

Characteristics, distribution and morphogenesis of subtidal microbial systems in Shark Bay, Australia

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ABSTRACT

The distribution, nature and extent of microbial deposits in Hamelin Pool, Shark Bay have been investigated and mapped with emphasis on the occurrence, external morphologies, internal fabrics, constructional mechanisms, microbial communities, growth rates and sediment associations in the intertidal and previously little researched subtidal zone.

Detailed georeferenced substrate mapping revealed extensive subtidal microbial deposits occupying approximately 300 km² of the total Holocene 1400 km² area of Hamelin Pool. The Microbial Pavement covers 227 km² of the subtidal substrate that together with columnar structures reveals a subtidal microbial habitat which occupies an area 10 times larger than the area of the intertidal deposits. Microbial carbonate is composed of aragonite (80–98%) that reveals high positive values of $\delta^{13}\text{C}$ (+4.46 to +5.88) and $\delta^{18}\text{O}$ (+3.06 to +3.88) as a characteristic of the highly evaporative environment with extensive microbial activity. Oldest dated heads are 1915 and 1680 ¹⁴C years BP, and the overall system was deposited in two stages; the first between 2000 and 1200 and the last from 900 years BP to the present. Slow growth rates vary from less than 0.1 mm/year to 0.5 mm/year.

Different internal fabrics were constructed according to their position in relation to the littoral zone by distinct microbial communities, and lateral fabric relations have been established. Evidence of shallowing-upward fabric sequences of microbial origin reflects relative falling sea levels during the late Holocene and is likely useful in ancient environmental interpretation. A sequence of events and mechanisms are described emphasizing differences between the stromatolitic, thrombolitic and cryptomicrobial deposits in Shark Bay. The new substrate map and depositional history for this distinctive and peculiar microbial habitat establish the significance of subtidal structures and emphasize the geoscientific importance of Hamelin Pool, especially with respect to early life studies and ancient analogues for understanding microbial activity, deposit characteristics, fenestral fabrics and distribution.

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1. Introduction

Shark Bay World Heritage area is located 800 km north of Perth on Australia's westernmost coast. The region is recognized for its natural beauty and scientific significance, particularly the conspicuous stromatolites and thrombolitic structures, produced by microbial communities.

The morphological features of these modern microbialites resemble those of fossilized assemblages thereby providing extensive modern analogues for ancient systems, which include some of the earliest life on Earth. The best studied example of the likely oldest evidence of life on Earth is in the Pilbara district of Western Australia, in stromatolitic rocks aged 3.47 billion years which separate from the stromatolites

include fossilized thread-like and globular bacteria (Schopf, 1993; Walter, 1999; Allwood et al., 2006; Van Kranendonk et al., 2008).

The microbial carbonate system in Hamelin Pool has developed in response to a slow progressive change in environmental conditions transforming a near open marine system into a restricted embayment landlocked to the east, south and west and semi-closed to the north by a barrier bank (Faure Bank, see Fig. 1), with abnormal salinity, high alkalinity and high evaporation (Logan et al., 1974a, 1974b). Microbial sediment started depositing at about 2000 years ago long after the Holocene maximum flooding of the sea level at about 6800 U/Th years ago (Chivas et al., 1990; Nakata and Lambeck, 1990; Collins et al., 2006). This was in response to a relative sea level fall of about 2.5 m, as a minor variation within the Holocene stratigraphic high-stand system tract (Jahnert and Collins, 2011). High stress conditions in an intertidal-subtidal environment have supported the development of a prolific microbial benthic domain which has produced organo-sedimentary deposits (mats, domical or columnar structures) mainly by trapping, binding and biologically promoted carbonate

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Fig. 1. Hamelin Pool, L'Haridon Bight and Henri Freycinet embayment at Shark Bay, WA. Image from Geoscience Australia.

precipitation (cf. Baumgartner et al., 2006; Dupraz et al., 2009), where processes of accretion exceed erosion (Logan et al., 1974b).

The existence of stromatolites in Hamelin Pool has been known since the 1950s (Playford and Cockbain, 1976). However, apart from the presence of subtidal stromatolite heads at the seaward termination of a limited number of surveyed tidal flat transects, there was little documentation of the nature and extent of subtidal habitat.

Logan et al. (1974a) were the pioneers in establishing the microbial deposits' external morphologies which include stratiform sheets, ridge-rill structures, discrete elliptical and circular columns, detached lumps and calyx structures. They also recognized and described internal fabrics providing a useful nomenclature. While terminology applied to describe systems similar to Shark Bay build-ups has varied and includes bioherm (Cummins, 1932), microbial lithoherm (Burne and Moore, 1987) and matrix supported organic reef (Riding, 2000) the Logan et al. (1974a, 1974b) nomenclature is, as far as possible, being followed in this paper. In addition newly documented fabrics and microbial deposits recognized in the subtidal zone follow the description and terminology reported in Jahnert and Collins (2011).

Playford and Cockbain (1976) and Playford (1990) recognized the occurrence of stromatolites in the intertidal and subtidal zones at depths of 3.5 m and also provided a depositional model with colloform deposits as the deepest in the subtidal zone.

Awramik and Riding (1988) argued that algal eukaryotes may play a substantial role in the formation and maintenance of subtidal columnar stromatolites in Shark Bay and are capable of trapping coarse sediment, proposing two major types or end members of recent marine stromatolites which they designated "eualgal-cyanobacterial stromatolites" that are generally coarse-grained and "cyanobacterial stromatolites" that are generally fine-grained.

Golubic (1982) described the coccoid cyanobacteria *Entophysalis major* as responsible for the brown, gelatinous, pustular or mammillate mats and columnar structures in Shark Bay, and explained the mat growth process of massive gel production with unidirectional vertical excretion causing cells to arrange in vertical rows with growth of mammillae on the surface of the mat.

A Hamelin Pool sea bed classification was provided by Burne and Veitch (1990) in a 1:100,000 map that contains a detailed bathymetric survey of the embayment and delineates an area of dark

diatom-rich organic ooze on the basin floor in the southwest of the embayment.

Chivas et al. (1990) determined vertical growth rates of ≤ 0.4 mm/year using radiocarbon dating supported by uranium-series methods and established the interval of 1250–1000 years ago for the development of the oldest stromatolites in Shark Bay. Reid et al. (2003) produced a detailed petrographic analysis of intertidal/subtidal microbial carbonate in Hamelin Pool recognizing the importance of microbial precipitation of micrite as a fundamental primary accretionary mechanism forming stromatolites in the subtidal zone. Burns et al. (2004) using a polyphasic approach of bacterial culture-dependent and culture-independent methods, reported the presence of a wide range of microorganisms associated with the biosedimentary structures identifying cyanobacteria, other bacteria and archaea in stromatolite samples.

The microbial substrates in Shark Bay are valuable assets for comparison with ancient systems (Walter, 1999; Flannery and Walter, 2012), because of their extensive distribution, different morphologies, external characteristics, internal fabrics and recognized microbial communities. Phanerozoic microbial deposits have a significant global chronological distribution, frequently serving as hydrocarbon reservoirs and also as hydrocarbon source rocks.

A new geoscientific survey conducted in Hamelin Pool (see Jahnert and Collins, 2011), the easterly embayment of Shark Bay, during 2008–2011 using remote sensing, underwater video and swath mapping examinations was applied to construct intertidal to subtidal georeferenced maps of the organic substrates and sediments thereby identifying the widespread nature and distinctive character of microbialites. The results establish the significance of the subtidal microbial habitat as an important previous information gap in our knowledge of an ecosystem of high conservation value in Hamelin Pool Marine Nature Reserve, albeit some decades after establishment of the World Heritage area.

The purpose of this paper is to redescribe the distribution, nature and extent of microbial deposits in Hamelin Pool, Shark Bay, focusing on the external and internal fabrics, and microfibrils; to re-evaluate the microbial depositional model; and also to investigate microbial growth processes, rates, ages and sediment associations.

2. Geology and environmental setting

The geographic features of Shark Bay are controlled tectonically by a regional normal fault system of N–S orientation which intersects a NNW–SSE oriented fold system responsible for confining the bays to the subsiding synclines while the peninsulas are over the anticlines (Butcher et al., 1984). Faults trending NE–SW with horizontal dextral movement have been recognized in image mapping and field work affecting the coastal morphology by producing minor indentations. Coastal rocky prominences and related re-entrances have been partially generated and controlled by this NE–SW fault system, which is responsible for creating headlands and protected minor re-entrances and controlling the sublittoral platform morphology, notably on the west flank of Hamelin Pool.

Shark Bay Marine Park is compartmented into three major embayments: Freycinet, L'Haridon Bight and Hamelin Pool (Fig. 1). Freycinet embayment in the western Shark Bay maintains the best connection with northerly oceanic waters so that despite the high evaporation, salinity is metahaline (40–56; Logan and Cebulski, 1970). Hamelin Pool, the easterly embayment, has restricted oceanic water influx and hypersaline waters (56–70), and progressively decreases in salinity to the north toward the tidal exchange channels crossing Faure Barrier Bank. L'Haridon Bight embayment contains metahaline conditions in the north and hypersaline waters to the south. Tidal flats bordering Shark Bay embayments have low substrate gradients (30 to 150 cm per kilometer) with shallow and restricted water circulation, resulting in hypersaline conditions and microbial deposits

which are widespread as mats or small elongate structures and discrete columns.

Physiographically Hamelin Pool is a “U” shaped embayment semi-closed to the north by a large sandy bioclastic carbonate and quartz bank (Faure Bank) produced mainly by seagrass bioaccumulation (Logan et al., 1974b). Tidally influenced areas can be subdivided into the supratidal zone that is inundated only under abnormal conditions (storm events and spring tides), intertidal zone affected by daily normal tides and subtidal zone as the permanently submerged areas. The Holocene sedimentary sequence was subdivided into five sedimentary units, based in their lithologic variation, vertical and lateral relations and mapability: (1) Hamelin Coquina, (2) Intertidal Veneer, (3) Sublittoral Sheet, (4) Bank Unit and (5) Basal Sheet located on the embayment plain (Logan et al., 1974b), where water depth is 10 m maximum (Fig. 2).

Hamelin embayment is bordered to the west by the Plio-Pleistocene Peron Sandstone (Butcher et al., 1984), a quartz rich eolian dune system that covers the Peron and Nanga peninsulas and extends south of Nilemah tidal flat (Fig. 1). The source of quartz sand on the west coast of Hamelin Pool is reflected in the quartzose marine sediments. Along the eastern margin, Hamelin embayment is bordered by the Cretaceous Toolonga Calcilutite and also by Tertiary carbonate rocks in the central-north portion, with their respective superficial calcrete and colluvium. Pleistocene sedimentary deposits also border the eastern margin of Hamelin Pool. They include the Dampier Formation which comprises the Carbla Oolite member, a nearshore unit expressed as N–S oriented

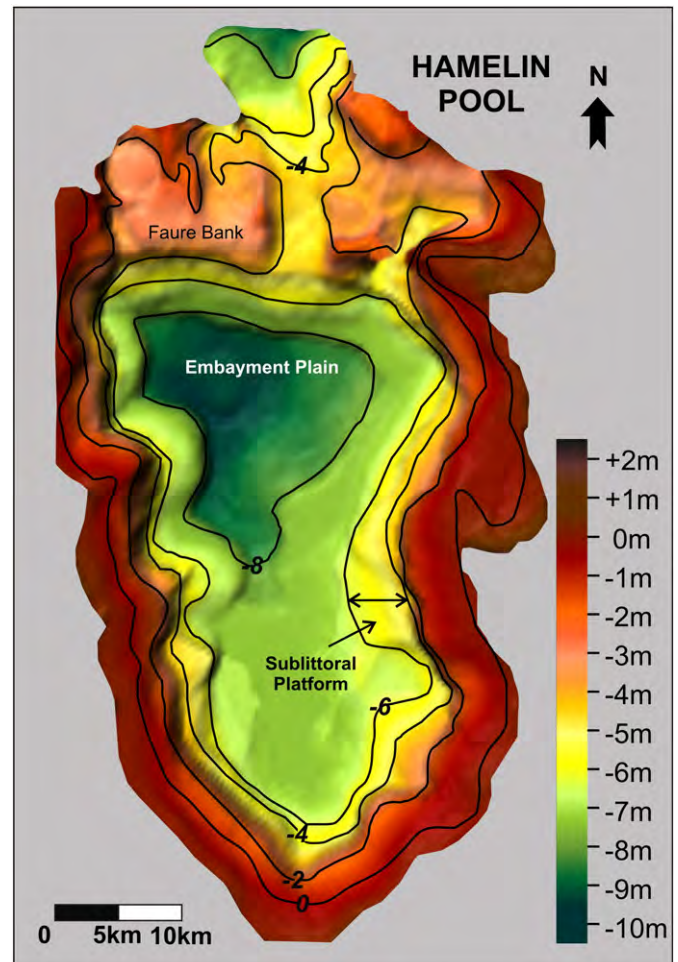


Fig. 2. Hamelin Pool 3D view with the general embayment shape based on bathymetry data from Department of Environment and Conservation (DEC).

ridges, the Dampier Limestone, a shelly calcirudite arranged as beach ridges, and the Bibra Formation, composed predominantly of shelly calcirudite overlying calcrete deposits (Read, 1976; Denman et al., 1985).

