CHAPTER 6: CONCLUSIONS AND FUTURE DIRECTIONS

This study considers the formation and evolution of terrestrial mound spring structures composed of calcareous spring deposits (mound springs). Previous studies of mound springs focused on either 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). Due to these studies' inherent limitations, little was known with respect to the environmental and hydrochemical factors important to the formation of mound springs, particularly with respect to the Lake Eyre South region, or the maintenance of spring flow after formation. As a result, conceptual models for the formation of mound structures developed prior to this study were regarded as inadequate with respect to the Lake Eyre South mound springs. By using a combination of hydrochemical, geological and geochemical investigations at a number of mound spring sites located in the Lake Eyre South region of South Australia, a new conceptual and hydrochemical model for the initial development, formation and ongoing evolution of these environments was formulated.

This study found that $CaCO_3$ precipitation was important with respect to both altering hydrochemistry within the spring environments, as well as changing the morphology surrounding spring vents through mound construction. Variations in carbonate textures were interpreted to be caused by differences in the flow of water within the depositional environment, distance from the spring and the abundance of vegetation at the time of precipitation.

A detailed description of the residual carbonate sediments was undertaken, which enabled identification of fossiliferous spring activity and consequently an improved historical picture of spring discharge and wetland extent. In particular, mound sediments composed predominantly of $CaCO_3$ were interpreted to be largely tufa; a key feature of this interpretation being the presence of textures synonymous with cyanobacterial mediation. Although the role of cyanobacteria in mediating tufa precipitation has been highlighted through experimental data (Chapter 3), more proof is required to fully determine this role quantitatively. Furthermore, there is currently little known about these cyanobacterial communities, with genera and species identification restricted to assessment via petrology (e.g. Chapter 3; Radke, 1990) due to a lack of taxonomic or DNA-based identification undertaken to date. With respect to temporal variation, similar sedimentological textures and chemistry were observed between relict and modern tufa samples, suggesting that neither the gross water quality or chemistry nor the surface environmental factors responsible for mound construction have changed markedly over time.

With respect to the controls on $CaCO_3$ precipitation in the modern mound spring wetland environment, CO_2 degassing from $CaCO_3$-enriched water is typically the main cause for $CaCO_3$ precipitation. CO_2 degassing and $CaCO_3$ precipitation affected pH significantly, which was found to change from slightly acidic conditions at the spring vent to alkaline conditions near the lower reaches of the spring tail. The very high CO_2 levels in groundwater suggest that the pressure difference between the surface and subsurface environments is the main cause for the degassing of CO_2 from water. Emergent springwater also has high CO_2 levels and consequently carbonate precipitation was largely limited to distal wetland areas in modern environments and is potentially important with respect to maintaining spring-coinduit aperture by inhibiting blockage from $CaCO_3$ precipitation. Once in the surface environment, CO_2 degassing was understood to be driven by turbulence within the near mound environment before the precipitation zone. Additionally, an increasing surface area contact of water with substrate and the atmosphere within the precipitation zone was also thought to contribute to CO_2 degassing and carbonate precipitation. Reactive transport modelling was used to interpret the potential for CO_2 degassing to be partly balanced by an additional hydrochemical process active within the wetland environment. This process was interpreted to be potentially net heterotrophic metabolism from micro-organisms and hydrophyte activity, although further work is required to confirm and quantify this inferred contribution. As springwater temperatures are comparable with the average ambient temperature, $CaCO_3$ precipitation cannot be driven by a large temperature differential in these examples; this is a finding that differs from other conceptual models presented by Goldenfeld et al. (2006), Kerr and Turner (1996), Pentecost (1995) and Pentecost and Viles (1994).

The effect $CaCO_3$ precipitation has on water chemistry indicates that by monitoring water chemistry in conjunction with spring flow, risk of spring blockage by either carbonate precipitation or mechanical sedimentation and therefore the viability of a given spring may be more accurately determined; a trend toward alkaline conditions at a given monitoring point may indicate that $CaCO_3$ precipitation is more likely. Additionally, many aquatic biota found in mound spring environments such as ostracods, diatoms and calci-fixating cyanobacteria are dependent on specific water quality (e.g. Forbes et al., 2010; Keatings, et al., 2002; Kominkova et al., 2000; Opfergelt et al., 2011; Schultze- Lam and Beveridge, 1994); the uniqueness of species found within GAB mound spring wetland environments may not be solely a product of spatial isolation, but also of unique hydrochemical circumstance. Consequently, an important future direction of research is to investigate the influence pH has on endemism in GAB mound spring wetland environments and the impact variations in spring discharge may consequently have on any pH-dependent aquatic environments.

