tr>
<tr>
<td>Guisfredi et al. (2014)</td>
<td>0.07</td>
<td>C-14 dating methods</td>
<td>21,500</td>
</tr>
</tbody>
</table>

Additionally, subtidal structures in the Carbla province exhibit initial microbial framework (Reid et al. 2003). Micritic frameworks could be encouraged by ground water influx or supersaturated waters, as is a critical factor for growth of lacustrine stromatolites (i.e.: Burne and Moore 1987, Moore and Burne 1994). Salinity logger data collected at Carbla Point displayed the largest flux of “fresh” water.

Carbla Province is one of the most astounding Provinces in Hamelin Pool, as a result of the massive structures occurring throughout. The classic structures at Carbla Point add to the unique profile of the Provience, but are not common outside Carbla Point. Classic zonation as described by previous research is prevalent in this Province as well as its counterpart Flagpole Province, to the south. As a result of the narrow tidal zone, the classic zonation is compressed in a fine shore parallel facies belt, making Carbla Province
an interesting place to study. Shelf physiography and water chemistry set Carbla Province apart from the remainder of the Pool.

5.2.8 Hutchison Province
Hutchison Province is appropriately named after Hutchison Embayment, a large hypersaline bay in the located in the Northeast region of Hamelin Pool. Although Hutchison Embayment is an extraordinary location, details regarding the formation are beyond the scope of this dissertation. Hutchison Province is a large bight, geographically situated between Kopke Promontory in the north, where it shares a border with Faure Province, and Yaringa promontory in the south, where it shares a border with the Carbla Province (Fig. 5.1).

Microbial buildups and diversity are similar to Nilemah Province. Elongate-clustered structures are the characteristic structure of Hutchison Province, covering over half (52%) of the 1.69 km$^2$ occupied by discrete microbial buildups. Structures are covered in pustular-mat in the intertidal and coccoid dominated smooth-mats in the subtidal zone. Additional common structures include individual and merged columnar (26%) and elongate (14%). Individual and merged columnar stromatolites have a patchy distribution. Ribbons of low-relief structures are found in the intertidal zone are colonized by soft pustular-mat. Ribbons suggest and underlying topographic high. Minor discrete microbial buildups present include tabular and composite, each representing only 4% of the total stromatolite sub-facies in Hutchison Province.

Breccia is a common facies type, spanning nearly the entire shoreline of Hutchison Province. Falling sea level exposed vast tidal flats in the bight with sheet mats and low-relief buildups. Erosion turned the stranded fields into chaotic fields of breccia in the
supratidal to upper intertidal zone. Relict, eroded structures show preferential cementation along the margins and have left behind sinuous snaking outlines of eroded stromatolites in the breccia fields (Fig. 5.19). Additionally, relict Pleistocene coral fragments have been uncovered. Behind the breccia fields are large dunes, possibly storm or tsunami deposits or from longshore drift when sea level was higher. Large salt-pans are common in Hutchison Embayment behind these topographic highs, sometimes colonized by blister mat or succulent plants.

Sheet mats comprise 26.18 km$^2$ of Hutchison Province, or 47% of mapped structures in Hutchison Province. Although the majority of sheet mat in this Province is in Hutchison Embayment, sheet mats are present in all forms on the Hamelin Pool shoreline including: continuous, ridge-rill and amoeboid. Flats, often sheltered by coquina mounds of pure *Fragum erugatum*, exhibit continuous sheet mats composed of smooth filamentous (*Microcoleus* sp.) mats and tufted (*Lyngbya* sp.) mats. Seaward of the unconsolidated coquina mounds, the nearshore area becomes dominated by continuous sheets of soft pustular-mat (*Entophyalsis* sp.), often sprinkled with abundant *Fragum erugatum* shells. Seaward, the continuous mat begins to separate into both ridge-rill structures (elongated at 90°) and amoeboid sheet mats where exposed to higher energy regimes.