Cyclone and storm activity in Shark Bay has been recorded by the Bureau of Meteorology since 1906. Approaching from the north and northeast, some systems have generated strong impacts on the coast within Shark Bay. As a consequence of storm activity, flooding and sublittoral bottom reworking, a carbonate shell ridge system was deposited in the supratidal areas of Hamelin Pool and L'Haridon Bight. The shell system corresponds to the Holocene most landward geological unit within the embayments, designated "Hamelin Coquina" (Logan et al., 1974a, 1974b; Berry and Playford, 1996; Jahnert and Collins, 2011; Nott, 2011). The sublittoral platform is also periodically affected by storm activity that reworks subtidal sediments and supplies bivalve skeletons to the deeper basin and subtidal microbial structures. The sublittoral platform is best developed on the east flank of Hamelin Pool, which is the most affected margin during storm activity. The tidal zones were subdivided into supratidal, intertidal and subtidal, according to the abnormal and fair weather water level variation. The supratidal zone is influenced by storms and abnormal tides while the intertidal zone is affected by normal tides and is defined as the area between the "prevailing low water level (PLWL)", the lowest water levels during summer windy conditions and "winter high water level (WHWL)", the highest level reached during the winter under slight southerly winds (Logan et al., 1974b). Daily tides in Shark Bay measured at Monkey Mia are microtidal and varied in range from 0.1 m to 1.8 m during 2009–2011 (Bureau of Meteorology-WA); however inside Hamelin Pool the astronomic oscillation is restricted and retarded by the Faure bank and most affected by winds.

Dominant fair weather winds at Shark Bay preferentially come from south and southwest, with a southeast dominance during mornings and a westerly contribution in the afternoons. Winds are particularly important during the summer months, when velocities of 40 km/h are responsible for exposure of extensive areas of microbial mats in the tidal flats or microbial structures at headlands. Seawater splashing against south facing coastal barriers and exposed microbial heads causes CO₂ degassing (see Read, 1976; Kerrick, 2001) probably inducing changing alkalinity conditions and facilitating deposition of a bio-induced (interpreted from thin section and SEM images) rugose micrite "tufa" on top of some structures.

The term stromatolite is used here to refer to microbial organo-sedimentary deposits with planar to sub-planar laminated internal macro-fabrics of benthic origin (sensu Kalkowsky, 1908) while thrombolite designates non-laminated benthic microbial deposits with clotted fabric (sensu Aitken, 1967). Cryptomicrobial deposits (sensu Kennard and James, 1986) refer to non-laminated microbial deposits with disoriented bivalves that also don't meet the clotted fabric characteristics as defined by other authors.

3. Materials and methods

Georeferenced maps were constructed using (ArcGIS software) high resolution (50 cm/pixel) Shark Bay orthophotos and aerial-photos (1:25,000 scale) from the Department of Environment and Conservation (DEC) and from Landgate-Western Australia. A multi-beam survey was performed by the Hydrographic Survey Vessel Alec Hansen II, from the Department of Transport, Australia at the end of July-2010, focusing on the measurement of the depth and physical characteristics of the substrate along pre-defined transects. Seven swaths were surveyed, composed of 52 lines, with lengths from 1.3 to 5.6 km, using acoustic backscatter (BS) data collected with a multi-beam echo sounder (MBES). Submarine videos were recorded during marine investigations following the multi-beam transects. Subtidal samples of microbial structures were collected in partnership with DEC which managed vessels and divers. A Differential Georeferenced Positioning System (DGPS) using Sokkia antenna

and Allegro System were used to record transect positions and high resolution elevations (± 5 cm) across tidal flats. The submarine video transects, perpendicular to the shoreline, were performed over the same transects as by the multi-beam survey. Fifteen videos were recorded mainly at the east side of Hamelin Pool (Fig. 4). Underwater videos were produced by drop-down video-camera, by diving or attached to the side of the vessel. Submarine videos, photos, samples and bottom substrate profiles have provided substantial material which was used in recognizing and classifying microbial structure morphology and distribution in the subtidal areas, supporting the construction of georeferenced habitat and sedimentary maps of Hamelin Pool and supplying accurate substrate elevations for each group of microbial structure. Aerial inspections helped in generating a photographic collection of organo-sediments which was useful for improving map accuracy.

Sampling involved a collection of 12 microbial heads from shallow depths by snorkeling and by scuba diving in the deeper portions. Small (20 cm height \times 5 cm diameter) aluminum tubes were used to obtain shallow material, mainly living mats, with freezing to preserve organic matter for laboratory analysis. Small glass vessels (10 cm height \times 10 cm diameter) were used to sample organic parts of heads. A taxonomic study of cyanobacteria was performed in the Microbiology Department at the Federal University of Rio de Janeiro, Brazil, using permanent and non-permanent section analysis with optical microscopy (Axio-Zeiss) and microphotos obtained with digital camera Axio MRC, Zeiss. Chemical analysis of microbial sediment and water samples involved X-Ray Fluorescence Spectroscopy (XRF), Inductively Coupled Plasma (ICP) Optical Emission and Mass Spectrometry, produced by Ultra Trace Analytical Laboratories, WA, and Petrobras S.A., Research Centre.

¹⁴C ages were obtained using analytical procedures from the Radiocarbon Dating Centre of the Australian National University. The ages in radiocarbon years were obtained using a Libby half-life of 5568 years and following the conventions of Stuiver and Polach (1977, Radiocarbon). Dates have been calibrated against the Marine-09 calibration curve (Reimer et al., 2009) in OxCal version 4.1 (Bronk Ramsey, 2009) assuming a delta R of 70 ± 50 . Carbon and oxygen isotopes from sediment samples were produced by the Federal University of Sao Paulo (USP). X-Ray diffraction (XRD) techniques were used to characterize the crystallographic structure and recognize mineralogic constituents of sediment, and were performed at the Mineralogy Laboratory of the Federal University of Parana, Brazil. Thin sections were produced by CSIRO-WA and analyzed in a Leica (DC200) microscope and imaged with Leica DC10/DC350F software at Curtin University. Scanning electron microscopy (SEM) was conducted at Curtin University on an EVO 40XVP (Zeiss, Germany) SEM using secondary electrons (SE) as well as backscattered electrons (BSE). Polished sections (7.5 \times 5 cm) were coated with platinum and crude samples of dried sediment (1 \times 1 cm) were coated with gold. Elemental analysis was performed using an Oxford Instruments energy dispersive X-ray spectrometer (EDS). Analysis of X-ray spectra was performed using Inca-Analyser software (Oxford Instruments, England).

4. Results

4.1. Microbial deposits and substrate morphology

The delicate balance between tidal energy, waves, exposure time and water depth results in sediment accretion or erosion in Shark Bay (Logan et al., 1974a, 1974b). Low water energy associated with high evaporation, sediment supply and topography are key elements for sediment accretion. The gross morphology of microbial deposits is related to interaction of these factors with the embayment coastal morphology and its related substrate gradient. The general coastal morphology of Hamelin Pool can be classified into three different types: headlands, bights and embayment tidal flats (Fig. 3; Logan et al., 1974a; Hoffman, 1976).

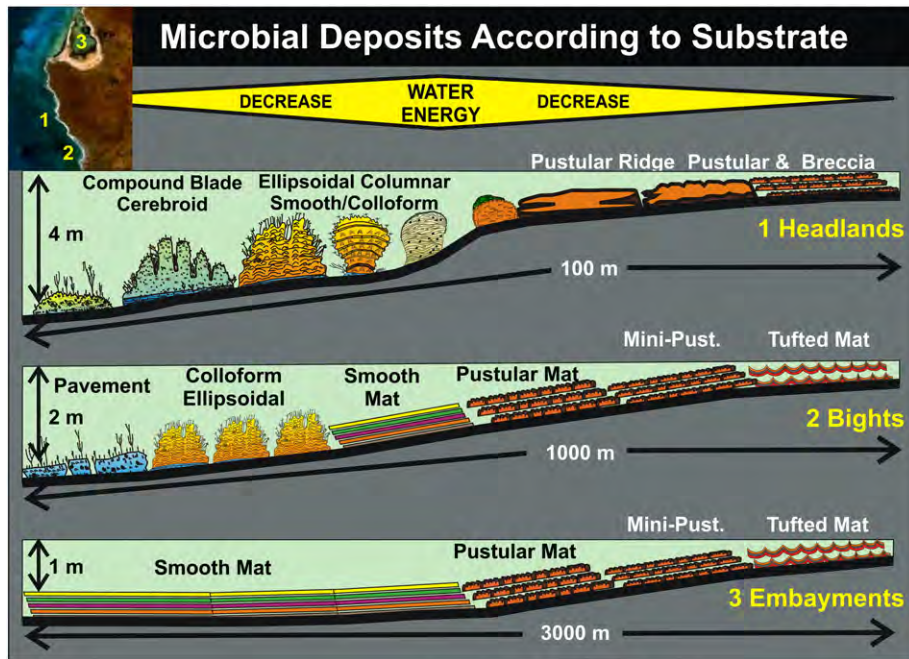


Fig. 3. Microbial deposit morphologies and types according to the substrate gradient. Headlands have steep gradients with growing heads while embayments have low gradients and are colonized by widespread mats.

- Headlands are characterized by steep gradients (Fig. 3) of 4 m/100 m, where the substrate favors growth of submerged microbial deposits (1.5 m high) as columnar, domical, conical and club shaped morphologies. Intense activity of waves and tidal currents is responsible for erosional effects on the microbial structures, which often exhibit basal thin necks, tunnels, and other evidence of erosion. The high energy of currents also supplies coarse carbonate grains and bioclasts that become trapped by microbial activity. Water depth controls the living microbial communities which respond with distinct communities, internal fabrics, external colors (pigmentation) and growth styles.
- Bights are subtle re-entrances with gradients about 2 m/km with microbial deposits forming mats or elongate structures and tabular Microbial Pavement in subtidal regions. The structures (about 50 cm height) have their long axes perpendicular to the shoreline and tidal current direction.
- Embayments occur in re-entrances of the coast, normally protected by the presence of coquina barrier ridges. The tidal flats have low gradients of about 30–50 cm/km and produce extensive deposits of microbial mats. Because of sea level fall during the last thousand years the microbial system is adjusting its position to seaward, so that landward areas are now exposed and under erosion producing brecciated microbial deposits, often expressed as breccia pavements.

Fluctuating tidal and wave energy controls the amount of carbonate particles available to be deposited and trapped by microbes which, depending on micro-habitat, construct laminar or non-laminar fabrics (Fig. 3). High energy water near Smooth and Colloform domains is rich in fine carbonate particles that, after storms, are slowly deposited supplying microbial communities with enough material to produce laminar fabrics. Deeper waters are depleted in fine carbonate particles and microbial communities stabilize sediment by inducing carbonate precipitation and trapping fine grains. Coarse particles such as bivalve shells and fragments, bioclasts and ooids are widely available and are supplied mainly during storms.

Hamelin Pool has an extensive sublittoral platform with a gently sloping top (0.5–3 m/km) and a more steeply sloping margin (>4 m/km), such platform that extends basinward to water depths as deep as 6 m (Fig. 4). This area is influenced by both waves and tidal currents

and is severely impacted by storms that rework and transport sediment composed mainly of bivalve shells, bioclasts, peloids and ooids. However, because the environment has become progressively isolated from the open ocean, changes in alkalinity and calcium availability (see isotopes and ages of microbial deposits below) strengthen microbial sediment stabilization of the platform surface. This induced carbonate precipitation and generates a microbial carbonate pavement that covers an area greater than 220 km² of the total 1400 km² of the embayment. Multibeam transect profiles (Fig. 4) show the platform extent and shallow morphology (Transects a, b, f, g in Fig. 4). Prominent structural noses, that often have distal oolite shoals are most likely expressions of preserved antecedent morphologies of Cretaceous limestone, which frequently outcrops along the eastern shore of Hamelin Pool.

4.2. Habitat map and microbial distribution

Submarine videos, photos, samples and bottom substrate profiles have provided substantial material which was used to identify, map and classify the morphology of microbial structures and their distribution in the subtidal areas, supporting the construction of georeferenced organo-sedimentary maps of Hamelin Pool and supplying accurate substrate elevations for each group of microbial structure type (Figs. 5 and 6).

The microbial carbonate system has developed in response to a progressive change in environmental conditions, transforming a more open marine system into a restricted tidal embayment with abnormal salinity and high evaporation, where microbial sediments started being deposited after the Holocene maximum sea level at about 6800 U/Th years BP (Collins et al., 2006). After this, the water level gradually dropped 2.5 m, to the present sea level, within the Holocene highstand system tract (Jahnert and Collins, 2011).

