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MICROBIALITES OF LAKE THETIS CERVANTES, WESTERN AUSTRALIA — A FIELD GUIDE

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Microbialites of Lake Thetis, Cervantes, Western Australia — a field guide

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Abstract

Lake Thetis is a small, saline lake occupying a collapsed doline on the Swan Coastal Plain near Cervantes that hosts several types of microbial mat and microbialites, the lithified structures constructed by some of the mat communities. Therefore, the lake is of considerable interest to the scientific community, who often visit the site for comparative purposes on their way to the more extensive and better known microbialites of Shark Bay. Its location, close to the popular tourist destination of the Pinnacles, ensures that many members of the general public visit the lake, often as part of guided tours.

Lake Thetis is a living laboratory that provides important insights into the development of microbial communities and the formation of microbialites. It is unusual in that both stromatolites and thrombolites are present, allowing comparison of the processes that give rise to these two different forms of microbialites. The juxtaposition of fenestrate microbialites and non-lithifying microbial mats makes Lake Thetis an ideal locality for studying biological and environmental controls on lithification, providing significant insight into the role of benthic microbial communities in the construction of microbialites. In addition, the lake presents a possible modern analogue for the formation of hydrocarbon systems in Precambrian rocks. The Department of Environment and Conservation (DEC) has taken over management of Lake Thetis, now a part of Nambung National Park, and has expanded tourist facilities in the area.

KEYWORDS: Lake Thetis, microbialite, thrombolite, stromatolite, benthic microbial communities, purple sulfur bacteria

Introduction

Several saline lakes in Western Australia contain examples of living microbialites, structures built by the interaction of microbial organisms with sediments or precipitates. Microbialites with laminae are known as stromatolites, whereas structures with a clotted fabric are known as thrombolites. Stromatolites are known from several recent localities and have a fossil record extending back to the Archean, although they are most common in the Proterozoic. Thrombolites are mainly known from the Phanerozoic and include modern day examples from Lake Clifton and Lake Richmond. Lake Thetis is unusual in containing both stromatolites and thrombolites in a single modern environment.

Lake Thetis is a small lake about a kilometre from the coastal town of Cervantes, readily accessible along a well-formed gravel road (Figs 1–3), and visited by both scientists and the general public. Many tourists see the lake as part of a tour of the nearby Pinnacles, and tour buses visit the location daily. The lake is clearly signposted, and is featured in local tourism brochures. There is a formed path and boardwalk running around Lake Thetis, with explanatory signs giving an introduction to the lake system and the microbialites. Scientists from a variety of geological and biological disciplines visit Lake Thetis (Fig. 4) on their way to study the more extensive, but rather different, stromatolites forming in Hamelin Pool, Shark Bay; or en route to the earliest known, 3500 million-year-old fossil stromatolites of the Pilbara.

Lake Thetis itself offers unique insights into microbialite formation, and has been the subject of detailed scientific study (Grey et al., 1990; Reitner et al., 1996; Arp et al., 2001). Specifically, Lake Thetis microbialites demonstrate the potential significance of benthic microbial communities (BMCs) in hydrocarbon generation and mineral accumulation. The lake is also notable for having a prolific community of purple sulphur bacteria that derive their energy from the photosynthetic oxidation of sulfide. This is a relatively rare ecosystem in a modern setting, which may have been more widespread in past oceans (Brocks et al., 2005). Although these bacteria typically grow near the lake bottom, they provide a colourful display when occasionally washed up on the foreshore.

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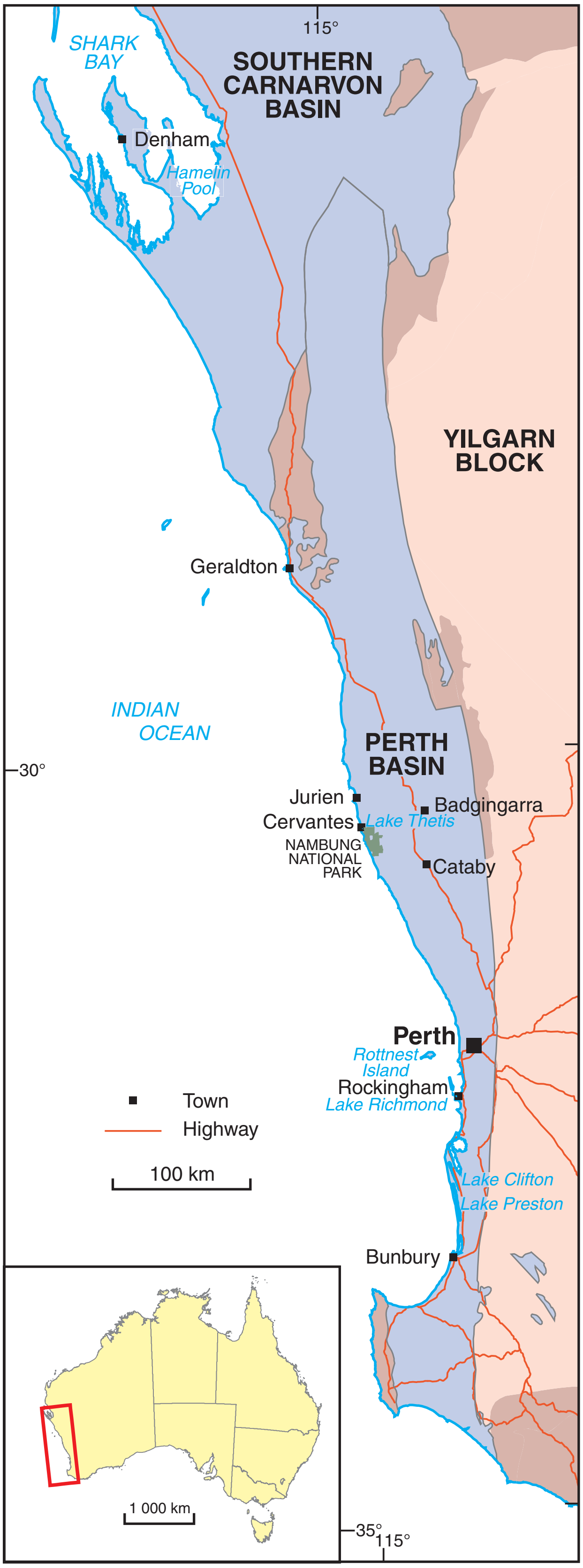

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Figure 1. Lake Thetis, Perth Basin, Western Australia, regional location (after Grey et al., 1990).

This field guide is intended to help visitors observe some of the main features visible at Lake Thetis, and to understand why these unassuming-looking structures are of such global interest.

Location

Lake Thetis (Figs 1–3) is a small, permanent, saline lake located on the Wedge Island (1936) 1:100 000 sheet (Mory, 1995) about 1 km southeast of Cervantes (at MGA 315500E 6623400N; 30°30'S, 115°04'E), and just behind the rapidly accreting recent dunes that form Thirsty Point (Fig. 2).

The small coastal township of Cervantes is 237 km (about a three-hour drive) north of Perth. It is reached

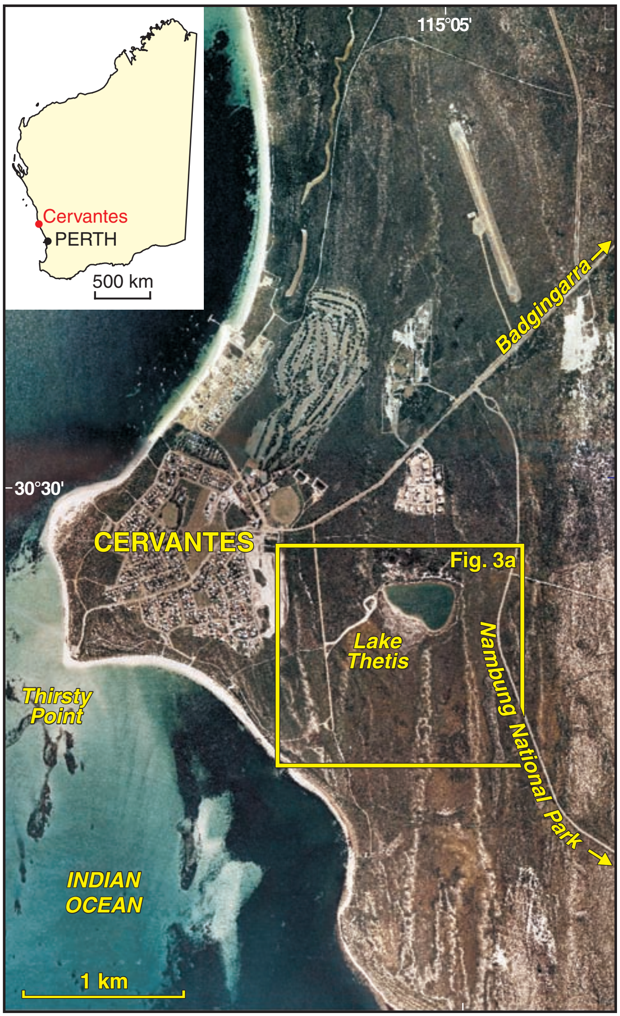

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Figure 2. Orthophoto mosaic image of Lake Thetis, Western Australia, showing regional setting and generalized geomorphology (reproduced by permission of the Western Australian Land Information Authority, CL 25/2009).

