CHAPTER 3: MOUND SPRINGS IN THE ARID LAKE EYRE SOUTH REGION OF SOUTH AUSTRALIA: A NEW DEPOSITIONAL TUFA MODEL AND ITS CONTROLS

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Abstract

The mound springs of the Lake Eyre South region of South Australia are rare but prominent, dome-shaped accumulations of largely $CaCO_3$ deposited by artesian springs. Despite similar formations being found worldwide, few intensive studies of the formation and ongoing evolution of these structures exist. In this study, samples from a selection of active mound springs were subjected to petrological and Scanning Electron Microscopy (SEM) techniques to gain insight into mound spring morphology. Additionally, microcosms containing three types of artificial substrate (marble, glass and copper) were placed within active mound spring environments to aid determination of the rate, spatial extent and the influence of microbial activity on carbonate precipitation. Finally, water samples from spring vents were analysed for water quality and major ions. Carbonate deposits were interpreted to be largely plant or microbial tufa. From the microcosms, thrombolitic-textured micrite was deposited on only the marble and glass substrates and only within spring tails distal from vents. Precipitation rates from the microcosm experiment of between 0.15 and 1.6 kg m^{-2}/year are similar to rates observed at cyanobacteria-associated, low-energy,

carbonate-depositing environments. These results suggest that tufa precipitation is linked to the development of extracellular polymeric substances. Conversely, it was interpreted that emergent springwater is calcite under-saturated based on water chemistry analyses and marble dissolution proximal to spring vents. A number of factors important to the formation of mound springs were determined; including the role of bio-mineralisation and hydrophytes in mound construction and the implications for time-limited and spatially dynamic precipitation on spring flow.

3.1 Introduction

3.1.1 Mound spring structures

The term "mound spring" is used to describe prominent, dome-shaped, freshwater deposits of spring carbonates and/ or clastic sediments associated with groundwater discharge within the GAB (Williams and Holmes, 1978). In the Lake Eyre South region in the south western corner of the GAB (Figure 3.1), mound springs are composed predominantly of spring carbonate (Habermehl, 1982; Williams and Holmes, 1978); similar structures found internationally are referred to as spring mounds (e.g. Crombie et al., 1997; Linares et al., 2010; Pentecost and Viles, 1994).

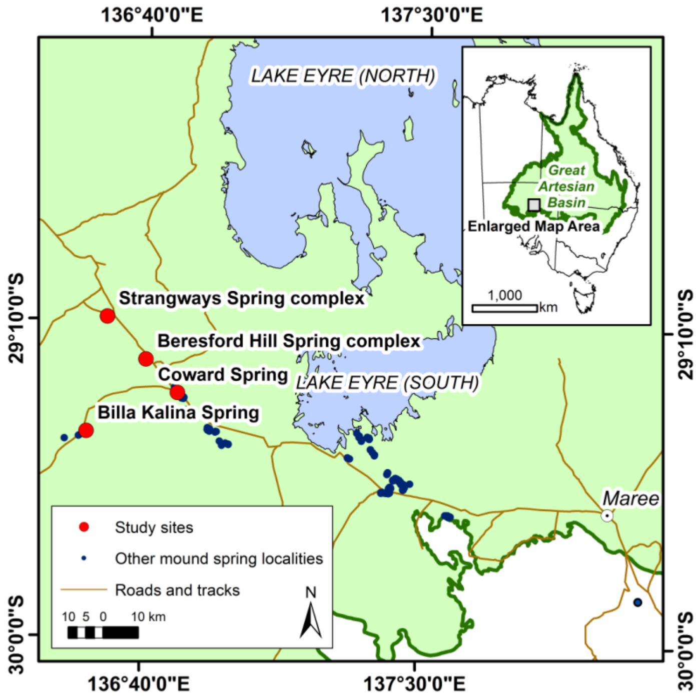

Figure 3.1: Locality map of study sites.

Despite previous references to GAB mound springs in the international literature (e.g. Ford and Pedley, 1996; Kerr and Turner, 1996; Mudd, 2000; Pentecost, 2005), a paucity of detailed description remains. Additionally, there are few local reports providing descriptions of mound spring sediments (Beal and Williams, 1984; Forbes, 1961; Radke, 1990). Indeed, there are few detailed studies of similar features found internationally (Linares et al., 2010; Pentecost, 2005; Pentecost and Viles, 1994).

Understanding the formation and evolution of spring carbonate mound springs is important for a number of reasons, including as a potential source of data for palaeohydrology, palaeoclimatology and neotectonic studies (e.g. Andrews, 2006; Hancock et al., 1999; Miner et al., 2007). Further, similar features have been identified on Mars and therefore mound spring morphologies may serve as terrestrial analogues for studying Martian palaeohydrology (e.g. Bourke et al., 2007). Finally, the preservation of mound springs, which hold great cultural and ecological importance (e.g. Ah Chee, 2002; Leek, 2002; Ponder, 2002) requires in-depth knowledge of their life-cycle.

Current interpretations concerning factors important to mound spring formation and extinction include the review by Linares et al. (2010), who found that for a mound structure to form, a flat topography is necessary to allow carbonate-precipitating waters to pool around the spring conduit. Mabbutt (1977) and Reeves (1968) postulated that the hydrostatic head and its relationship to spring flow are important to mound formation. Bourke et al. (2007) and Pentecost (2005) considered this relationship to be a limiting factor, with flow rate and mound accumulation slowing with continued mound construction. Pentecost (2005) also hypothesised that the relative carbonate saturation of springwaters has an important influence on mound geometry, with high and steep mounds reflective of high calcite saturation and flatter mounds a product of springwaters closer to equilibrium. Kerr and Turner (1996) used tank-based experimentation to postulate that mound morphologies are dependent upon precipitate-crystallisation triggered by super-saturation and that rising temperatures within water trapped and insulated in the mound crater eventually leads to mineral under-saturation. This water then dissolves part of the mound to form a gutter-like break-out. A number of authors considered that a significant temperature difference between emergent springwater and ambient surface conditions is necessary for mound formation, as this provides a means with which springwater becomes supersaturated with carbonate (Bargar, 1978; Goldenfeld et al., 2006; Kerr and Turner, 1996; Pentecost and Viles, 1994).

Past hypotheses are based on relict mound structures (e.g. Akdim and Julia, 2005; Brookes, 1993; Crombie et al., 1997; Linares et al., 2010), artificial re-creations of mounds using Na_2CO_3 rather than $CaCO_3$ (Kerr and Turner, 1996) or mounds formed in hot-spring (thermogene) environments (e.g. Bargar, 1978; Goldenfeld et al., 2006; Hancock et al., 1999; Pentecost and Viles, 1994). Of these cases, the mounds described in Linares et al. (2010) most resemble those found in the Lake Eyre South region, but due to their fossiliferous state, cannot be used to describe formational factors related to spring flow and water chemistry. The use of Na_2CO_3 as an analogue for $CaCO_3$ in the experiments of Kerr and Turner (1996) is a limitation, given the different thermodynamic properties of these two minerals. Finally, comparisons with mounds formed in thermogene spring environments are also restricted due to the necessarily large differential between springwater and ambient temperatures required.

3.1.2 Spring carbonate classification

The terminology used to classify spring carbonates in the international literature is diverse (Jones and Renaut 2010). Much of this diversity stems from debate as to whether division should be based on the emergent temperature of springwater compared to the ambient temperature, or to the temperature of springwater at the point of precipitation. However, the spring carbonate facies and morphotype classification system by Ford and Pedley (1996) is the most commonly cited (e.g. Arenas et al., 2000; Carthew et al., 2003; Forbes et al., 2010; Jones and Renaut, 2010; Ozkul et al., 2010; Viles et al., 2007) and so has been adopted here. Ford and Pedley (1996) distinguished travertine as a highly crystalline carbonate consisting of thin laminae and shrub-like microbial accretions precipitated from thermogene springwater, whereas tufa is described as a fine-grained micritic carbonate with textures highly influenced by microbial activity, precipitated at ambient and sub-ambient water temperatures. They further refined the facies classification of tufa based upon formational process, sedimentological criteria and petrologic features. Morphological classification was based upon variations in deposition related to the substrate. Classifications included a) fluvial tufa encompassing barrage dam formations in streams, b) perched spring-line tufa consisting of high-angle, lobate deposits and more distal, sheet-like deposits, c) lacustrine tufa and d) paludal (swamp) tufa deposited in low-angle, poorly drained areas.

This study employs a combination of facies description, experimental data and water chemistry to test assumptions concerning mound spring formation and to determine if other factors require consideration. Additionally, information concerning the spatial extent and the depositional rate of modern mound spring carbonates is provided. Finally, the findings are discussed in relation to the facies and morphotype end members described by Ford and Pedley (1996) to place these structures into context.

3.2 Study Area

3.2.1 Regional geology and hydrogeology

The GAB is Australia's largest artesian basin, covering approximately 1.7 million km^2 of the Australian landmass (Habermehl, 1980) (Figure 3.1). The GAB is composed of a series of transgressional alluvial, fluvial and marine sequences deposited during the Jurassic and Cretaceous periods (Krieg et al., 1995). The aquifer units within the GAB most pertinent to this study include an inter-layered siltstone and sandstone called the Cadna-owie Formation and coarse-grained, unconsolidated sandstone with conglomerate bands named the Algebuckina Sandstone (Wopfner, 1972; Wopfner et al., 1970). The confining unit for the main GAB aquifer is a predominantly grey marine shaly Cretaceous mudstone called the Bulldog Shale (Freytag, 1966). The hydrochemistry of the GAB has been the subject of a number of studies (Radke et al., 2000). Those pertinent to this study are summarised below:

Jack (1923) was the first researcher to note that GAB groundwater has two potential sources; a highly alkaline groundwater originating from the eastern sea-board of Australia and a sulphate-rich groundwater from central Australia. Herczeg et al. (1991) suggested that groundwater hydrochemistry evolves along flow lines that are characterised in the east by increasing TDS caused by water-rock interactions including carbonate dissolution. Western groundwater hydrochemistry was interpreted to be affected by evaporite dissolution; however, Love et al. (2000)

determined that most solutes were concentrated by evaporation and diffusion of salt from overlying saline aquitards. Torgersen (1994) estimated residence times of between 900,000 years and 1.5 million years using ^{36}Cl data for groundwater flowing from the eastern recharge areas, while Love et al. (2000) estimate groundwater velocities from the western recharge areas of approximately 0.24 +/- 0.03 m/yr. Finally, Lehmann et al., (2003) estimated residence times of between 200,000 and 400,000 years using ^{81}Kr data for groundwater flowing from the western recharge areas.