The organo-sedimentary substrate deposits of Hamelin Pool were mapped (Fig. 5) and classified according to their hinterland, supratidal, intertidal and subtidal domains (Fig. 6). Hinterland deposits are composed of quartz sandstone (Peron Sandstone) that comprises the embayment western side. Peron Sandstone is an eolian Pliocene-Pleistocene deposit generated during glacial phases (Butcher et al., 1984). Intertidal depressions contain spherical and ellipsoidal depositional basins consisting of granular gypsum and quartz sediment fills, termed “birridas”. The

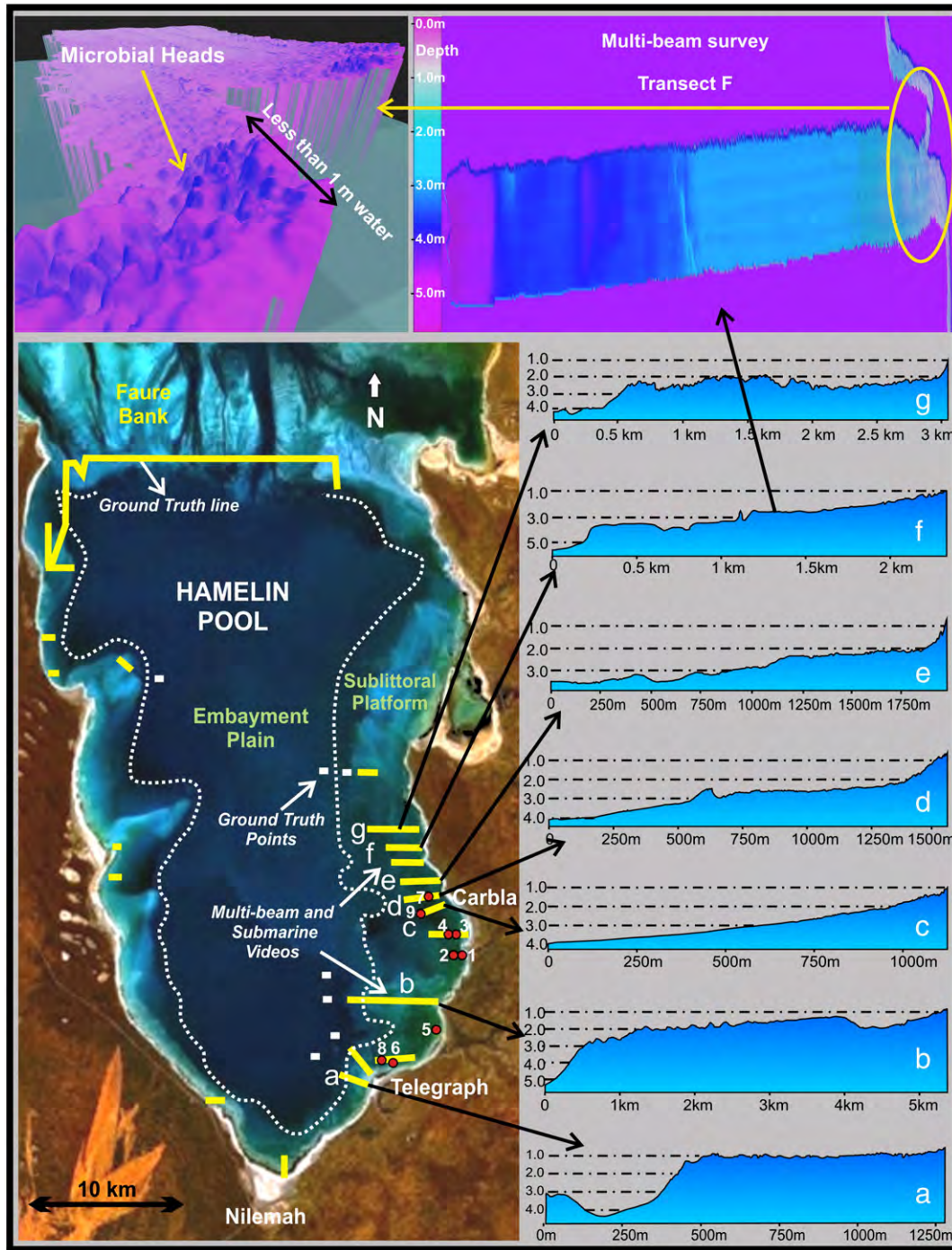


Fig. 4. Hamelin Pool image showing the location of multi-beam profiles and submarine videos. Note the variable morphologies and very shallow substrate associated with headlands (e.g., transects a, b). At top, detail of multi-beam profile (f) showing the presence of microbial heads in very shallow waters (<2 m).

eastern Hamelin embayment hinterland is dominated by limestone of the Toolonga Calcilitite (Cretaceous) and the Quaternary superficial cover that includes calcrete, quartz sand, laterites, alluvial and colluvial deposits. The eastern flank also contains emergent shoals composed of oolitic limestones of the Carbla Oolite (Pleistocene) expressed as elongate bodies parallel to the paleoshoreline, and landward of the present shoreline.

The supratidal zone is influenced by storms and abnormal tides and thus exposed to erosional processes most of the time. Here microbes survive in topographic lows and local depressions as detached sites of ephemeral mats receiving only sporadic wetting. The microbes are adapted to survive in high substrate temperatures and grow in blister, tuft or pinnacle forms. The supratidal zone in Hamelin Pool occupies

nearly 80 km², and contains two organo-sedimentary units which are exposed and prograding seaward, as described below:

- Hamelin Coquina is the upper unit of the Holocene system that refers to a supratidal beach ridge system which overlies thin Pleistocene units and the Pleistocene Bibra Formation. It is composed predominantly of bivalve skeletons, deposited as shore-parallel ridges above the normal spring high tide level. The Hamelin Coquina is prograding toward the embayment center over Holocene supratidal microbial deposits as a consequence of sea level fall (Logan et al., 1974b).
- Bioclastic-oolitic/quartz sand and breccia occupy extensive areas between the coquina deposits and the area reached by normal

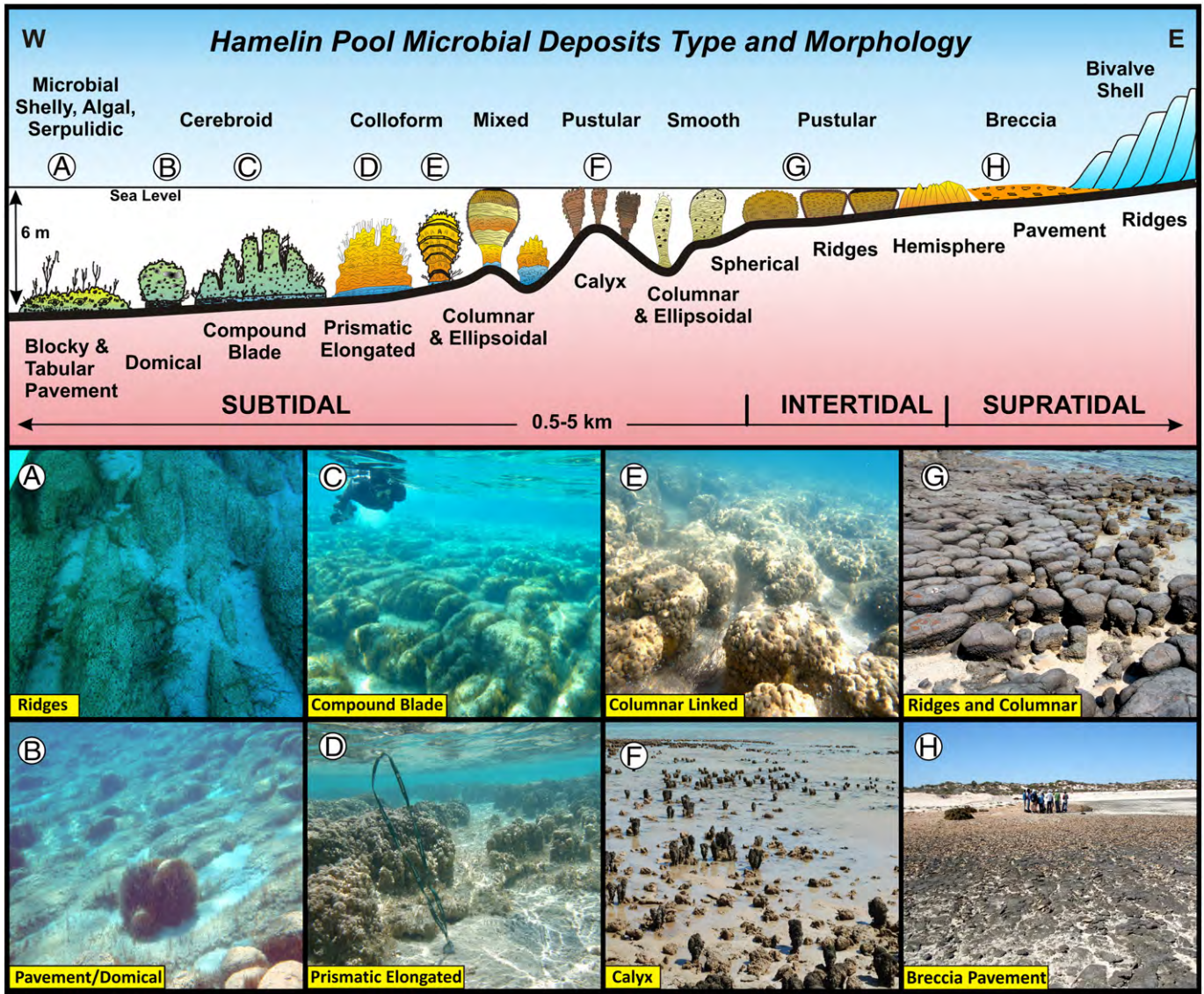


Fig. 5. Schematic depositional model for microbial deposits in Hamelin Pool highlighting the distribution, characteristics and morphologies according to the tidal zones. Photos are selected from different surveyed transects, tidal zones and their respective deposits.

tides. Breccia pavements (Fig. 5H) occur as lithified crusts that are developing over older Microbial Pavements and heads, generated by processes that include desiccation, cementation and disruption by gypsum crystallization (Logan et al., 1974a, 1974b). Bioclastic/oolitic sands are composed of skeletons of bivalves, micro-gastropods, serpulids and foraminifera and spherical to sub-spherical well sorted, fine to medium white ooids, brown peloids and gypsum crystals. This unit is enriched in quartz grains in deposits located on the western flank of Hamelin Pool. Supratidal areas are the domain of film and blister microbial mats. Film mat refers to a black veneer that covers breccia clasts and lithified exposed material in sites that may have a connection with underground water or sites that receive any kind of water spray. Blister mat develops over flat muddy wet substrates that receive sporadic water supply mainly during abnormal tides or storms.

Intertidal organo-sediments occupy a relatively small area (22 km²) but are important because they accommodate extensive microbial mats and heads in shallow waters. The intertidal zone is a domain of Pustular and Tufted microbial deposits.

- Pustular mat spreads as brown dark sheets of small colonies, inhabiting the upper intertidal to the upper subtidal zone and depending on

the substrate gradient develops mats, ridge-rill or sub-spherical structures. Tufted mat occurs in the upper intertidal zone, growing in scallops that accumulate water and sediment within the created relief. Tufted mat normally develops over shallow muddy substrate able to sustain sediment moisture, normally landward of Pustular deposits.

Subtidal microbial deposits are extensive, occupying approximately 300 km² of the total Holocene 1400 km² area of the Hamelin Pool Marine Reserve. Subtidal microbial deposits that grow as structures cover 54 km². Subtidal deposits were classified according to their actual microbial superficial dominance, however many structures were partially constructed in different conditions of sea level presenting internally different fabrics. Hamelin Pool areas lacking microbial carbonates are dominated by seagrass and related bioclastic and quartz sand, particularly near the Faure bank to the north of the embayment. Mobile sheets of bioclastic and quartz sand occur in areas affected by strong tidal currents, such as parts of the sublittoral platform and over the Faure bank. The “Embayment Plain” comprises bivalve coquina, serpulids and algae with a superficial veneer of organic rich material. The bio-sedimentary subtidal deposits (see Jahnert and Collins, 2011) are summarized as follows:

- Laminated microbial Smooth stromatolites have beige flat surfaces, and occur as stratiform sheets and as build-ups. Internal fabrics are composed of flat sub-horizontal millimetric laminae made of fine grained carbonate sediment interbedded with laminae of microbial organic matter that become lithified as micrite laminae.
- Laminated microbial Colloform stromatolites construct build-ups of brown/yellow colors with small (1–5 cm) hemispherical globular shapes rich in fine grained peloids. Internal layers are composed of ooids/peloids that alternate with thin laminae of lithified micrite generating a coarse laminoid wavy internal fabric with sub-horizontal elongate to arcuate voids.
- Non-laminated cryptomicrobial Cerebroid structures are the deepest subtidal build-ups growing as domical, ridge-like or prismatic elongate morphologies of white to cream colors. Cerebroid structures contain superficial cavities that receive coarse grains/fragments and are commonly bored by bivalves. Patches of micrite are sparse in a bioclastic/oolitic sediment rich in bivalve shells, serpulids and colonized by algae.
- Cryptomicrobial Tabular Pavement occurs as flat substrates which are being lithified as bioclastic grainstone that contains *Fragum* bivalves, serpulids, micro-gastropods, foraminifera and algae.
- Cryptomicrobial Blocky Pavement is similar to the facies described above but is disrupted/reworked producing partially to wholly disconnected blocks, rich in *Fragum* bivalve shells and colonized by serpulids that occupy voids and protected spaces, often growing at the base of the microbial carbonate blocks.
- Bioclastic/oolitic/peloidal sand occurs in the sublittoral region as a result of longshore currents and storm activity producing sand-floored depressions adjacent to microbial deposits.
- Bivalve coquinas constitute extensive deposits of *Fragum* bivalve shells, which inhabit the sublittoral platform waters between –1.5 and –6 m. Bivalve shells are super-abundant in Hamelin Pool. Some of the disarticulated shells are swept into deeper portions of the bay, others fill depressions as gravel, and a large amount is transported shorewards by storms and deposited in the supratidal zone as exposed beach ridges.
- Bioclastic sand with variable amount of quartz grains comprises the substrate of seagrass domain in channels, patches or as ridges oriented E–W perpendicular to the tidal action.
- Bioclastic and quartz sand occurs in substrates colonized by seagrass but in disconnected sparse stands and linear transverse ridges such as those found over Faure bank.
- Bioclastic and quartz sand also occurs in shallow areas to the north on the Faure Bank where tidal velocity is amplified, constructing channel lags, channel bars, subtidal deltas, and sand sheets with sand waves and megaripples.
- Bivalve coquinas with serpulids, algae and a superficial organic mud dominate the deeper portions in the Embayment Plain.

4.3. Microbialites and macrofabrics

Distinct internal fabrics result from microbial processes of trapping and binding, carbonate induced-precipitation, organic matter content, amount and type of sediment input, presence of voids, presence of skeletons, bioturbation and macropore orientation. Subtidal microbial carbonate deposits are designated as Pustular, Smooth, Colloform, Cerebroid and Microbial Pavement (Figs. 8 and 9). They have distinct internal fabrics, related to the dominant microbial communities (Burns et al., 2004; Allen et al., 2009; Jahnert and Collins, 2011), their growth habits and environmental conditions.

