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HOLOCENE CARBONATE ENVIRONMENTS IN SOUTH AUSTRALIA AND WESTERN AUSTRALIA

Report on a field excursion to the Coorong Lagoon area and Yorke Peninsula (S.A.), and Hutt Lagoon, Shark Bay, and Lake MacLeod (W.A.)

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ABSTRACT

In March and April 1978 a group of BMR and CSIRO scientists concerned with Holocene and ancient sedimentary carbonate and evaporite sequences examined the following localities: Coorong Lagoon area and Yorke Peninsula (S.A.), and Hutt Lagoon, Shark Bay and Lake MacLeod (W.A.). The prime purpose was to increase the group's familiarity with such environments, but some new observations and measurements were made. This report highlights observations and new research of particular interest: these relate especially to hydrological studies in the Coorong Lagoon region, and sedimentology and crystallography of gypsum in Marion Lake, very large subaqueous, gypseous stromatolites in Inneston Lake, subtidal stromatolites and organic, sulphidic sediments in Hamelin Pool, and vast salt and gypsum deposits in Lake MacLeod. Chemical data on the water in newly discovered probable sink holes in Hamelin Pool are presented.

1. INTRODUCTION

M.R. Walter

In March-April 1978, a number of BMR and CSIRO scientists involved with the Baas Becking Laboratory and the McArthur and Georgina Basins Projects visited South Australia and Western Australia to : 1) allow members of the Georgina Basin and McArthur Basin Projects to examine areas of Holocene carbonate sedimentation known to be at least partly analogous to Proterozoic and Palaeozoic sequences; 2) allow members of the Spencer Gulf Project to compare that area with other well studied areas of carbonate sedimentation (including making carbon-fixation and sulphate-reduction measurements in Hamelin Pool for comparison with results from Spencer Gulf); 3) promote the exchange of ideas between the members of the excursion.

The itinerary was as follows:

28 March 1978	Coorong Lagoon area, S.A.
29 March	Yorke Peninsula (Cape Spencer, Deep Lake, Inneston Lake, Marion Lake), S.A.
1 April	Hutt Lagoon, W.A.
2-7 April	Hamelin Pool, Shark Bay, W.A.
8 April	Lake MacLeod, W.A.

Two low level flights of one hour duration each were made over Hamelin Pool on 6 April. A dinghy was used on Hamelin Pool, and observations were made by snorkling in Hamelin Pool and Inneston Lake.

The following persons participated in part or all of the excursion : J. Bauld, R.V. Burne, J. Ferguson, M.J. Jackson, J. Kennard, I.B. Lambert, M.D. Muir, G.W. Skyring and M.R. Walter.

Guidance in South Australia was provided by C.C. von der Borch, D. Lock and J. Warren (Flinders University); W.V. Preiss (Geological Survey of S.A.) and P. De Deckker (Zoology, University of Adelaide) also attended this portion of the excursion. Guidance in the Hamelin Pool area was by P.E..Playford (Geological Survey of W.A.) and in Lake MacLeod by B. Bolton (University of W.A.). The Lake MacLeod excursion was attended by I. Reid (BHP, Perth) and 6 students and staff from the Department of Geology, University of W.A.

In this report we do not attempt to comprehensively describe all of what we saw: a bibliography is included to enable ready access to the extensive literature on these areas. Rather, we have highlighted observations of special significance and new ideas and research.

2. HYDROLOGY

R.V. Burne & J. Ferguson

Hydrology is probably the major environmental constraint on the occurrence of the evaporites, carbonates, and even stromatolites observed during the excursion. On a general scale theoretical explanations are available for the various hydrological regimes encountered, but there are very few supporting data to confirm these theories, or to elucidate the details of the processes involved. In all cases basic hydrological, water chemistry, and isotope distribution data are necessary to provide a reliable explanation for the processes which led to the observed results.

Four hydrological associations account for the various sedimentary associations observed:

(1) Sea-water systems

(2) Sea water/groundwater interactions

(3) Groundwater systems

(4) Fossil brines and fossil associations

(1) Sea-water systems

The chemical oceanography of the Shark Bay area and of Hamelin Pool in particular has been studied sufficiently well to provide an environmental context in which to place the unique occurrence of a stromatolite-dominated shallow water eco-system (Logan & Cebulski 1970). The elevated salinity of Hamelin Pool must also be a determining factor in the evolution of the abundant submarine and intertidal examples of carbonate cementation observed, and a study of pore water geochemistry in relation to this problem would be useful.

Two situations in which Hamelin Pool brines concentrated sufficiently to form evaporite minerals were observed. The first is where gypsum is forming interstitially in the capillary zone above the water table in an infrequently inundated supra-tidal zone at Hutchison Embayment, a situation analogous to the formation of gypsum in the sabkhas of the Persian Gulf. The second, which was observed for the first time on this excursion, is where gypsum is being precipitated from standing brines evolving in silled basins formed by small karst depressions in the high intertidal zone on-shore of the Snake Bank (western shore of Hamelin Pool). These basins are flooded only at extreme high water, and a hot dense brine has evolved within them by solar heating of the lower layer. This underlies a stratum of normal sea water, and bivalve shells and vertebrae of sheep were observed "floating" at the brine interface.

Results of chemical analyses and calculated ion ratios for two water samples from a "Snake Bank" pit at Shark Bay are presented in Table 1. Although supporting isotope data are necessary to define the origins of the waters with some degree of certainty, the chemical data suggest that they are mainly derived from seawater.

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This is most evident in the sample from the pit top which is about twice as saline as seawater but has similar $^{Na}/_{Cl}$, $^{Mg}/_{Cl}$, $^{K}/_{Cl}$ & $^{SO_4}/_{Cl}$ ratios. Its $^{Ca}/_{Cl}$ ratio is marginally lower than that of seawater, possibly indicating calcium carbonate precipitation. The samples from the pit bottom are about 6 times seawater in concentration but are far from being saturated with respect to sodium chloride. Their $^{Na}/_{Cl}$ ratio is similar to that of average seawater but $^{Mg}/_{Cl}$ & $^{K}/_{Cl}$ values are marginally low, perhaps indicating precipitation-resolution contributions. $^{Ca}/_{Cl}$ & $^{SO_4}/_{Cl}$ ratios are both low probably as a result of precipitation of calcium sulphate from the brine.