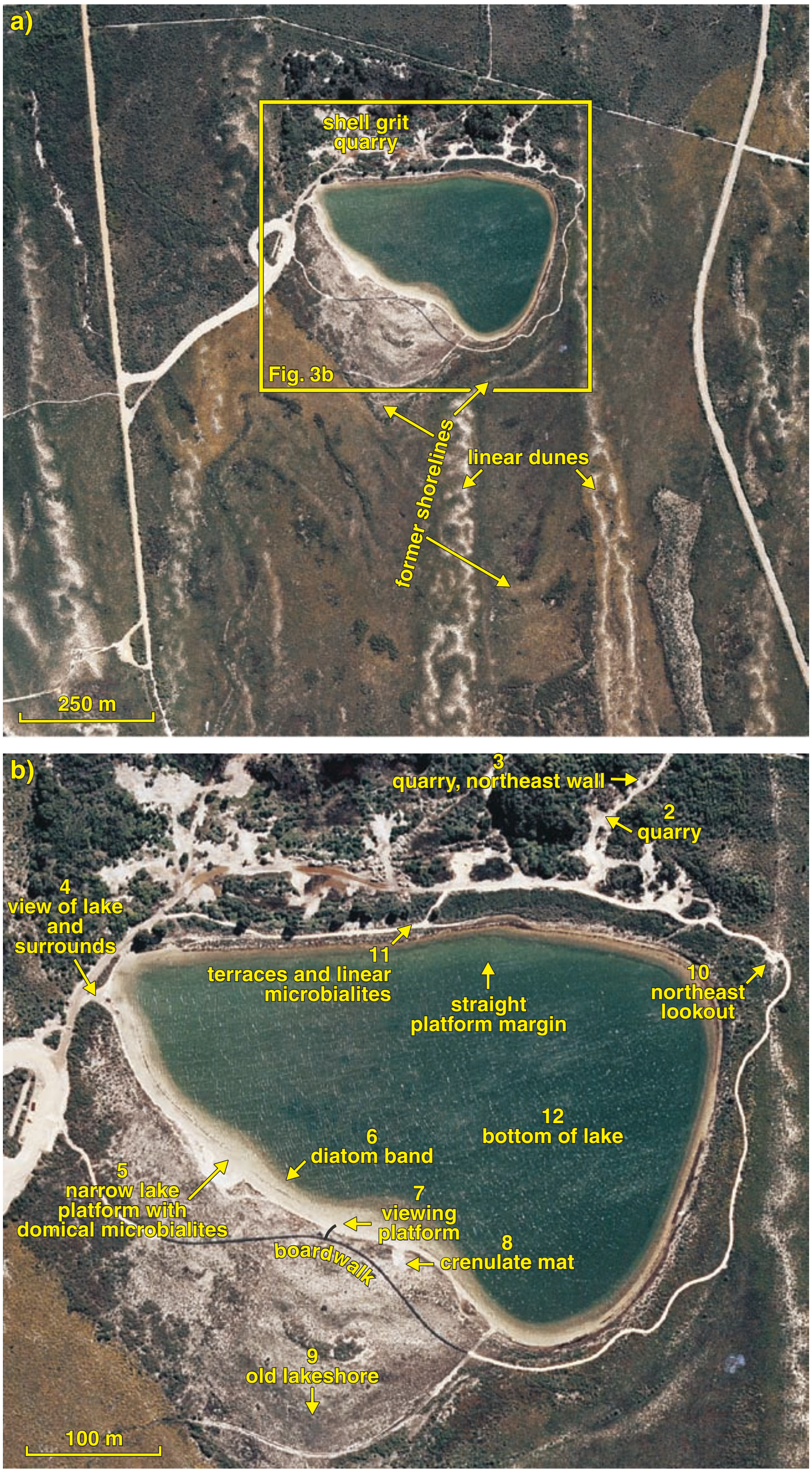

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Figure 3. Orthophoto mosaic images of Lake Thetis: a) Lake Thetis showing relationship to linear dunes south of the lake and parallel to the coast, and the position of the now-rehabilitated shell-grit quarry to the north of the lake. Note the series of old raised terraces south of the lake marking former shorelines, now largely obscured by vegetation; b) detail of lake showing main localities mentioned in the text (numbered). The main southwest platform and straight edge of the northern shore are clearly visible (reproduced by permission of the Western Australian Land Information Authority, CL 25/2009).

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Figure 4. **Precambrian paleobiologists Academician Mikhail Aleksandrovich Semikhatov (left) of the Geological Institute in Moscow, and Professor Andrew Knoll (right) of Harvard University follow the signposts on a visit to Lake Thetis.**

by travelling north along the Brand Highway and then west at the Cervantes Road turnoff about 30 km north of Cataby and south of Badgingarra. Fuel, supplies, and accommodation are available at Cervantes, Cataby, Badgingarra, and Jurien. If travelling further north from Cervantes, a road through Jurien provides a scenic alternative to the Brand Highway. Cervantes was named after an American whaling ship blown ashore on one of the islands in 1844. Lake Thetis is named after the schooner *Thetis*, used by JW Gregory to explore this part of the Western Australian coast from 1847–1848.

To reach Lake Thetis from Cervantes, travel along the Cervantes Road and take the first turnoff to the right (south), just past the water tower. This is an unsealed road (the old Pinnacles Road) with a signpost indicating the direction to Hansen Bay and the stromatolites (Fig. 4). About 300 m south of the turnoff, turn left to take a track to the east (signposted to Lake Thetis). The lake is a further 300 m along the track, with a parking area and picnic facilities overlooking the western shore. Access around the lakeshore is by a formed track and boardwalk.

The lake contains domical microbialites (Burne and Moore, 1987), best exposed on the southwestern shore. Some of the lithified structures are laminated, and can therefore be classified as stromatolites, whereas others have a non-laminated, clotted fabric, much like peanut brittle. Other forms of microbial mat, mostly unlithified, are also present. The best time to view the microbialites is when the lake level is at its lowest in late summer (usually around Easter), before the winter rains begin. The site was previously a reserve managed by the Dandaragan Shire Council, but it has now been placed under the authority of the Department of Environment and Conservation (DEC, previously the Department of Conservation and Land Management, CALM) as part of Nambung National Park. Any material sampling, regardless of quantity or purpose, requires written permission from the managing authority.

Geology and hydrogeology

Lake Thetis lies about 1.5 km inland from the present Indian Ocean shoreline, and occupies a collapsed doline at the northern end of an interdunal depression in the Holocene Quindalup Dune System (Grey et al., 1990). It is a small triangular lake, with the longest, northern shore about 300 m in length. The lake is bounded to the east and west by longitudinal dunes, with a third dune located between the other two terminating at the southern end of the lake (Figs 2, 3). From the distribution of old shorelines visible on air photos, it seems the water body probably began as an interdunal lake cut off from the Indian Ocean, similar to the present day Lake Clifton and Lake Preston. However, the current configuration and situation of the lake appears more similar to that of the saline lakes on Rottnest Island (Playford and Leech, 1977; Playford, 1983), many of which probably occupy collapsed dolines in the underlying Tamala Limestone. Therefore, it seems likely that the present-day Lake Thetis is the northern remnant of a larger, originally linear, lake that infilled a sinkhole (Fig. 5). Details of the underlying regional geology can be found in Mory et al. (2005).

Lake Thetis is a permanent water body with a maximum water depth of 2.25 m. Although summer and winter lake levels only vary in the order of 50 cm, the gently sloping nature of the foreshore means that a strip of the southwestern shore up to 10 m wide can be affected. In winter, the stromatolite domes are often totally submerged; in summer, most of the platform is emergent. Local reports suggest that the lake level varies with tides through a subterranean connection to the sea, but this has not been substantiated by observation, and waterlevel variations are more probably related to seasonal rainfall. Winter squalls result in sheet-like runoff that carries large amounts of sediment and nutrients into the lake, and can raise the lake level very quickly. The amount of sediment in the lake is currently at greater than normal levels due to recent ground disturbances in the area.

Other than rainfall and ground water, there is no obvious surface drainage into the lake. In winter, the deflation basin surrounding the lake forms a marshy area, while a shell-grit quarry (now rehabilitated) to the north of the lake (Fig. 3) contains perched, ephemeral pools. The lakeshore mostly consists of a narrow platform, which drops steeply to a lakebed covered by a thick mat of purple sulfur bacteria overlying unconsolidated sediment. Various benthic microbial communities (BMCs) are found at different levels in the lake, on the platform, and on the marshy areas of the deflation basin (Fig. 6a,b).

The lake is surrounded by several carbonate terraces that represent former shorelines. Three distinct terraces can be identified around the lakeshore (Figs 7, 8), and there are traces of older shorelines on aerial photographs and oblique aerial views (Fig. 3). The lowest bench is permanently submerged, and probably developed as sea level fell following the post-glacial sea level rise. A lithified carbonate platform extends up to 10 m (Fig. 9) into the lake, where there is an abrupt change in slope to the unconsolidated floor of the central part of the lake (at 2–2.5 m water depth). The platform surface consists of

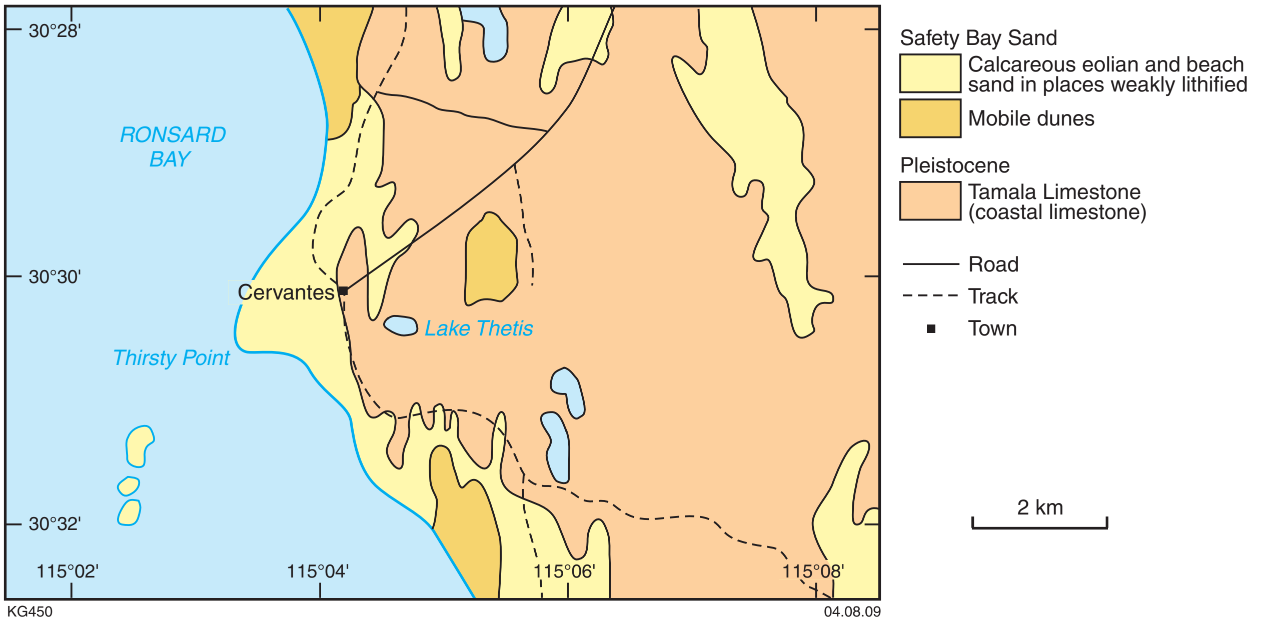

Figure 5. **Local geology near Cervantes and Lake Thetis (part of Wedge Island 1:100 000 sheet area; Mory, 1995) showing location on the Tamala Limestone and buildup of eolian beach sand at Thirsty Point. This is analogous to the development of Lake Richmond near Rockingham, another lake that probably formed in a collapsed doline and which also contains microbialites.**

an indurated crust (1–5 cm thick) that includes a massive white papillate to botryoidal surface layer (0.1 – 1.0 cm thick), and a fenestral cream-coloured lower layer (0.5 – 4.0 cm thick). The basal section is often green because of associated micro-organisms (Grey et al., 1990).