Pavement, covering a total area of 27.84 km$^2$, includes nearshore transitional pavement (31% of pavement in Hutchison Province) composed of a weakly cemented coquina hardground often tarnished black from subaerial exposure, colonized by small buildups with a mix of pustular and coccoid dominated smooth-mats. Buildups are often scalloped with the elongation of the lobe perpendicular to shore. Further from shore, tabular
pavement becomes the dominant facies type (covering 68%), mixed with areas of floatstone.

The sediment regime in Hutchison Province is variable. The shoreline is covered by *Fragum* Rudstone. Many of the small bivalves found in the large dunes on shore are found intact. Upon death of the bivalve, decay of the organism produces gas, causing the closed bivalve to float to the surface and be carried to shore. Additionally, live and dead *Fragum* beds are abundant on the shelf off shore. Live *Fragum* beds, piled high with living *Fragum* are a darker brown than the surrounding sediments as a result of organics. Swimming or walking in areas of abundant *Fragum erugatum* growth, the sediment water interface is extremely warm. *Fragum* is thought to occur in large numbers (4000/m²) and complete its life cycle within one year (Berry and Playford 1997, Morton 2000, Playford et al. 2013).

This accounts for the substantial accumulation of *Fragum* sp. shells not only in this area, but also in Hamelin Pool in general. Islands of *Fragum* sp. are also found emergent from intertidal areas creating boundaries from sheet mats and cemented coquina crust and structures. Additional sediments include floatstone and skeletal grainstone. As the shelf grades down slowly into the basin from ~3 m to ~8 m, basin sediments are dark grey to black skeletal grainstones but have a thin layer of floccules covering them.

The ~6 km ramp that comprises the majority of the shoreline has a gentle 0.038° slope (0.067% gradient) (Fig 5.17) in this region. The synthetic transect from the Nilemah Province shares the same gradient to the subtidal zone as Hutchison Province, suggesting the degree of slop is responsible for the structure morphologies and facies transitions.
Figure 5.19: Facies map of Hutchison Province in Hamelin Pool. Hutchison Province is dominated by continuous sheet mats and elongate-clustered discrete microbial buildups. The low-grade ramp and extensive intertidal zone contributes to distinct facies types, associations and abundant pustular-mat. Antecedent topography is evident offshore in lines of breccia, indicating reworked crests.
Figure 5.20: Idealized transect illustration of Faure Province (West) displaying the most abundant facies types in Zone 1 (tidal zone), Zone 2 (sublittoral platform) and Zone 3 (basin/embayment plain). All zones are correlated by color (after Fig. 3.13). Synthetic transect location is shown in white on the location map.
One large difference in facies types between the two Provinces is the dominance of breccia along the shorelines of Hutchison Province, while breccia facies is relatively absent in Nilemah Province. The representative transect of Hutchison Province (Fig. 5.20) depicts the seaward zonation of a transect through the tidal flat trending from east to west along the low-grade ramp. The shoreline has abundant breccia fields of eroded structures followed by a kilometer of sheet mat. (Zone 1) Continuous sheet mat trends to elongate-clustered stromatolites sometimes forming in ribbons or bands parallel to shore. Although the representative transect terminates on the diagram at 1500 m continuation would transect pavement and abundant grainstone, floatstone and rudstone into a basin of fine grainstone to floatstone, often covered with a diatom mat.

Environmental parameters affecting the region include one of the smallest measured salinity ranges (30.9‰ – 80.7‰) with an average of 65.6‰ (Table 4.4; Fig. 4.4). Temperature range (13.9° - 32.0°C) was normal with an average temperature of 22.5° C (Table 4.5; Fig. 4.6b). The western margin exhibited the largest range in tide over the 20 months measured. Hutchison Province tidal range spanned 2.03 m, with a mean water level of 0.04 cm, much lower than the mean sea level in Carbla Province (Table 4.6; Fig. 4.7). Currents measured in Hutchison Province are on par with the rest of Pool (excluding Nilemah Province) at 0.14 m/s. The abnormal disturbance threshold was highest (0.28 m/s), shared with Carbla Province, and experienced stronger than normal currents only 6.2% of the time. The strongest currents reached peak velocity of 0.74 m/s, the highest reading in Hamelin Pool during the two months of data collection measured in 2013 (Table 4.10; Fig. 4.12B).
Energies are higher in the northeast but have less extreme environmental parameters/water chemistry than in the Nilemah Embayment. This would indicate that similar structure types are likely a result of the low-grade ramp, but merits more investigation.