Table 1. Chemical Characteristics of Shark Bay Water Samples

Snake Bank

	Pit Top	Pit Bottom	Average Seawater
Cl	42 000	115 920	
Mg	2 780	7 480	
Ca	845	1 060	
Na	23 410	64 680	
K	815	2 210	
Sr	5.4	6.4	
SO_4	5 980	14 010	
$^{Na}/_{Cl}$	0.557	0.558	0.556
$^{Mg}/_{Cl}$	0.0662	0.0645	0.0667
$^{K}/_{Cl}$	0.0194	0.0191	0.0201
$^{SO_4}/_{Cl}$	0.142	0.120	0.140
Ca/Cl	0.0201	0.00914	0.0212

Hutt Lagoon is a sea water dominated system of a lagoon, fed by slow sea water seepage through a coastal dune barrier, in which evaporation has proceeded to the stage of halite formation. It is a natural example of the process exploited in solar salt works.

(2) Sea Water/Groundwater Systems

The evolution of both the Coorong lakes at Salt Creek, and the lakes at the southwestern tip of the Yorke Peninsula, are the results of sea water-groundwater interactions. Groundwater appears to be also influencing the evolution of Hutt Lagoon, and possibly Hutchinson Embayment evaporitic sediments.

The following comments on the hydrology of the Coorong area are based on conversations with David Lock, and on a recent publication by von der Borch, Lock & Schwebel (1975).

Presently "active" Coorong lakes can be divided into three mineralogical types, each type reflecting a different combination of seawater/groundwater influences and hydrological regimes. The "halite lake" contains large quantities of the more soluble evaporite minerals, most obviously Na Cl. The marine water table is at, or close to, the lake surface and the water chemistry and the composition of the sediments is consistent with a seawater dominated regime, perhaps modified by the effects of bacterial sulphate reduction.

In contrast, the "dolomite lake" is the furthest inland, the furthest above sea level and there is no evidence of present-day marine influence. Characteristic features of this lake are the relative absence of halite, the abundance of dolomite in the uppermost sediments and the presence of a lithified carbonate "terrace" at the lake-margins. This terrace is several metres wide in the active lakes, and in older lakes has extended to completely seal the lake surface. The dominant hydrological regime in this area has been termed "seepage reflux". In winter, when rainfall is at its maximum, the unconfined groundwater aquifer in the dunes rises above the levels of the lake surface, which then floods. With the onset of summer this floodwater evaporates and its density rises to the point where it is greater than that of the underlying groundwater. The water then sinks and in doing so allows relatively fresh water in the dunes to seep inwards at the lake margins. This water is high in CO_2 and is supersaturated with respect to certain calcium carbonate phases. When it enters the lake the CO_2 is evolved and carbonate phases precipitate and "cement" the lake sediments near the seepage zones. The "flushing" effect of the downwards moving groundwater prevents the accumulation of the most soluble evaporite minerals but, in some circumstances, may allow the accumulation of large quantities of calcium sulphate minerals.

The "aragonite-magnesium calcite lakes" are an intermediate situation. The "seepage-reflux" mechanism is operating but, in this case, the underlying seawater wedge is sufficiently close to the lake surface to allow a certain amount of seawater to become entrained in the refluxing groundwaters. This seawater is introduced to the lake via the dune-seepage system and has a major effect on the mineralogy of the precipitated carbonates.

The groundwaters have a high Mg/Ca ratio, presumably deriving their Mg ions from skeletal carbonates in the surrounding dunes, during the formation of calcrete (the skeletal material is high-Mg calcite, whereas the calcrete is low-Mg calcite). Precipitation of dolomite lowers the Mg/Ca ratio, and the groundwater brines evolve during their seaward movement, precipitating carbonate phases with lower and lower Mg/Ca ratios as the coast is approached.

The hydrology of the Marion Lake area has not been studied except in the most general way. The observed phenomena have been ascribed to the results of the interaction of an intrusive sea water

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wedge and the seasonal variation of fresh water lenses in the local dunes. Once again the occurrences of evaporite minerals need to be explained by a detailed hydrological study, an important aspect of which would be the study of the evolution of water chemistry within the large stromatolites of Inneston Lake and the effect of this on their internal lithification.

Although Hutt Lagoon is largely of sea water concentration, the diluting influence of groundwater from both natural resurgences and the discharge of pumped bores is noticeable along its eastern shore. These areas are colonised by a rich algal mat, and are also marked by localised deposits of gypsum. Similar groundwater influences may be present around the shoreline of the Hutchinson Embayment.

(3) Groundwater Systems

The Shark Bay peninsulas and Yorke Peninsula are both areas where numerous dry gypsum lakes occur in circular depressions lying close to the normal water table. The depressions of the Shark Bay area, known as birridas, received some attention during the excursion. They are unusual in that they contain a central vegetated mound composed almost entirely of soft, friable to earthy gypsum, surrounded by a "moat" about a metre lower than the central mound. The moat contains algal mats, laminated gypsiferous sediments and bears resurgence channels on its surface; it is also water-logged. It would appear that the moat is maintained as a depression by the discharge of sulphate-rich groundwaters from the surrounding dunes during periods of elevated water table, and that these waters concentrate in the subsurface in the centre of the birrida and add to the gypsum pile by subsurface evaporation.

(4) Fossil Brines and Fossil Associations

Fossil sea-water brines trapped within formations are a major influence on the diagenetic phenomena observed in the gypsum deposits of Marion Lake, and in the gypsum and halite deposits of Lake MacLeod.

The gypsiferous stromatolites and associated evaporites of Marion Lake, and the halite and gypsum deposits of Lake MacLeod are all related to past hydrological systems.