3.2.2 Climate and hydrology

The study area is situated within an arid climatic zone; the mean annual-average temperature for the nearest town (Maree) is 24°C, while the average rainfall is approximately 125 mm/year, with rainfall predominantly sourced from sporadic, weak, winter-dominated events (Allan, 1990). Average pan evaporation rates for the nearby Cooper Creek system have been calculated at 2,500 mm/year (Hamilton et al., 2005).

The surface drainage for the study area is predominantly to the east towards Lake Eyre South. The topography of the region is minimal, with variations commonly provided by sand dunes, drainage channel incision and the buttes and mesas of extinct mound springs.

3.2.3 Fauna and flora

Common native aquatic fauna genera that occur within the mound spring environments and may therefore be found as bioclasts include two hydrobiid gastropod genera *Fonscochlea* and *Trochidrobia,* the amphipod *Afrochiltonia*, the isopod *Phreatomerus latipes* and the ostracod *Ngarawa Dirga* (Ponder, 1998; Tap and Niejalke, 1998).

Large parts of mound spring-supported wetlands are densely vegetated (Figure 3.2A and 3.2B); the most common genera include the reeds *Phragmites australis* and *Typha*, the sedges and rushes *Cyperus, Baumera, Fimbristylis, Gahnia* and *Juncus,* and the grasses *Sporobolus* and *Distichlis*. Additionally the samphires *Arthrocnemum, Haloscaria* and *Sarcocorni* grow in highly saline environments associated with mound springs (Fatchen, 2001a; Holmes et al., 1981; Lange and Fatchen, 1990).

3.3 Methodology

3.3.1 Fieldwork

Forty-nine specimens of rock and soil material were collected from four mound spring localities between June 2008 and August 2009. These localities were the Beresford Hill Spring complex including Warburton (water sample prefix WSL) and Beresford Springs (LBSL); Billa Kalina Spring (MSL), Coward Spring and the Strangways Spring complex (SSL) (Figure 3.1). Most samples originated from the former two sites. Field notes taken during mapping and sampling may be found in Appendix 2.

Figure 3.2: Morphology of mound springs. A) Mound structure at Billa Kalina Spring. Note the mound structure is approximately 2 m high; outer layer of mound is composed of lobate ooidal phytoherm tufa (a). Mound pool (b) has a thick growth of *Phragmites.* B) Typical vegetation coverage within upper and middle reaches of mound spring wetland. The microcosm is visible at the centre of the photograph. Warburton Spring, sample site WSL5. C) Photo-composite of the spring pool at Warburton Spring. Note the gap between top of the mound and the spring pool water. The vegetated area at the center of the mound is approximately 24 m in diameter. D) A break-out incised into a mound structure, Billa Kalina Spring. E) Close-up view of tufa within outer layer of the Billa Kalina Spring mound. Note well-defined plant casting (a).

3.3.2 Petrology

Forty polished and 22 covered thin sections were manufactured. Additionally, five stained polished thin sections from Beresford and Warburton Springs were made using the stains Alizarin red S and potassium ferricyanide (Friedman, 1959; Lindholm and Finkelman, 1972). Petrological descriptions were undertaken using a Motic PM-28 series petrological microscope and photographed using an Olympus BH2 petrological microscope with an Olympus C5060 Wide Zoom digital camera attachment. Commonwealth Scientific and Industrial Research Organisation (CSIRO) Land and Water Laboratory, Waite Campus, Adelaide provided X-Ray diffraction (XRD) and X-Ray fluorescence (XRF) geochemistry to aid interpretation. Results of XRD and XRF analysis may be found in Appendix 3, while detailed slide descriptions of each sample may be found in Appendix 4.

3.3.3 Scanning Electron Microscopy (SEM)

Scanning electron microscopy was performed on samples of recently formed spring carbonate between 1 and 5 mm in diameter. Before analysis, these were washed in distilled water for 20 minutes and then dehydrated in graded alcohols before being air-dried at 60 C° for 2 hours. The resulting specimens were mounted on stubs using double-sided carbon tape, sputter-coated with gold and observed in either an ETEC Autoscan scanning electron microscope (SEM) or Phenom desktop SEM (Gascoigne, pers. comm., 2009).

3.3.4 Water chemistry

Water quality and chemistry samples were collected concurrently with sedimentological and morphological fieldworks. Water quality sampling locations were selected to provide an even and practicable coverage over the length of the spring discharge area and also to target sites within the environment that may be reflective of changes in the gross rate of carbonate precipitation (Table 3.1 and Figure 3.3).

Table 3.1: Brief site description for each placement site, Warburton and Billa Kalina Springs.

Substrate	Distance from vent following thalweg (m)	Site Description
Warburton Spring		
WSL1	0	Centre of pool over vent.
WSL2	9	Northern edge of spring pool.
WSL3	22	Upper tail, within tail gutter. 5m from edge of pool.
WSL4	61	Bottom of tail gutter.
WSL5	88	Top of tail delta.
WSL6	120	Upper tail delta.
WSL7	150	Lower tail delta. Oncoidal mud flats.
WSL8	182	Lower tail delta. Oncoidal mud flats.
Billa Kalina Spring		
MSL1	0	Centre of pool over vent.
MSL2	8	Northern edge of spring pool.
MSL3	11	Within tail gutter. Under small waterfall.
MSL4	19	Top of tail delta.
MSL5	27	Tail delta. Oncoidal mud flats.
MSL6	38	Tail delta. Oncoidal mud flats.
MSL7	48	Lower tail delta. Oncoidal mud flats.

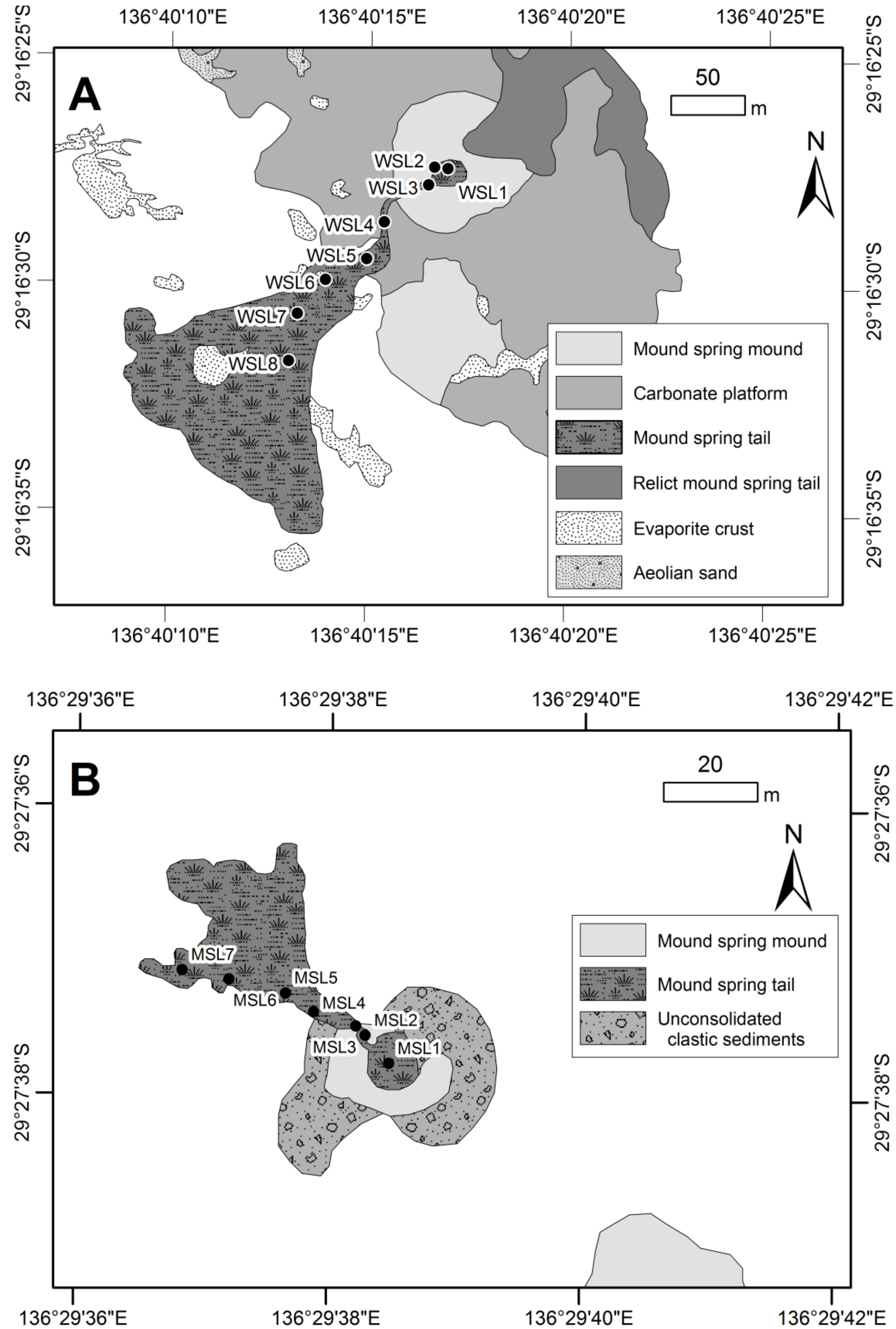

Figure 3.3: Microcosm placement localities and geological mapping at A) Warburton Spring and B) Billa Kalina Spring. Note the deltaic shape of spring tail wetlands.

Salinity and pH measurements were taken using an YSI™ 650 MDS water quality meter, which was calibrated for pH using 4.5 and 7.0 pH calibration standards and TDS using a 1,000 mg/L standard. Calibration was undertaken before each spring site was sampled. Alkalinity was measured in the field using a Hach™ portable digital titration kit using a Bromcresol green-Methyl red indicator. Additionally, the ambient air temperature was measured using a Testo 615 air temperature and humidity meter.

Water from each spring vent was collected after filtration through 0.45µm filter paper in acid-washed 125 ml polyethylene (PE) plastic bottles. Samples designated for cation analysis were acidified with a few drops of 1M hydrochloric acid.

All water analysis was completed at CSIRO Land and Water. The saturation index for calcite (SI_c) and the partial pressure of carbon dioxide (PCO_2) were calculated using the hydrochemical modelling package PHREEQC-2 (Parkhurst and Appelo, 1999) using the hydrochemical database WATEQ4 (Truesdell and Jones, 1974).

3.3.5 Microcosm experiment

Experiments involving the placement of microcosms (i.e. a small vessel containing substrates either analogous to the local environment or emplaced to determine a particular property) were undertaken a number of times between October 2008 and July 2010 at Warburton and Billa Kalina Springs (Figure 3.3). These experiments were designed to determine the rate, spatial extent and influence of microbial activity on calcite precipitation and were based on similar microcosm experiments (Chafetz et al., 1991; Liu et al., 1995; Merz-Preiss and Riding, 1999). Placement times were selected so different seasonal conditions could be examined separately as well as when logistical considerations were favorable.