The lake is underlain by Middle Holocene shell beds containing abundant *Katelysia rhytiphora* Lamy 1935 (Fig. 10) and other bivalves (Grey et al., 1991). The shell beds outcrop in the quarry, and beneath the water tower in Cervantes. Serpulid tubes, sinuous calcareous shells produced by a species of marine worm, are also present in some parts of the quarry. Shells from the quarry gave a carbon-14 date of 5600 ± 260 years BP (Mory, 1995). This indicates that the shell beds are probably equivalent to the Vincent Member of the Herschel Limestone on Rottnest Island, which was dated at 4800 to 5900 years BP (Playford, 1988). As with other lakes on the Swan Coastal Plain, the Lake Thetis basin probably formed more recently than the Middle Holocene, at about 3000 to 4500 BP. The shell beds formed in a marine, shallow-marine tidal to intertidal environment, when the lakes were still open lagoons.

Climate

Climate statistics are available for the nearby localities of Jurien and Badgingarra (Bureau of Meteorology, 2008). Mean maximum temperatures range from 25–30°C and mean minimum temperatures from about 12–13°C. Summer maxima reach 40°C. Rainfall is about 540–550 mm, with only a few millimetres falling in summer months, and the heaviest falls occurring between June and August. The annual evaporation rate is considerably higher than the annual rainfall at about 1700 mm per year.

Prevailing wind directions are a significant factor in the distribution of the stromatolites. In summer, prevailing winds are southwesterly during the day with easterlies at night. In winter, gales are northwesterly. The prevailing wind direction causes considerable exposure to wave activity on the northern shore where mats and stromatolites are poorly developed, so that domical stromatolites are found only on the more sheltered southwestern shore.

Hydrology and water chemistry

Hydrology and water chemistry are significant factors in the formation of various microbialites in Western Australian lacustrine environments. As each lake has a unique set of characteristics, different types of mat, and therefore microbialites, have developed in each of the lakes (Moore, 1987).

A piezometer placed on the lakeshore near the current viewing platform in the 1990s showed that the surface water was fresh, and that no shallow groundwater fed into the lake. Lake recharge was a result of the flooding of these slight hollows, and then by surface flow into the lake.

In the lake itself, salinity readings vary seasonally from about 39 to 53 g/L, mainly as a result of high evaporation rates during summer months (Grey et al., 1990). The lake rarely shows signs of stratification in the upper part of the water column, possibly because of frequent agitation

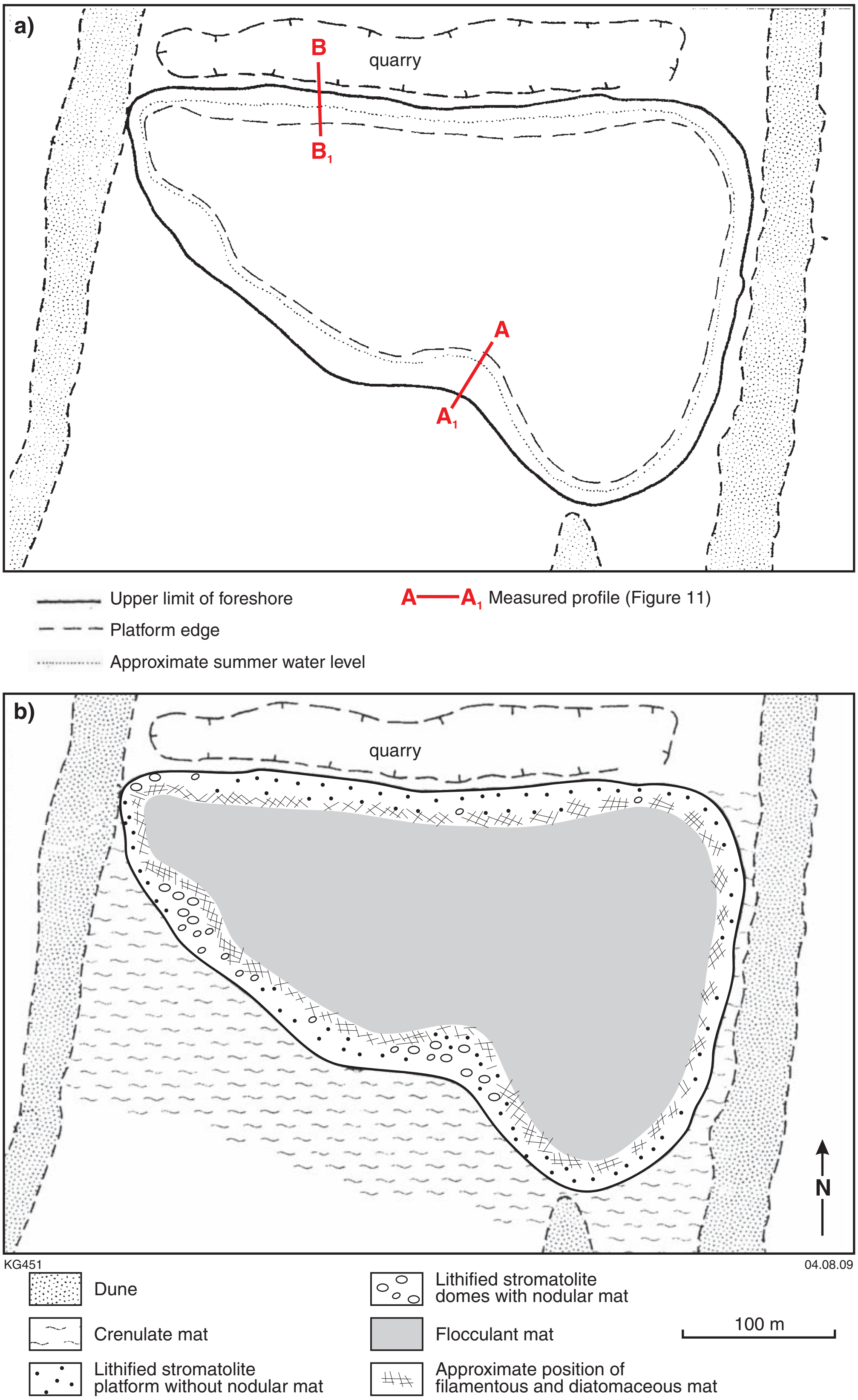

Figure 6. Lake Thetis: a) physiographic features, and position of measured profiles shown in Figure 8; b) distribution of microbial mat types and microbialites (after Grey et al., 1990).

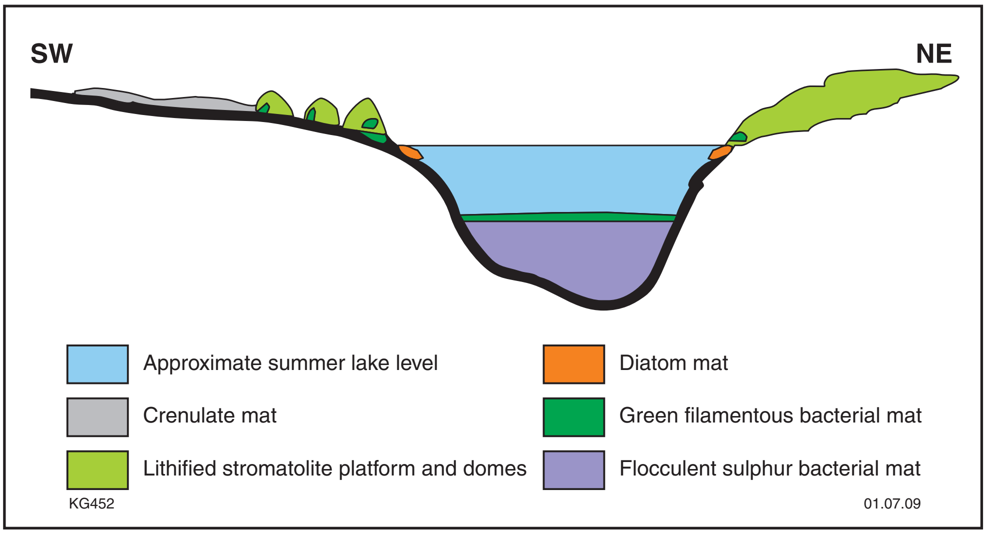

Figure 7. **Lake Thetis, diagrammatic profile showing distribution of benthic microbial community types (after Grey et al., 1990). Profile not to scale.**

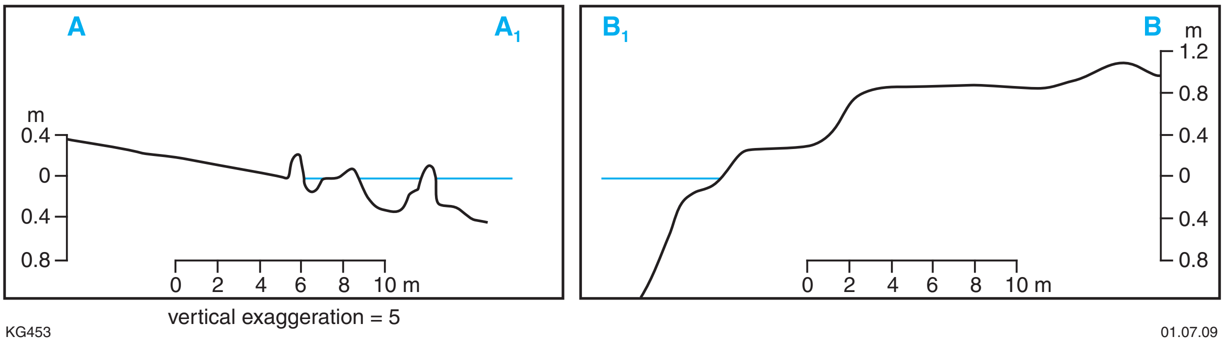

Figure 8. **Lake Thetis, measured profiles of southwestern shore (A–A_1), and northern shore (B–B_1). See Figure 6a for position of the sections (after Grey, 1990).**

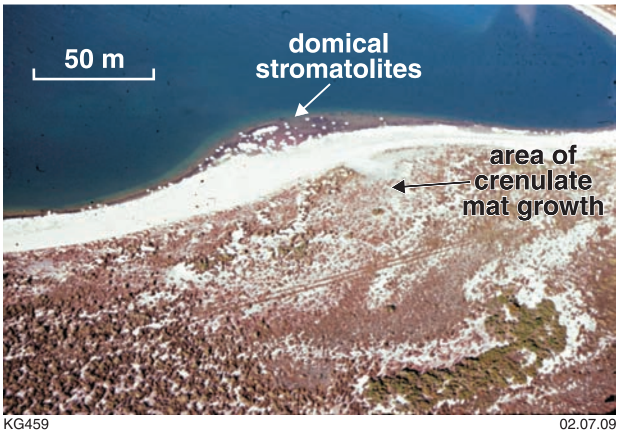

Figure 9. **Oblique aerial view of the southwest platform of Lake Thetis, circa 1990, showing both the domical stromatolites, and the old car park area where crenulate mat grows in winter months (arrowed).**

Figure 10. ***Katelysia rhytiphora* shell bed, as exposed near the lookout at the northeast corner of the lake.**

by strong winds, although the presence of purple sulfur bacteria on the lake bottom indicates anoxia in the lower layers near the sediment-water interface. Lake waters show slight calcium depletion, but otherwise, ionic proportions are similar to seawater (Grey et al., 1990). Total alkalinity (carbonate plus bicarbonate) is only slightly higher than standard seawater (0.5% meq/L). Lake Thetis is slightly more basic than seawater (pH ranges from 8.28 – 8.6).