M.D. Muir

3. CALCRETES, KARST, CONIATOLITES, CRUSTS AND TEEPEE STRUCTURES

Calcretes seen on this excursion take a number of forms.

Tamala Limestone at Natta Outcamp (W.A.) This is composed of a number of large, irregular pisoliths set in a fine-grained carbonate matrix. The pisoliths bear a striking resemblance to the so-called oncolites from the Amos Formation of the McArthur Group. The pisoliths are up to 10 cm in diameter, and have (at least) one outer zone of finely laminated calcite. The inner nucleus is of a number of forms, from angular fragments of calcitic quartz arenite to fine grained lithoclasts of a variety of origins. In some cases, several generations of laminated zones can be detected. The calcrete cements a carbonate sand aeolianite of Pleistocene age. The present surface is irregular with a mound-like appearance. In the calcrete there are numerous irregular fractures in several directions normal to the present surface, and at varying angles to it. These are long fracture zones (up to 100 to 150 cm long), with internal stratification parallel to the sides of the fractures, and are obviously solution channelways at some times.

Cemented pisoliths in the Tamala Limestone (W.A.) These pisoliths are smaller than those described above, on average about 2 - 3 cm in diameter. The rims are very regularly laminated, with individual laminae about 1 - 2 mm thick. They always have lithoclast nuclei which may be carbonate sand, carbonate cemented quartz sand, or black, fine-grained material which is carbonaceous, and often foetid when freshly broken. The outlines of the pisoliths are irregular, and the pisoliths are often interlocking. Near Natta Outcamp, pisoliths were found nested on a surface of laminar calcrete, thus indicating way-up. In other cases, e.g. near the blow-holes on the coast near Lake MacLeod, the pisoliths occur in "beds" parallel to the present surface, or in solution pipes (30 - 60 cm wide by about 1.5 m deep).

Cemented flakes and chips. Fragments resembling pisolith nuclei are frequently cemented together in calcrete - carbonaceous, carbonate and quartz sand fragments. These are angular and very often take the form of flattened chips. The source of the fragments is not known, but they may be residual from previously formed calcrete which has been partly dissolved out. The carbonaceous fragments may be soil residuals.

Massive calcrete. This occurs in the calcreted Pleistocene aeolianites in the Coorong, Cape Spencer, and Zuytdorp Cliffs areas. Aeolianites which are mainly carbonate sands become lithified by massive and laminar calcrete. The laminae are irregular, and sometimes more or less flat, and sometimes domed. Terra rossa is often developed as a surface soil and in solution pipes. Lateral variation in thickness and splitting of calcrete layers was observed at Cape Spencer. A zoned sequence occurs in the calcrete layers (up to 4 m thick) at Cape Spencer, comprising a rootlet layer at the top, overlying a massive zone with some root casts, and at the base a 1 m thick nodular layer.

Solution tubes with stratified travertine. These bear a strong resemblance to stromatolites in cross-section, but the laminae are concave upwards and often fluted. They commonly occur in lithified lake margin sediments in the Coorong ephemeral lakes, and are also found in calcreted aeolianites. They are 10 - 20 cm in diameter.

Meniscus cements. These are formed as a result of precipitation of carbonates from the capillary fringe of the groundwater table. They occur in any type of pre-existing sediment, but are most readily recognised in Pleistocene aeolianites.

Calcrete enrusted tree roots. These have been observed in fossil soil horizons in the Younghusband Peninsula (Coorong), at Cape Spencer, and at Lake MacLeod. The first examples occur in Holocene dunes. The other two are in Pleistocene dunes.

Calcrete grain size. Calcrete ranges in size from fine to coarse-grained. They generally contain grains from the original sediment, but laminar calcretes may not. They are often brecciated and pisolitic, and are subject to re-solution and karst development.

Karst. The Shark Bay overflight showed abundant dolines and buried channels because of buried karst in (presumably) Cretaceous chalk. This chalk is normally pure limestone but on the coast, it becomes altered to soft green dolomite. Around margins of sinkholes, the chalk becomes hard white brecciated dolomite and is recemented. Large Holocene stromatolites encrust these circular sinkhole margins.

North of Booldah Well and north of Hutchinson Embayment, sinkholes occur in the highest supratidal and onshore environments. The water is fresh at the Hutchinson's occurrence and probably so at Booldah. Similar sinkholes occur in sub-tidal environments too. If fresh water is released through the sinkholes, it must affect the hydrology of Hamelin Pool significantly and the distribution of stromatolites and animals.

Also, if the flow of fresh water at Hamelin Homestead is artesian and related to an underground drainage system (as it appears to be from the air) then bores sited on other buried channels (which can be seen on air photos) should produce good flows of fresh water.

Since this particular chalk extends at least as far north as Exmouth Gulf and similar sinkholes have been observed on the eastern shore of Exmouth Gulf then the possibilities of good underground water, in this area too, look promising.

Crusts and coniatolites

Biogenic crusts. In the Coorong Lagoon, there are extensive encrustations of beach rock and calcreted aeolianite by serpulid worms. These seem to stabilise the surface of otherwise very soft and readily eroded sediment.

Coniatolites. The term 'coniatolite' is used by Purser and Loreau (1973, pp.343-376 in The Persian Gulf, B.H. Purser, ed., Berlin, Springer-Verlag) to include lithified aragonite crusts on beaches (splash travertines) and dripstones formed by run-off of marine water on the undersides of cliff and bank overhangs. Coniatolites are usually composed of fine prismatic aragonite growing normal to the surface on which it is nucleated. They are laminated parallel to the nucleation surface, although minute irregularities soon become exaggerated, giving rise to the characteristic rough textured surface on the coniatolite. Individual laminations, representing a desiccating phase, are frequently coated with a thin film of amorphous organic matter. In well-developed coniatolites, laminations frequently mimic the shapes of stromatolitic laminae. Algal unicells are occasionally trapped in the laminae (often in depressions which would presumably remain moist longest).