Cocoid bacteria dominate the intertidal environment constructing Pustular deposits with non-laminated clotted fabric and are appropriately

designated Thrombolite (see Logan et al., 1974b, p. 185). Cocoid bacteria also dominate the deep subtidal zone in Colloform, Cerebroid and Microbial Pavement, here producing coarse laminated Stromatolites in Colloform deposits and cryptomicrobial non-laminated carbonate in Cerebroid and Microbial Pavement. Filamentous bacteria are the dominant group in Smooth mats and heads in the subtidal zone, producing carbonate with a fine laminoid fabric and characterized as Stromatolite (Table 2).

The organic matter that constitutes a considerable portion of the sedimentary fabrics is strongly modified when exposed to desiccation and oxidation, mainly by creating open space, producing fenestral porosity (Logan et al., 1974a). In many cases, fenestral fabrics remain well preserved in the geologic record and are a distinctive characteristic of many rock sequences and their environments (Riding, 1991; Walter, 1999; Grammer et al., 2004).

Stable isotopes of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ obtained from subtidal microbial carbonate sediment (12 samples) revealed positive values of carbon and oxygen isotopes. The overall $\delta^{13}\text{C}$ values vary between +4.5 and +5.9 while the $\delta^{18}\text{O}$ varies from +3.1 to +3.9. Smooth and Colloform carbonates display the highest $\delta^{13}\text{C}$ values (+5.4, +5.7, +5.7, and +5.9). The isotopic relationships suggest that all the samples were deposited in a highly evaporative environment (water depleted in the light element O^{16}) with extensive microbial activity (water depleted in the light element C^{12}).

4.4. Geochronology

Nine microbial heads were analyzed to determine ages and obtain growth rates. The sampling involved a careful selection of heads, collected to, as far as possible, cover the different microbial build-ups occurring from the supratidal zone (head 1) to the subtidal zone in water depth of 4 m (head 9). The samples were projected onto a regional single transect (Fig. 10) in order to permit a comparison between ages, depths, external morphologies and sizes.

The selected microbial structures display different external morphologies: from columnar to domical and tabular, (Fig. 10) with external surfaces tending to dark colors in Pustular and over shallow water domains, presumably because of the microbial pigments present. Structures are composed predominantly of carbonate grains, bioclasts and micrite arranged in different fabrics, which likely represent the prevailing conditions at the time and so furnish an evolutionary chronological history when ^{14}C dated. Bivalve shells and other visible coarse skeletal bioclasts (that could contaminate ages) were removed from samples subjected to ^{14}C dating analysis, which were composed mostly of fine carbonate particles (mud and silt size), sampled at the top, middle and base of the heads, where possible, to establish a trendline of growth rates.

The high resolution ^{14}C dating age values (Figs. 10 to 13 and Table 1) for this collection are substantially older (1915–1680 years BP) when compared with the results obtained by Chivas et al. (1990), who recognized the interval of 1250–1000 years BP as the time of growth of the first stromatolites. Evidence of an earlier higher sea level than at present is manifest in head 1 (Fig. 10) aged 1680 (base), 1300 and 1120 (top) years, located today in the supratidal zone, exposed 30 cm above the sea level. Externally it has a columnar morphology characteristic of the subtidal zone and an internal vertical fabric sequence of Cerebroid–Colloform–Smooth (base to top); reflecting a sequence of fabrics generated while submerged in the subtidal zone but at decreasing depths (see Fig. 13).

An interpretation of ages versus fabrics and water levels permits recognition of a growth depositional history in two stages (Fig. 11), the first between 2000 and 1100 years ago. This was a period when

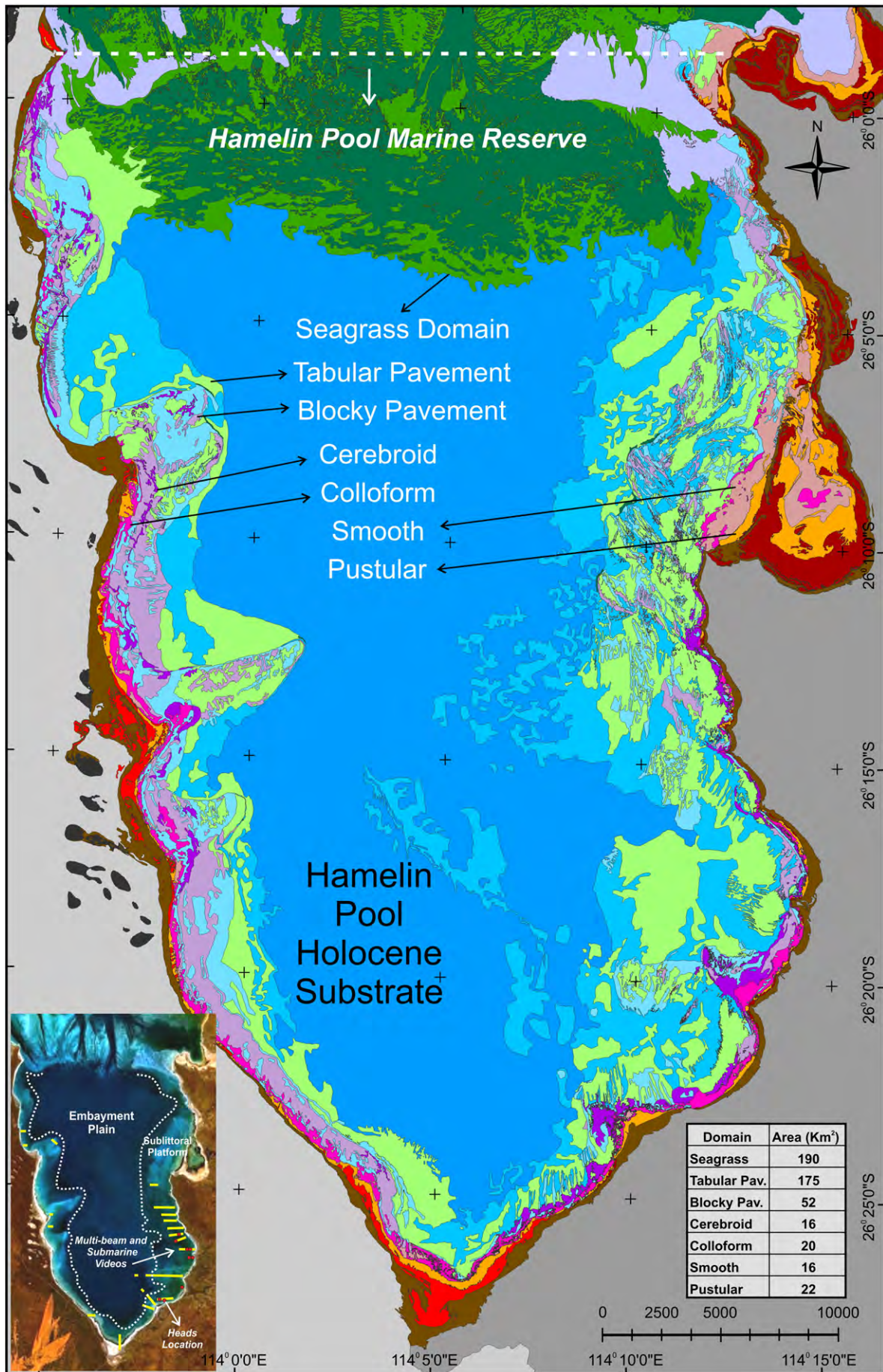




Fig. 7. Substrate and sediment description with legend colors referred to in the Hamelin Pool organo-sedimentary map in Fig. 6.

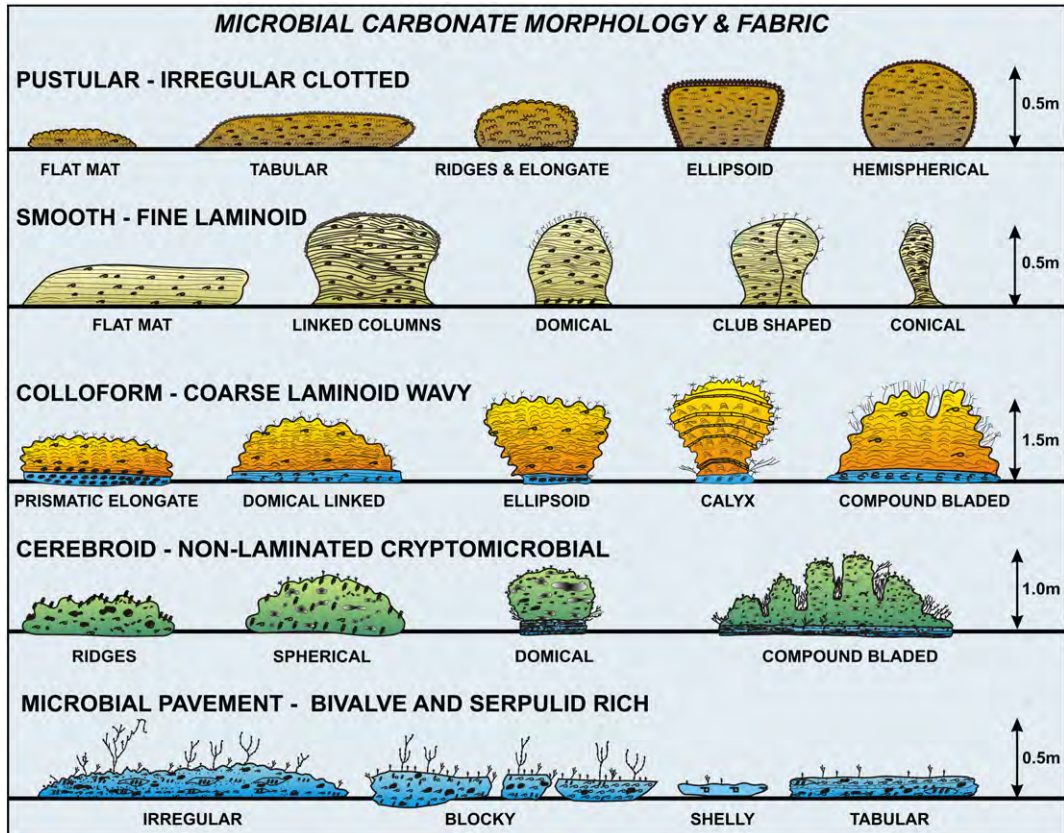


Fig. 8. Summary of subtidal microbial fabrics and morphologies. Smooth and Colloform with laminoid fabrics are termed Stromatolite, Pustular with clotted fabric as Thrombolite and Cerebroid and Microbial Pavement are referred to as cryptomicrobial carbonate because they don't possess a clear clotted fabric sensu Aitken (1967).

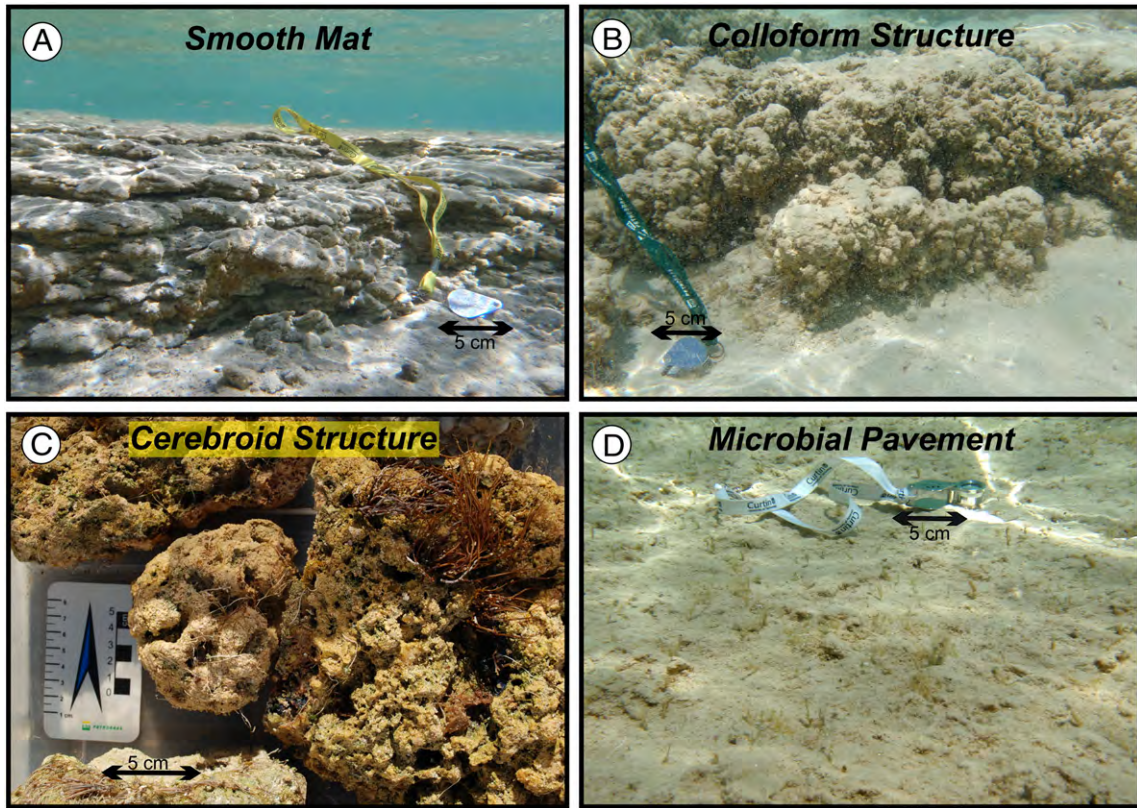


Fig. 9. Photographs of examples of the principal microbial deposits and their external characteristics: (A) Well developed laminar fabric in Smooth mat; (B) Colloform structures, external view (globular appearance; rich in fine carbonate particles); (C) Cerebroid structure; note convoluted external form with cavities, and algal ornamentation; (D) Microbial Pavement; flat, lithified bioclastic carbonate with abundant bivalve shells, serpulids and soft bodied algae. Sediment of microbial origin (90 samples) from supratidal to subtidal zones submitted to mineralogic analysis by XRD revealed a predominance of aragonite in the carbonate fraction of between 80% and 98%. Minor amounts of Mg-calcite and calcite and rare dolomite comprise the other carbonate minerals. Quartz is variable (10–40%) and higher in samples from the south and west of Hamelin Pool reflecting Peron Sandstone proximity. Halite is minor (1–10%) and gypsum only occurs in supratidal samples (1–10%).