Microcosm housings were constructed from 120 mm lengths of 50 mm diameter semi-transparent vinyl tubing and 20 mm x 45 mm lengths of non-porous foam cut to fit within the tube. Each housing contained 40 mm x 20 mm tablets of 9 mm thick marble, 1 mm thick copper and 1 mm thick glass (Figure 3.4).

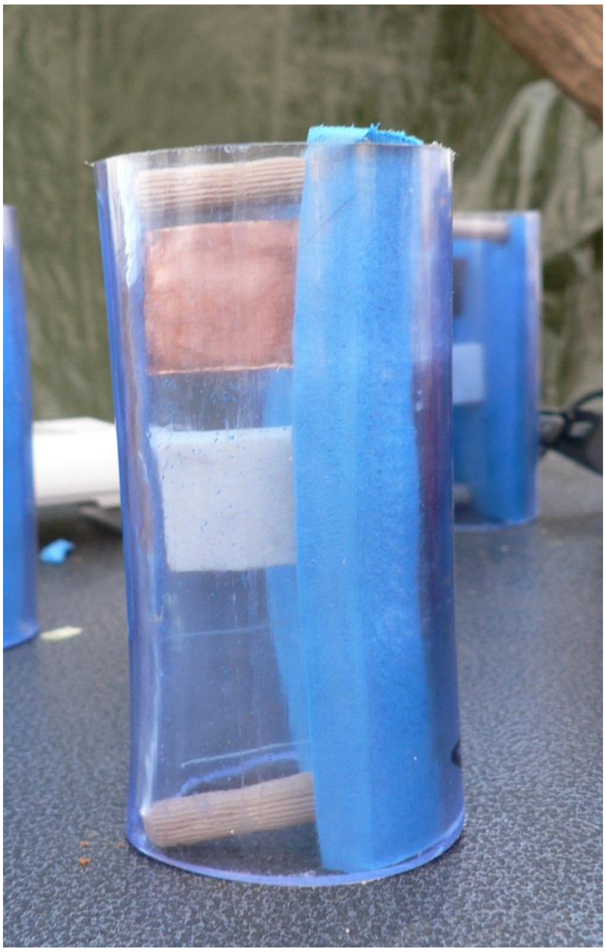

Figure 3.4: Photograph of a microcosm showing construction. Copper, marble and glass substrates are shown from top to bottom.

Marble was chosen for its gross resemblance to spring carbonate mineralogy, while copper was employed to determine the influence of biotic processes on $CaCO_3$ precipitation (Chafetz and Folk, 1984; Chafetz et al., 1991). Glass was used as a comparative inert substrate.

To ensure that the marble tablets were not overly unstable in the wetland environment, the following pre-placement protocol adapted from Liu et al. (1995) was followed: The tablets were first oven-dried at 60°C for 24 hours, before being weighed using Libor EB3200HV electronic scales. The tablets were then submerged in distilled water for 24 hours, weighed and dried at 60°C for a further 24 hours. A final weight was taken and compared to previous weights to determine if there were any significant divergences. In the majority of cases, the second dry weight matched the first, with the remainder of cases possessing a variance of 0.01 g or 0.05%. Copper and glass tablets were also weighed before use. Microcosms were emplaced at sites coincident with water quality sampling locations.

After collection, each substrate was carefully removed from the holder, washed of any loose sediment using distilled water and then dried for 24 hours at 60°C. The substrates were then inspected and weighed; the post placement weight was then compared to the pre-placement weight to determine any appreciable changes.

The placement at Warburton Spring between July 2009 and July 2010 contained a variance in that microcosms placed in close vicinity to the vent contained tablets fashioned from local spring carbonate rather than marble. This was done to determine whether the composition of the marble tablets was influencing previously obtained findings despite the results from pre-placement protocols. To ease the manufacture of tablets, spring carbonate that was not overly friable or vuggy was used. Although a dry weight for spring carbonate tablets before and after placement was obtained, the pre-placement protocol designed for marble tablets was not adopted because the spring carbonate tablets represented refashioned material that was being returned to an environment very close to its original deposition. Therefore, any erosive or dissolutionary process enacting on these tablet were likely to be equally applied to the spring carbonate material surrounding the placement.

3.4 Results

3.4.1 Mound spring morphology

The mound springs described in this study all have a pool in the vicinity of the vent with the surrounding mound barrage structure composed of spring carbonate (Figure 3.2A and 2E). Mounds are typically between 2 and 5 m in height, although some extinct mounds may be up to 20 m. Mound structures included in this study varied in areal extent from approximately 305 m^2 (Billa Kalina Spring) to approximately 5,400 m^2 (Warburton Spring) (Fig.3). The height of water in the central pool was always lower than the lip of the mound (Figure 3.2C) and exited via a break in the lip similar to the break-out described by Kerr and Turner (1996) (Figure 3.2D). Water then disperses into a densely vegetated delta-shaped fan or “spring tail” (Figure 3.3) where most active carbonate precipitation was observed. The areal extent of the study sites inclusive of the surrounding wetland and associated carbonates varied from approximately 1,240 m^2 (Billa Kalina Spring) to 120,000 m^2 (Warburton Spring) (Figure 3.3). Water depths within the central pools varied from less than 30 cm to several meters, while depths within the spring tails were consistently between 1 and 3 cm.

Sediments associated with GAB springs in South Australia cover approximately 230 km^2 based on published 1:1,000,000 scale geological mapping (Whitaker et al., 2008). This represents approximately 0.06% of the surface area of the GAB in South Australia.

The overall size and steepness of the mound structure varied between sites. Smaller mounds such as at Billa Kalina Spring and Beresford Spring are between 1.5 m and 2 m in height, with near horizontal dips (0-5°) at the mound peaks, increasing up to 50° at the mound base. In contrast, the large mound at Warburton Spring is approximately 4.5 m high, but has a shield-like structure with mound wall dips no greater than 5°.

3.4.2 Petrology

3.4.2.1 Common primary fabrics

The vast majority of both fossiliferous and modern carbonate samples are plant or microbial tufa (Ford and Pedley, 1996; Jones and Renaut, 2010; Pedley, 1990). Tufa is composed of low magnesian calcite (<5% $MgCO_3$), as defined by Burton and Walter (1991).

Primary to this is the observation that samples were composed of micrite with either a clotted (Pratt and James, 1988) or peloidal (McKee and Gutschick, 1969) fabric; such fabrics are synonymous with accumulation via the adhesion of carbonate particles to microbially-produced extracellular polymeric substances (EPS) (Pedley et al., 2009; Riding, 2000). The microstructure of peloidal and clotted samples viewed under SEM appears similar to that described for other microbially-mediated terrestrial carbonate deposits (e.g. Calvet and Julia, 1983; Ozkul et al., 2010; Vazquez-Urbez et al., 2010), being primarily composed of crypto- and microcrystalline anhedral carbonate crystals generally <1 μm in diameter, microfibers (Figure 3.5A and 3.5C) and larger pseudo-radiating whisker crystals (Fig. 3.5B), with strong associations between precipitate, cyanobacteria and other filaments (Fig.3. 5C, 3.5D and 3.5F). Clay, detritus, pollen (Figure 3.5B), spores and diatoms (largely *Cymbella sp.*?) (Figure 3.5D and 3.5E) were also evident.

The vast majority of mound spring sediment samples contained bioclasts; readily identifiable fragments include gastropods, ostracods and charophytes. Macrofaunal bioclasts either appear intact or to have been bored by microbial activity similar to that described by Bathurst (1966) (Figure 3.6A). Voids formed within or by the dissolution of bioclastic material are also common; however void formation via insect larvae activity could not be confirmed in either modern or relict tufa deposits.

Spring carbonate samples contained up to 20% detrital silicate, while unconsolidated sediments collected from the mound spring pools typically comprised between 70 and 100% detrital silicate. Detrital silicates consisted primarily of clay and generally well-rounded, quartz silt and sand. The most likely source of siliceous material is considered aeolian activity rather than transportation to surface via spring flow. Other minor sedimentary components found specifically in unconsolidated pool and tail sediments included organic matter up to 16%, carbonate mud typically up to 30% and minor pyrite.

Further subdivision of tufa into discrete facies reflects changes in fabric formed in response to localised variations in microenvironment related to topography and vegetation coverage. The spatial relationship between the various facies types is illustrated in a schematic cross section of Billa Kalina Spring (Figure 3.7) and Table 3.2 summarises important characteristics.

3.4.2.2 Phytoherm Framestone Facies

Phytoherm framestone tufa (Ford and Pedley 1996) is the most common form and is found around the spring vent to areas within the tail delta (Figure 3.7). This facies type forms in highly vegetated environments where calci-fixating cyanobacteria adhering to hydrophytes build a tufa deposit (Buccino et al., 1978; Pedley, 1990; Pedley et al., 2003). Consequently, many voids are interpreted to be hydrophyte fenestrae (Figure 3.6B), although voids and fabrics can appear complex in older, consolidated material.