Dark coloured irregular encrustations on the tops of lithified stromatolites at Carbla Point and Flagpole Landing were interpreted on field evidence as coniatolites, but this identification needs to be confirmed in the laboratory.

Lithified crusts. These occur at the margins of mature lake or marine basins and usually form over less lithified sediment below. Lithification is accomplished by precipitation of a carbonate cement in a fine-grained carbonate sediment. When the lithified crust covers the entire lake surface the hydrological evolution of the lake ceases because the lithified crust prevents free movement of groundwater.

Halite forms continuous but ephemeral crusts, often very thick (up to 2 m), which may form on anoxic saline muds, or floating on brines. The surface of the crusts is often pitted by small brine pools which have intense biological activity including sulphate reduction in their lower levels. Examples of these were seen at Spencer Gulf (Fisherman Bay), and on a salt lake inland from the northern end of the Coorong, and also at Salt Creek and Hutt Lagoon, W.A. These halite crusts can be dissolved in a single wet season.

Gypsum forms hard crusts sometimes with the development of pustules of prismatic crystals on the surface. These crusts are longer lived than the halite crusts and under suitable conditions will be preserved. At Deep Lake, the gypsum crust takes the form of large polygons, about 1 - 2 m in diameter, with the pustules forming around the margins and often capped with halite. The gypsum occurs in the lake centre and consists of large (10 cm long x 2 cm wide) prismatic crystals with fairly abundant swallow-tail twins. The lake margins are characterised by carbonate crusts and algal growth.

Carbonate crusts. In these the sequence of events appears to be that mud-crack polygons (of varying sizes from 10 - 30 cm diameter) become lithified at some time not yet clearly defined. Movement of water from underlying unlithified sediment causes precipitation of carbonates in the mud-cracks, thus welding a number of small polygonal units together, forming larger plates, 30 - 50 cm diameter with polygonal outlines. The margins of these larger plates act as acquifers for ascending groundwater, and the plates enlarge by

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inorganic precipitation of carbonates along their margins. In some cases, algae occur along the cracks and may be active, also causing precipitation of the carbonates. The enlargement of the plates causes an increase in pressure, and plates will often buckle at the edges, or over-ride one another to form teepee structures (see below).

Eventual welding together of these plates seals off the lake from further groundwater activity and sedimentation ceases. Lithified crusts of this type were seen at Spencer Gulf (Fisherman Bay), the Coorong Lakes south of Salt Creek, Deep Lake, Inneston Lake, Marion Lake, Hamelin Pool at Booldah Well, and marginal to some of the birridas of the Shark Bay area.

Teepee structures. Most of the lakes visited represent seasonally exposed water tables. Their filling and drying out are expressions of the rise and fall of the water table resulting from seasonal changes in humidity. The aquifer is frequently layered with lenses of fresher water floating on brines. There is an overall slow groundwater movement towards the sea, and less soluble minerals are precipitated furthest from the sea. In the Coorong region the lakes furthest from the sea precipitate dolomite, magnesite, and magnesian calcites. Nearer the marine area, lakes precipitate high Mg-calcite + aragonite, then aragonite, then (although not presently in the Coorong, but seen at Marion Lake) gypsum, and halite (Hutt Lagoon). The salts are precipitated from ground waters (land derived) and not sea water. Both gypsum and halite are precipitated from standing waters in the Coorong lakes, but these are ephemeral and are redissolved each season and then move down the brine gradient towards the sea.

All the lakes occur in natural small basins in Pleistocene calcreted dune systems. The Coorong Lagoon itself is separated from the ocean by a Holocene dune ridge, and similar beach ridges at Spencer Gulf separate small lake basins of ephemeral hypersaline lakes. Hutt Lagoon is also separated from the Indian Ocean by a long Holocene dune ridge that is occasionally breached in the south. Lake MacLeod and Hamelin Pool are separated from the ocean by calcreted Pleistocene aeolianites.

When the lake surface intersects the water table, the lake is filled and the marginal areas between lake and dune are affected by the capillary fringe of the water table. Water in this zone wells up around the margins of lithified polygonal plates causing precipitation of salts in the channelways, called teepee structures. In carbonates, teepees are very disruptive and cause the formation of large fracutres in lithified crust which may extend for many metres into the lake centre. The groundwater dissolves salts in the teepee when this is first formed, because the water is relatively fresh, but later in the cycle, precipitation takes place. As an example, at Marion Lake, gypsum crystals enclosing algal filaments are dissolved away, and the filaments are then coated with aragonite, and form the 'box-work' limestone of von der Borch et al. (1977). Teepee structures are often ephemeral. A very large structure at Deep Lake in September 1976 was apparently not present in March 1978.

Carbonate teepees are rather irregular in outline. Halite teepees tend to form a series of rectangles around the lake margin. Halite crusts become very thin (less than 1 cm) in the teepee zone, and show signs of considerable lateral growth and buckling. One such structure seen at the halite lake to the north east of the Coorong Lagoon had the crust at the teepee margin peeled back and overturned for a distance of 20 cm on each side of the teepee. A pure white halite is precipitated in teepee centres, even if the substrate is foetid black mud.

4. EVAPORITES

R.V. Burne & M.J. Jackson

(1) Gypsum

Several types of gypsum occurrence were observed. Gypsum is being precipitated beneath a standing brine in Lake Inneston and in the silled basins on shore from Snake Bank, Hamelin Pool. In the latter occurrence the gypsum occurs as a thin (1 cm) crystalline crust associated with algae. It also forms needle-like crystals precipitated on dendritic vegetation that has fallen into the basin. Discrete gypsum crystals are growing within the supratidal sediments of Hutchinson Embayment as a result of the evaporation of sea water brines within the capillary zone. Discoidal gypsum is being precipitated from sulphate-rich groundwater by evaporation at springs and resurgences in the birridas of the Shark Bay area and at the margin of Hutt Lagoon. Extensive recrystallisation has taken place in the older gypsiferous deposits of both Lake MacLeod and Marion Lake. However, where recrystallisation has not occurred the original gypsum at Marion Lake is of the millet seed type. Well preserved ripples and cross-stratification indicate that subsequent to their formation the gypsum crystals have been moved and re-deposited by traction currents. Smaller diagenetic gypsum crystals are present within the box-work limestone facies both within teepee margins and within algal laminated sediments.

