Chapter 7

Palaeoclimate Research in Wollondilly and Kooringa Caves

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BACKGROUND

Caves are useful repositories for a variety of natural deposits, including speleothems, pollen, bones and sediments (Jennings 1985). The study of these deposits can provide important information on a range of environmental phenomena, such as past climates (palaeoclimate), surface flora and fauna, regional geomorphology and geological history.

Speleothems are secondary deposits of calcium carbonate (CaCO₃), which accumulate in karst caves, and are formed from meteoric waters that have percolated through the overlying soil and bedrock. These waters absorb carbon dioxide to form carbonic acid, which then dissolves the bedrock. They eventually become saturated with dissolved calcium carbonate. As the waters enter a cave (e.g. as drips), carbon dioxide (CO₂) degasses due to the low partial pressure of the cave atmosphere (Figure 7.1). This causes the waters to become supersaturated with respect to calcite, resulting in calcium carbonate deposition as speleothems. These form, amongst other things, stalagmites, stalactites, straws, flowstone and shawls (Harmon et al. 1978).

Speleothems, especially stalagmites and flowstones, are widely used as palaeoclimate archives for a variety of reasons:
* they can be dated precisely by uranium-series methods;
* they are sensitive to external climate-driven processes;
* their closed crystalline structure protects them from contamination, ensuring that the environmental signals they preserve remain intact;
* their position underground protects them from weathering and erosion.

Thus speleothems constitute one of the few terrestrial deposits capable of preserving a palaeoenvironmental record comparable to marine sediments and ice-cores (Winograd 2002, Lauritzen & Lundberg 1999).

Up to now, most speleothem studies have been conducted in the Northern Hemisphere, where they have been used to constrain the timing and severity of glacial-interglacial cycles and to provide higher-resolution information on periods of moisture deficit or surplus. Speleothem growth is dependent on sufficient recharge rainfall, a supply of biogenic soil CO₂ and above-freezing temperatures (Atkinson et al. 1978, Gordon et al. 1989). Such conditions are usually met during warmer (and often wetter) interglacials (Baker et al. 1993). Extreme cold periods (glaciations) can produce permafrost or ice, which inhibit CO₂ production and the movement of surface water into the vadose zone (Spott & Mangini 2002). In many parts of the world, glaciations also bring drier conditions, which can also lead to disruption of speleothem growth in ice-free areas (Gordon et al. 1989). However, not all parts of the globe experience fluctuations between warm-wet and cold-dry climates. In some places, the warmest

![Figure 7.1. Speleothem formation and the hydrological cycle processes (after Lauritzen & Lundberg 1999).](image-url)
surface conditions but initiated by piston flow characteristics, causing source change within the aquifer (Tooth & Fairchild 2003). High-resolution geochemical analysis of speleothems will be used to detect such changes but their causes may be unrelated to individual climatic events. Instead, the changes may have more to do with aquifer depth, complex flow characteristics due to bedrock heterogeneity. Thus far research suggests that speleothems precipitated at such depths and via such complex hydrology may not be suitable candidates for palaeoclimatic reconstruction solely based on their trace element records, especially at high (inter-annual) resolution.

**ANCIENT STALAGMITES**

Two broken stalagmites have been recovered from the Midwarre Extension and have been analysed for trace elements and the stable isotopes of oxygen and carbon. Plate 7.7 shows stalagmite WM3, which has a basal age of 79.1 ± 1.1 ka. This age was determined by Thermal Ionisation Mass Spectrometry (TIMS) uranium-series dating at the Australian National University. Other dates attempted at the tip and halfway along the growth axis were unsuccessful due to the extremely low uranium concentrations. Speleothems in southeastern Australia are typically very low in uranium (Goede et al. 1996) and those at Wombeyan are unfortunately at the lower end of this spectrum, with their content averaging 20 ppb. Even taking larger samples cannot overcome the difficulty of obtaining accurate ages.

Ages for the other stalagmite (WM1/WM2) are of great interest since the growth period of the stalagmite spans approximately 50,000 years through almost the entire duration of Marine Isotope Stage 5 (MIS 5). The basal age is 133 ± 3.7 ka, while the age of the tip is 83 ± 1.9 ka. At 121 ± 2.8 ka there is a growth hiatus suggesting a decrease in recharge due to lessening effective precipitation or perhaps increased evapotranspiration. The basal age suggests that growth may have been triggered by warmer, wetter conditions, as recent studies have placed the commencement of sub-stage 5e at around the same time (e.g. Spott & Mangini 2002). This assumption will need to be corroborated with further evidence.