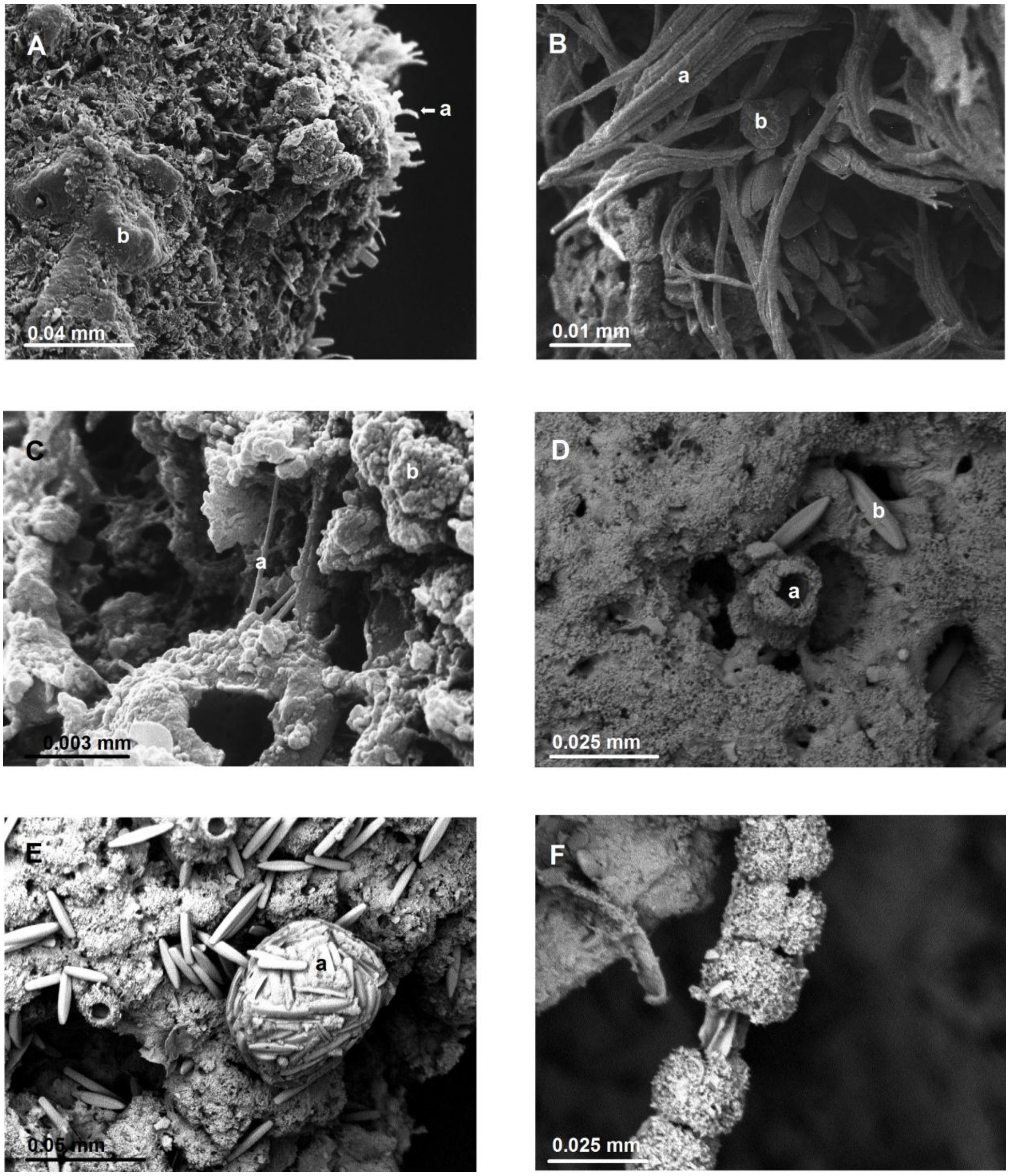

Figure 3.5: SEM images of modern phytoherm facies tufa collected from Billa Kalina Spring (A, B and C) and of calcareous precipitate from a microcosm placement at Warburton Spring (WSL6, July 2009 to July 2010) (D, E and F). A) Whisker crystals composed of encrusted filaments of possible bacteria (a) and accretions of cryptocrystalline anhedral carbonate (b) nucleating on anhedral micritic clot. B) Closer view of whisker crystals (a). A possible pollen particle (b) is located near the centre of the image. C) A closer view of the cryptocrystalline anhedral carbonate material (a) and encrusted filaments (b). D) Thrombolitic textured micrite with possible cyanobacterial sheath (a) and diatoms, possibly *Cymbella sp.* (b). Diameter of sheath is approximately 6μm. E) Probable ostracod fecal pellet composed largely of diatoms. F) Micrite encrusted filament. Micrite accretions appear segmented.

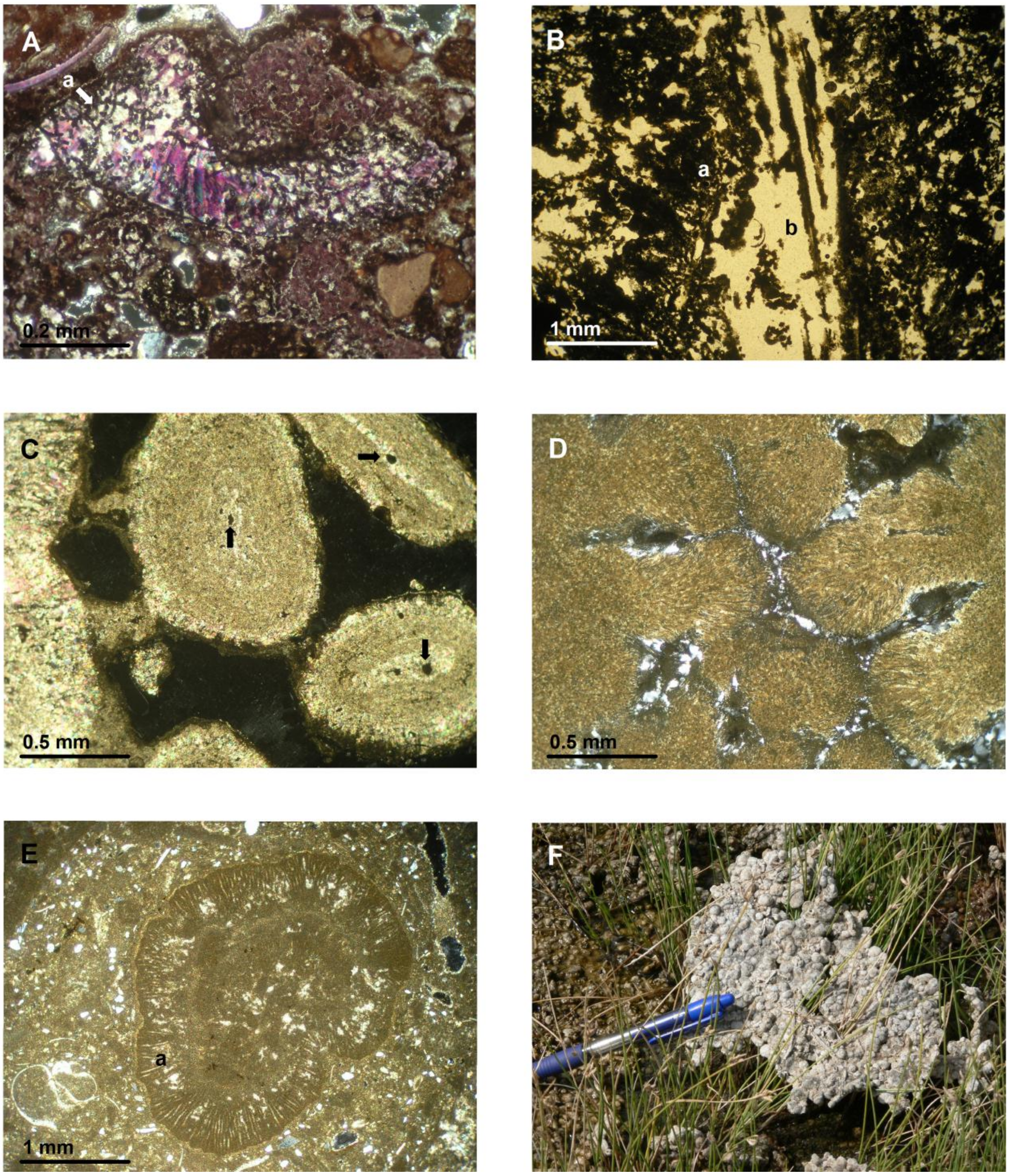

Figure 3.6: Thin section photomicrographs and field occurrences of important primary fabrics and processes A) Bioclast with evidence of microbial boring activity. Note dark colored, cross-cutting bores emanating from the edge of the clast (a). Microherm boundstone tufa from Beresford Spring. Stained thin section, Crossed polars. B) Fenestral void (plant casting) (a). Dendritic, microbial textures interpreted to be the product of *Rivularia sp.* surrounding void (b). Phytoherm framestone tufa from Warburton Spring. Plane light. C) Concentric deposition of carbonate (arrowed examples) around voids after organic nuclei, leading to the development of flattened ooids. Ooidal phytoherm framestone tufa from Beresford Spring. Crossed polars. D) Thrombolitic texture in micritic matrix: Y-branching, dendritic form with micrite and microspar-filled thalli evident. Texture interpreted to be

formed by *Rivularia sp.* Microherm boundstone tufa from Beresford Spring. Crossed polars. E) Porostromate oncoid in matrix of calcareous mud and siliciclastic particles. Thalli (a) in oncoid filled with microcrystalline carbonate cement. Oncoidal tufa from Warburton Spring. Plane light. F) Gently accreted mat of oncoids that has been lifted from the water column by new season hydrophyte growth, Billa Kalina Spring.

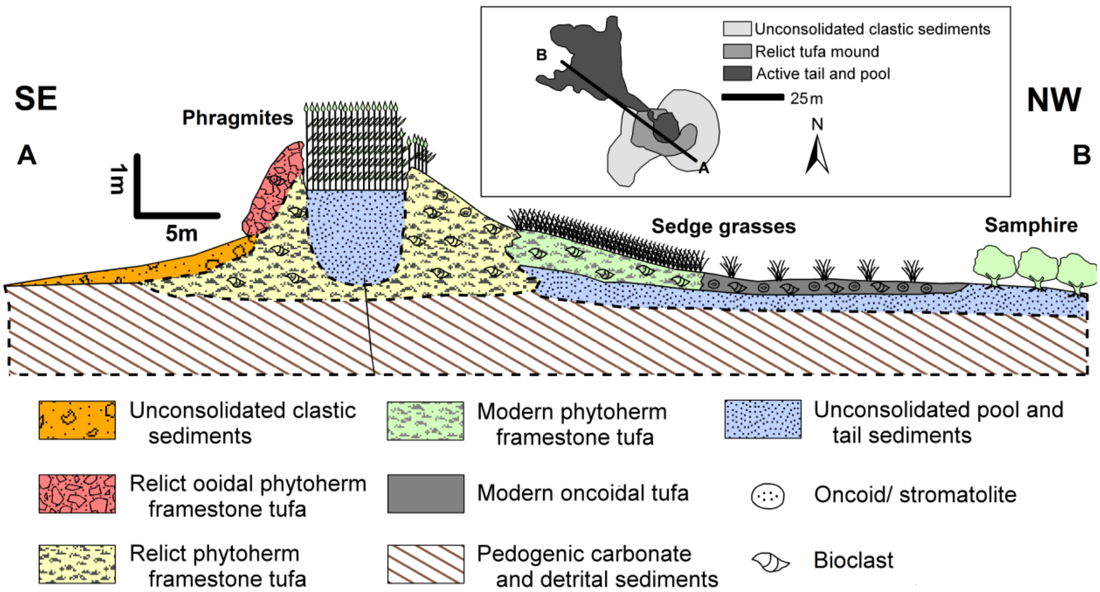

Figure 3.7: Schematic cross section based on the main spring at Billa Kalina Spring. Cross section is approximately 100 meters in length. Depths partially based on electrical resistivity data (Halihan et al., 2010). Inset: Plan view of the mound spring at Billa Kalina Spring.

3.4.2.3 Microherm and Oncoidal Facies

Microherm tufa describes dense boundstone composed of thrombolitic and dendritic-textured micrite that is formed via the calci-fixating activity of microbes. Specifically, the abundance of y-branching, filamentous or honeycomb-like fenestrae are highly suggestive of *Rivularia sp.* (Figure 3.6D). Additionally, some fossiliferous samples are composed of interlaminated bands of isopachous spar and micritic cements. Although microherm tufa, like ooidal phytoherm framestone tufa, is found on the flanks of mature mounds, the change in fabric appears in situations where the underlying mound substrate is unsuitable for hydrophyte anchorage.