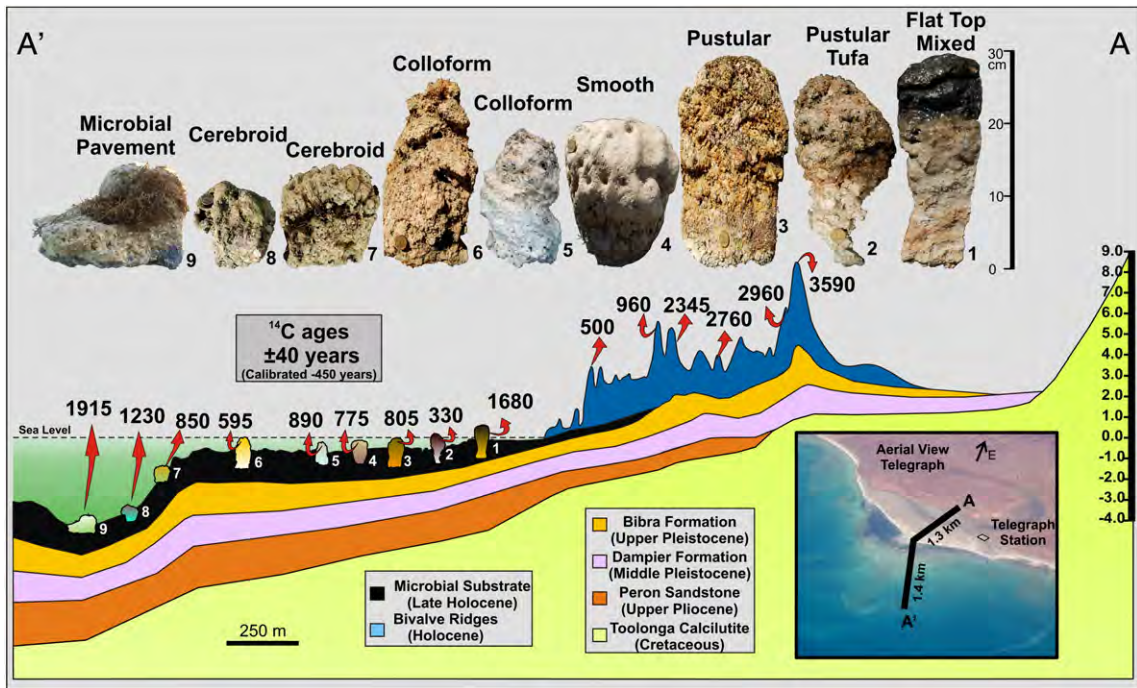


Fig. 10. Regional cross-section based on DGPS (land) and multi-beam (water) surveys located north of Telegraph Station area with projected microbial samples and respective ^{14}C ages calibrated by subtracting 450 years from the conventional ages. The stratigraphy is based on boreholes drilled over the ridge system (in blue) and is projected offshore. The location of samples is shown in Fig. 4. The supratidal Hamelin Coquina storm ridge transect (morphology and ages) is shown for comparative purposes. Note basinward (upper surface) ages; also relict, emergent head 1 at landward end of transect.

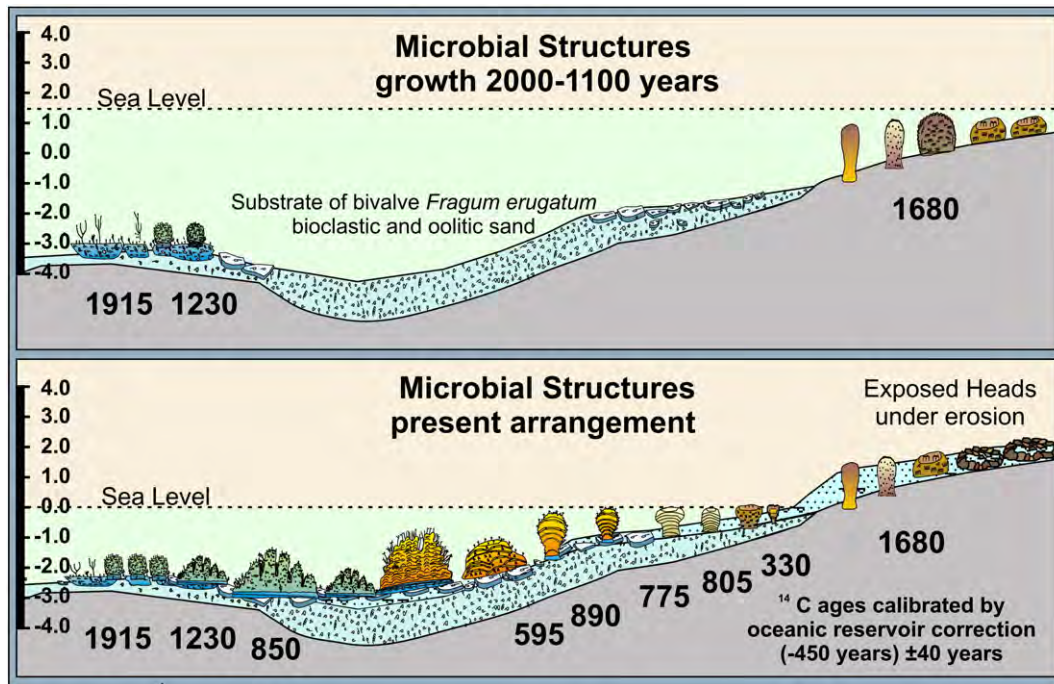


Fig. 11. Schematic sections illustrating evolutionary history of microbial build-ups in Hamelin Pool.

the sea level was higher than today and build-ups were developing as columnar, ellipsoidal, and spherical forms and as large microbial hemispheres (+2 m diameter) in the subtidal zone, which partially remain exposed today in the supratidal/intertidal zone around Hamelin Pool. Evidence of this first event can be found at the observation deck at Telegraph Station, where large microbial hemispheres and some columnar microbial structures are exposed, near the shoreline. There is also evidence of old tidal flats with microbial mats as recognized at Nilemah and Hutchinson, today exposed in the supratidal zone, some producing breccia pavements. The second phase of microbial carbonate deposition occurred from 900 years ago to present day during the lowering of sea level, on the order of 1.5 m, to present level. During this second phase the microbial domain expanded considerably as the sublittoral platform became shallower and marked by increase in fine carbonate particles (peloids) responsible for deposition of the majority of laminated stromatolites (Fig. 11). Holocene microbial structures record evidence of changing environmental conditions and water depth producing vertical depositional sequences, which represent shallowing-up sedimentary sequences.

Growth rates obtained from Shark Bay microbial structures are variable from less than 0.1 mm/year (10 cm/ky) to little more than 0.5 mm/year (50 cm/ky) highlighting the slow process of stromatolite accretion. The presence of stromatolite structures with 1.5 m of height indicates a higher growth rate of 0.75 mm/year (75 cm/ky) using the same constructional age period of 2000 years. The relation between interval growth rates versus fabrics doesn't permit the establishment of characteristic trends on the data available, however the higher overall growth rate values using trendlines indicate that subtidal Colloform and Cerebroid heads have faster constructional development.

The ^{14}C growth rates obtained here (ranging from <0.1 to 0.54 mm/year) are more variable when compared with values obtained by Chivas (1990) who determined by ^{14}C dating values between 0.1 and 0.34 mm/year, for microbial structures in Hamelin Pool. Playford and Cockbain (1976) after an investigation period of 5 years measuring growth rates (with non-corrosive nails) in heads of intertidal and subtidal zones of Hamelin Pool, confirmed that many stromatolites have reached a state of equilibrium, with no growth, but they recorded one head with the maximum growth rate of 1 mm per year (100 cm/ky).

The relationship between the internal fabric and the water depth (relative to HWL) where the microbialites were generated has been established. Non-laminated/disrupted cryptomicrobial fabrics with a high content of bivalve shells, ooids, and serpulids are characteristic of "deep water" (–1 to –6 m) growth as build-ups (Cerebroid) or microbial tabular or blocky pavement. Coarse and fine laminoid fabrics correlate to relative shallower waters (–5 cm to –1.5 m) that are enriched in fine carbonate particles producing Colloform and Smooth structures. Shallow water (0 to –40 cm) domains are colonized by Pustular deposits with internal irregular to clotted fabrics. These relationships (Fig. 8) assist in the interpretation of depositional environment and paleo-water levels. Columnar forms exposed today in the supratidal zone exhibit non-laminated fabrics at the base (Cerebroid) followed by coarse laminated (Colloform), well laminated (Smooth) and a flat eroded top with a dark film veneer. These fabrics sequence are a shallowing-upward succession that started depositing in waters deeper than 1 m (e.g., see the sample labeled "columnar flat top" in Fig. 12) and support the Late Holocene sea level fall inferred from other sea level proxies in Shark Bay.

4.5. Microfabrics

Internal fabrics preserved in the microbial build-ups in Shark Bay vary significantly denoting changes in the environment and microbial ecosystems adapted to produce carbonate deposits in different water depths and environmental conditions which are characterized as follows:

- (A) Irregular clotted fabric characterizes Pustular thrombolitic deposits. Pustular mats consist of coccoid cyanobacteria, characterized at the surface by thick brown mucilage. These are produced by the copious amounts of a highly hydrated translucent gelatinous mucilage that are organomineralized after periods of exposure (Golubic and Hofmann, 1976; Golubic, 1980, 1982, Fig. 13A). Micrite is generated also by the endolithic activity that fuses and micritizes carbonate peloids (SEM images analysis).
- (B) Well laminated (Smooth) stromatolites form beneath of filamentous cyanobacterial mats responsible for producing exopolymers that trap sediment, producing a flat and slippery surface

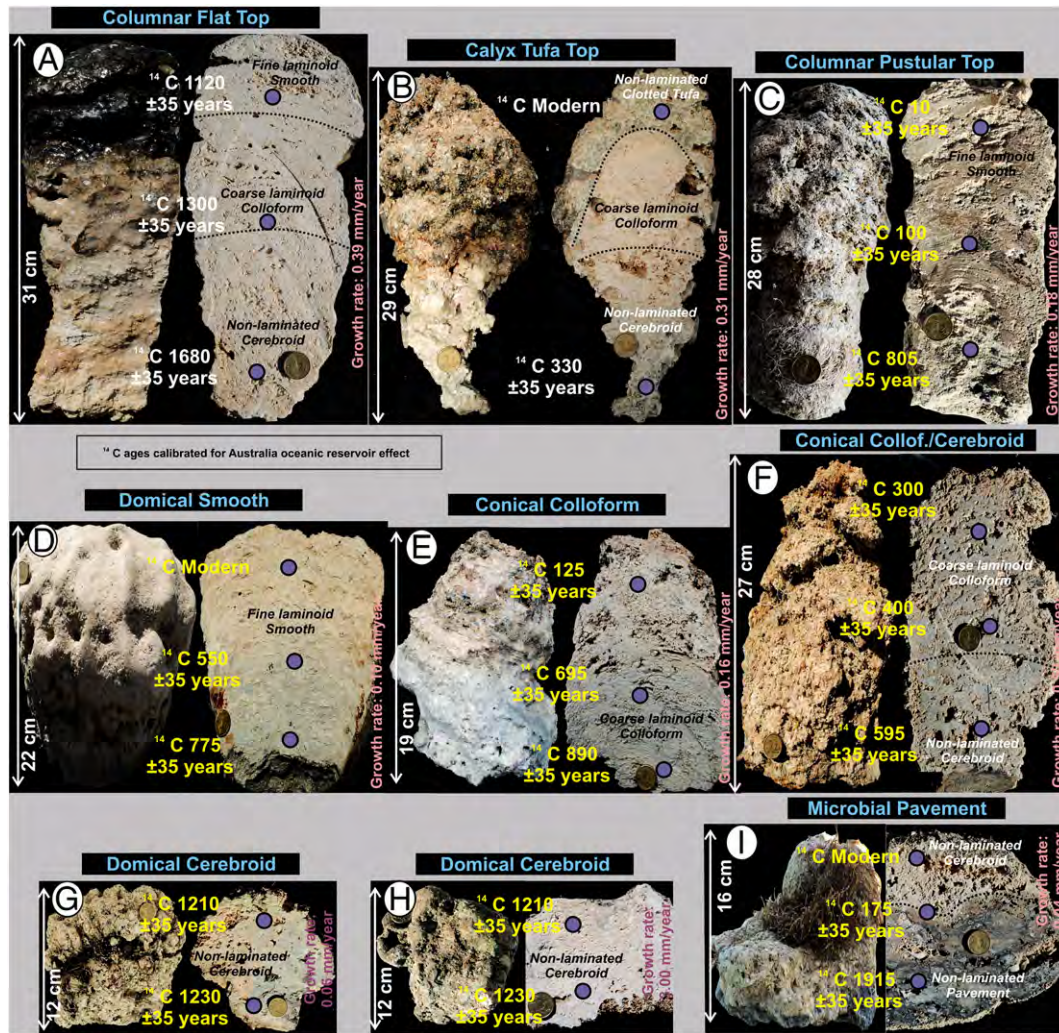


Fig. 12. Microbial build-ups sliced showing internal fabrics, the sampling points and calibrated ^{14}C ages with growth rates. (A) Columnar flat top structure with an internal shallowing-upward carbonate sequence represented by a basal non-laminated fabric passing upward to coarse laminoid and to fine laminoid fabric; (B) Calyx head with ornamented non-laminated fabric at top; (C) columnar head with internal fine laminoid fabric and colonized by Pustular at surface; (D) domical structure with Smooth top and internal fine laminoid fabric; (E) conical Colloform structure with a coarse laminoid internal fabric; (F) conical structure with non-laminated fabric at base passing upward to a coarse laminoid fabric; (G and H) domical Cerebroid structure with internal non-laminated fabric; (I) Microbial Pavement with a non-laminated fabric passing upward to a Cerebroid morphology.

morphology (Figs. 13B and 14A). The fabric reveals alternation of grain/bioclast-enriched laminae with peloidal organic rich laminae generated during storms and subsequent quiescent periods.