Figure 7.9 shows changes in Mg and Sr concentrations through time for WM3. They are correlated strongly, and at about 64 mm from the tip, display elevated levels consistent with a sustained drying of the aquifer. At this point the diameter also decreases indicating a reduced growth rate, which can also be triggered by reduction in drip water supply. Prior to this point the Mg/Ca is 0.67± 0.15, which indicates that in comparison to presently precipitating calcite in this chamber the dripwater had a high matrix flow component and probable low discharge rate. After 64 mm from the tip, Mg/Ca rose significantly to 1.49 ± 0.48, with an accompanying elevation in Sr/Ca. This could suggest a dramatic reduction in recharge and prior calcite precipitation reflecting the drying of the aquifer.

Conversely it may be argued that the dramatic changes in the upper 64 mm might reflect the

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Plate 7.7. Cross-section of stalagmite WM3 showing sampling points for geochemistry and geochronology. Janice McDonald.
The study sites

Cave descriptions

Two caves (Kooringa and Wollondilly) have been chosen as study sites due to ease of access to active cave drips and the presence of broken fossil stalagmites. Both caves are extremely well decorated with many types of speleothems. These caves are well above the present level of Wombeyan Creek so all water influence is from rainfall percolating through the bedrock directly above the cave. Further cave descriptions can be found in Dyson et al. (1982).

Kooringa Cave was selected due to the rapid response of its driptowers to rainfall events (M. Chalker pers. comm.), enabling it to be used to model for baseflow conditions. The thin discontinuous soil cover (mean depth of ~3 cm; plate 7.1) and the shallowness of the bedrock above the drip sites (~15 m) also suggest a likely rapid response.

Wollondilly Cave is also being studied, in both the upper level (the Mulwaree extension) and at depth (the Paddy Fields). Due to the caves size and vertical range, the drips being studied provide good spatial distribution and exhibit a range of flow regimes.

Cave temperatures well away from entrances reflect the mean annual surface temperature (MAT) and this, in combination with stable isotopes, has been used in previous studies to determine paleotemperatures (Lauritsen & Lundberg 1999). Figure 7.2 shows the temperatures of the investigated chambers in Wollondilly and Kooringa Caves. Wollondilly (lower) has a mean temperature of 10.19°C ± 0.02, while the mean temperature in Kooringa is 10.90°C ± 1.41°C. Lower Wollondilly shows a lower temperature with smaller standard deviations due to its greater depth and distance from openings. Ideally, conditions in lower Wollondilly would more than likely simulate mean annual surface temperature. The temperatures in Upper Wollondilly (Mulwaree Extension) are quite elevated (14-15°C), however, to date only nine months of data are available and the mean temperature cannot be calculated. Humidity in this section of the cave is high ~ 99.5% (Michie 2003 pers. comm.).

The bedrock in which the caves are formed is Wombeyan Marble and described in Dyson et al. (1982). Geochemical analysis of the bedrock (table 7.1) has been undertaken to determine the ratio of trace elements to calcium. Deviations from this ratio in the driptowers may indicate extraneous sources of trace elements (e.g. precipitation, dust, soil) or the effect of chemical processes.

Climate and water budget

The climate at Wombeyan is warm to cool temperate with uniform rainfall (mean annual 900 mm). The site experiences high summer evapotranspiration due to a mean daily summer temperature of 24.7°C, compared with the mean annual maximum 17.9°C and annual mean daily min 6°C (Bureau of Meteorology 2003). Such climatic conditions should result in maximum recharge to the cave system during the winter months (figure 7.3). However, conditions such as the 2002 ENSO-induced

<table>
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<th>Element</th>
<th>Mean (SD)</th>
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<tr>
<td>Mg</td>
<td>2523 (315)</td>
</tr>
<tr>
<td>Sr</td>
<td>202 (12)</td>
</tr>
<tr>
<td>Fe</td>
<td>218 (64)</td>
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<tr>
<td>Al</td>
<td>60 (48)</td>
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<tr>
<td>Mn</td>
<td>36 (6)</td>
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<td>Na</td>
<td>27 (5)</td>
</tr>
<tr>
<td>Zn</td>
<td>10 (14)</td>
</tr>
<tr>
<td>K</td>
<td>36 (16)</td>
</tr>
<tr>
<td>Co</td>
<td>1.6 (0.8)</td>
</tr>
<tr>
<td>Ba</td>
<td>&lt;3.0</td>
</tr>
<tr>
<td>Cr</td>
<td>&lt;1.0</td>
</tr>
</tbody>
</table>

Table 7.1. Geochemical analysis of Wombeyan Marble presented as ug/g. All results based on three samples except Co.

Plate 7.1. Surface above Kooringa Cave showing the sparse vegetation, thin discontinuous soils and extensive exposed bedrock. Janece McDonald.
drought (525.8 mm annual rainfall) impact dramatically on water availability and change the expected recharge patterns as obtained using the mean water budget (Figure 7.4).