Oncoidal tufa (Ford and Pedley, 1996) describes grainstone commonly deposited in lower tail environments in which a high proportion of the sample mass is composed of oncoids (Pedley, 1990) (Figure 3.6). Oncoids (e.g. Bathurst, 1975; Hagele et al., 2006; Monty, 1981) are elliptical and ovoid calcareous stromatolites that form grains composed of fringe carbonate cements. Oncoids from these examples range between 2-20 mm in diameter and contain thin, radiating fenestrae after thalli (Figure 3.6E) and have sub-spherical to wavy laminations. Oncoids appear hemispheroidal in cross section, suggesting minimal overturning during growth and are therefore similar to those found in shallow standing water bodies (Pedley, 1987) or in lacustrine settings (Jones and Wilkinson, 1978; Riding, 1979). Like microherm tufa, oncoidal tufa forms in microenvironments that have shallow, sluggish water and sparse macrophytic growth (Figure 3.7).

3.4.2.4 Ooidal Phytoherm Framestone Facies

Ooidal Phytoherm framestone tufa forms on mature mound structures. Consequently, this facies type is only found in close proximity to spring vents and is largely confined to younger deposits on established mounds (Figure 3.7). The highly oriented castings of plant-stems, the high percentage of voids between reed castings and the lobate to crudely bedded form of deposition are the most distinguishing features of this facies type in outcrop (Figure 3.2A and 3.2E). Such features are strongly suggestive of deposition in either very steep or waterfall-like environments.

Table 3.2: Summary of tufa facies types identified at selected GAB mound springs.

Facies Type	General Description	Distinguishing features	Location of Formation
Phytoherm Facies	Tan, brown or orange-buff micritic limestone. Variable percentage of voids (20-40%). Macrophyte fenestrae prevalent.	Clotted and peloidal-textured micritic matrix. Bioclasts and macrophyte fenestrae prevalent.	General mound and tail environment. Associated with abundant hydrophyte occurrences.
Ooidal Phytoherm Facies	Tan, orange-tan or gray limestone. High percentage of voids (30-50%). Well preserved and orientated macrophyte fenestrae. Lobate depositional form.	Matrix composed of laminated concentric ooids, some flattened and peloids. Inter-granular micritic and meniscus cement. Large macrophyte fenestrae.	Late stage deposit on mound structures. Occurs where water is most turbulent.
Microherm Facies	Tan to grayish brown limestone. Generally low (1-20%) percentage of voids. Thrombolitic texture abundant.	Thrombolitic textures within micritic matrix prominent. Microbial fenestrae related to thalli and Oncoidal carbonate grains common.	Found on framestone structures where hydrophyte growth sparse to absent and the water column thin (5-10 mm).
Oncoidal Facies	Tan to grayish brown limestone. Generally low (1-20%) percentage of voids. Oncoids abundant.	Oncoidal carbonate grains common in generally clotted micritic matrix.	Oncoids most common in lower tail environments. Can also be found on framestone structures where hydrophyte growth is absent and the water column thin (5-10 mm).

It is noted that no oncoid grains as described in oncoidal tufa are found in ooidal phytoherm framestone samples. Instead, the sample matrix contains a large proportion of grains interpreted as ooids (Figure 3.6C); ooids are rounded grains 0.2-1 mm in diameter that are composed of either micritic or microspar cements that may display regular concentric laminations (Braithwaite, 1979; McGannon, 1975). Ooids within GAB mound spring tufa was first described by Radke (1990) as rarely occurring particles thought to form in pool ore near vent environments. Unlike the much larger oncoid grains, evidence of a microbial origin in quiescent waters such as hemispheroidal growth, porostromate structure or the presence of thalli are not observed; rather their small, well-rounded form and concentric laminations suggest progressive accretion around a central nucleus in turbulent, carbonate-precipitating springwaters (Folk and Chafetz, 1983; Guo and Riding, 1998; Nicoll et al., 1999). In the samples examined, this nucleus is thought to be often organic, as a void at the centre of the ooids is commonly observed. The only possible evidence for microbial origin is the presence of laminae in some samples; a feature noted previously by Chafetz and Meredith (1983) and Guo and Riding (1998). Alternatively, the described features may also be much smaller, laminar oncoids, with their size limiting positive identification as such. Regardless, their restriction to areas of steep gradient in the vicinity of spring vents suggests an important formational distinction between these and the much larger oncoids.

Although differential erosion may enhance the prominence of GAB spring carbonates over time, the occurrence of ooidal phytoherm framestone tufa discounts a mound-formation process completely reliant on topographic inversion, as is interpreted for spring mounds in the Western Desert of Egypt (Crombie et al., 1997).

3.4.2.5 Diagenetic features

Diagenetic features such as cements, fractures, bioturbation or rhizoturbation, dissolution voids and neomorphic areas are common in fossiliferous mound spring carbonate samples. Their capacities to obscure primary depositional textures make them important to recognise.

Rhizoturbation within the subaerial environment during deposition appears responsible for much of the complexity and clastic carbonate grains observed. Rhizoturbation caused by hydrophyte growth was evident in the modern wetland; "mats" of gently accreted oncoid pebbles or reed castings were observed being lifted from the water during seasonal summer growth. These would eventually dry, disaggregate and fall back into the water (Figure 3.8F). Complexity via post-deposition compaction, consolidation, fracturing and solution enlargement is also noted in older samples. Fractures and the resultant infill cementation can be relatively extensive, with individual accumulations reaching several decimeters in diameter.

Carbonate cements most commonly seen as fringes or cavity fill include isopachous fibrous and bladed spar. These spar occurrences often display laminae perpendicular to the long axis and commonly have transitional contacts with the micritic matrix (Figure 3.8A).

Such fabrics have been identified by Pedley et al. (2003) and Pedley et al. (2009) as indicative of carbonate precipitation on EPS-biofilms in marsh environments. Boundstone composed predominantly of spar cements can form thick alternating laminae with clotted and peloidal micrite (Figure 3.8B). Peloidal micrite and detrital terrigenous material from the matrix is also a common late-stage void fill.

Neomorphic alteration is a replacement of the micritic matrix with microspar and is related to the development of a calcrete overprint (Folk, 1974; Viles and Pentecost, 2007). This replacement has a heterogeneous distribution and is observed cross-cutting older textural features (Figure 3.8C).

Similarly, pedogenic carbonate is indicative of subsurface precipitation as either a displacement or replacement material within the vadose or phreatic zone (Wright and Tucker, 1991). Pedogenic carbonates contain a high percentage of phyllosilicate and siliciclastic material (15-20%) and voids are largely formed via desiccation fractures and root castings (Wright and Platt, 1995) or by dissolution.

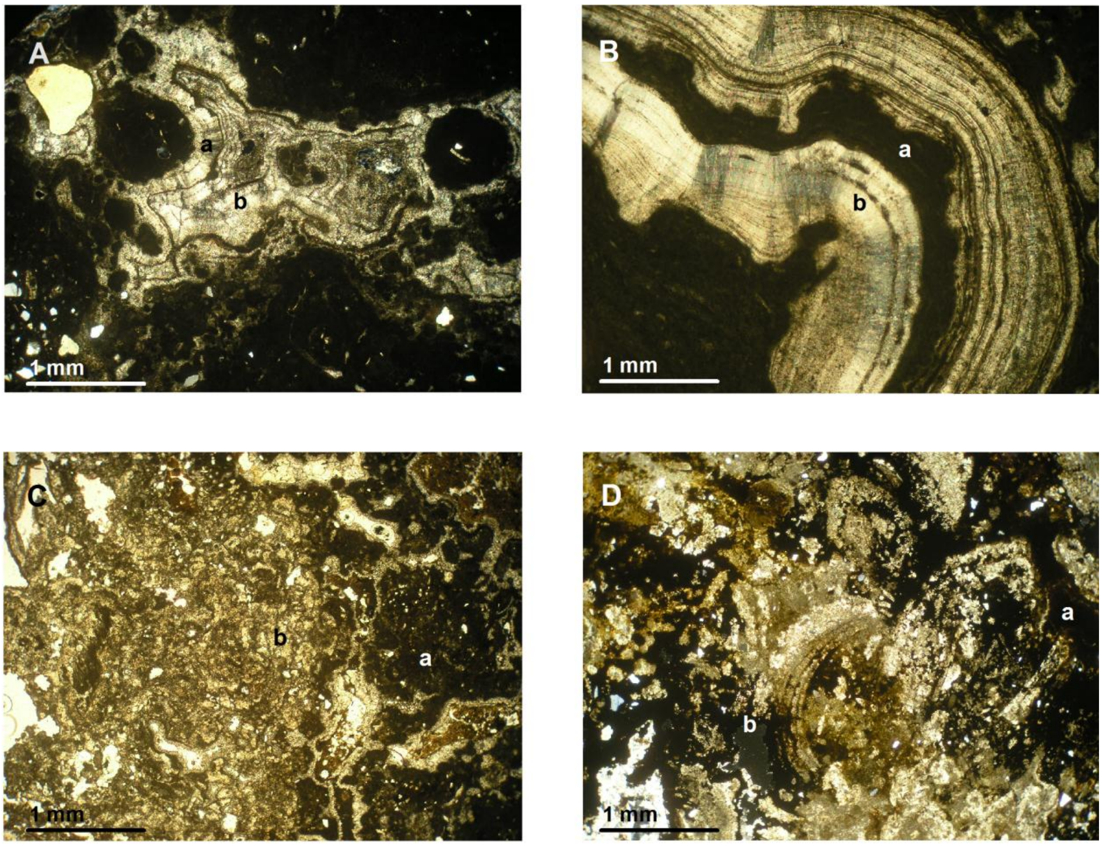

Figure 3.8: Thin section photomicrographs of important diagenetic fabrics. A) Void fill consisting of laminated fibrous (a) and bladed (b) carbonate cement. The carbonate matrix is peloidal to clotted with micritic inter-particle void fill. Boundary between micritic matrix and spar void fill appears transitional. Microherm boundstone tufa from Beresford Spring. Crossed polars. B) Laminations composed of clotted and peloidal micrite (a) and bands of laminated fibrous sparry cementation (b). Microherm boundstone tufa from Coward Springs. Crossed polars. C) Neomorphic alteration of calcareous mud (a) to microspar (b). Phytoherm framestone tufa from Billa Kalina Spring. Plane light. D) Iron and manganese oxide void fill (a) Oncoidal tufa from Billa Kalina Spring. Note corroded nature of carbonate textures (b). Crossed polars.