- (C) Coarse laminoid (Colloform) stromatolites develop in subtidal areas deeper than Smooth domains, where fine carbonate particles are still available and the ecosystem can develop both vertically and horizontally since adequate space is available. Cocoid cyanobacteria and diatoms produce enough mucilage to trap and bind grains/bioclasts and presumably biologically induce mineralization to produce lithified laminae. These form lithified columns constructed vertically, leaving horizontal voids (Fig. 13C).
- (D) Non-laminated cryptomicrobial (Cerebroid) structures are deeper subtidal build-ups characterized by external irregular cavities that receive coarse material and are commonly bored by bivalves. Significant amounts of *Fragum* bivalve shells, ooids and serpulids are a characteristic of these deposits. Lithification results from peloidal grain micritization and fusion, dark micrite precipitation and fibrous aragonite cement in pore spaces (Fig. 13D). Cerebroid structures are a domain of cocoid cyanobacteria.
- (E) Microbial Pavement refers to light gray carbonate cryptomicrobial deposits with tabular or blocky surface morphologies. These are being lithified into bioclastic grainstone that includes skeletons of *Fragum erugatum* bivalves, serpulids, micro-

gastropods, foraminifera. Pavements are externally colonized by *Acetabularia* (calcified green algae), *Fucales* (brown algae) and *Gigartinales* (red algae).

A taxonomic study of the dominant superficial living cyanobacteria is summarized in Table 2. Cocoid cyanobacteria dominate shallow ecosystems producing Pustular deposits, followed by the filamentous cyanobacteria group that produces Smooth mat and structures. The permanently submerged build-ups, Colloform, Cerebroid and Microbial Pavement, represent an ecosystem dominated by cocoid cyanobacteria. In water depths of -4 m some filamentous cyanobacteria from *Phormidium hypolimneticum* and *Lyngbya fragilis* were detected in the surface of Microbial Pavement living within the cocoid domain.

4.6. Constructional mechanisms

Subtidal microbial structures differ regarding their external morphologies and internal fabrics. These reflect sediment availability, bivalve skeleton supply, substrate morphology and depth, wave activity, tidal runoff and sea level. The microbial community constructs these deposits through different stages and processes of early (syndimentary) diagenesis which interact as follows:

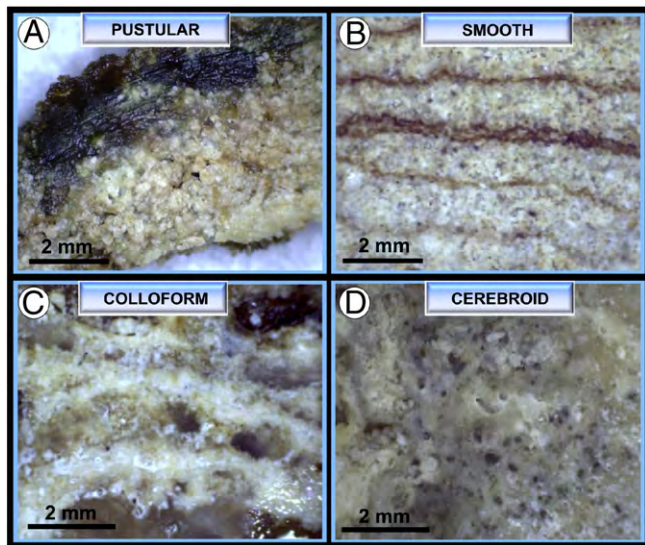


Fig. 13. Macrophoto detail of the different fabrics that produce microbial build-ups in Shark Bay. (A) Brown dark Pustular with thick mucilage and carbonate particles (peloids) trapped; (B) Smooth internal fabric consisting of grain/bioclast-enriched laminae alternating with organic rich laminae with peloids; (C) Colloform coarse laminoid fabric with lithified micritic laminae interbedded with bioclastic and ooidal laminae, sustained by lithified columns constructed vertically, leaving horizontal voids; (D) Cerebroid internal fabric showing non-laminated micrite and bioclastic and ooidal grains. Serpulid exoskeletons are abundant inside the Cerebroid fabric.

1. Superficial micrite generation:

Precipitated micritic carbonate observed in SEM images occurs within an organic gel (probably EPS) and is produced by the microbial communities (Fig. 14A, B and C). Such organic gels which are recognized in hand sample and SEM expand over the surface of structures, connect discrete particles, stabilize sediment and initially sustain the structure. The organic gel also surrounds bacterial filaments, connects material and apparently is generating micrite (biologically inducing precipitation; Fig. 14A). A detailed image shows a filamentous sheath surrounded by micrite particles generated within the organic gel (probably EPS, Fig. 14B), and crystallization of aragonite that also surrounds bacteria filaments (Fig. 14C).

The process of grain accretion is driven by filamentous bacteria in the Smooth mat domain and coccoid bacteria in Colloform, Cerebroid and Microbial Pavement domains. Sediment accretion is conducted mostly by cyanobacteria through photosynthetic production of exopolymer (Visscher et al., 2000; Reid et al., 2003; Dupraz and Visscher, 2005) that traps and binds grains and particles and also attracts calcium ions to negatively charged sites (Pentecost, 1991).

2. Bioturbation, micritization and recrystallization

Bioturbation, micritization and recrystallization (Fig. 14D, E and F) produce grain fusion and recrystallized micritic layers responsible for indurated laminae between soft grainy/bioclastic sand in Colloform and Smooth heads. They also produce discontinuous patches of micrite within deeper Cerebroid and Microbial Pavement structures. Carbonate grains are severely attacked by microorganisms that produce a honeycomb-like surface in ooids (Fig. 14D) creating a rugose surface with micro-canals and light colored recrystallized microcrystals (Fig. 14E). Soft grains of peloids are micritized and fused producing an extensive newly recrystallized micrite (Fig. 14F). This process is driven by microbial endolithic activity, with an estimated density of 200,000 bacteria/mm² (see Golubic, 1982), largely by heterotrophic bacteria that penetrate carbonate grains and bioclasts for nutrition and protection (Campbell, 1982), thus producing grain fusion, micritization (Macintyre et al., 2000; Reid et al., 2003)

and recrystallization. The most frequent sources of organic carbon for the support of heterotrophic endolithic activity are the primary products of photosynthetic bacteria and organic matrix of skeletons (Campbell, 1982).

3. Pervasive micrite generation

Occurrence of a last generation of micrite is visible in thin sections and SEM images in all sediments generated, both surficially and within heads in aphotic zones. It is characterized as a dark crypto and microcrystalline micrite, which fills spaces and envelopes grains and skeletons (Fig. 15G, H, I and J). This micrite resembles a texture of fine foam, distinct from other micrite generated by cyanobacteria and endolithic bacterial activity. Grains are connected and stabilized by this micrite (Fig. 15G) that reveals in detail (Fig. 15H, I and J) a fine texture that occurs before the last process of aragonite crystal growth.

This micrite is responsible for most of the deeper water sediment stabilization and is presumably the result of the activity of sulfate-reducing bacteria. (cf. Visscher and Stolz, 2005).

4. Fibrous aragonite precipitation

Aragonite crystal growth in void spaces is the last diagenetic product during the construction of microbial structures. The process is recognized as an important step for the final stabilization of sediment in the subtidal cryptomicrobial structures although it is almost negligible in shallow subtidal Smooth domains. Aragonite crystals are arranged depending on the space available, as a pervasive crystal system or as microcrystals (Fig. 15K) and also well developed needles inside larger voids (Fig. 15L).

5. Discussion

Microbial activity in Hamelin Pool in Shark Bay prospers in response to special environmental conditions in this partially barred basin with restricted water exchange, high evaporation and hypersalinity. The hypersaline environment ensures a very low diversity of eukaryote species; however the presence of the bivalve *Fragum erugatum* which adapted and proliferated early during the first stages of hypersalinity around 4000 years ago guarantees a large supply of bioavailable carbonate. While the ultimate source of carbonate is yet unknown, the linkage between high microbial activity and coquina productivity was established by 2000 years ago, perhaps promoted by sea level fall, reduced storm intensity and water chemistry enriched in calcium ions due to evaporation. Processes of shell abrasion, dissolution and activity of microbial bioturbation might also have acted as a source of calcium ions which progressively enriched the system. Fabrics of the oldest microbial deposits (Cerebroid and Microbial Pavement) indicate that bivalve shells were fundamental also as biomass supplier to microbial construction. The extensive colonization of intertidal and subtidal areas (0 to -2.5 m) by microbes produced changes in aqueous CO₂ partial pressure as a result of consumption during photosynthesis. Also the process of CO₂ degassing (see Kerrick, 2001) produced by splashing waves, converts the system into a more alkaline environment which facilitates carbonate organomineralization (cf. Read, 1976). Water parameters measured continuously in the south of Hamelin Pool recorded falls in the dissolved oxygen content of about 50% during nights, perhaps due to aerobic oxygen consumption, emphasizing the high amount of CO₂ consumed and O₂ produced during the day by photosynthesis.

Microbial communities also affect conditions by attracting minor amounts of metals (iron, nickel, lithium, strontium, rubidium, molybdenum and lanthanum); these are enriched in microbial samples from Shark Bay, and this process could influence O₂ partial pressure within the microenvironments. Gerdes (2007) reported that the presence of iron in cyanobacterial filaments maintained the oxygen partial pressure at reduced levels as bacteria used iron to react with oxygen and thereby stabilize excessive oxygen content. Ferric hydroxides are used to produce a variety of pigments responsible for the variable colors visible at the surface and within the fabrics of

Table 1
Summary of microbial build-ups ^{14}C ages, conventional and calibrated for marine reservoir effect using: (1) the Marine-09 calibration curve (Reimer et al., 2009) in OxCal version 4.1 (Bronk Ramsey, 2009) assuming a delta R of 70 ± 50 and (2) subtracting 450 years to compare with previous dating of Chivas et al. (1990).

Head type	^{14}C age years convent.	Error \pm years	^{14}C age years calibrated NW-Australian	Error \pm years	^{14}C age years calibrated subtracting 450 years	Head height (mm)	Dating distance from base (mm)	Interval between samples points (mm)	Age interval	Interval growth rate (mm/yr)	Growth rate using older and younger ages (mm/yr)	Growth rate using trendline (mm/yr)	Correlation coefficient	
1	Cerebroid	2130	30	1626	75	1680	310	45	125	380	0.32895	0.4018	0.3905	0.9807
	Colloform	1750	35	1232	59	1300	310	170	100	180	0.55556			
	Smooth	1570	30	1048	73	1120	310	270	40	1570	0.02548			
2	Cerebroid	780	30	356	60	330	280	40	220	705	0.31206	0.3121	0.3121	1.0000
	Colloform			Modern		Modern	280							
	Pustular/Tufa	75	20	Modern		Modern	280	260	20	75	0.26667			
3	Smooth	1255	35	725	60	805	270	60	80	705	0.11348	0.2138	0.1756	0.8077
	Smooth	550	35	Modern		100	270	140	90	90	1.00000			
	Smooth	460	35	Modern		10	270	230	40	460	0.08696			
4	Smooth	1225	35	705	55	775	210	30	70	225	0.31111	0.1172	0.1037	0.8853
	Smooth	1000	40	545	55	550	210	100	70	1000	0.07000			
	Smooth	30		Modern		Modern	210	170	40	30	1.33333			
5	Colloform	1340	35	820	68	890	190	25	45	195	0.23077	0.1634	0.1582	0.9867
	Colloform	1145	35	626	61	695	190	70	80	570	0.14035			
	Colloform	575	35	Modern		125	190	150	40	575	0.06957			
6	Cerebroid	1045	35	571	49	595	270	60	75	195	0.38462	0.5424	0.5207	0.9524
	Colloform	850	30	421	61	400	270	135	85	100	0.85000			
	Colloform	750	30	337	62	300	270	220	50	750	0.06667			
7	Cerebroid	1300	30	772	68	850	120	20	70	1270	0.05512	0.0551	0.0551	1.0000
	Cerebroid	30		Modern			120	90	30	30	1.00000			
8	Cerebroid	1680	30	1179	67	1230	115	30	60	20	3.0000	3.0000	3.0000	1.0000
	Cerebroid	1660	30	1153	72	1210	115	90	25	1660	0.0151			
9	Cerebroid/Pav.	2365	30	1909	73	1915	160	40	60	1740	0.03448	0.0428	0.0409	0.9740
	Cerebroid/Pav.	625	30	145		175	160	100	40	595	0.06723			
	Cerebroid/Pav.	30	30	Modern		Modern	160	140	20	30	0.66667			