Microbialites and stromatolites

Microbialites are defined as 'organosedimentary deposits that have accreted as a result of a benthic microbial community trapping and binding detrital sediment and/or forming the locus of mineral precipitation' (Burne and Moore, 1987). Therefore, microbialites are structures produced by a combination of the activities of organisms and sedimentary processes (Fig. 11). They are generally raised above the sediment surface, and are covered, or partially covered, by a thin mat of bottom-dwelling microscopic organisms. This microbial mat normally consists of a diverse array of bacteria with one or several types of cyanobacteria as the dominant primary producers (for example, see Planavsky and Ginsburg, 2009). Although cyanobacteria are sometimes referred to as blue-green algae, they do not have the essential features of true algae, which are eukaryotes, having a membrane-bound nucleus and organelles. Non-eukaryotic microorganisms, including cyanobacteria, belong either to the domain Archaea or Eubacteria, and lack both a membrane around the nucleus and organelles. Other types of bacteria present in the microbialite ecosystem include aerobic and anaerobic bacteria, and Archaea, which actively decompose the mat. Some true algae (mostly diatoms) are also present in the benthic ecosystem.

Most of the primary producers that contribute to microbialite formation are photosynthetic; that is, they use sunlight as their main source of energy and produce oxygen as a byproduct of their metabolic activities. Consequently, to obtain maximum light exposure photosynthetic microbes tend to migrate upwards through the mat, thereby increasing the height of the microbialite. Lithification takes place as a result of biomediation — a microclimate is produced around each organism, altering factors such as pH and temperature, and causing minerals that are near saturation levels in the surrounding water to be precipitated (Chafetz and Buczynski, 1992). In the Archean and Proterozoic, the production of oxygen by microscopic organisms was responsible for converting the previously unbreathable mix of greenhouse gases to our present breathable atmosphere. Cyanobacteria, like most leafy plants and green algae, use the pigment chlorophyll to trap incoming solar radiation. There are three types of chlorophyll: chlorophyll A is found in most photosynthetic organisms; chlorophyll B is found in leafy plants; and chlorophyll C in some green algae. Although cyanobacteria use only chlorophyll A, they have additional pigments, such as phycobilins, which give living cyanobacteria their characteristic, dark blue-green appearance. The active layer of a microbialite, referred to as a biofilm (Xavier and Foster, 2007), consists of mat-forming bacteria embedded in a gelatinous secretion known as extracellular polymeric substance (EPS). During periods of photosynthetic activity, the microbes push up through the accumulated layer of EPS, precipitate, and sediment to reach the sunlight (Fig. 11). In these layers the ratio of organic material to inorganic material is low, and the laminae appear light in colour. In periods of inactivity, the microbes colonize the surface and form a dense mat on which the next layer of minerals accumulate. The ratio of organic material to inorganic material is high in such layers, and they appear dark (Fig. 12). Although it is easiest to think of the light and dark layers as forming during the day and night respectively, the controls are not always diurnal, with seasonal controls or storm deposits occasionally of greater significance.

Bacteria, particularly cyanobacteria, play a crucial role in microbialite construction, although the role of algae in this construction is currently unclear. As mentioned previously, microbial metabolism causes small changes to the environment surrounding each organism, and can cause minerals, especially calcium carbonate, to precipitate (Castanier et al., 2000). The specific microbial processes that lead to carbonate precipitation can be examined by using carbon isotopes, as both photosynthesis and heterotrophic metabolic activities (organic matter remineralization) can induce carbonate precipitation. During photosynthesis, cyanobacteria preferentially take up carbon dioxide containing the lighter carbon isotope, ^{12}C. This carbon dioxide uptake increases the pH and induces carbonate precipitation, with the precipitate enriched in heavy carbon (^{13}C). However, the microbial communities also contain non-photosynthesizing bacteria that live on the decay products of the mats. When these bacteria degrade organic matter, the process is the inverse of photosynthesis and isotopically light carbonates are usually formed. Stated in another way, some of the inorganic carbon that combines with calcium to form the limestone in the latter case is derived from organic matter, which is depleted in the heavier isotope. The carbon isotopes of the Lake Thetis microbialites indicate that photosynthesis is driving the carbonate precipitation and stromatolite formation (Grey et al., 1990). By contrast, carbonate precipitation in stromatolites at Hamelin Pool, and in similar marine stromatolites from the Bahamas, is probably triggered by bacterial decay (Reid et al., 2000; Andres et al., 2006). The different styles of carbonate precipitation are probably a result of differences in the microbial communities.

Although the process of biomediated precipitation, as described above, is probably the most important mechanism for microbialite formation, especially in the fossil record (Kazmierczak and Kempe, 2005), in some cases coarse particles are instead trapped and bound by the mat. This trapping mechanism is particularly important at Hamelin Pool, where the highly mucilaginous mats trap and bind shell-grit and sand. By contrast, Lake Thetis provides a living example of predominantly precipitated microbialites, and as such, provides an important analogue for the abundant precipitated stromatolites of the Proterozoic.

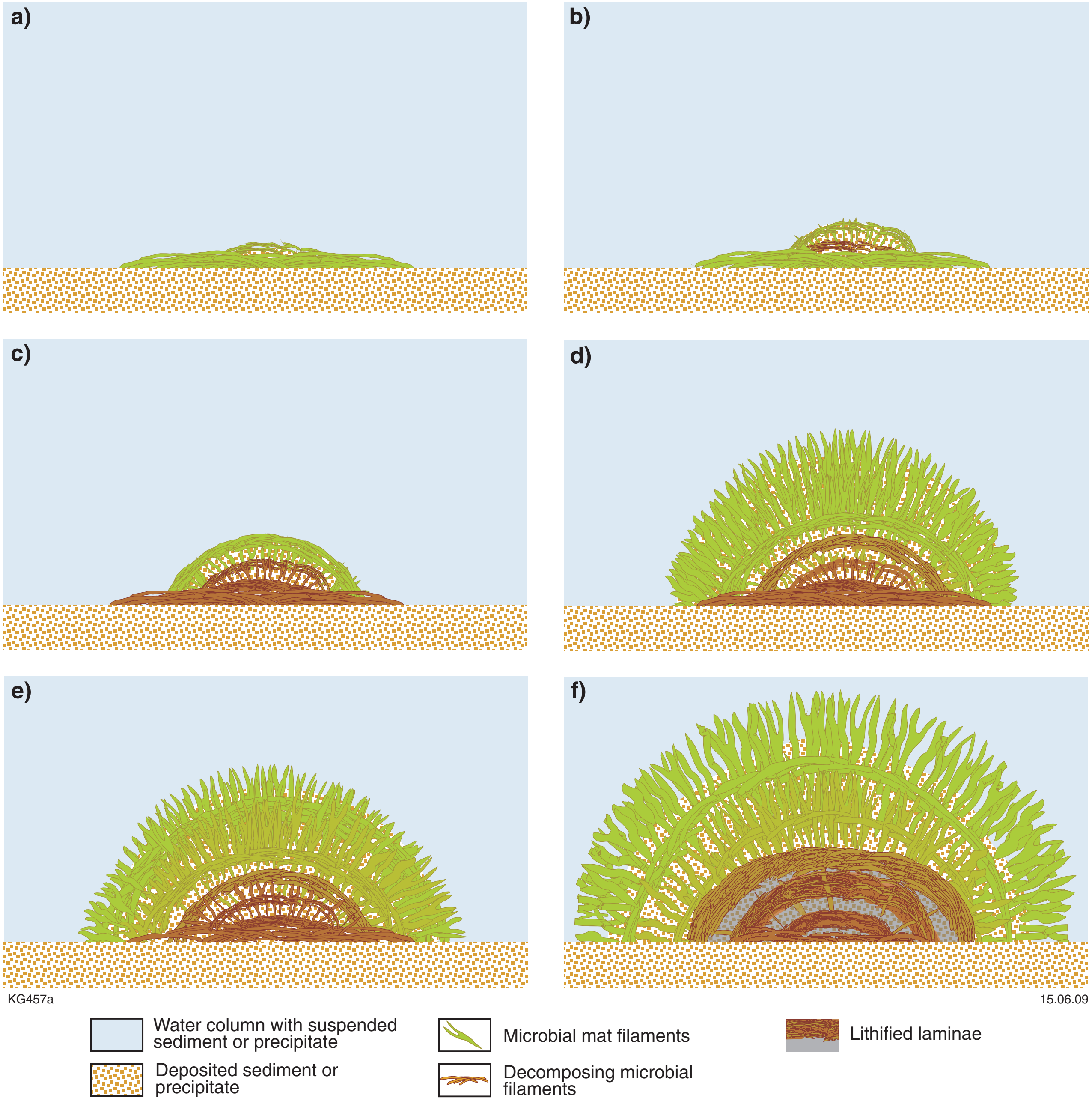

Figure 11. Simplified diagram of microbialite construction. Construction results from the interplay of deposition and microbial activity. At times of high activity (e.g. daylight), the microbes push up through the accumulated precipitate or sediment. At times of low activity (e.g. at night) the microbes form a dense layer parallel to the stromatolite surface. This gives rise to light and dark laminae, respectively. Lithification occurs after each layer is deposited and the microbes start to decompose; the deeper the layer, the fewer the traces of microbes. a) Unlithified mat develops into a small mound at the sediment–water interface; b) mat is covered by precipitate or sediment during a period of inactivity, with some microbes pushing up through the sediment layer to start to form a new microbe-rich layer; c) additional layers, alternately microbial-rich and microbial-poor, accumulate. At the same time, microbes in older layers die and decompose; d) microbes continue to push up through the uppermost layers of sediment to form a living mat at the surface; e) periods of high mat activity alternate with periods of reduced mat activity. For filamentous microbes this gives rise to a radiating pattern of vertical filaments interspersed with a layer of horizontal filaments. The alternating organic-poor and organic-rich patterns are retained as alternating light and dark laminae, even after mat closer to the core has died and decomposed; f) lithification takes place progressively as the layers accrete, so that in any one dome, there is commonly a core of lithified material with little trace of the original mat-forming organisms followed by several millimetres to centimetres of partially lithified laminae with some microbial traces, and finally an outer layer of unlithified sediment and living mat.