Some samples contain appreciable amounts of goethite and manganese oxide, usually in the form of inter-laminated deposits, precipitate grains or void fill. Carbonate material in these samples can appear corroded (Figure 3.8D). Finally, areas within the wider mound spring environment may be covered by subaerial slope-wash composed of tufa debris ranging in size from silt to gravel up to 0.5 m in depth.

3.4.3 Water chemistry

Water chemistry results for sampled spring vents are included in Table 3.3 and detailed water quality results for Warburton and Billa Kalina Springs are provided in Table 3.4. Flow from springs varied between <0.1 L/sec (Beresford Spring) up to 3 L/sec (Warburton Spring) (Halihan pers. comm., 2008).

Water chemistry resembled groundwater typical for the region, (Radke et al., 2000) with prominent concentrations of Na, Cl, SO_4 and Ca. All springwaters were brackish, with EC measurements between 5.2 and 11.3 mS/cm. ORP indicated that emergent springwaters were generally reducing and alkalinity was relatively consistent between sites, ranging between 216 and 361 mg/L (CO_3^{2-}). pH values suggest springwaters are near neutral upon emergence, but become progressively alkaline with distance from the spring vent (Figure 3.9). PCO_2 values for all emergent springwaters were approximately three orders of magnitude greater than average atmospheric values and SI_c values generally ranged between being under-saturated to slightly over-saturated, with one exception of relative over-saturation at Beresford Spring.

Although most emergent water temperatures ranged between 20.7 and 27.6°C, which is similar to the average ambient air temperature for the region, a predominantly super-ambient meteogene groundwater supply is likely given the lack of significant chemical or temperature variance between samples collected at different times of the year, indicating little local seasonal influence. It is noted that the temperature and EC values for both Warburton and Billa Kalina Springs varied within the tail environment in keeping with variations in seasonal conditions (Figure 3.9).

3.4.4 Microcosm experiment

Results from the microcosm placements are presented in Table 3.4. Only microcosm placements at Warburton Spring were successful in relation to spring carbonate precipitation. Precipitation was found on the marble and glass tablets as a grayish tan thrombolitic micrite (Figure 3.10A).

SEM imagery of precipitate material recovered from a marble substrate placement (WSL6, July 2009 to July 2010) displayed a prevalence of possible cyanobacterial sheaths within a thrombolitic micritic matrix (Figure 3.5D and 3.5E) as well as micrite-encrusted filaments (Figure 3.5F).

Table 3.3: Major ions, PCO_2 and SI_c results for springwater vent samples from Warburton Spring, Billa Kalina Spring and Strangways Spring.

Sample Station	Date	pH	T °C	EC (mS/cm)	ORP (mV)	CO_3^{2-} (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^{+} (mg/L)	K^{+} (mg/L)	Cl^{-} (mg/L)	SO_4^{2-} (mg/L)	PCO_2 (matm)	SI_c
Warburton Spring														
WSL1	Oct-08	6.91	27.3	6.408	-58	356	74.0	38.1	1,278	39.3	1,485	269	79.7	-0.08
WSL1	Mar-09	7.06	27.3	6.047	-109	322	80.1	38.4	1,356	43.3	1,470	277	50.8	0.05
WSL1	Jun-09	7.03	27.6	5.211	-86	347	75.6	41.3	1,340	47.5	1,580	290	58.9	0.03
Beresford Spring														
LBSL1	Oct 08	7.87	20.7	6.558	-10	342	74.2	37.3	1,335	46.1	1,558	262	7.5	0.75
Billa Kalina Spring														
MSL1	Oct-08	6.66	24.0	8.684	-133	234	129.5	29.4	1,524	49.3	2,154	370	73.8	-0.35
MSL1	Mar-09	6.88	23.9	7.876	-139	246	152.6	30.4	1,745	55.7	2,134	379	46.4	-0.05
MSL1[a]	Jun-09	7.08	16.7	9.131	-167	362	201.0	41.5	2,100	79.5	2,825	466	43.6	0.29
Strangways Spring														
SSL1	July 09	6.60	24.6	11,310	-	216	218	43.2	2,120	78.9	3,105	593.2	89.1	-0.27

[a] Result may be affected by an inability to find the spring vent due to dense vegetation.

Using the method outlined in Jacobsen and Usdowski (1975), precipitation rates determined at Warburton Spring based on microcosms not compromised by burial processes are between 0.15 and 1.6 kg m^{-2}/year (Table 3.4). Although no carbonate precipitation was successfully collected at the Billa Kalina site, this was due to difficulties keeping microcosms clear of silt and vegetation and wildlife disturbances (i.e. dingoes), rather than an unsuitable environment for spring carbonate formation.

No notable precipitate was found on the copper tablets. Although some copper tablets affected by burial reported weight gains, closer inspection revealed that in all instances the accreted weight was due to the light adhesion of silt and mud by copper oxide.

In all instances, it was noted that the marble or spring carbonate tablet placed directly over the spring vent had partially dissolved and was evidenced by a loss of weight as well as etching on the polished surface of the marble. Additionally, one spring carbonate tablet placed within the break-out portion of the upper tail at Warburton Spring (Sample site WSL3 July 2009 to July 2010) also displayed partial dissolution, although given the turbulence of water at this location compared to the quiescent conditions in the spring pool; this weight loss may have been partly attributable to erosion. Weight-loss rates of between 0.12 and 0.48 kg m^{-2}/year (Table 3.4) were determined despite the presence of goethite precipitate on many these tablets (Figure 3.10B).

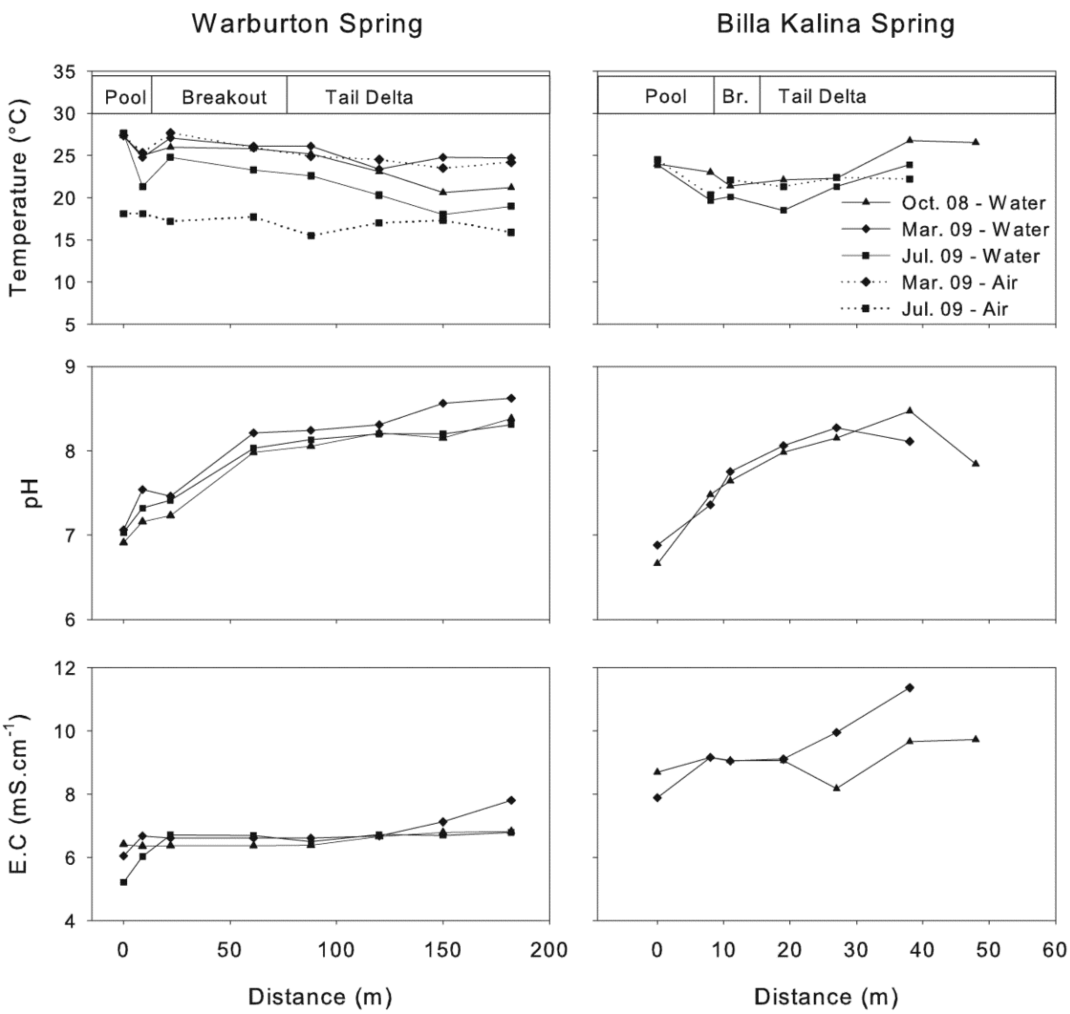

Figure 3.9: Graphs of water and ambient air temperature, as well as pH and E.C. at each microcosm placement site at Warburton and Billa Kalina Springs. The largest variation between emergent and ambient temperature occurred at Warburton Spring during winter (July), although a trend towards equilibration is also evident. Little difference between emergent and ambient temperature is evident during late summer/early autumn (March). pH displays a relatively consistent trend towards more alkaline conditions throughout the year. E.C. is relatively consistent throughout the examined part of the wetland except in March where an interpreted evapotranspiration-driven increase is observed.

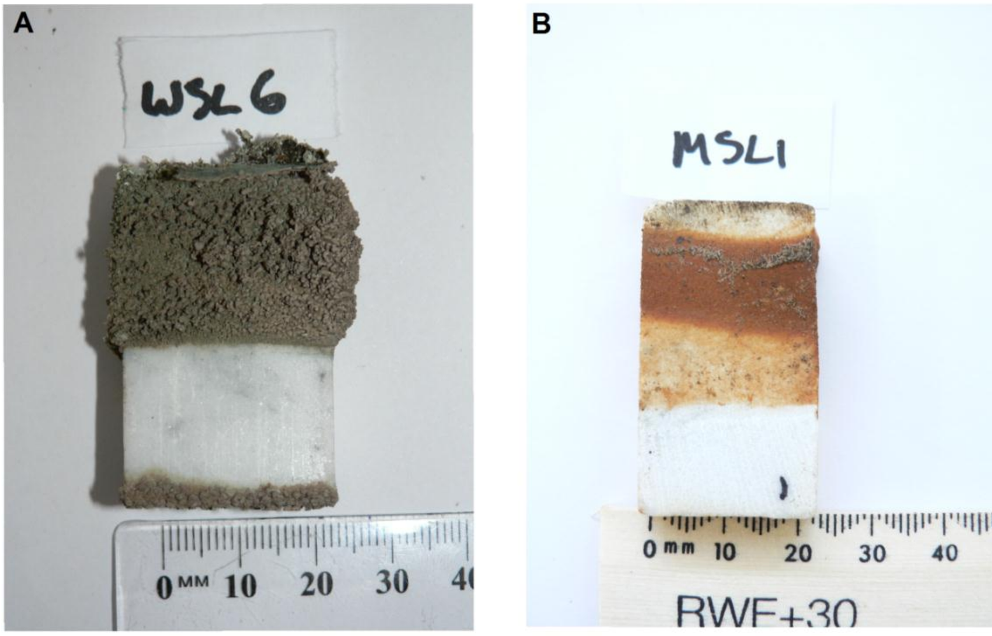

Figure 3.10: Examples from microcosm experiments. A) Marble tablet from sample site WSL6 with thrombolitic tufa precipitation. Substrate emplaced between July 2009 and July 2010 at Warburton Springs. B) Marble tablet from sample site MSL1 with goethite precipitate. Substrate emplaced between October 2008 and March 2009 at Billa Kalina Spring.