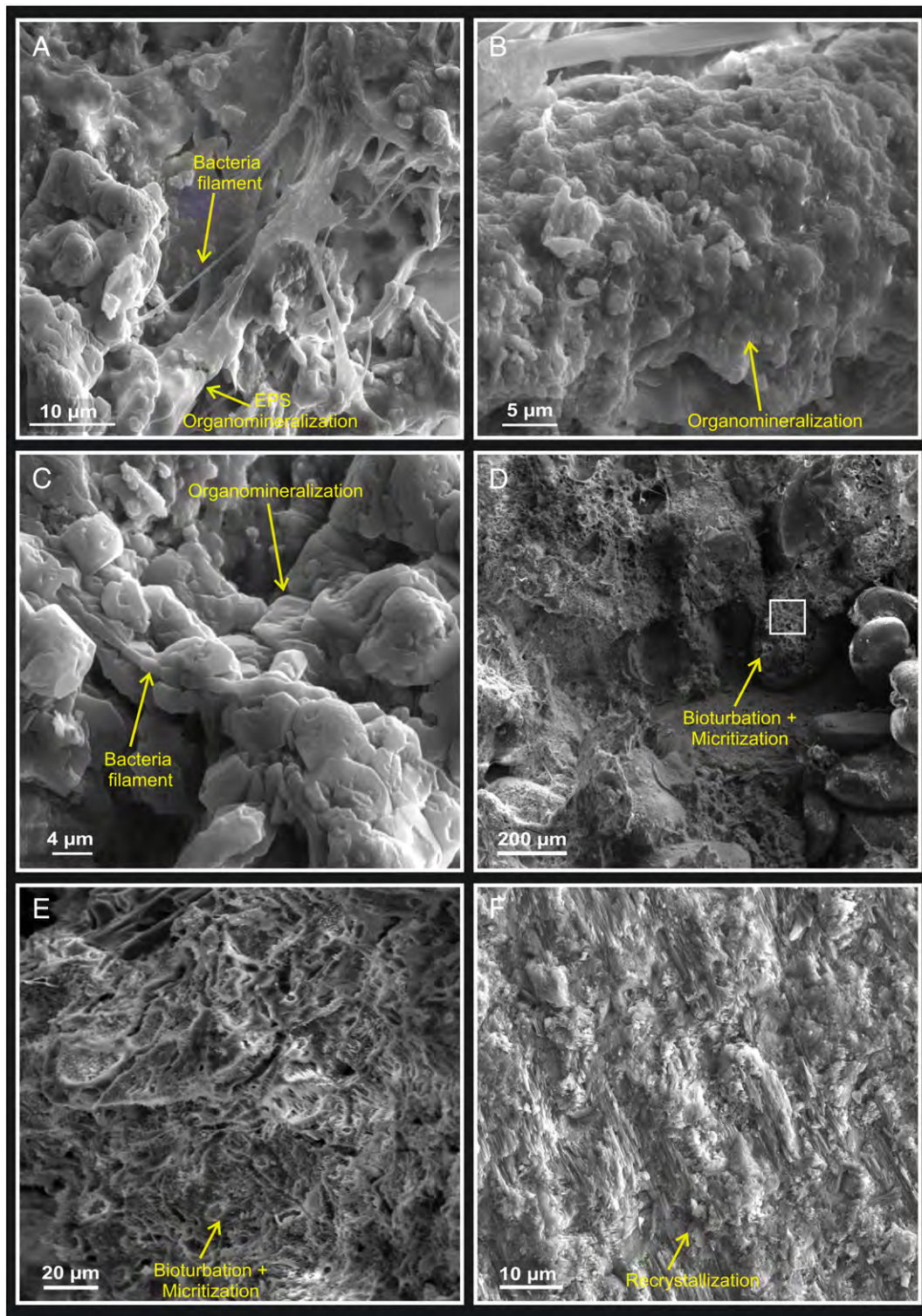


Fig. 14. Scanning electron photomicrographs from samples and thin sections (coated with gold or platinum), showing the sequence of events that involves trapping and binding (stage 1) and organomineralization in filamentous cyanobacterial domains (A, B and C) and (stage 2) activity of endolithic microbial bioturbation, micritization and recrystallization (D, E and F). The first stage 1 (A, B and C) reflects the activity of filamentous bacteria in Smooth heads from living (dried) material from Nilemah. (A) The organic gel surrounds bacterial filaments, connects material and apparently is generating micrite; (B) detail of filamentous sheath surrounded by micrite particles generated within the organic gel (probably EPS); (C) superficial crystallization of aragonite that also surrounds bacteria filaments; (D) carbonate grains severely attacked by microorganisms that produce a honeycomb-like surface in ooids; (E) detail of rugose surface with tunnels and light colored recrystallized microcrystals; (F) soft peloid grains are micritized and fused obliterating peloid boundaries and producing an extensive new recrystallised micrite. Images from Smooth head located at Nilemah and Cerebroid heads at Carbla Point and south of Carbla Point.

microbial origin also may function as a barrier protecting the cyanobacteria from sulfide sourced deposits from deeper anoxic layers (Stal, 1994).

A summary of the stages producing laminated and non-laminated microbial fabrics is schematically represented in stages by scanning electron microscopy (SEM) and thin section images (Fig. 16). The

Table 2

Summary of cyanobacteria taxonomy recognized from surface samples of microbial structures. Taxonomy based on analysis of 16 samples located mainly in the subtidal zone of Hamelin Pool.

Species / Microbial deposit	Pustular	Smooth	Colloform	Cerebroid	Pavement
<i>Entophysalis granulosa</i>	X		X		
<i>Gloeocapsa punctata</i>	X		X	X	X
<i>Chroococcus minutus</i>	X	X		X	
<i>Chroococcus turgidus</i>	X	X	X	X	X
<i>Chroococcus microscopicus</i>	X				X
<i>Chroococcus prescottii</i>	X			X	
<i>Schizothrix friesii</i>		X			
<i>Phormidium hamelii</i>		X			
<i>Microcoleus chthonoplastes</i>		X			
<i>Chroococcus minimus</i>		X			
<i>Gloeotheca vibrio</i>			X		
<i>Cyanosarcina thalassia</i>			X		
<i>Aphanocapsa litoralis</i>			X	X	
<i>Chroococcus ergovici</i>			X	X	X
<i>Chroococcus giganteus</i>				X	
<i>Chroococcus turicensis</i>				X	X
<i>Entophysalis conferta</i>					X
<i>Chroococcus quaternarius</i>					X
<i>Phormidium hypolimneticum</i>					X
<i>Lyngbya fragilis</i>					X

constructional mechanisms of microbial heads depend on many factors and also on the presence and availability of coarse grains/bioclats and fine carbonate particles and peloids. During storms coarse material is emplaced on the heads and after storms the deposition of peloids and fine carbonate particles predominates in shallower waters near Smooth and Colloform domains. Deeper portions are less well supplied by peloids and fine grained carbonate particles. This makes a difference regarding microbial activity, which is deficient in micrite produced within fused peloids thus micrite patches are produced rather than laminated fabrics. A dark micrite that envelopes and connects grains and bioclats, observed in thin section and SEM (represented in green color on the diagram in Fig. 16) is responsible for significant deeper water sediment stabilization and is a stage in structure construction related to sulfur-reducing bacterial activity (cf. Reid et al., 2000, 2003; Riding, 2000; Dupraz and Visscher, 2005; Visscher and Stolz, 2005; Baumgartner et al., 2006).

The constructional process of microbial heads in the deeper subtidal zone involves: (1) after storms, a limited supply of peloids are deposited in isolated patches over depressions located in the irregular surface of heads this becoming bound by superficial coccoid bacteria; (2) restricted activity of peloid fusion and micritization by endolithic activity; (3) extensive and pervasive activity of grains/bioclats envelopment by bio-induced micrite; (4) extensive growth of aragonite crystals filling void spaces.

Microbial deposits in Shark Bay are notable not only because of their abundance and variable external morphologies but also in view of the diverse microbial communities involved, that produce very distinctive internal fabrics. This study analyzed a sequence of microbial deposits from shallow to relatively deeper water seeking to advance in the establishment of the relation between fabrics and water depth (Fig. 17). The vertical fabrics association described within microbial structures, also reflect water level changes, because of the sea level regression in the last 2000 years of ca. 1.5 m. In the relatively small number of heads available for study, few were constructed by only one fabric. Basal fabrics are often related to water depths > 1 m, which are here termed non-laminated cryptomicrobial. They are complex with a significant amount of macroscopic eukaryotes responsible for bioturbation, disruption, skeletal framework and detritus accumulation. Within these

fabrics, micrite occurs as bio-induced patches and disconnected clots distributed in coarse grainy sediment, resembling structures described as eukaryote stromatolites in the Bahamas (Feldman and McKenzie, 1998). The microbial structures of Hamelin Pool frequently display vertical sequences of internal fabrics revealing a shallowing-up sedimentary sequence, reflecting Late Holocene sea level fall and emergence.

Aitken (1967) defined thrombolites as “non-laminated cryptalgal bodies characterized by a macroscopic clotted or spongy fabric... with a microfabric consisting of centimeter-sized patches or clots of microcrystalline limestone (grain-size 8–20 μm) with rare clastic particles...”. Kennard and James (1986) later introduced the term mesoclots as “discrete colonies or growth forms of calcified, internally poorly differentiated, and coccoid-dominated microbial communities” and also proposed the term cryptomicrobial (a modification of cryptalgal from Aitken) fabrics for “poorly differentiated, either mottled, patchy, or vague sediment fabrics that are attributable to constructional microbial activities, but that have been largely obscured by other organic and inorganic processes”.

Cerebroid structures and Microbial Pavement have a non-laminated fabric with micritic patches of mesoclots produced by coccoid bacteria, but some have grains and fragments. Also when examined in thin section and scanning electron microscopy the fabrics reveal two micrite generations: an early micrite that occurs as patches resulting from peloid micritization, fusion and recrystallization and a late micrite occurring as bio-induced micrite that envelopes grains and particles and (see Jahnert and Collins, 2011). Because of the absence of clear evidence of coccoid organomineralization in the patches of micrite in Cerebroid and Microbial Pavement internal fabrics, it was considered appropriate, in this paper, to describe the fabrics as “cryptomicrobial non-laminated”. Following Shapiro (2000) “mesoclots are composed of a variety of microstructures including peloids, grumulous fabric, cement, and calcimicrobes...” and on that definition the deeper subtidal structures and fabrics of Shark Bay (bio-induced patches and disconnected clots; see above) appear suitable to be termed thrombolites, but more investigation and sampling is needed to clarify this.

Although the microbial deposits in Shark Bay are referred to as laminated structures and stromatolites (Logan and Chase, 1961; Davies, 1970; Logan and Cebulski, 1970; Golubic, 1973; Playford, 1973; Logan