At Lake MacLeod a gypsum layer some 3 m thick overlies a 1 m thick halite layer. As at Marion Lake the gypsum has been reworked by currents following its precipitation; it is bedded and cross bedded, and contains slump-structures and drag folds in graben-like features. At the base of the gypsum is a thin red-brown clay layer that is interpreted as being deposited from storm or sheet flood. Although the underlying "columnar halite member" is composed mainly of halite it also contains thin grey laminae (5 cm to 20 cm apart) which contain silt, organic matter and gypsum (origins of which are not known).

(2) Halite

A thick halite crust is forming on Hutt Lagoon. It incorporates microorganisms and probably represents the mode of formation of the thick fossil halite deposits of Lake MacLeod which contain several organic-rich partings.

Small, ephemeral hopper crystals are forming on the surface of some pans in the Coorong area, Deep Lake and Yorke Peninsula, and large hopper crystals have grown interstitially in the clay sediments of Lake MacLeod.

5. STROMATOLITES

M.R. Walter

Gypseous stromatolites. Inneston Lake contains nodular unbranched columnar and bulbous stromatolites with a relief of up to 3 m, and, in some cases, near vertical sides. These are apparently permanently subaqueous. Internally they feel hard, although we were told that a crowbar can be readily driven into them. The outer 20 cm at least is composed largely of algal mucus and gypsum and is soft and gelatinous. Gypsum is precipitating throughout the lake. The stromatolites have never been cored and their internal structure is unknown. The algal mat is composed of filamentous cyanophytes (Phormidium, Spirulina), unicellular algae (possibly cyanophytes or green algae), moderately abundant diatoms, and other algae (M.R. Walter, unpublished report, 1975).

Subtidal stromatolites in Hamelin Pool. First reports on Hamelin Pool stromatolites emphasised their intertidal occurrence. Playford and Cockbain have drawn attention to the occurrence of subtidal stromatolites but even their work did not prepare us for the extent of the occurrence. Snorkling off Carbla Point, Flagpole Landing and 1.5 - 2.5 km south of Flagpole Landing, and the overflight, showed that perhaps as much as 30 - 40% of the sublittoral shelf consists of thickets of indurated columnar, nodular and bulbous stromatolites. Commonly these have a relief of 30 - 50 cm but some large bulbous and nodular forms (e.g. off Carbla Point) have a relief of more than 2 m. All have a mamillate surface form with mamillae 1 - 2 cm wide. Relief on the mamillae varies and off Carbla Point, they extend up as small columns several centimetres high superimposed on larger bulbous, nodular and columnar forms. These strikingly resemble Precambrian and Palaeozoic columnar branching stromatolites, and should be studied in detail. To date little is known about them. They are well lithified but appear to be coated with an actively growing gelatinous algal mat.

Playford and Cockbain's experiments indicate spasmodic accretion and erosion of the surfaces of these structures, so that there is no nett growth. However, the observations are very restricted. The stromatolites protrude from an indurated substrate coating the sublittoral platform. The age of induration is unknown.

Little is known about the basin in the centre of Hamelin Pool. There are apocryphal reports of "huge mushroom-shaped structures" there.

Inclination and orientation. The complexities of interpreting the inclination and orientation of stromatolites were emphasised by our observations during the excursion. Attention has been drawn to these complexities by Playford and Cockbain, and they now have additional data. Elongate nodular and bulbous stromatolites in the intertidal zone are generally perpendicular to the shoreline, as Hoffman and others have described. However, there are also elongate subtidal forms, and many of these are almost parallel to the shoreline. Playford refers to these as "seif" stromatolites because of their resemblance to seif dunes.

He believes that their morphogenesis may be the same as that of seif dunes, and be controlled by the dominantly southerly winds. This suggestion was supported by our observation during the flight of spume patterns on the water surface with the same spacing and orientation as the underlying stromatolites.

As has been previously reported, inclined columnar stromatolites at Carbla Point lean into the southerly winds, and bulbous and nodular forms bulge to the south, again indicating wind control.

Clearly, caution must be exercised when interpreting elongate fossil stromatolites. However, once it has been established that the stromatolites in question are intertidal in origin, then it seems reasonable to deduce that the fossil shoreline was oriented perpendicular to the stromatolite elongation.

J. Bauld

6. ALGAL MATS - MICROORGANISMS AND PRIMARY PRODUCTIVITY

Environments of microbiological interest were found in all of the regions visited. The field trip was most productive and the accomplishments are briefly described below:

(i) 47 samples were collected and preserved for later examination of microbiota

(ii) sufficient live material was brought back to Canberra to set up 37 enrichment cultures for isolation and further study of the microbial components of various mats and living stromatolites

(iii) radioisotope experiments (4) were carried out at Shark Bay (Hamelin Pool) in order to estimate the primary productivity (photosynthetic CO_2 fixation) of selected intertidal algal mats and some components of subtidal stromatolites. As with our Spencer Gulf studies these experiments were coordinated (same time, same sites) with Graham Skyring's radioisotopic estimates of bacterial sulfate-reduction in an attempt to directly link contemporaneous carbon and sulfur cycling (see also section 7)

Field Observations

(1) Of the areas visited in South Australia Lake Inneston exhibited the greatest potential for studies of primary productivity and microbiology. This lake is highly saline and contains large, stromatolite-like structures of up to 3 m relief. Cursory examination during diving showed a patchy, thin, softly-gelatinous layer over a gypsum (?) crust (ca. 1 m thick). Beneath this were extensive gelatinous aggregations of variously pigmented microorganisms. Some deeper areas appeared black suggesting active sulfate-reduction. Although large, these intriguing structures are mechanically weak and fragile. The major interests here are the identification of the component microbial flora, their various contributions to the primary productivity of the structure and their role in morphogenesis.