5.3 Conclusions
Through our systematic, mapping-based study, we found that Hamelin Pool facies have distinct associations and zonations in different regions throughout the Pool. In particular, stromatolite morphologies develop in spatially constrained identifiable provinces characterized by unique regional characteristics. As Hamelin Pool contains the largest assemblage of modern stromatolites and associated microbial buildups, these results provide impetus to develop quantitative models linking regional stromatolite morphology with paleo-environmental conditions—including energy regime and sediment production and load in conjunction with physiography of the area of stromatolite growth.

The next phase in the study will focus on morphometric interrogation of high-resolution imagery captured in the 2014 field program. Select areas within each Province were chosen that showcased the key growth structures to be able to quantify the differences between the eight Stromatolite Provinces of Hamelin Pool.
"Amid all the revolutions of the globe the economy of Nature has been uniform, and her laws are the only things that have resisted the general movement. The rivers and the rocks, the seas and the continents have been changed in all their parts; but the laws which direct those changes, and the rules to which they are subject, have remained invariably the same” (Playfair 1802). The one difference in the equation so eloquently described by Playfair, is the evolution of biology and the effects biological processes have on the rock record and how they have evolved through time. Stromatolite building microbial mats have survived the tests of evolutionary time, dominating the fossil record 80% of Earth history (Awramik 1992). Therefore, if the “present is key to the past” (Lyell 1830), developing meaningful relationships between modern environments and stromatolite biology may be the Rosetta stone for interpreting this enduring system.

Environmental parameters such as wind, current, tides (albeit larger), variable temperatures and salinities were similar in ancient times as today. The main difference between the ancient and modern is the presence of higher organisms that did not exist during early Earth. For this reason alone, many ancient stromatolitic structures may be difficult to interpret when comparing to the modern. Ancient stromatolite building microbial mat communities could thrive in assumedly any environment. The rock record demonstrates stromatolite building microbial communities reaching their highest population and greatest morphological diversities between 2800 and 1000 million years before present (Awramik 1971, Riding 2000). At this time in geological history, evolution of higher forms of life begat superior competitors for food, space and other resources. Although stromatolite building microbial communities prevailed, they were
impelled to unfavorable or inhabitable, extreme environments for “evolved” organisms, resulting in their Proterozoic decline at 1000 to 540 million years before present. The Phanerozoic Eon produced records of stromatolites associated with extreme environments, leaving signatures throughout the rock record.

Presumed to have met their ultimate demise of extinction, modern stromatolites were discovered in 1954 by Phil Playford in Hamelin Pool. This invaluable discovery offered us the first window to the accretion mechanisms of structures that dominated an amount of time incomprehensible to the human mind. The assemblage of stromatolites in Hamelin Pool included microbial build-ups with sizes, shapes and textures analogous to ancient structures and even the microbe *Entophysalis* sp. has an ancient lineage to *Eoentophysalis* (Golubic and Hofmann 1976). Applied with caution, especially to Precambrian structures, when constraints by higher organisms was not an issue, modern assemblages in Hamelin Pool can be the bridge to understanding life on early Earth.

The current study of Hamelin Pool has led us to the following conclusions regarding modern stromatolites:

1. Stromatolite sampling and intensive ground-truthing in Hamelin Pool revealed that no simple correlation exists between microbial surface mat, internal structure and morphology.

2. Structures described by morphology is an improved methodology that has greater implications than water depth (provided by microbial mats).
3. Mapping stromatolite structures has exposed a unique distribution of morphologically distinct buildups with a unique “package” of facies associations in different regions throughout Hamelin Pool.

4. Major factors contributing to stromatolite growth and distribution include regional and local physiography/physically constrained geographic areas, biological composition of microbial communities, water chemistry, available substrate/antecedent topography local energy regime and sediment load (Fig. 6.1).