A reactive transport model was successfully developed to describe the controls on carbonate precipitation. In addition to aiding the determination of CO_2 degassing controls, this model was used in conjunction with results from major ion and stable isotope mass balance calculations to determine that evaporation was not significant in relation to carbonate hydrochemistry in modern mound spring wetland environments, particularly in the near-vent environment. Conversely, large infiltration rates were interpreted to be important to the spring-wetland water balance based on the results of reactive transport and water balance modelling. Rates of infiltration were broadly estimated as a proportion of the total water balance using a fixed wetland spatial extent. Although this approach was considered adequate with respect to the purposes of this study, the potential for the hydrological wetland environment to expand and contract proportional to seasonal change is recognised. Additionally, the nature of infiltration is not clear based on our current understanding. It is hypothesised that infiltration rates may be heterogeneous across the wetland, being greater where detrital sediments near the periphery of the wetland and fracturing occur, while potentially being lower where lime mud and tufa deposition has formed an impermeable barrier. Therefore, to fully appreciate the hydrology and hydrochemistry of the entire wetland environment, inclusive of both surficial and sub-surface areas, a more accurate determination of infiltration is required.

Reactive transport modelling in combination with discharge data was also found to be useful with respect to estimating the maximum spatial extent of the mound base during early spring wetland development or the maximum mound "footprint". Differences between measured mound footprints and those predicted using reactive transport modelling may be indicative of gross changes in discharge rate from a given spring over time. The successful outcome of this investigation suggests that reactive transport modelling can be used to estimate the initial flow required to form a given mound footprint, if reasonable assumptions concerning the stability of springwater hydrochemistry over time can be made. Consequently, this approach may be used to estimate baseline spring flow data prior to groundwater exploitation. Such information would be valuable when attempting to place current-day spring flow monitoring into context. Although the approximations used for parameters such as water column height and vegetation density were considered adequate with respect to the purposes of this study, an application of this reactive transport model to active wetlands for the purposes of understanding the dynamics of wetland hydrochemistry may require a more accurate determination of these parameters given the identified sensitivity of the model.

The new conceptual model for mound formation developed during this study stipulates that the formation of the spring pool by the construction of a circular barrage of carbonate cement takes place at the point in the environment where sufficient degassing of CO_2 has occurred to permit the precipitation of $CaCO_3$ in the initial shallow wetland environment formed by a new spring. However, as the pool barrage grows, water turbulence is dampened by the depth of the pool and the surface area contact of water is also decreased, both of which will lower the capacity of water to degas CO_2. As a result, it is hypothesised that this slowing of CO_2 degassing within the deepening pool eventually leads to a pause of further $CaCO_3$ precipitation within the confines of the spring pool and mound environment, as sufficient degassing of CO_2 from newly emergent springwater is no longer possible. The near-neutral SI_c and pH values for pool water, the evidence for dissolution of marble and limestone tablets and the presence of iron oxide precipitate from microcosm placements provide evidence for this hypothesis. Consequently, the capacity of emergent springwater trapped within the spring pool changes from one of net precipitation to net dissolution and erosion, eventually leading to the development of a tail gutter or “break-out” through which water escapes to form a wetland delta at the mound base, to which $CaCO_3$ precipitation shifts. The orientation of tail gutters and spring tail wetlands may be highly influenced by fracturing related to tectonic activity. However, the capacity of fracturing to form a permanent breach may be effected by the hydrochemistry of springwater and in particular, CO_2 degassing rate and the concentration of reductive iron, as both of these factors control the capacity of pool water to precipitate $CaCO_3$ at the time the fracturing occurs (Appendix 1).

This aspect of the conceptual model suggests that mound construction via $CaCO_3$ precipitation varies temporally in response to changes within the depositional environment and therefore differs from those presented by Linares et al. (2010), Pentecost (2005), Williams and Holmes (1978) and others, who suggested that the rate of flow and mound construction slows as the mound height approaches that of the hydrostatic head. Evidence presented here in conjunction with dating evidence from Prescott and Habermehl (2008) suggest that flow stabilises at some point after mound construction; any subsequent decrease in flow is thought to be related to either mechanical processes or a drop in the potentiometric surface. The development of a break-out and stabilisation of mound growth is very similar to the model presented by Kerr and Turner (1996), however avoids the problems with differing precipitate mineralogy, thermodynamics and the large temperature contrasts that are not comparable to the Lake Eyre South examples. Table 6.1 provides a summary of previously published conceptual models for mound formation, as well as a summary of the conceptual model presented in this thesis.