3.5 Discussion

3.5.1 Water chemistry, microcosms and implications for mound formation

Although the water chemistry for the springs included in this study are comparable to ambient-meteogene and super-ambient-meteogene travertine springs summarised by Pentecost (2005), SI_c values and field observations indicate that GAB groundwater is incapable of carbonate precipitation upon first emergence. Likewise, partial dissolution of marble and spring carbonate tablets placed in the vicinity of spring vents, the low $CaCO_3$ content of unconsolidated pool sediments and the presence of dissolution features such as break-outs also suggest that waters are initially under-saturated with respect to $CaCO_3$. Therefore, the chemistry of emergent springwater indicates an excess of dissolved CO_2 that requires degassing before carbonate precipitation is possible. This, combined with the changes in water quality parameters towards ambient conditions (Figure 3.9), strongly implies that spring carbonate precipitation occurs in surface waters that are close to ambient.

This delay between groundwater emergence and precipitation of tufa has important implications for the maintenance of spring flow and the formation of spring conduits. As carbonate precipitation within spring conduits may cause the cessation of spring flow (Hancock et al., 1999), it follows that the spatial extent of carbonate precipitation contributes to the life expectancy of a mound spring and that subsurface dissolution of carbonate minerals within aquitard units may aid the growth or formation of conduits.

The similarities in the water chemistry of spring vent samples suggest that the variations in morphology are more likely to be caused by flow rates than differences in water chemistry. This indicates that while Pentecost (2005), suggests that the relative saturation of springwaters with respect to $CaCO_3$ influences mound geometry, factors such as flow rate need consideration.

The lack of carbonate precipitation on the copper tablets implies that microbial activity is an important mediator for the precipitation of carbonate, as copper is generally toxic to algae (Huntsman and Sunda, 1980). The thrombolitic textures displayed in carbonate precipitates and the micro-textural similarities of precipitates with other tufa samples reinforces this idea. The rates of precipitation calculated from the Warburton Spring microcosm experiments are consistent with the rates observed at cyanobacteria-associated, low-energy, carbonate depositing environments (Gradzinski, 2010; Pentecost, 2005; Vazquez-Urbez et al., 2010) and equate to accumulation thicknesses up to 3 mm/year. Such observations concerning the bio-mediated origin of carbonate minerals have been highlighted previously via laboratory-based experimentation with isolated species (e.g. Baskar et al., 2006; González-Muñoz et al., 2010; Lee, 2003) as well as via experiments using natural seed water or field based conditions replicating or within cool and temperate stream environments (e.g. Kandianis et al., 2008; Pedley and Rogerson, 2010; Pedley et al., 2009). However, this is believed to be the first time such a role has been highlighted in the construction of surficial, non-submerged, mound spring structures.

3.5.2 Depositional environment and implications for morphotype classification

Using the Ford and Pedley (1996) classification system, the depositional environment for both fossiliferous and modern tufa at the selected study sites is predominantly that of either a swamp (paludal) or shallow braided stream environment. Properties suggestive of this include:

Table 3.4: Results from the marble and spring carbonate substrates from microcosm experiments and water quality measurements.

Sample site	Dist. from Vent (m)	Precip. rate[a] (Kg m^{-2}/year)	pH	Water Temp (°C)	Air Temp (°C)	EC (mS/cm)	Notes
Warburton Spring October 2008 to March 2009							
WSL1	0	<-0.20	6.91	27.3	-	6.408	Polished surface etched. Goethite and gypsum precipitate.
WSL2	9	N.D.[c]	7.16	25.0	-	6.353	Lost.
WSL3	22	N.D.	7.23	26.0	-	6.369	Lost.
WSL4	61	N.D.	7.98	25.8	-	6.369	Lost.
WSL5	88	0.36	8.05	25.2	-	6.388	Tufa-precipitate.
WSL6	120	N.D.	8.21	23.1	-	6.654	Lost
WSL7	150	0.05	8.15	20.6	-	6.780	Microcosm buried.
WSL8	182	0.16	8.38	21.2	-	6.812	Microcosm buried.
Warburton Spring March 2009 to May 2009							
WSL1	0	N.D.	7.06	27.3	27.4	6.047	Lost.
WSL2	9	N.D.	7.54	24.8	25.3	6.679	Lost.
WSL3	22	N.D.	7.46	27.1	27.7	6.613	Microcosm partially buried. Goethite-precipitate.
WSL4	61	0.06	8.21	26.1	25.9	6.603	Microcosm partially buried. Goethite precipitate.
WSL5	88	0.15	8.24	26.1	24.9	6.607	Microcosm partially buried. Tufa precipitate.
WSL6	120	1.40	8.31	23.4	24.5	6.672	Tufa-precipitate.
WSL7	150	N.D.	8.56	24.8	23.5	7.117	Microcosm buried.
WSL8	182	N.D.	8.62	24.7	24.2	7.801	Microcosm buried.

Table 3.4: Results from the marble and spring carbonate substrates from microcosm experiments and water quality measurements (cont.).

Sample site	Dist. from Vent (m)	Precip. rate[a] (Kg m^{-2}/year)	pH	Water Temp (°C)	Air Temp (°C)	EC (mS/cm)	Notes
Warburton Spring July 2009 to July 2010							
WSL1[b]	0	<-0.09	7.03	27.6	18.1	5.211	Goethite-precipitate.
WSL2[b]	9	N.D.	7.32	21.3	18.1	6.027	Goethite-precipitate.
WSL3[b]	22	<-0.12	7.41	24.8	17.2	6.706	Black oxide staining.
WSL4	61	N.D.	8.03	23.3	17.7	6.697	Lost.
WSL5	88	0.04	8.13	22.6	15.5	6.504	Microcosm clogged. Small amount of tufa-precipitate.
WSL6	120	1.58	8.20	20.3	17.0	6.718	Tufa-precipitate
WSL7	150	N.D.	8.20	18.0	17.3	6.697	Microcosm buried.
WSL8	182	N.D.	8.31	19.0	15.9	6.788	Microcosm buried.
Billa Kalina Spring October 2008 to March 2009							
MSL1	0	<-0.48	6.66	24.0	-	8.684	Polished surface etched. Goethite precipitate.
MSL2	8	<0.04	7.48	22.0	-	9.161	Black oxide staining.
MSL3	11	N.D.	7.64	21.4	-	9.055	Lost.
MSL4	19	N.D.	7.98	22.1	-	9.050	Lost.
MSL5	27	0.04	8.15	22.3	-	8.178	Microcosm buried.
MSL6	38	N.D.	8.47	26.8	-	9.662	Microcosm buried.
MSL7	48	0.04	7.84	26.5	-	9.715	Microcosm buried.

Table 3.4: Results from the marble and spring carbonate substrates from microcosm experiments and water quality measurements (cont.).

Sample site	Dist. from Vent (m)	Precip. rate[a] (Kg m^{-2}/year)	pH	Water Temp (°C)	Air Temp (°C)	EC (mS/cm)	Notes
Billa Kalina Spring March 2009 to May 2009							
MSL1	0	N.D.	6.88	23.9	24.5	7.876	Lost.
MSL2	8	N.D.	7.36	19.7	20.3	9.156	Microcosm partially buried. Black oxide and goethite staining.
MSL4	19	N.D.	8.06	18.5	21.3	9.098	Microcosm buried.
MSL5	27	0.03	8.27	21.3	22.4	9.954	Microcosm buried.
MSL6	38	N.D.	8.11	23.9	22.2	11.36	Microcosm buried.

[a] Negative precipitation rate indicates dissolution; samples which had multiple species deposited are listed as greater than or less than instead of a single rate.

[b] Substrate composed of spring carbonate.

[c] N.D.: No discernible change in weight outside the margin of error for the methodology was noted, therefore no rate was determinable.

The primary textures in the majority of tufa samples indicate a depositional environment where water is shallow, sluggish and in which hydrophytes and microbial organisms abound. Previous work in paludal tufa environments suggests these tufas are highly porous, composed predominantly of clotted, peloidal and shrub textured micrite and void-filling spar and microspar cements. Recognizable voids are often hydrophyte fenestrae or dissolution cavities formed by vertical root cavities becoming interconnected, but void structures can be complex (Alonso-Zarza and Wright, 2010; Crombie et al., 1997; Heimann and Sass, 1989; Pedley, 1990; Pedley et al., 2003).

The higher proportion of terrigenous material is a feature of paludal tufa (Pentecost, 2005). Heimann and Sass (1989) noted between 4 and 15% sand and silt-sized quartz grains in spring carbonate samples deposited in sluggish water flow conditions from the Hula Valley, Israel, while Crombie et al., (1997) described spring carbonates deposited in marshy environments as having a high proportion of clastics.

Iron oxide staining apparent in hand specimens also lend evidence to formation within a vegetated, paludal environment (Alonso-Zarza and Wright, 2010; Nicoll et al., 1999; Pentecost, 2005). Pentecost (2005) describes the source of this iron as waters with low redox potentials caused by microbial activity as is found in saturated soils.

The identification of mound structures associated with point-source springs within fossiliferous paludal tufa deposits similar in morphology to the mound springs presented here were regonised by Pedley and Hill (2003) using ground penetrating radar (GPR); consequently the association of such mound structures with paludal tufa deposits is not unknown. That being said, the exposures of some later stage tufa at these study sites display features that have more in common with the perched-spring line morphology, such as lobate drape structures, large to cavernous voids and an abundance of concentrically laminated ooids and meniscus cement (Forbes et al., 2010; Ozkul et al., 2010; Pedley et al., 2003). Additionally, the petrological and modern evidence for hydrophyte abundance suggests that these provide an important framework upon which tufa accumulation is based. This results in structures similar to the barrage structures observed in fluvial environments (Pedley, 1990; Ford and Pedley, 1996).