5. Stromatolites of Hamelin Pool and interpretation of surrounding facies can be used as a powerful analog for better understanding of ancient structures, interpretation of subsurface reservoirs, the quest to find life on other planets and improved conservation and environmental management of the region.

Ginsburg (1991) suggested nature vs. nurture roles, indicating that an inseparable duality may exist in formation of stromatolite structures where microbes (nature) may influence the internal structure whereas environment (nurture) may influence morphology.

Various morphologies in Hamelin Pool can be compared to structures dating back to the Precambrian. In the modern, organism types suited to the environment begin to colonize the substrate and are shaped by various influences (Fig. 6.1). In the Precambrian, biology could have had a larger effect on structure morphology as lack of competition may have allowed stromatolite building microbial communities to thrive lived in various to any/all environments, where they were able to express their desired biological growth structures.
If this hypothesis holds true, it may explain why using stromatolite morphology for stratigraphic interpretations seems to hold up as with investigations conducted by Grey (1984, 1994). Stromatolites during Precambrian times had very distinct structures that were commonly narrow, tall, erect, conical, or branching. Younger stromatolites beginning in the mid-Paleozoic become broader and unbranching, trending toward morphologies similar to structures found in the modern (Walter 1972).

There are however, many structures in the Precambrian resembling modern buildups. One example, as mentioned in Chapter 5 (Fig 5.6), is the stromatolite formation at Great
Slave Lake in the Northwest Territories. These longitudinal stromatolites look curiously similar to the elongate-nested stromatolites found to the south of headlands on the western margins of Hamelin Pool (Hoffman 1974). Using Hamelin Pool stromatolites as an analog to these 1.9 Billion year old structure would indicate Great Slave Lake stromatolites formed in the lower intertidal to subtidal zones, in an area with moderate, directional energy and the long axis would have been perpendicular to an ancient shoreline, in the direction of wave translation.

Other examples include, late Cambrian structures from the Petite Jardin Formation in Western New Foundland with similar columnar morphologies, analogous to Hamelin Pool columnar stromatolites. Mid to late Devonian reef complexes in the Canning Basin exhibit shallow water stromatolites in back reef deposits that accreted in shallow seas. Additionally, an outcrop at Windjana Gorge exhibits a reef flat environment of preserved stromatolitic columns. These ancient structures all show close similarities to structures found in Hamelin Pool that accreted in a similar shallow environment (Playford and Cockbain 1976, Playford et al. 1976, 2009).

The macrostructure of Cenozoic, lower-middle Miocene structures of the east African Rift include bioherms 0.1 m - 2 m in size that acquired their domal morphology as the result of an underlying topography such as large pebbles, former stromatolites or other asperities. Often the stromatolitic growth formed only a microbial crust several centimeters in thickness around pebbles or boulders (Casanova 1994). Modern stromatolites in Hamelin Pool often nucleate on pebbles or cobbles because they are topographically higher and allow the microbial community to build a community above migrating sand waves. This phenomenon could help better interpret the east African Rift
setting. Stromatolite morphologies from this Miocene formation include columns, coalesced columns and large flattened bioherms (Casanova 1994), similar to intertidal zone structures in Shark Bay. Deeper structures in Hamelin tend to have more rounded surfaces, but moving into the upper intertidal zone, several of these surfaces severely flatten at the surface, which is perhaps a result of accommodation space. Variations in morphology can therefore be attributed to local ecological parameters and the available substrate.

Another interesting aspect regarding the Carboniferous structures is the siliciclastic input from terrigenous material that the microbial community incorporated into the structure, which also parallels with the terrigenous quartz input into Hamelin Pool stromatolites, also incorporated (Bertrand-Sarfati 1994). Elongate-nested structures form dominantly along the western margin of Hamelin Pool, in the vicinity of the eroding Peron Sandstone. The amount of siliciclastic input in the stromatolitic structures may also influence the shape.