(2) Field observations show similarities between the microbial communities in Deep Lake (Yorke Peninsula) and Hutt Lagoon (W.A.). Specifically, I refer to the community which colonizes the restricted environment beneath the salt crust (often several cm thick) and the top few mm of the underlying reducing sediment (which still contains free water). The microbial flora appear to exist in a narrow zone where tolerable levels of light intensity, moisture, salinity and nutrients coincide. This would be an opportunity to study quantitatively the link between carbon and sulfur cycling in these restricted hypersaline environments and to compare them with e.g. Lake MacLeod (W.A.) and the old salt workings at Point Paterson in Spencer Gulf. Stromatolitic mats were observed in Hutt Lagoon (see also section 2).

(3) The Hamelin Pool region of Shark Bay contains a wide variety of algal mats and stromatolites which occur in sub-, inter-, and supratidal environments. Although carbonates predominate there are also some gypsum areas containing algal mats e.g. Hutchison Embayment.

There is an exciting array of algal mats and stromatolites in Hamelin Pool. Some of these e.g. smooth, tufted and blister mats, are of the same type as those found in Spencer Gulf. Others e.g. pustular, colloform and gelatinous, are found only in Hamelin Pool, together with permanently subtidal stromatolites. In addition to the substantial geological data already available (see section 11 there has been some descriptive work on the constructing micro-organisms. However, there is a dearth of information concerning the metabolic activities and biological dynamics of the microbial communities which build these geologically significant structures.

Primary Productivity of Hamelin Pool Algal Mats

The results obtained from *in situ* primary productivity experiments are shown in Table 2 together with mat pigment content, accretion rates (Logan et al., 1974) and sulfate-reduction rates (G.W. Skyring, pers. comm.). Table 3 gives the results of chemical analyses of seawater collected from our experimental area. Primary productivity rates for the flat stratiform mats (smooth, tufted and colloform) are expressed per unit area. Unfortunately, the topography of the other mats precludes this and their productivities are standardized to chlorophyll *a* content (chlorophyll *a* is a pigment in the algae which traps the light energy utilized to fix CO_2 and form organic carbon).

The high productivity of colloform mat (113 mgC $m^{-2} h^{-1}$) reflects the relatively constant nature of the subtidal environment. The photosynthetic efficiency (primary productivity per unit chlorophyll *a*) of colloform mat is about an order of magnitude greater than for the other stratiform mats.

Unlike colloform mats, the other two stratiform mats occur in the intertidal zone and, in consequence, may be subjected to considerable desiccation stress. Both primary productivity (mgC $m^{-2}h^{-1}$) and photosynthetic efficiency (mgC mg $chla^{-1}$ h^{-1}) are lower than for colloform mat. Both of these mat types, smooth and tufted, also occur in the intertidal zone of the Spencer Gulf study area.

Tufted mat productivity (85mgC $m^{-2} h^{-1}$) was greater than that for smooth mat (17 mgC $m^{-2}h^{-1}$) and reflects its presence in environments where water is retained for longer periods than on smooth mat, which occurs on better drained sediment surfaces. It is probable that the area of smooth mat sampled was exposed to prolonged desiccation prior to our excursion, since smooth mat in Spencer Gulf shows much higher primary production rates (up to 184 mgC $m^{-2}h^{-1}$).

TABLE 2. PRIMARY PRODUCTIVITIES AND PIGMENT CONTENT FOR ALGAL MATS IN HAMELIN POOL, SHARK BAY.

Experimental area 2.8 km southwest of Flagpole Landing

	PRIMARY PRODUCTIVITY		SULFATE REDUCTION***	MEASURED ACCRETION RATE ****	CHL* a CONTENT ($\bar{x} \pm s$, n=8)	
MAT TYPE	$mgC\ m^{-2}h^{-1}$	$mgC\ mgchl^{*}a^{-1}h^{-1}$	$m\ mol\ m^{-2}\ d^{-1}$	$(mm\ y^{-1})$	$mg\ m^{-2}$	$mg\ g^{-1}$ protein
Intertidal mats						
Smooth (STN 6)	17	0.24	4.6	$\leq$ 10	124 $\pm$ 23	3.27 $\pm$ 0.88
Tufted	85	0.16	nd	$\leq$ 10	714 $\pm$ 170	18.60 $\pm$ 4.78
Pustular (STN 5)	nd	9.12	undetectable	2	nd	$(1.80 \pm 0.50) \times 10^{-3}$
Subtidal mats**						
Colloform	113	2.25	nd	probable < 1	92 $\pm$ 34	2.34 $\pm$ 0.80
Internal	nd	1.00	nd	nd	nd	$(1.10 \pm 0.41) \times 10^{-3}$

nd not determined

* chl = chlorophyll

** from subtidal stromatolite column. Colloform is surface mat: internal mat is of gelatinous, resilient consistency

*** data from G.W. Skyring, Section 7

**** Logan, Hoffman & Gebelein (1974) AAPG Mem. 22: 140-194.

TABLE 3. ANALYSIS OF WATER COLLECTED FROM 2 m DEPTH ON SUBLITTORAL PLATFORM 2.8 km SOUTHWEST OF FLAGPOLE LANDING (Water filtered prior to analysis, through 0.45 μm filter).

PARAMETER	mg l^{-1}
Ca	700
Mg	2450
Na	19900
K	715
SO_4	5200
Cl	35814
TDS (calc.)	64858
NH_4-N	0.20
NO_2-N	0.008
NO_3-N	0.09
Total N	0.85
Total P	0.30
PO_4-P	0.23

pH = 8.0 at T = 27C } Field determinations
Conductivity = 76178 $\mu S.cm^{-1}$ (25C) }

Inorganic N:P, 0.298 : 0.230 = 1.30:1

NO_3-N: PO_4-P = 0.09 : 0.230 = 0.39 :1

Pustular mat exhibited very high photosynthetic efficiency compared to the other mat types examined, but did not support detectable sulfate-reduction (Table 2). On the other hand, the production of organic matter by smooth mat was sufficient to support the sulfate-reduction rate determined in the sediment immediately beneath the living mat (Table 2).