3.5.3 The tufa mound spring conceptual model

Morphological classification of tufa mound springs based on the Ford and Pedley (1996) system is difficult; not only are the gross morphologies of mound structures not covered, but features pertaining to a number of the mentioned categories are evident and the predominance of one or the other is highly dependent on the age of a particular mound. Difficulties with this classification system have been encountered previously outside cool and temperate climate zones (Carthew et al., 2003; Jones and Renaut, 2010; Viles et al., 2007). In such cases, ambient conditions, flora and fauna assemblages and the pre-existing environment all lead to variations in rock fabric and morphology not highlighted in the original classification scheme.

Beyond the scheme of Ford and Pedley (1996), there have been other schemes that include mounds with the spring source located centrally within the structure (e.g. Pedley and Hill, 2003; Pentecost, 1995; Pentecost, 2005; Pentecost and Viles, 1994). However, many of these models are based on a number of features and assumptions that are not wholly applicable in the presented examples. Difficulties with applying current mound spring models are summarised below:

Models presented by Goldenfeld et al. (2006), Kerr and Turner (1996), Pentecost (1995) and Pentecost and Viles (1994) assume instantaneous precipitation of calcite dependent on a large temperature differential between subsurface and surface environments, neither of which, appear to be the case in the Lake Eyre South region.

Models presented by Linares et al., (2010) and Pentecost (2005) have suggested that the rate of flow and mound construction slows as the mound height approaches that of the hydrostatic head. However, evidence indicates that this is only the case until such a point in time as pool-waters become under-saturated with respect to carbonate, as inferred by the experimental results of Kerr and Turner (1996). Supporting this are age-dates of between 10,900 ±1,500 years and 740,000 ±120,000 years for tufa from a selection of active mound spring environments in the Lake Eyre South region (Prescott and Habermehl, 2008). These ages suggest that flow stabilises at some point after mound construction.

The laboratory-based model by Kerr and Turner (1996) indicated that under-saturation development in mound spring pool-water is a function of mound barrage development insulating pool water and thus reducing heat loss compared to initial mound formation conditions. However, the precipitate mineralogy, thermodynamics and the large temperature contrasts present in these experiments are not comparable to the Lake Eyre South examples.

Pedley and Hill (2003) described the formation of lens-shaped, low-amplitude and flat-bottomed spring mound structures in paludal, ambient-temperature, fresh-water conditions similar to that associated with the mound spring structures presented here. Mound development was interpreted to centre on a point-source, calcite-bearing spring, while nutrients for biofilm development were derived from organic-rich pool environments surrounding the structure. However, Pedley and Hill (2003) suggest that formation occurred within a larger, submerged, non-tufa depositing pool environment colonised primarily with open vegetation. Additionally, the fossiliferous and concealed nature of these structures, only really evident through the use of ground penetrating radar (GPR), limited the interpretation of formations; in some cases, mounds structures were best described as a collection of pool-floor irregularities.

Finally, none of these models stipulate the existence of vegetation or calci-fixating microbial activity; features that predominate in the presented examples.

Therefore a new model for the formation of tufa mound spring structures is proposed.

The model commences with water from a new spring forming a circular, shallow, highly vegetated swamp; an environment with a high surface area contact with springwater synonymous with phytoherm framestone facies development (Figure 3.11A). The formation of the spring pool by the construction of a barrage of spring carbonate cement takes place at the point in the environment where sufficient degassing of CO_2 has occurred to permit the precipitation of $CaCO_3$ (Figure 3.11B). Continued mound barrage growth eventually increases the turbulence of water exiting the pool by increasing the flow gradient, leading to the development of drape structures synonymous with ooidal phytoherm framestone facies.

The ultimate development of under-saturation in spring pool waters may be caused by a slowing of CO_2 degassing in response to the deepening of the central spring pool during mound growth. The deepening of this pool may temper turbulence at the point of springwater emergence and decrease surface area exposure of water to both underlying substrate and the atmosphere compared to the initial spring environment. As turbulence and surface area exposure have been previously cited as causes for increased CO_2 degassing (e.g. Dreybrodt and Buhmann, 1991; Lu et al., 2000; Pentecost, 2005, Zhang et al., 2001) it follows that progressive decreases in these variables will have the inverse effect. The under-saturation of trapped pool water eventually leads to a breach. The break-out observed on many mounds represents this breach, through which pool water escapes to form a wetland delta to which carbonate precipitation shifts (Figure 3.11C). The break-out out may be widened at least partially by erosion given the turbulence of water exiting the pool.

The resultant lower water levels within the mound pool causes a shift of vegetation away from the mound structure, leading to the formation of the consolidated mound structures commonly observed and the development of facies types typical of sparsely vegetated areas such as microherm and oncoidal facies.

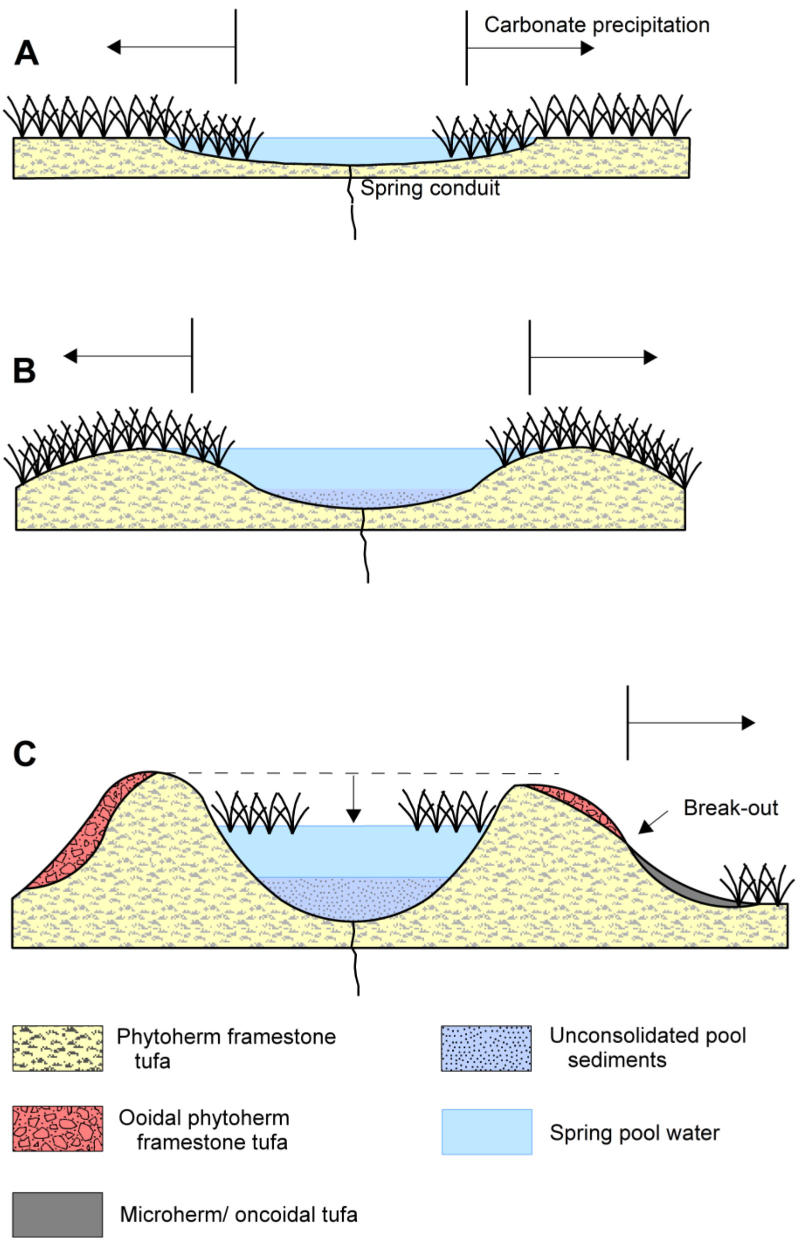

Figure 3.11: Conceptual model for tufa mound formation. A) Discharge from a new spring conduit forms a circular swamp after radial flow away from vent. Carbonate precipitation triggered at the point where sufficient PCO_2 degassing has occurred. B) Continued precipitation eventually builds a mound barrage structure, enclosing a central spring pool. C) Sustained mound growth deepens the pool and dampens turbulence, slowing PCO_2 degassing that results in carbonate under-saturation developing in spring pool waters. A break-out subsequently develops and tufa precipitation shifts to the tail environment.

As discussed in Appendix 1, fracturing of the mound structure, either by tectonism or localised slumping, may contribute to the formation of a preferential pathway and the development of a break-out by providing a focus for corrosion and erosion of the mound spring wall by escaping springwater. However, the observation of Hancock et al. (1999) concerning the requirement of active tectonism to maintain fracture-related spring conduits against suturing via carbonate precipitation may also have relevance to fracture-related break-out development in mound spring structures. In examples where mound spring pool waters still degas sufficient CO_2 to permit active mound growth, suturing of fracture-related breakouts may be also possible, particularly if flow though the fracture is more turbulent than conditions within the pool. Consequently, the development of permanent mound spring break-out features is thought to require appropriate hydrochemical conditions for maintenance purposes, although formation by primarily mechanical fracturing cannot be dismissed.

Any subsequent decrease in flow is thought to be related to either mechanical processes such as the accumulation of sediments within the conduit or a drop in the potentiometric surface caused by either the development of a new spring nearby at a lower elevation or a decrease in head within the discharging aquifer.

3.6 Conclusions

The following conclusions concerning the nature of spring carbonates in the Lake Eyre South region of South Australia and the mound structures they produce were made:

Microbially-mediated carbonate precipitation within reasonably quiescent, ambient, densely vegetated conditions can produce mound structures composed of predominantly plant and microbial tufa with morphologies grossly comparable to those found in thermogene environments.

Depositional environments resemble either swamps or shallow braided streams. However, later stages of mound development are synonymous with features pertaining to more turbulent depositional environments. Such features made classification using the spring carbonate morphotype system of Ford and Pedley (1996) difficult.

The dissolution of marble substrates, low SI_c values and the occurrence of morphological features attributable to carbonate dissolution indicate that the precipitation of tufa is a temporally and spatially dynamic process. This finding has important implications for the longevity of spring flow and the development of new spring conduits.

Existing models for the formation of terrestrial carbonate mound structures described in the literature are inadequate with respect to the Lake Eyre South mound springs as they are based on features and assumptions that are not wholly applicable. Consequently a new model has been developed that specifically incorporates key factors related to the water chemistry and resultant tufa precipitation. As many of these factors are commonly attributable with tufa found elsewhere, application of this model may extend beyond the Lake Eyre South region.