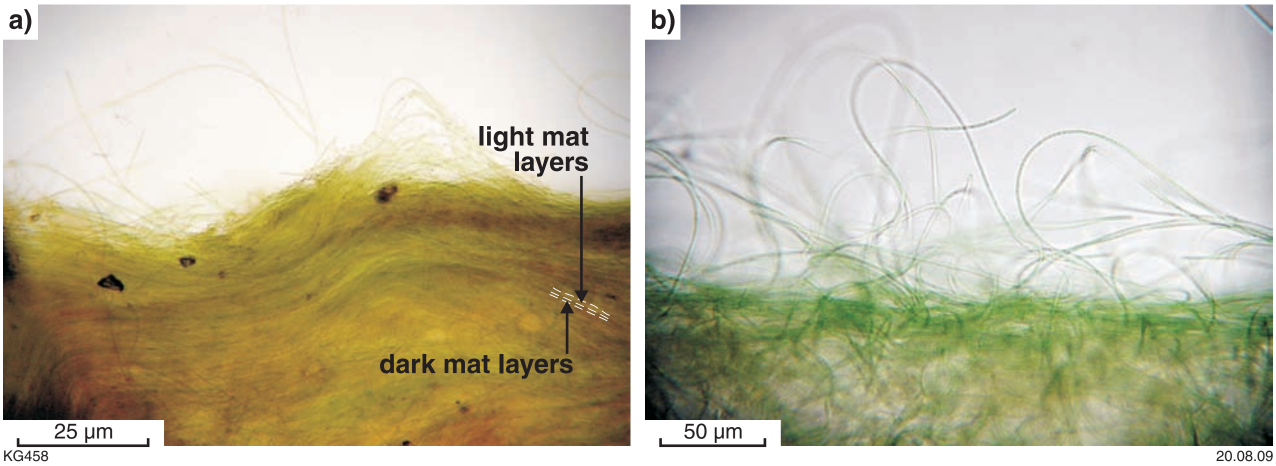

Figure 12. Wet mount of non-lithified microbial mat (genus *Phormidium*) showing typical alternation of dark and light layers formed as a result of the different level of activity: a) low magnification showing dark and light laminae (examples arrowed); b) higher magnification showing individual filaments and their orientation. Filaments are about 1 µm in diameter.

Four major groups of microbialites have been identified in the fossil record (Fig. 13): stromatolites (Kalkowsky, 1908), which are characterized by the presence of laminae; thrombolites (Aitken, 1967), characterized by the presence of clots (examples are found at Lake Richmond near Rockingham, and Lake Clifton south of Mandurah, Fig. 1); dendrolites (Riding, 1991), which have flame-like or shrub-like internal structures; and structureless forms known as leiolites (Riding, 1991). Thrombolites are mainly recorded from Cambrian or younger rocks. Dendrolites and leiolites are not very common in the geological record, with dendrolites apparently restricted to Cambrian and Ordovician rocks, and leiolites difficult to recognise. Most fossil microbialites are stromatolites, and they have a diverse range of shapes and laminar structures.

Lake Thetis, Hamelin Pool, and other Western Australian stromatolite-bearing lakes provide a living laboratory for studies of how stromatolites form and of the processes that have played a significant role in Earth's evolution.

Types of benthic microbial communities (BMCs) at Lake Thetis

In more favourable environments, eukaryotic flora and fauna are abundant, depleting prokaryotic populations through scavenging, grazing, burrowing, and by providing direct competition for resources and niches. However, the severe climatic conditions and high salinity at Lake Thetis combine to exclude many eukaryotic species from the lacustrine environment, and, because the eukaryotes are largely excluded, a diverse, primarily prokaryotic, benthic microbial community (BMC) flourishes in their stead (Figs 14a–h, 15a–f). Unlike domical microbialites, which are best developed on the southwest shore (Figs 6a,b, 7–9, 16), mat types are present in roughly concentric zones around the lake, reflecting a relationship to water levels (Figs 6a,b, 7). Five mat types have been recognized (Table 1), which vary in extent and significance

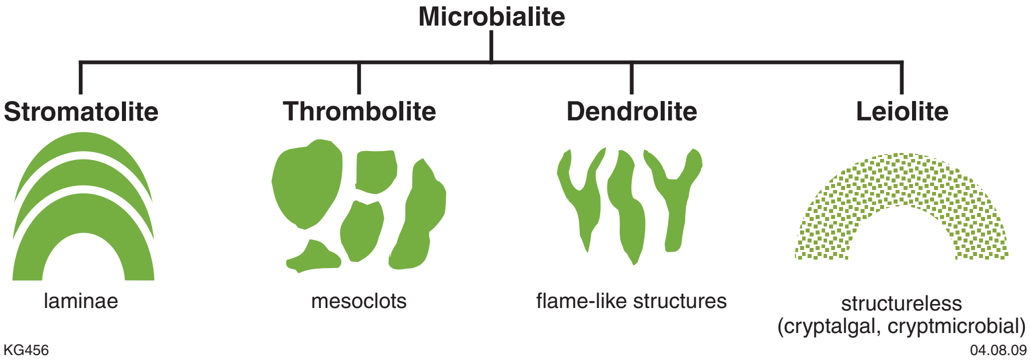

Figure 13. Types of microbialites. Stromatolites, with a laminated internal structure, are the most common in the geological record. Thrombolites, with a clotted fabric, are more time restricted than stromatolites and are found in some modern saline lakes. Dendrolites and leiolites (with a branching, flame-like microstructure or with no microstructure, respectively) are rare in the rock record.

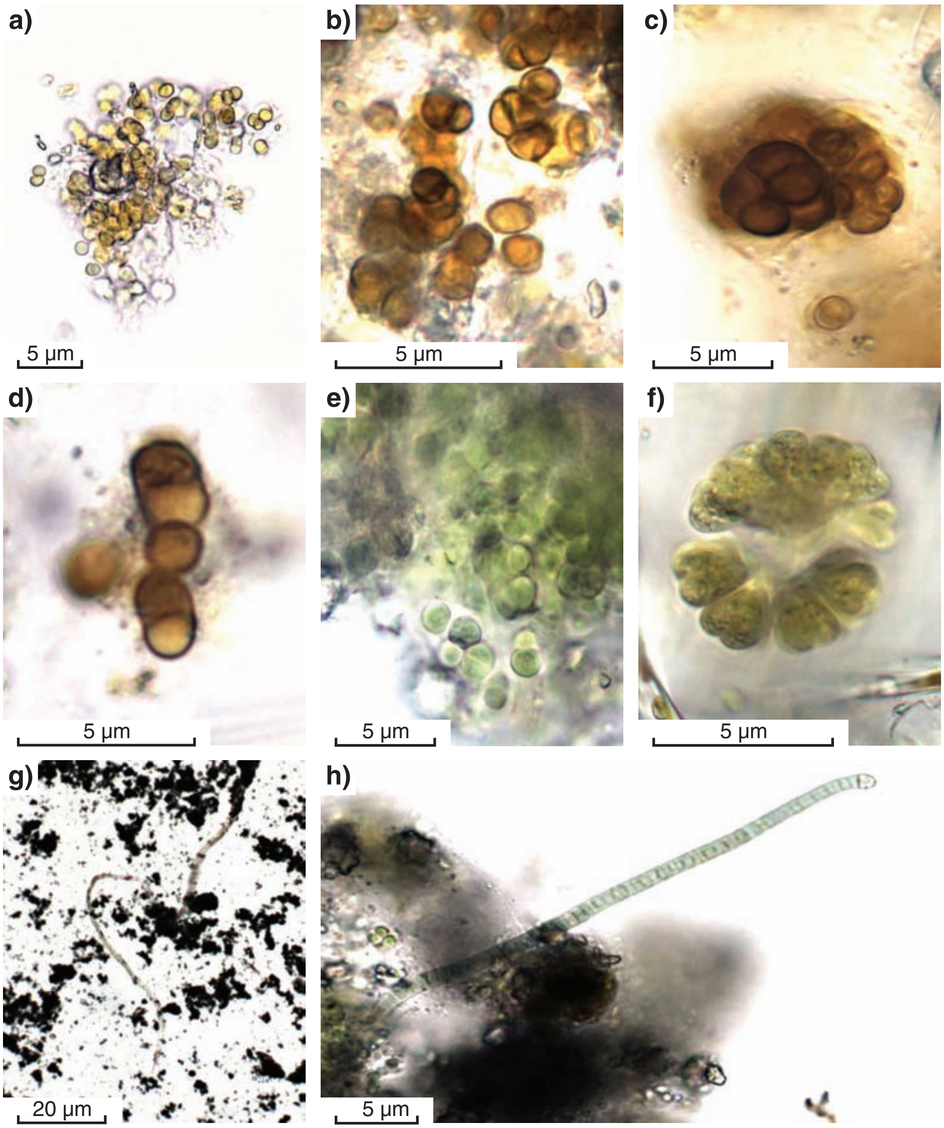

Figure 14. **Examples of microbial organisms found at Lake Thetis. All photomicrographs from wet mounts in water: a) *Entophysalis* sp., a chroococcalian cyanobacterium that forms much of the blue-black mat coating the domical stromatolites; b, c, d) details of coccoid bacteria, probably mainly *Entophysalis* sp. with some *Gloeocapsa* sp.; e) *Gloeocapsa* sp., at various stages of division; f) ?Gomphosphaeria salina Komárek and Hindák 1988, a cyanobacterium belonging to the order Synechococcales with linked radiating cells (rare); g) soil particles from the crenulate mat held together by poorly preserved, thread-like cyanobacteria, possibly *Calothrix* sp.; h) *Oscillatoria* sp., a filamentous cyanobacterium (rare in the nodular mat, but common in crevices and as a surface to the flocculant mat).**