In contrast to the relatively high primary productivity rates of colloform mat, its measured accretion rates were "probably less than 1 mm per year" (Logan, et al., 1974) which is considerably less than that for either smooth or tufted mat (Table 2). Logan et al. (1974) observed that colloform mats occupied environments that were mainly erosive. This was clearly demonstrated during our field trip when cyclonic weather conditions sloughed material from the subtidal stromatolite columns and the flat mats around them. This material was transported to the shoreline environment where it provided ample organic matter to support bacterial sulfate reduction (see section 7).

The chemical data given in Table 3 show that the water on the sublittoral platform of Hamelin Pool is concentrated seawater with a salinity about twice that of oceanic seawater. N:P ratios were found to be about 1:1. Algae from coastal marine waters normally contain N:P in the ratio of 5-15:1 which indicates that N is limiting for primary production in this environment.

Further Exploration and Research

Some questions which came to mind during our examination of the Shark Bay stromatolites were:

(i) for the mat types common to both Spencer Gulf and Shark Bay -
are there detectable differences in primary productivity (and sulfate reduction) due to environmental differences between these areas, e.g. temperature, exposure, tidal regime?
are there differences in preservation potential? if so, what causes such differences?

(ii) which mat types, because of their component microbes and fabric, best promote sulfate-reduction?

(iii) do algal mats composed of non-filamentous algae e.g. pustular, exhibit comparable primary productivity to filamentous mats e.g. smooth? Are they able to trap sediment as efficiently? Is there comparable preservation?

(iv) what is the role of microbial production and decomposition as compared to sedimentlogical processes in the accretion, or otherwise, of the subtidal stromatolites?

(v) to what extent is stromatolite morphogenesis controlled by the resident microorganisms and do the resident meiofauna play an important role?

(vi) is total community metabolism, e.g. primary productivity, of the subtidal stromatolites and mats of the sublithoral platform comparable to that of the seagrass community of the Faure Sill?

G.W. Skyring & L.A. Chambers

7. ORGANIC SEDIMENTS, SULPHATE REDUCTION, AND SOURCES OF IRON

The presence of black iron sulfide (not pyrite) in sediments closely associated with some algal mats in the Shark Bay area suggests that bacterial sulfate reduction is occurring. The most sulfidic zones were in finely laminated, smooth algal mat sediment 2 to 5 cm below the surface and in coarsely laminated, highly organic sediments which accumulated in shallow depressions in the intertidal zone. The coarsely laminated sediments did not appear to be capped by growing algal mat. Much of the organic matter in these organic sediments appeared to originate from the fragile, organic material (and accompanying microflora) which coated the columnar stromatolites growing in the intertidal and subtidal zones. It is possible that a significant proportion of the iron in these sediments was extracted from the sea water by the stromatolitic biota. The distribution of sulphur isotopes in the sulphides and porewater sulphates is consistent with dissimilatory sulphate reduction. In the organic rich sediments very rapid sulphate reduction has depleted the sulphate reservoir and the porewater sulphate was enriched in ^{34}S (^{34}S + 25°/oo) relative to seawater sulphate (+ 20.6°/oo). The sulphides were enriched in ^{32}S (^{34}S = -11.5°/oo). Sulphide associated with smooth algal mat was more enriched in ^{32}S (^{34}S = -23°/oo) while porewater sulphate showed no change from seawater sulphate. These observations may be important in considering the role of stromatolitic growth in the biological production of large quantities of hydrogen sulfide, an important, naturally occurring precipitant for iron and heavy metals. Quantitative data obtained for sulfate, sulfide and iron concentrations and sulfate reduction rates in these sediments are given in Table 4.

TABLE 4. SULFATE, SULFIDE AND IRON CONCENTRATIONS, AND SULFATE REDUCTION RATES IN HAMELIN POOL SEDIMENTS AND WATERS

SEDIMENT TYPE AND STATION NO.	SULFATE IN INTERSTITIAL WATER m M	SULFIDE µmol g^{-1}	IRON µmol g^{-1}	SULFATE REDUCTION RATES µmol g^{-1} d^{-1}	m mol m^{-2} d^{-1}
Thickly laminated black					
1	32.8	88	77	1	19
2	43.2	56	57	2	46
3	30.2	34	30	0.5	14
4	46.9	51	ND*	1	29
Pustular Mat					
5	35.4	0	9	0	0
Smooth Mat					
6	34.4	6	37	0.08	5
Inter columnar stromatolite					
7	37.5	4	11	0.10	5

ND* Not determined

8. ANIMALS, AND THEIR INFLUENCE

M.R. Walter

It is widely believed that Holocene stromatolites are developed only where grazing animals are rare or absent. Observations made on this excursion indicate that this is a simplification, at least. In Hamelin Pool there is an abundant fish fauna, including several species. Straight, cylindrical faecal pellets were observed frequently in the subtidal environments; they are up to 3 - 4 mm in diameter and are presumably produced by fish grazing on the cyanophyte mats (Davies has described evidence of fish grazing from near the Faure Sill). During Cyclone Alby, water turbulence broke up the faecal pellets producing a structureless, water-rich organic sediment that accumulated in topographic lows and in the intertidal zone. This was generally only a few millimetres thick. The intertidal deposit was several centimetres thick. Additional macrofauna includes sea-snakes, bivalves (predominantly one species, and that stunted) and rare gastropods.

Small (0.5 mm) red ostracod-like crustaceans were abundant on tufted mats south of Flagpole Landing, in Hamelin Pool, but none were observed on other mat types. De Deckker collected ostracods from mud in Deep Lake; the salinity was 82^{o}/oo; the only ostracod was Diacypris n.sp. (P. De Deckker, pers. comm. 1978).

Cyanophyte mat samples were taken from all localities visited, in a search for nematodes. Warren Nicholas of ANU reports that all contain nematodes, some in considerable abundance; some also contain oligochaetes and polychaetes.