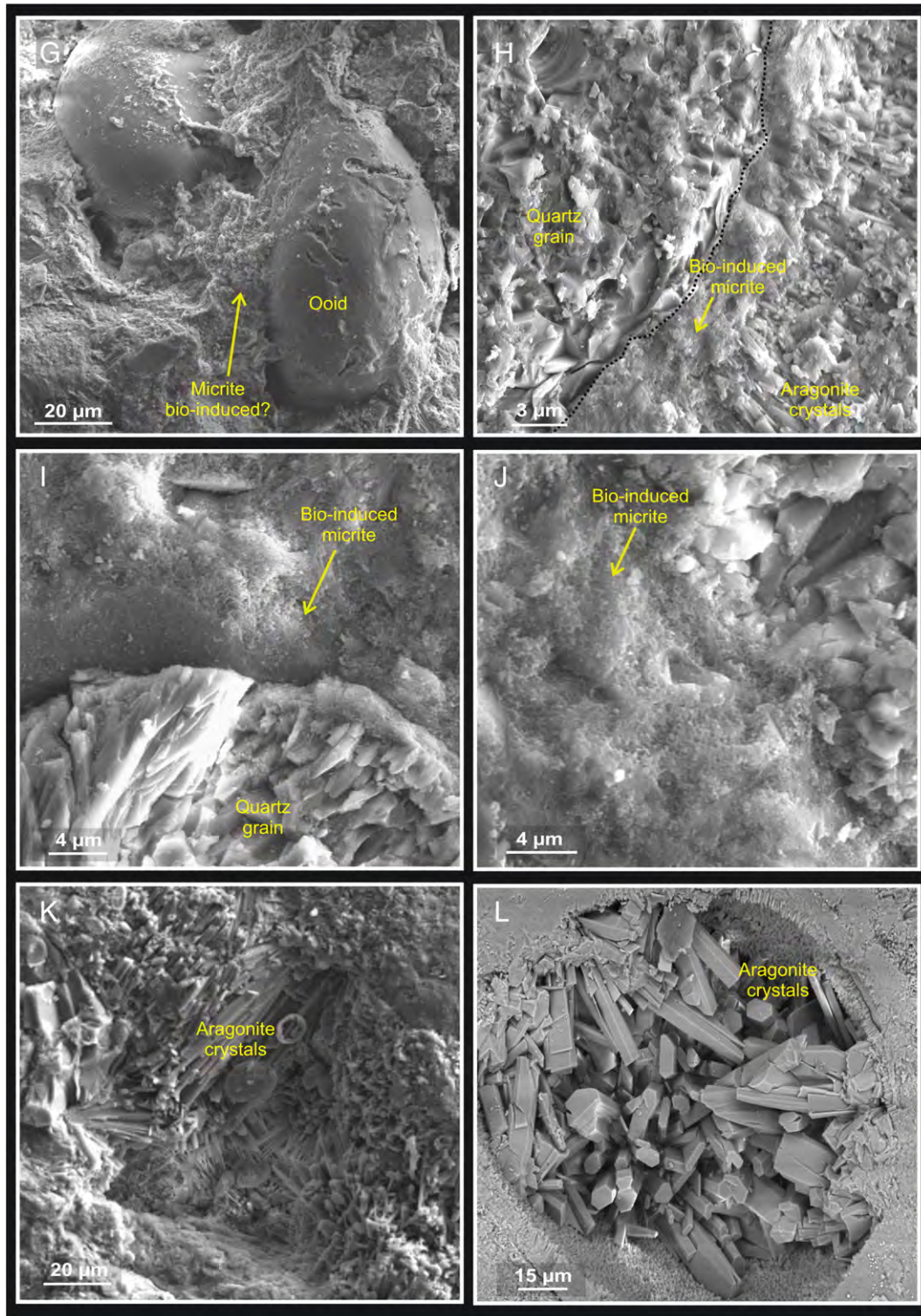
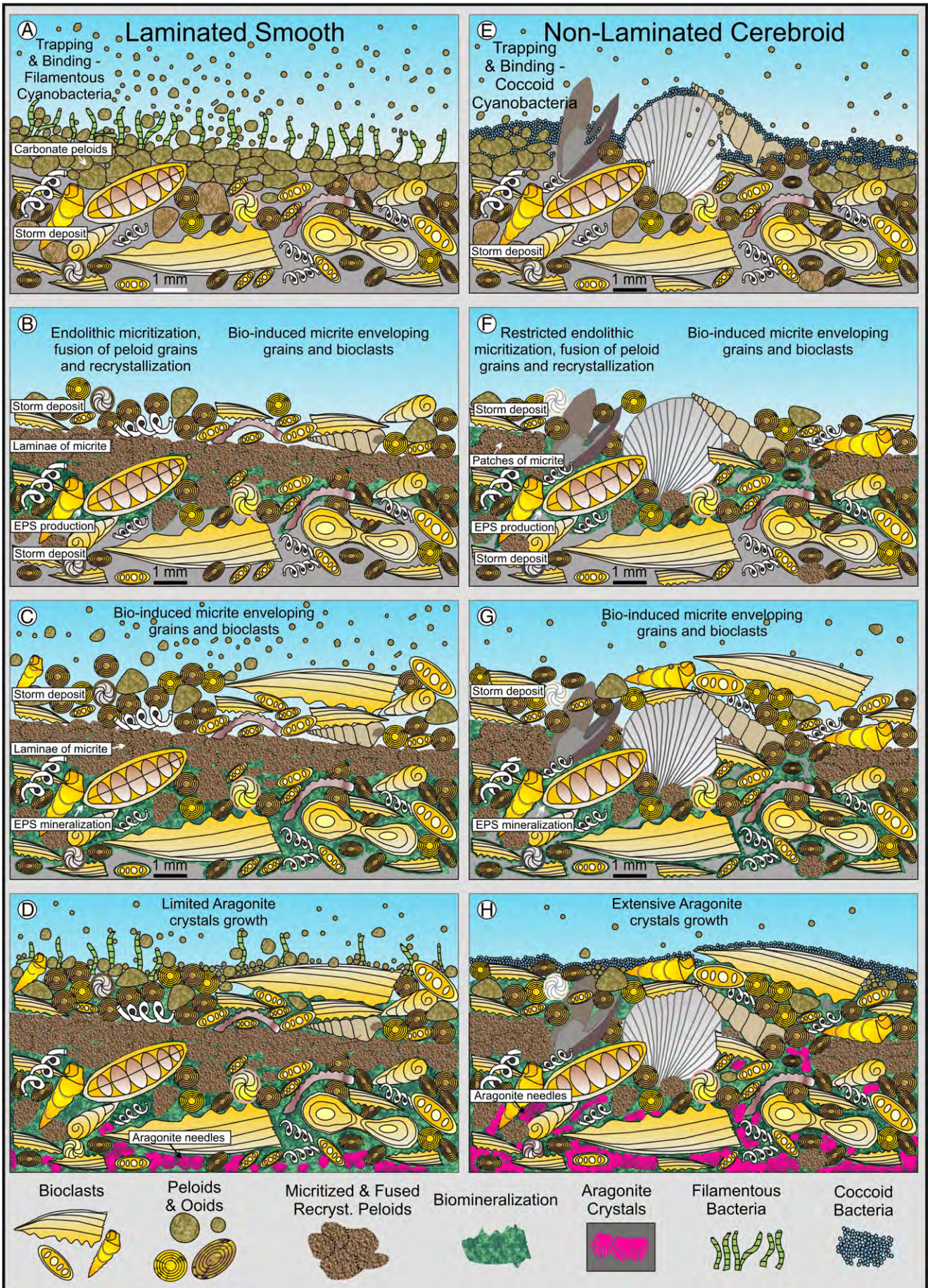


Fig. 15. Early diagenetic mechanisms involved in microbial deposits, showing (stage 3) generation of organic micrite enveloping grains and bioclasts (G, H, I, J) and (stage 4) fibrous aragonite precipitation in void spaces (K, L). (G) Ooids grains connected with a fine texture micrite; (H, I, J) details of fine texture micrite which precedes the last process of aragonite crystal growth; (K) aragonite crystals arranged depending on the space available, as a pervasive crystal system or as microcrystals; (L) well developed aragonite needles inside larger voids. Images from Cerebroid heads located at Carbla and south of Carbla Point.

Fig. 16. Schematic sequence with the inferred mechanisms involved in the construction of microbial laminated Smooth stromatolite (A, B, C and D) and non-laminated cryptomicrobial Cerebroid (E, F, G and H) structures in Shark Bay. Microbial features have been exaggerated in scale for emphasis. In Smooth domain in upper subtidal conditions: (A) After storm activity and carbonate grains/bioclast emplacement, fine material in suspension is deposited creating a layer of peloidal grains with trapping and binding by filamentous microbes; (B) bioturbation, micritization and fusion of peloids, creating lithified laminae of micrite after recrystallization; (C) syndepositional processes of micrite generation which envelopes grains (green color in diagram); (D) the last process is aragonite crystals growing in voids.



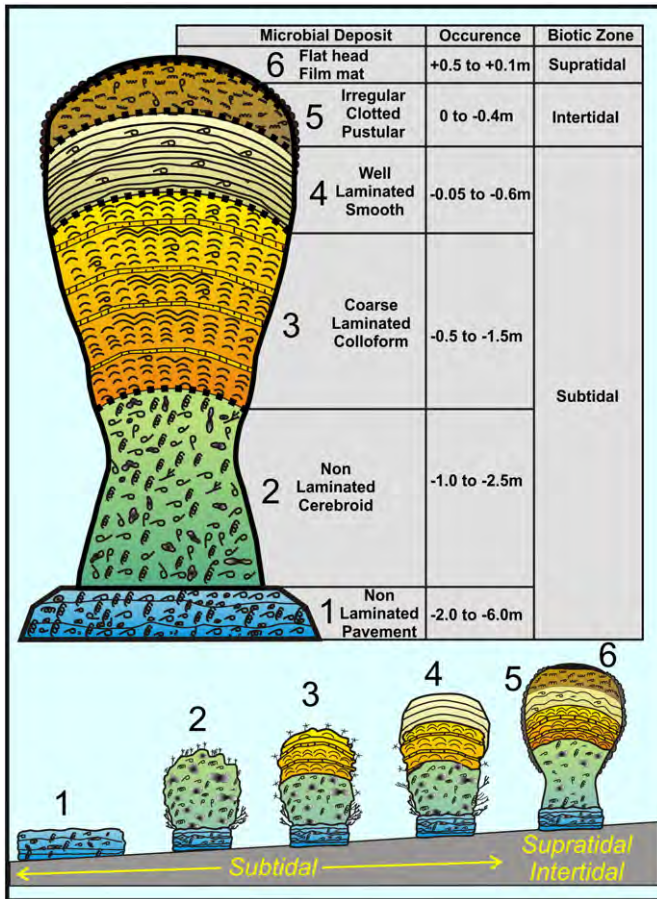


Fig. 17. Schematic microbial head with idealized sequence of internal fabrics and their relative water depths. The structures often display a vertical sequence of internal fabrics in shallowing-upward arrangement or show truncated fabric sequences depending on environmental setting and timing of growth history.

et al., 1974a, 1974b; Hofmann, 1976; Playford and Cockbain, 1976; Reid et al., 2003 and many others), environmental changes, sea level variation and Bacteria/Archaea and diatoms in diversified communities may provide an explanation for the co-existence of stromatolites, thrombolites and cryptomicrobial deposits growing contemporaneously in Shark Bay. Aitken (1967) considered thrombolites as a subtidal phenomenon and stromatolites as intertidal to supratidal deposits, as did Bova and Read (1987) and Koerschner and Read (1989). Our data reveal that Pustular fabrics are shallow intertidal forms and their vertical growth style produces mesoclotted fabrics and thrombolites. Subtidal occurrences have stromatolitic and cryptomicrobial fabrics.

Kennard and James (1986) and Feldman and McKenzie (1998) questioned the existence of modern carbonate systems with thrombolites arguing they share calcification with algae or have poorly defined clots which coalesce to form mesoscopic fabrics different from the Paleozoic thrombolites. Pustular deposits in Shark Bay are producing mesoclots in an environment controlled by bacteria without any eukaryotic organisms sharing space. Also the modern thrombolite deposits of Lake Clifton and Lake Walyungup located south of Perth, Australia are constructed by classic mesoclots produced by filamentous cyanobacteria. These lacustrine thrombolites occur from shallow to deeper waters (2 m), displaying different external morphologies (Moore and Burne, 1994), but with the same internal clotted thrombolitic fabric, providing an important example of modern thrombolite deposits.

Logan et al. (1974a) recognized that the interaction between microbial mats, sediments and processes of lithification and oxidation affect the deposits to create fenestral fabric porosity. Fenestral fabrics constitute an important element with applications in recognition and

interpretation of ancient environments. Fenestral fabrics in Shark Bay are irregular within a bushy-like framestone in Pustular, a fine to medium sub-horizontal laminoid fenestral fabric in Smooth deposits, a coarse laminoid porous fabric in Colloform deposits. We recognize that subtidal deeper deposits (Cerebroid and Microbial Pavement) will produce an irregular fenestral fabric with voids between skeletal particles and bivalve shells and abundant shelter porosity. The effective microbial influence and control in some of the subtidal deposits may be difficult to recognize when transformed to rocks because of the lack of diagnostic microbial fabrics and the amount of eukaryote skeletons. The presence of bivalve shells of *Fragum erugatum*, serpulids, foraminifera, micro-gastropods, crustaceans, *Acetabularia* (green algae), *Gigartinales* (red algae), *Fucales* (brown algae) and other bivalve borers living on subtidal build-ups obstructs the normal growth of the heads producing irregular surfaces that may cause the head to split into branches, and also disturb and disrupt lamination. The peripheral growth of non-calcified algae however, protects lower parts of heads from tidal current abrasion and erosion.

6. Conclusions

Hamelin Pool is a shallow hypersaline environment with high microbial activity and diversity, and microbial carbonate deposition. The subtidal microbial structures and deposits are in fact, very extensive in the subtidal zone, occupying 10 times the space of supratidal and intertidal deposits. More than 80% of the microbial deposits occur in the subtidal zone and share space with eukaryotic organisms, especially the bivalve *Fragum erugatum*. These diverse and vulnerable deposits in the World Heritage area's peculiar environment have developed during the last few thousand years of stable hypersaline conditions and falling sea level. Microbial build-ups prosper in water depths to a maximum of 2.5 m, constructing a microbial framework, although microbial influenced/induced deposits extend as semi-lithified surfaces and hard-ground to water depths of 6 m. These microbial tabular and blocky pavements occupy more than 220 km².

Subtidal deposits in Hamelin Pool have been recognized and mapped based on external organo-facies, composition and morphologies as Pustular, Smooth, Colloform, Cerebroid, Tabular or Blocky Pavement, Bioclastic/Peloidal Sandflat, Bivalve Subtidal Coquina, Seagrass Domain and Bioclastic/Quartz sand. Subtidal structures have distinctive internal fabrics, with aragonitic micrite arranged in millimetric laminae or sub-spherical micrite patches which have different forms and fabrics such as well laminated (Smooth), coarse laminoid (Colloform), irregular clotted (Pustular) and non-laminated cryptomicrobial (Cerebroid and Microbial Pavement) producing microbial deposits with stromatolitic fabric (Smooth and Colloform), thrombolitic fabric (Pustular) and cryptomicrobial fabric (Cerebroid and Microbial Pavement). The aragonitic subtidal structures are produced by trapping and binding particles (agglutination), micritization, fusion and recrystallization of peloids as well as biologically-induced carbonate precipitation, and lastly aragonite cement-filling of voids. The morphologies of the microbial structure consist of ellipsoidal, spherical, calyx, prismatic elongate, ridge-like, compound bladed and domical forms, reaching 1.5 m in height. They depend on slope and wave energy or tidal movement, take on varied morphologies or produce widespread underwater pavements. Subtidal microbial structures have a complex microfabric of micritic composition containing ooids, peloids and bioclasts mainly of bivalve shells, with serpulids, foraminifera, micro-gastropods, and secondary quartz grains. *Acetabularia* (green algae), *Gigartinales* (red algae), *Fucales* (brown algae) and some living bivalves are external encrusters on microbial structures.

This study of microbial system morphogenesis in Hamelin Pool, Shark Bay redefined the depositional model to include a new subtidal constructional microbial system. The findings emphasize the significance of a Holocene microbial system as one of the most important assets for the interpretation of ancient microbial deposits especially

in view of the limited modern examples available to compare with the variety described from the rock record.

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