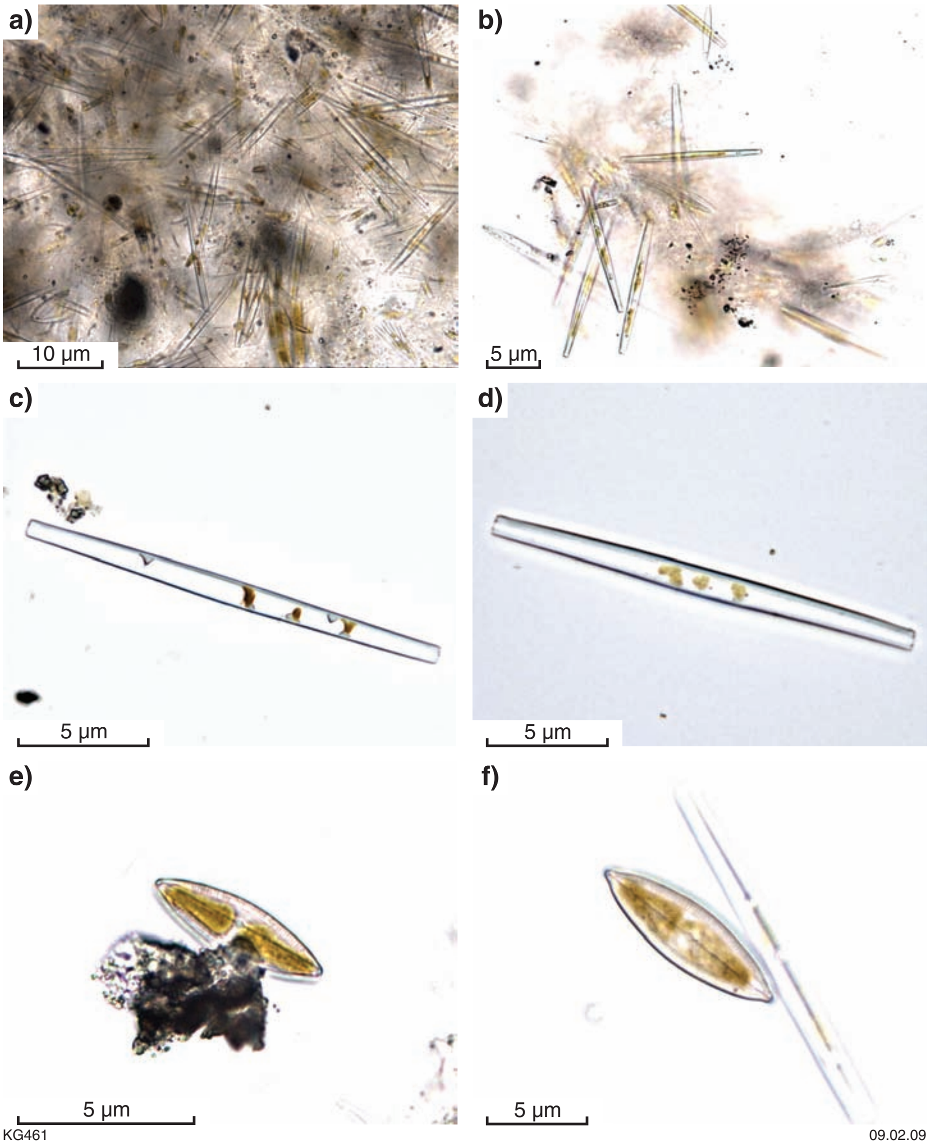

Figure 15. Examples of microbial organisms found at Lake Thetis. Diatoms from submerged surface area close to the nodular mat: a) dense mat of mainly pennate diatoms in mucilage (EPS); b) cluster of pennate diatoms with degraded cell contents; c, d) details of diatom frustules resembling the genus *Fragillaria*, with degraded cell contents; e, f) pennate diatom frustules resembling the genus *Navicula.*

throughout the year, changing mainly with lake level and temperature.

Crenulate mat (Fig. 17) is common on the high foreshore area, particularly in areas clear of vegetation that remain moist after the lake level has fallen. The mat develops during seasonal flooding, but is most active after emergence and as the weather starts to warm up. Thread-like filaments bind the sediment together and give it some cohesion (Fig. 14g). The surface lifts to form a reticulate pattern of ridges and blisters a few centimetres in diameter, probably as a result of trapped gas released from the decomposing mat below. During summer months, this mat dries out and becomes desiccated and friable. Bacteria of the genera *Calothrix*, *Scytonema*, and *Gloeocapsa* are commonly found in this mat type (Grey et al., 1990).

Nodular mat is found mainly on the sides of domical stromatolites (Fig. 18a,b), and is best seen in the splash zone, where it forms an almost black coating. It consists of aggregations of nodules (0.5 – 10 cm diameter) that produce the wavy laminae seen in vertical sections through the stromatolite domes (Fig. 19a,b). The mat consists mainly of coccoid cyanobacteria (Fig. 14a–e), including members of the genera *Gloeocapsa* and *Entophysalis*, which together appear to form nodular structures through microcrystalline carbonate precipitation, mainly within cyanobacterial biofilms composed of EPS (Grey et al., 1990; Reitner et al., 1996). Other micro-organisms are also present, but form a smaller percentage of the microbial population (Fig. 14f,h). In the outer parts of some domes, the nodular mat forms simple branching columns (Figs 20, 21).

Table 1. Characteristics of the five microbial mat types in Lake Thetis

Characteristics	*Crenulate*	*Nodular*	*Filamentous*	*Diatomaceous*	*Flocculant*
Location	High foreshore above HWL	Littoral – mid foreshore	Lower marginal shelf, permanently submerged	Marginal shelf, below 1.5 m	Permanently submerged
Substrate	Coarse, calcareous sand	Lithified stromatolite domes and reef; angular fragments	In microbialite cavities; below platey fragments on shore; top of flocculent mat	Lithified stromatolites and plates	Deep centre of basin
Microenvironment	Varies seasonally	Mainly restricted to splash zone	In cracks, underside of plates, and as a fragile benthic mat over flocculant mat	Restricted to 25–30 cm water depth	Surface approximates oxic / anoxic interface
Seasonal variation	Summer — desiccated Winter — damp	Changes in extent and relative position of mat with changes in water line	Very little	Movement corresponds to change in water depth	Occasional dispersion throughout water column and concentration at water's edge
Gross morphology	Reticulate ridges and blisters	nodules in clusters, irregular surface, abundant mucilage	Film and / or fragile coating	Mucilaginous coating	Gently undulating with distinct sediment–water interface when surface undisturbed: up to ~50 cm thick
Colour	Black to olive green	Black to grey–green	Bright green	Beige / brown/orange	Purple–pink with brown to blue–green patches on surface
Laminations	Alternating layers of organic–rich sediment and mud	Poor	None	None	None
Microbes (general)	Predominantly filamentous but some coccoid cyanobacteria	Coccoid cyanobacteria	Filamentous cyanobacteria	Diatoms	Filamentous and coccoid cyanobacteria, diatoms, purple sulfur bacteria
Genera present	*Calothrix*, *Scytonema*, *Gloeocapsa*	*Gloeocapsa*	*Oscillatoria*	–	*Oscillatoria*, cf. *Synechocystis*, cf. *Thiocystis / Thiocapsa*

SOURCE: after Grey et al. (1990)

Filamentous mat (Fig. 22) is present in areas of lower light penetration. It is found in cavities within the older subfossil portions of the microbialites, in secondary cavities, on the base of loose fragments, and on the upper surface of the flocculant mat. More rarely, it is found on the surfaces and sides of the deeper water microbialites. It is characterized by filamentous cyanobacteria (Fig. 14h) such as *Oscillatoria* and *Scytonema*. The latter is found mainly in cavities where the filaments are enclosed by fibrous aragonite.

Diatomaceous mat (Fig. 23) forms an orange–brown gelatinous band in the shallows, usually just below, or sometimes coating, the nodular mat. The lithified surfaces of many stromatolites are coated with abundant diatom frustules (Fig. 15a,b); particularly common are the rod-shaped (Fig. 15c,d) and spindle-shaped (Fig. 15e,f) varieties. The distribution of the diatom mat is probably tightly constrained by light levels, as it is nearly always about 25 cm below the water surface, and migrates to maintain this position as water depths change.

Flocculant mat (Fig. 24) is found on the floor of the lake beneath a layer of *Oscillatoria* filaments (Grey et al., 1990). It consists of carbonate mud, shell fragments, aragonite, and red–purple organic material composed mainly of purple sulfur bacteria such as *Thiocystis* and *Thiocapsa*. Silica is in places deposited inorganically as light-brown organic particles, containing traces of calcium, sulfur, and chlorine. Drill cores taken from the lake in 1985 (Grey et al., 1990) and again in 1995 (GSWA, unpublished data) indicated that the underlying lake floor includes irregular sandy laminae, and fine sand-sized irregular carbonate micronodules with purple layers of sulfur bacteria.

Types of microbialite at Lake Thetis

Both subfossil and actively forming hemispheroidal and cylindrical microbialites are present along the shallow lake shelf of Lake Thetis (Figs 9, 16, 18–21), and are estimated to have been forming for at least 2000 years (Grey et al., 1990). The subfossil microbialites are heavily eroded and exposed along the shoreline in summer months as a result of recent drops in the lake level. Although the


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Figure 16. Domical stromatolites exposed in summer months on the southwest platform (pre-boardwalk). The purplish colour in the water is sulfur bacteria mat washed up from the bottom of the lake; height of the domes approximately 50 cm.

exposed microbialites are fully lithified, they are fragile and readily damaged if walked on. The actively forming microbialites — marked by the presence of a calcifying mat (either filamentous or nodular) — are found on the shallow, semi-submerged platform around the lake margin. Most microbialites undergo complete emergence and submergence as a result of seasonal changes in lake levels.

In many microbialites, a gradual transition takes place from the well-laminated fabric (stromatolitic) at the top of the microbialites to an irregularly-clotted fabric (thrombolitic) at the base (Fig. 19a,b). Initial carbonate precipitation consists of fine-grained aragonite interspersed with abundant organic matter. Laminae are composed of dense layers of these fine-grained precipitates alternating with highly porous laminae composed of cyanobacterial cells with interspersed precipitate. Elongated voids (fenestrae) are present between some laminae (Fig. 19a). In some domes, the laminated carbonate forms columnar structures (Figs 20, 21) similar to columnar stromatolites present in the fossil record (Grey et al., 1990), but in most, the laminated carbonate forms as a gently convex cap on broader columns or domes.

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Figure 17. Crenulate mat on the high foreshore near the southwest platform of Lake Thetis.

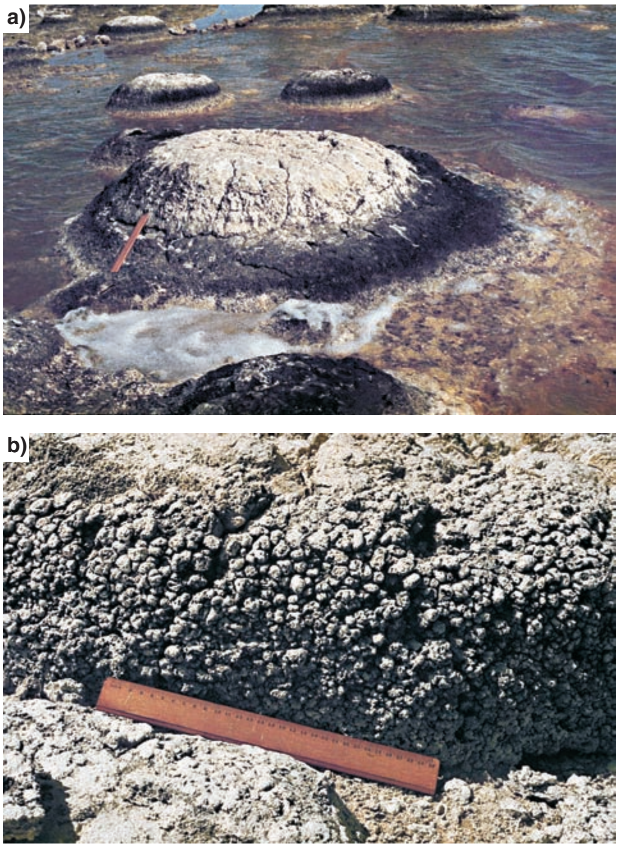

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Figure 18. a) Nodular mat on the side of domical stromatolites on the southwest platform of Lake Thetis. The position of the mat varies with the lake level; b) Detail of nodular mat on the side of domical stromatolites on the southwest platform of Lake Thetis. Ruler length 30 cm.