Although this model can be used to explain the relationship of modern-day wetland hydrochemistry to the relict mound structures and palaeo-environmental interpretations drawn from petrology, direct evidence in the form of either experimental data similar to that described in Kerr and Turner (1996) but using $CaCO_3$ as the precipitate, or description of an actively growing calcareous mound spring, which was not possible during this study, is required to confirm the ideas presented in this conceptual model.

Finally, natural discharge from the GAB aquifer to surface has been interpreted to be aided by faulting. Within the Lake Eyre South region, this appears correlated with northwest-southeast transpressional shear zone related to the Proterozoic Adelaide Fold Belt underlying the GAB. In addition to the possible influence of break-out development, the influence of neotectonics is regarded as critical with respect to spring formation because these structures and lineaments develop networks that readily form conduits for the migration of groundwater to surface. By extension, the alteration of porosity and permeability conditions in the vicinity of these networks has important implications for understanding the hydrogeology of the GAB.

Table 6.1: Summary of publications relating to conceptual models for mound spring formation, compared to the conceptual model presented in this thesis

Key Publication	Model Description	Data gap	This Study
Williams and Holmes (1978)	Identified the importance of faulting in providing spring conduits. Described formation as involving the accumulation of sediment and precipitate around the vent of a spring.		Calcareous mound spring structures form as a result of a complex interaction between springwater hydrochemistry and the surface environment
Mabbutt (1977), Reeves (1968)	Theorised that the hydrostatic head and its relationship to spring flow are important to mound formation. Hydrostatic head must be higher than the spring opening		Adopted from Mabbutt (1977) and Reeves (1968)
Linares et al. (2010)	Stated that a flat topography is necessary to allow carbonate-precipitating waters to pool around the spring conduit.		Adopted from Linares et al. (2010)
Goldenfeld et al. (2006), Kerr and Turner (1996), Nelson et al. (2007), Pentecost (1995), Pentecost and Viles (1994)	Suggested thermogene spring conditions are important with respect to driving carbonate precipitation. Assumed instantaneous precipitation of $CaCO_3$ upon springwater emergence.	Required temperature differential between emergent springwater and ambient conditions not apparent in Lake Eyre South examples.	Evidence for erosion or dissolution features such as break-outs and results of hydrochemistry and microcosm experiments suggests precipitation is unlikely to be instantaneous. Emergent springwater found not to be capable of immediately precipitating $CaCO_3$ due to high CO_2 partial pressures in groundwater associated with mound spring environments.
Radke (1990)	Suggested evaporation was an important factor.	Lack of geochemical or hydrochemical evidence to support importance of evaporation.	Stable isotope and chloride mass balance used to rule out significant role for evapotranspiration in $CaCO_3$ precipitation in near vent environments. Evapotranspiration may have a role in distal spring tail wetland environments. Infiltration implied to allow for observed water loss.

Table 6.1: Summary of publications relating to conceptual models for mound spring formation, compared to the conceptual model presented in this thesis (cont.)

Key Publication	Model Description	Data gap	This Study
Kerr and Turner (1996)	Laboratory-based experiments using Na_2CO_3 replicated many features observed in mound springs, including crater and “break-out” development.	Although such features are observed on mound springs, Na_2CO_3 has different thermodynamic properties compared to $CaCO_3$.	The rate limited degasing of CO_2 in near-ambient temperature springwaters interpreted to produce similar precipitation effects observed during Kerr and Turner (1996) experiments. Heterotrophic metabolism interpreted from modelling to thought to partially offset the loss of CO_2 from springwater.
Bourke et al. (2007), Nelson et al. (2007), Linares et al., (2010), and Pentecost (2005), Williams and Holmes (1978)	Relationship between hydrostatic head and spring flow is a limiting factor; spring flow will slow and eventually cease when hydrostatic head and mound height become similar.	Thermoluminescence dating published by Prescott and Habermehl (2008) suggests spring activity may be longer lived than the time required for mound construction.	Evidence for erosion/dissolution features such as break-outs suggests hydrochemical stabilisation of mound construction. The delay in the onset of $CaCO_3$ precipitation due to rate limited CO_2 degassing and the interpreted slowing of degassing brought about by mound growth is used to explain the development of dissolution and erosion features as well as providing a mechanism for mound growth and flow stabilisation. Subsequent decreases in flow are thought to be related to either mechanical processes or a drop in the potentiometric surface.Break-out development may have an important aid in neotectonic-related fracturing.

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