P. De Deckker (pers. comm. March 1979) has provided the following information on the fauna inhabiting the algal mats of the Coorong ephemeral lakes. There are three types of animals. The smallest are the nematodes. Next larger are the 200μm wide polychaete worms Jasmineira sp. (identified by P.A. Hutchings) which live within soft, gelatinous tubes in the algal mats. The largest are the boring beetles Clivina sp. (identified by E. Matthews); these bore into the mats when they are dry, forming holes 2 - 5 mm wide and up to 30 cm deep. There are also reports of brine shrimps and ostracods feeding on the mats.

It is apparent that even in the most saline environments at least minute animals are present, sometimes in abundance. The ecology of these animals is presently unknown, but they must rely ultimately on the primary production of cyanophytes or photosynthetic bacteria. Thus they may be significant in the carbon cycle of these environments, and in producing the ultimate sedimentary fabrics. In particular, their sheltering and food-gathering habits should be investigated in relation to the formation of fenestrate carbonates. Herein may be an explanation for the rarity of fenestrate fabrics in Precambrian carbonates. In any case, they cannot be ignored in any study of stromatolite morphogenesis or the carbon budget.

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In the field Burne pointed out the similarity between stromatolite reef and coral reef ecosystems, e.g. in the presence of boring bivalves, encrusting calcareous "worms", and crustaceans (within fenestrae). Higher algae grow on many of the subtidal stromatolites. Submarine lithification produces similar results in both ecosystems.

9. ENVIRONMENTAL MODELS

M.J. Jackson & J. Kennard

COORONG

Setting Coastal plain, topography markedly linear alternating belts of rises and hollows (dunes and interdune flats in this case). Laterally extensive area (200 x 90 km).

Climate Humid winters and dry summer in a semi-arid area: therefore alternations of precipitation excess and deficiency.

Hydrology Complex, but mainly considered to be controlled by continental groundwaters. Reflux theory of Lock used to explain origin of evaporites and polygons. Vertical (up and down movements) now considered more important than previously, and related to density variations during seasons. Minor effects of marine saline influx evident nearest coast (e.g. Halite Lake). Active flow of water from dunes into and through interdune flats important.

Geologic Record

1. Could be laterally very extensive (hundreds x hundreds km)
2. Thin regressive sequence (few metres thick) overall.
3. Delicate groundwater model probably precludes chance of building up great thicknesses.
4. Linear arrangement to mineralogy and sedimentary structures on a large scale may be recognisable.
5. On small scale, teepees with gypsum and distinctive types of stromatolites evident.

MARION LAKE

Setting Isolated within extensive dune system, but formerly connected to marine waters. Small in extent compared to Coorong.

Climate Very similar to Coorong, alternating wet and dry seasons.

Hydrology Seasonal outflow of groundwater from calcareous dune system surrounding lakes most important, but little detail available.

Geologic Record

1. Protected marine facies succeeded by restricted lacustrine facies within widespread aeolian facies.
2. Probably not in laterally extensive sheets - interconnected fossil lake-forms more likely.
3. Gypsum diagnostic; originally millet-seed type with sedimentary features such as ripples, but extensive diagenetic changes possible.
4. Lateral facies change from gypsum in lake centres to a boxwork carbonate unit with stromatolites and numerous polygons and teepees. Teepee crests have distinctive thinly laminated stromatolites.

5. Aeolian gypsiferous fringe formed by deflation of intermittently dry lake surface present.

SHARK BAY - HAMELIN POOL

Setting Large marine embayment (50 x 30 km), limited connection to ocean via shallow sill. Low relief hinterland, no terrigenous sediment input. Wide shallow sublittoral shelf and tidal flats (2 - 10 km).

Climate Semi-arid, lower rainfall than South Australian examples. Winds, and resulting tides, important.

Hydrology Dominated by marine influence, little data available on effects of continental groundwaters. Restricted mixing with normal sea water and high evaporation rates result in approx 2 x normal sea water salinities; consequent restricted faunal diversity and poliferation of algae (reduced grazing faunas).

Geologic Record

1. Overall thin regressive sequence.
2. Zonation of stromatolites - pronounced lateral zonation of algal mat types and morphologies in response to exposure, water depth, water and wind current directions and erosion.
3. Numerous breaks and disruptions to sequence due to storms - wind generated tides and waves.
4. High salinities not necessary in Pre-Cambrian to ensure proliferation and survival of algae.

LAKE MACLEOD

Setting Former very extensive (120 x 50 km) marine embayment now completely cut-off from ocean cf. Marion Lake. Algal mats and mangroves restricted to southern margins adjacent to barrier to ocean.

Climate As for Shark Bay.

Hydrology Evaporitive pan, predominantly surface run-off with limited marine interchange through barrier.

Geologic Record

1. Laterally extensive uniform stratigraphy.
2. Vertical sequence of marine carbonate; halite, gypsite with periodic terrigenous silt/clay influxes.
3. Restriction of stromatolites and predominance of marine carbonates adjacent to marine barrier.
4. Halite distinctly laminated.

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10. FUTURE WORK

M.R. Walter

It was apparent that although some aspects of the Hamelin Pool environment and sediments have been studied in depth, much significant work remains to be done, e.g. in the following fields:

1. Groundwater movement and chemistry;

2. Karst features and their relation to the present hydrological regime;

3. Tidal pattern - largely unknown (e.g. are the "subtidal" stromatolites ever exposed, and for how long are other mat types exposed to the air?);

4. Role of grazing and burrowing animals in shaping stromatolites, controlling their growth rates and producing fenestrate fabrics;

5. Distribution of subtidal stromatolites;

6. Dating of older stromatolites;

7. Estimation of gross primary production and sulphate reduction of a large area within Hamelin Pool;

8. Census of the flora (including microflora) and fauna (including meiofauna) of Hamelin Pool;

9. Subtidal carbonate cementation.

See also sections 2 and 6.

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