The lower, thrombolitic parts of domes have a clotted fabric consisting of irregularly shaped carbonate masses (which form the framework components) and large, enclosed void spaces. The clots are composed of fine-grained, extremely dense carbonate that typically has limited-to-indiscernible amounts of organic matter. It is difficult to distinguish distinct crystals in the dense carbonate, and the surfaces of crystals that can be detected are commonly pitted and irregularly shaped. The mesoclots have extremely low porosity due to the late-stage precipitation of abundant fibrous carbonate cement.

There is a continuous gradation between the two end-member fabrics of laminae and mesoclots (Fig. 19a). The transitional fabrics have limited amounts of organic matter and retain some of the porosity present in the microbialite mat. There are small amounts of late-stage fibrous cements. Carbonate crystals from the initial precipitates can be distinguished, but have indistinct crystal faces.

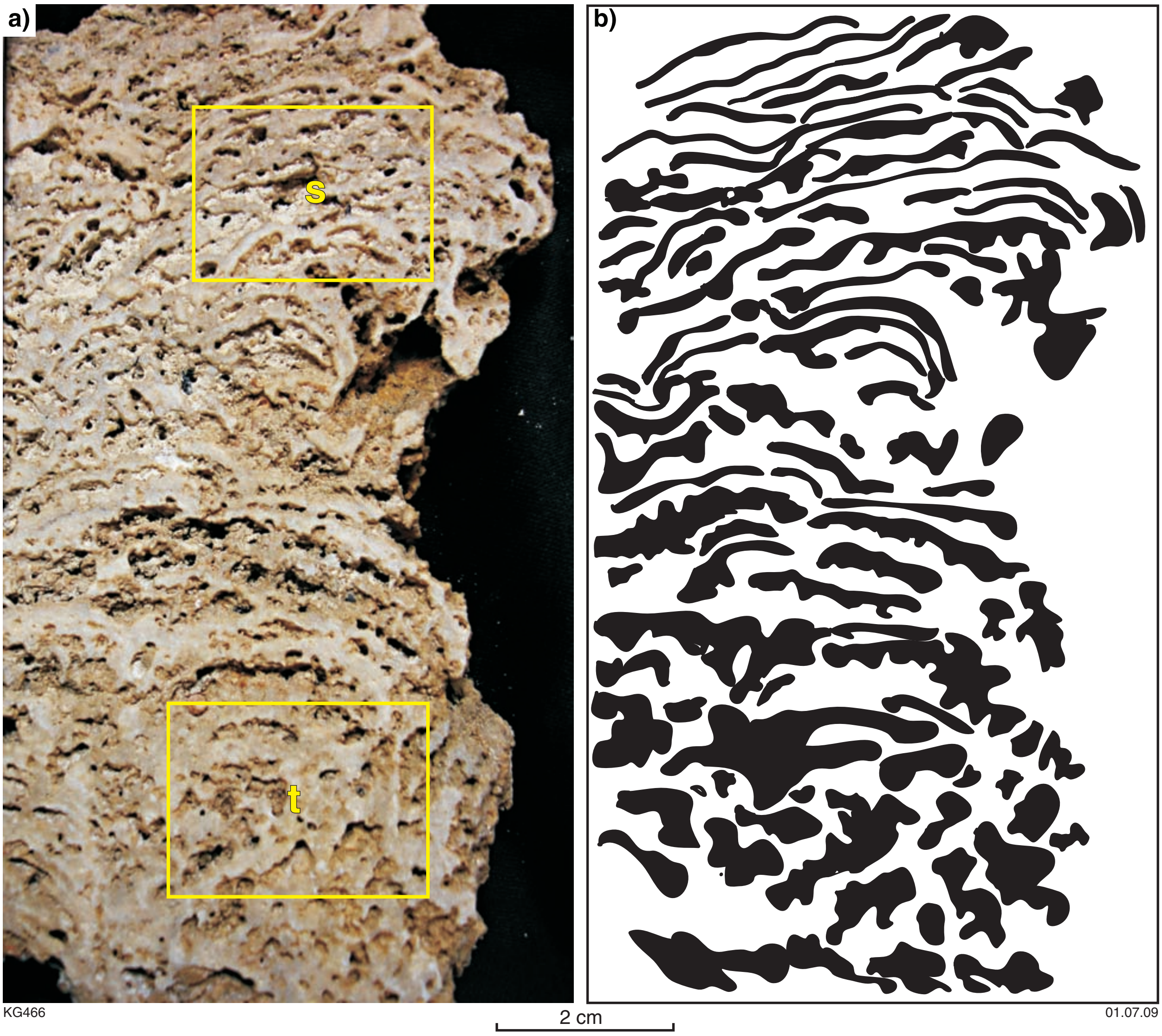

Figure 19. GSWA F 51453, vertical section through outer part of a dome from the southwest platform of Lake Thetis: a) the surface shows a transition from a well-laminated, stromatolitic fabric (s) to an irregular, clotted thrombolitic fabric (t); b) a map of the framework elements of the microbialite, specifically, the dense part of the lamination couplets.

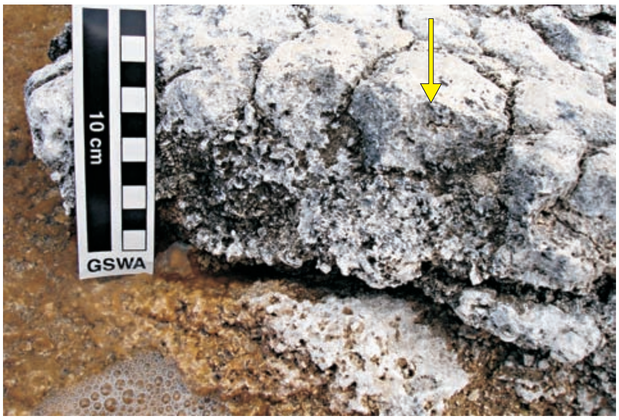

Figure 20. Formation of small columns (arrowed) on the upper part of domical stromatolites.

Figure 21. Simple branching columns in the outer (nodular) layer of one of the domical stromatolites, seen in vertical profile.

Many features of the Lake Thetis microbialites formed after initial carbonate deposition in the surface microbial mat. For instance, degradation of the surface microbial community causes the formation of irregular voids. These voids, and the initial porosity in the microbialites, are later filled by carbonate cement. Carbonate initially precipitated by the microbial mat undergoes recrystallization; this process forms the indistinct crystal faces that are present in the thrombolitic section of the microbialites.

The presence of fenestrae and voids in the lithified microbialites makes Lake Thetis a useful model for investigating Proterozoic hydrocarbon generation (Grey et al., 1990). The abundant sulfur bacteria colonising the lake bottom would be a suitable source for hydrocarbon generation, with smaller quantities of organic material contributed by the benthic microbial mats associated with the microbialites. Microbialites can be highly porous due to the presence of voids, particularly in thrombolitic areas that have not been secondarily cemented. Consequently, the microbialite buildup would act as a suitable reservoir for hydrocarbons. The crenulate mat, which binds fine-grained sediment on the lakeshore, forms an impervious layer, as can be seen by the way it ponds rainwater on its surface. Such a layer would act as a seal in a petroleum system. Paleoenvironments similar to that at Lake Thetis were probably more common in the Precambrian record (Kazmierczak and Kempe, 2005) than today, and this makes small, saline lakes like Lake Thetis important analogues for hydrocarbon exploration.

Field localities

Specific localities described below are shown in Figure 6a.

Locality 1: Base of water tower

The base of the water tower, located at the entrance to Cervantes, is now fenced off and largely inaccessible. The outcrop has been partially buried, but a few features are visible through the fence. A benchmark used for a traverse to the lake and a plane table survey (Fig. 8) lies at the base of the water tower (Grey et al., 1991). The tower is situated on a slight rise composed of rubbly limestone containing abundant fossil shells, mainly bivalves, and including the characteristic *Katelysia rhytiphora* (Fig. 10), which may still be found on the disturbed ground surrounding the tower. The shell bed indicates a shallow, marine, sandy bay environment that can be correlated with a similar horizon found beneath coastal lakes throughout the Perth Basin. Carbon-14 dating of shells from the water tower indicates an age of 5600 ± 260 years BP (Mory, 1995), making the site equivalent to the Middle Holocene Vincent Member of the Herschel Limestone on Rottnest Island, which has been dated at 4800 to 5900 years BP (Playford, 1988). The shell bed beneath the water tower is a few metres higher than the same unit in the quarry to the north of the lake, probably as a result of local faulting (Grey et al., 1991).

Locality 2: Quarry

The gravel quarry to the north of Lake Thetis (Fig. 3) has now been largely rehabilitated and fenced off, so that many of the features visible in the 1990s are now obscured by infill or vegetation. At one time, traces of the *Katelysia* shell bed were visible throughout the quarry and were found to contain a diverse assemblage indicating a former shallow marine, sandy bay environment. A piezometer located in the quarry in the late 1990s indicated a perched, fresh watertable and no obvious shallow groundwater runoff feeding the lake.

Locality 3: Quarry, northeast wall

A vertical section through the *Katelysia* shell bed used to be visible in the low wall at the northeast end of the quarry (Fig. 3). The bed contains abundant bivalves and dense clusters of serpulid worm tubes. The latter may be related to similar serpulid encrustations on Rottnest Island, which formed at the same time as the Vincent Member of the Herschell Limestone, when sea level was about 2.4 m higher than present, and which were dated at 5040 ± 290 BP (Playford, 1988). The section is now largely obscured as a result of burial of the quarried surfaces and rehabilitation of the quarry, although some fragments can be found in the rubble. Patches of the shell bed can be seen beside the track in the northeast corner of the lake, particularly near the northeast lookout.

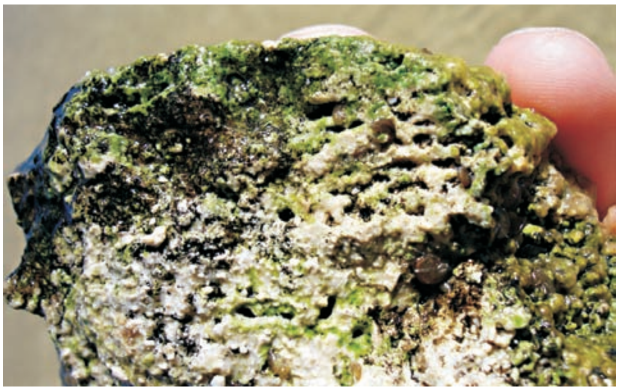

Figure 22. Filamentous mat on the under surface of a stromatolite fragment, southwest platform of Lake Thetis.

Figure 23. View of southwest and eastern (distant) shores (pre-boardwalk) with diatomaceous mat forming the dark line offshore (arrowed). At the time of photography, the diatom mat was close to the break of slope.

Figure 24. Flocculant mat of purple sulfur bacteria washed up on the southwest platform of Lake Thetis. Mound height approximately 50 cm.