Although only a small number of correlating studies have been mentioned, there are countless others that are similar to Hamelin Pool stromatolites. Indeed, Hamelin Pool structures are relevant to interpreting shallow coastal water environments of ancient Earth history. Variations in extrinsic environmental controls exist in the different environmental settings of Hamelin Pool that cause the signature features within the Provinces. These differences may offer a variety of solutions to interpret ancient stromatolite structures. Extrapolations between communities must be exercised with great caution even though vast parallels are present. Hamelin Pool structures have applicability to countless stromatolite formations in the rock record around the globe.
Trompette (1982) compares relative influence of size of microbialite structure in comparison with the environmental and biological influences (Fig. 6.2). In this model, the larger structures (bioherms and columns) are mainly influenced by environmental pressures and not at all by biological factors, whereas the morphology of microbial communities and internal structure laminations are influenced strongly by biological factors and not by environmental parameters. Building upon knowledge learned in the modern, a stable, competitive environment does not produce stromatolite-building communities as victors. As such, I present a new model for both ancient (Fig. 6.3) and modern (Fig. 6.4) growth. In the ancient, biology had a larger influence on stromatolite
development. In the Precambrian, higher organisms that could outcompete the stromatolite building communities did not exist and therefore stromatolite building microbial communities could thrive in any environment providing light was available for photosynthesis, evidence for why stratigraphy based on ancient growth forms is applicable. In the modern environment, such as Hamelin Pool, the controlling factor on stromatolite development is the environment. In the modern, stromatolitic structures

![Diagram](image)

**Figure 6.3:** Conceptual model illustrating influence of microbial (biological) influences versus physical environmental influences on precambrian stromatolite formation (revised from Trompette 1982, Ginsburg 1991, and Andres and Reid 2002). Note the perceived biological importance in ancient structures where stromatolite building microbial communities could presumable thrive in many different environments and did not rely on environmental controls to exclude higher organisms.
Figure 6.4: Conceptual model illustrating influence of microbial (biological) influences versus physical environmental influences on modern stromatolite formation (revised from Trompette 1982, Ginsburg 1991, and Andres and Reid 2002). Note the perceived importance of environmental pressures on stromatolite building microbial communities in the modern environment that require extreme environmental conditions to exclude higher organisms so that they may thrive.

thrive only in extreme environments that exclude higher forms of eukaryotic life. Environment controls not only the ability for stromatolite building microbial communities to thrive, but also impacts internal lamination by changes and/or cyclicity in environmental conditions and/or affecting internal fabric and laminations. The energy regime controls the gross morphology of the structure. Morphologies of modern structures can therefore be used as proxies to ancient structures, in the ancient, however not all morphologies in the ancient can be related to the modern. Given that stromatolites require an extreme environment to flourish, the next 100 years could be a perilous path
for this delicate system. Rising sea levels could result in either of the following outcomes:

1. Slow sea rise - Faure Sill is able to “keep up” with the rise, continually baffling sediments and restricting flow into Hamelin Pool. In this scenario, the stromatolite building system will continue to thrive. Relict stromatolites currently stranded in the supratidal zone will see new microbial growth, current intertidal zone stromatolites will find themselves in the subtidal zone with a microbial community better suited for deeper waters, and subtidal stromatolites should continue to flourish although the deepest ones may cease accretion.

2. Rapid sea level rise – Drowning of the Faure Sill resulting in water of normal salinity flooding into Hamelin Pool. This scenario is catastrophic to the modern stromatolite building system. Stromatolite building microbial communities would be extinguished as stable marine environmental conditions allow higher organisms, capable of outcompeting prokaryotic communities for space and nutrients as well as increased grazing, thereby preventing growth and stromatolite accretion.

As the latter scenario is probable, it is critical to study the modern system now, before the mechanisms of growth no longer exist. In the context of time, Hamelin Pool offers only a peek into a moment of modern stromatolite building communities. This glimpse of time may be key in understanding a mechanism that has existed for thousands of millions of years, rates humans are incapable of understanding as they have, and will continue to, outlast all who study them.
Stromatolites existed before our time, and will continue to exist long beyond our time. Outside of providing an analog to ancient stromatolites, Modern stromatolites are perhaps a guide to the health of the planet, as there is no better measure than a resilient ecosystem that has survived the test of time.
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