Locality 4: View of lake and surrounds

The approach to the lake is at the northwest corner, and from the slightly elevated car park it is possible to see the triangular shape of the lake and the successive benches that form the northern shore (Fig. 8). The lake is about 2–3 m deep at its deepest point, and lake levels fluctuate seasonally. The water is usually turbid, so it is difficult to see the bottom beyond the platform. If water conditions are suitable, the sharp straight edge of the platform margin can be seen along the northern shore. This may indicate the wall of the collapsed doline.

Locality 5: Narrow lake platform with domical microbialites

As the boardwalk crosses the shoreline near the viewing platform, look to the northwest where the shore of Lake Thetis is characterized by the presence of elevated, mound-shaped microbialites (Figs 9, 16, 18–21, 24). This is also a good point to examine the seasonal variation in lake level. In winter months, the water sometimes reaches the base of the vegetation surrounding the lake, leaving little of the shoreline or living microbialites visible. In summer, the lake level drops nearly to the edge of the platform, and the mound-like microbialites are exposed, mainly along the southwestern shore (Figs 9, 16). When conditions are suitable, a thin line of orange diatom mat is visible bordering the lake near the water's edge (Fig. 23; see Locality 6).

Most of the domical structures have eroded tops as a result of wave activity, and in some cases the centres are eroded down to an older, inner core (Fig. 24). The domes are mostly about 1 m in diameter, but range overall from about 50 cm to nearly 2 m in diameter. The outer margins are near vertical, although some domes have a break of slope near the base and can be seen to be sitting on a wider, older base (Figs 8, 16, 24).

Where the top of the dome is preserved it tends to be nearly flat; however, most domes are partially eroded, and have a hollow centre, allowing the two-fold nature of the microbialites to be observed (Fig. 24). Where exposed, the inner core has a slightly domed, but fairly smooth surface and tends to be thrombolitic (composed of mesoclots; Fig. 19a,b). The younger, outer rim has a much rougher surface, and is often nodular (Fig. 18b). In some eroded domes, this outer rim is formed by laminated stromatolites (Fig. 19a,b) with incipient columns that may be up to 5 cm high (Figs 20, 21).

The columns in Lake Thetis microbialites occasionally branch (Fig. 21), although this branching is of a very simple, dichotomous type, especially when compared to the high degree of complexity seen in some fossil stromatolites. Branching is a common phenomenon in fossil stromatolites, particularly Proterozoic ones, which can show highly complex branching patterns. However, even simple branching is a feature seen only rarely in modern microbialites. The controls on microbialite branching are not understood, but there is some evidence that branching is a response to shifting microbial-versus-sedimentary control on stromatolite morphology (Planavsky and Grey, 2007). Branching Proterozoic stromatolites show consistent patterns in column diameter and branching mode that lie within narrow ranges of variation, features suggestive of some form of inherent biological control. Therefore, the Lake Thetis branching microbialites are an important modern analogue that requires further study to allow better understanding of a common feature of fossil stromatolites.

Locality 6: Diatom band

The diatom band is usually close to shore at this point and consists of a narrow orange band about 25 cm below the water surface (Fig. 23). The band migrates with changing lake levels, and is presumably dependent on the amount of light penetration. The band tends to be most obvious in the summer months when water temperatures are higher. The mat is highly mucilaginous and consists of stalked diatoms. Diatoms are a common component of the lake sediment and can be present in large numbers on microbialite surfaces if conditions are favourable (Fig. 15a–f). At times they appear to be a whitish, slimy coating, but are rarely as well developed as at Hamelin Pool, where they can give the microbialites the appearance of being coated in white, sandy sediment.

Locality 7: Viewing platform

The best development of domical stromatolites can be seen to the southeast of the viewing platform, where the carbonate platform broadens out along the southwest shore (Figs 6, 9, 16, 24). The older generation of microbialites are visible as slightly raised, flattened, tabular mounds. Taller, more rounded domes have developed on top of the platform. Like those elsewhere along the southwest shore, they have an older, smooth-surfaced, thrombolitic core, possibly marking an erosional level from a previous still-stand. This is overlain by a younger rim with a nodular surface and some branching developed.

Sediment input has recently increased as a result of tourist facility upgrades and some domes are currently obscured by sandy sediment (Fig. 25). Normally, dry surfaces are white and hard with no obvious mat, but living cyanobacterial mat can be seen on wet surfaces, forming a black to dark blue-green layer that is only a few millimetres thick. Surfaces become dark and slimy when wet, as can be observed on days when the onset of the afternoon sea-breeze generates waves that splash against the sides of the domes.

Filamentous cyanobacteria (Oscillatoriaceae) are often present on the under surfaces of broken fragments of microbialites sitting on the platform, and in cavities within the domes, wherever light penetration is reduced (Fig. 22). This filamentous mat is also present as a thin layer above the flocculant mat found in the middle of the lake and on microbialites present in deeper portions of the lake shelf.

Locality 8: Crenulate mat

A small embayment in the vegetation just opposite the viewing platform marks the site of an old parking area. This area, plus other hollows adjacent to the lake, floods during winter months. Lake levels sometimes reach these points at maximum flooding, but they are more commonly filled by a few millimetres of ponded rainwater, providing sites for the development of ephemeral crenulate mat (Fig. 17). A dark blue-green mat of sparse filaments grows on the mud at the bottom of the pond and the mud may remain moist well into the dry season. The mat gives the

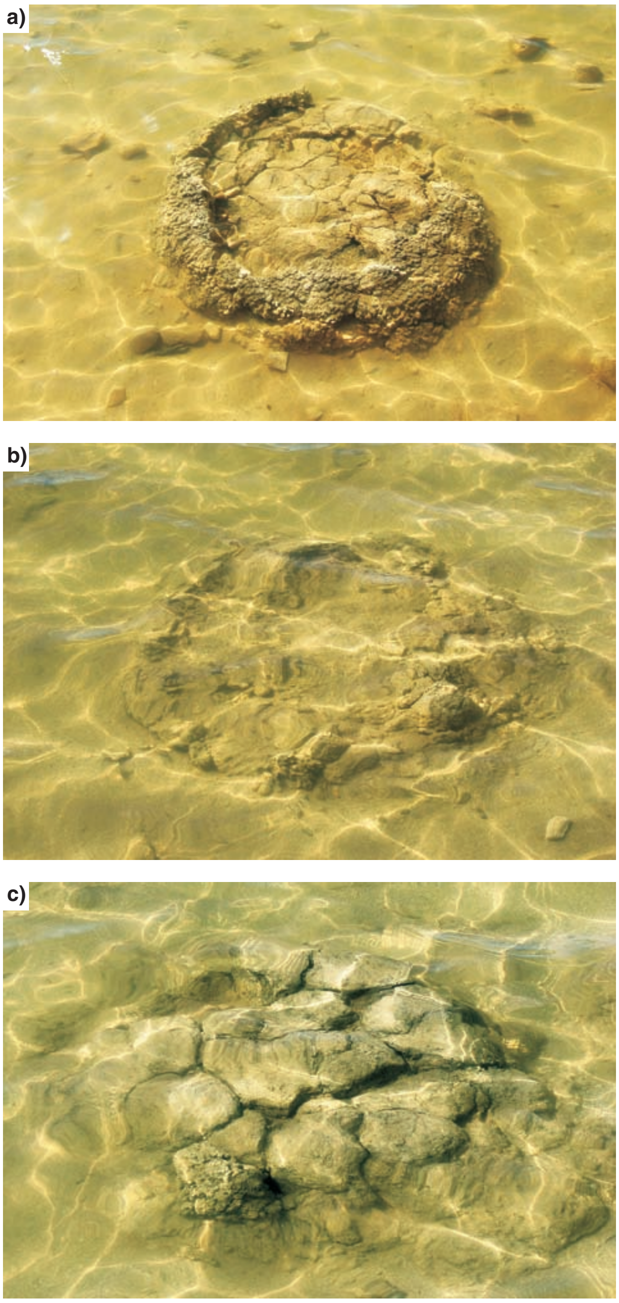

Figure 25. Microbialites partially buried by recent sediment influx; for emphasis, compare part a) with Fig. 18, and part b) with Fig. 24. All examples are from the southwestern shore of the lake.

muddy substrate cohesiveness, and the surface becomes wrinkled and blistered through the accumulation of gases below the mat. The blisters are hollow and covered by a cap of laminated mat. This mat usually dries out in summer months and may disappear completely, although traces of the mat may remain for many months. In winter, squalls can cause rapid flooding of the more impermeable mat surface developed in the hollows which surround the lake.

Because the land surface slopes steadily towards the lake shore, runoff from the vegetated areas likely carries sediment and nutrients that sustains the flocculant mat on the lake bottom.

Locality 9: Old lakeshore

The gap between the dunes to the southwest marks the site of the original, more, extensive interdunal lake, which the topography suggests was similar to the present-day Lake Clifton and Lake Preston. The lake dried out in a series of still-stands marked by older shorelines that are visible on air photos and Google Earth, and as benches around the northeastern and northern lake shores (Fig. 3). However, there is little trace of these shorelines visible on the ground because they are obscured by wind-blown sand and revegetation projects. The area occupied by the current lake is probably deeper than the interdunal lake because it appears to occupy an old sinkhole that now forms a collapsed doline in the underlying Tamala Limestone.

Locality 10: Northeast lookout

As the northeastern and northern shores are slightly more elevated than the southwestern shore, the lookout provides good views across the lake and along the northern shore. This shore consists of a series of benches that are formed by microbialite terraces, indicating at least three previous lake levels (Fig. 8). The terraces are weathered and partially overgrown, but the outlines of microbial domes are still traceable.

Locality 11: Terraces and linear microbialites

Where the track approaches the northern lakeshore, the lowest terrace is seasonally submerged and the microbialites are coated by blackish to blue-green living mat. The microbialites tend to be coalesced, and form elongate mounds parallel to the shoreline. Unlike those on the more-sheltered southwest shore, these microbialites do not form discrete domical structures, and there is no evidence of branching. It is possible that the higher wave energy of the northern shoreline limits the development of the mat, and prevents the development of features typical of the southwestern shoreline.

Locality 12: Bottom of lake

The deeper part of the lake is filled by a flocculant mat of purple sulfur bacteria topped by a thin layer of green filamentous bacteria. The mat is not normally visible except through the use of scuba gear, due to a lack of water clarity. Two weight belts are usually required to reach the bottom because of the high salinity. Periodically, the lake overturns, either as a result of high summer temperatures that set up a conductive flow pattern, or as the result of a severe storm. When this happens, the flocculant mat is brought to the surface and washes up on the shore, turning the shallows bright purple (Figs 16, 24).

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Appendix

Systematic citations

In this field guide, scientific names (genera and species) are quoted without their systematic citations; that is, without the linked citation stating the author(s) of the taxon in question. For the sake of completeness, a list of these citations is presented here. However, as these names refer to the authors of taxa, not references, they are not necessarily included in the reference list. Most of the citations listed below are sourced from the following two publications:

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