Continuous monitoring

On the surface (near Guineacor Cave) a recording pluviometer has been erected to monitor rainfall volume, intensity and timing (Plate 7.2). Within the cave several sets of monitoring equipment have been set up (Plate 7.3).

Each of the drip sites being monitored is currently precipitating calcite as either a flowstone or a stalagmite. Geochemical analysis of this calcite is

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**Figure 7.3.** Mean water balance for Wombeyan based on long-term mean rainfall and temperatures and Class A Pan evaporation data from Cowra (Meteorological Station 70263). These figures indicate that maximum recharge to the cave is during the winter months, while there is a strong moisture deficit during summer (Dotted line $P = E$, where $P$ = precipitation, $E$ = evaporation).

**Figure 7.4.** Actual water balance (circles) for Wombeyan Caves showing considerable deviation from the mean water balance (triangles). Apart from a high rainfall event in February, the El Niño event of 2002 left Wombeyan Caves with a water deficit for the remainder of the year. Southern Oscillation Index (SOI) values show sustained negative values during the water deficit period. Dotted line is $P = E$.

**Plate 7.2.** Solar powered recording pluviometer and directional dust collection apparatus above the caves, near Guineacor Cave. Janece MacDonald.

**Plate 7.3.** Cave water drip monitoring, water and calcite collection apparatus (Site K1, the Museum in Korrunga Cave). The drip sensor (A) is an infrared fork detector and each drip is recorded by the data logger (B). Calcite is precipitated (D) and collected on the glass ball (C), while drip water is collected in a bottle during monthly visits. Janece McDonald.
matrix flow paths in the maintenance of cave dripwater discharge and, in turn, the precipitation of calcite during dry spells. This would suggest that reduced effective precipitation would need to occur for periods in excess of several years for calcite precipitation to cease, since rainfall for 2001 and 2003 were also below average (639 and 610 mm respectively) and matrix flow was maintained.

Increasing drying of the aquifer can also result in the formation of air pockets in the bedrock fissures, into which the calcium-saturated water can degas and precipitate calcium carbonate (calcite) before the waters reach the cavern (Fairchild et al. 2000). This process is known as prior calcite precipitation and is indicated by increasing and covarying Mg/Ca and Sr/Ca in the dripwater, since the concentration of the trace elements Mg and Sr increases with respect to calcium as the calcium carbonate precipitates (Fairchild et al. 2000). Such dripwaters enriched in trace elements under such conditions should precipitate a stalagnite with a chemical signal reflecting low-flow conditions (Baker et al. 2000).

For drip site K1 (the Museum, Kooringa Cave) (plate 7.4), the overall correlation between Mg/Ca and Sr/Ca is: r = 0.87 (n = 19). However, from May 2002 to March 2003, when the water budget was in deficit (figure 7.4), this correlation became r = 0.97 (n = 11) and the Mg/Ca ratios were elevated. This trend reflects prior calcite precipitation and, if found in the modern calcite (analyses of which are in progress), will confirm that the speleothems are recording these important periods of interannual aridity.

Based on drip discharge and chemistry in Kooringa Cave it can be seen that there are two dominant flow regimes. In the first type, macro pore flow through fissures, joint bedding planes and fractures always shows a response to rainfall. The second type is slow ‘matrix flow’, which dominates during periods of low or zero recharge (figure 7.8). As recharge diminishes, the rapid macro pore flow decreases and its proportional contribution to the total drip discharge becomes less important, with an accompanying increase in the relative contribution from matrix flow. A hydrological model for this cave based on relationships between rainfall, dripwater discharge rates and dripwater chemistry has been developed. This simple model will form the basis for a more complex model explaining the hydrology of the extensive, deeper caves.

**Wollondilly Cave and Mulwaree Extension**

Compared with Kooringa Cave, Wollondilly Cave the hydrology of this cave is very complex with the drip water response to rainfall events showing time lags, nil response, flow-switching or response to only the highest rainfall intensities. The chemistry of the drip waters is also complex, which will have implications for the geochemistry of any precipitated calcite and consequently the interpretation of each speleothem’s palaeo-environmental history. This reinforces the need...
to understand the hydrology of sites where fossil speleothems have been collected for analysis. This will assist in the interpretation of the chemical and hydrological signature.

Two drip water sites in the Mulwaree extension (W1, W2) show a response to rainfall events, but there is a considerable time lag of the order of weeks. This possibly results from calcite obstructing macropore flow routes due to calcite precipitation build up, slowing down the flow. As this is the oldest level of the cave, such obstructions are to be expected.

Another dripwater site being investigated in the Mulwaree Extension, (W3) shows a relatively rapid, but inconsistent, response to rainfall. Numerous grikes above Wollondilly Cave allow rapid inflow from rain events, and promote the accumulation of soil and organic matter and tree-root penetration. The flow path from the surface may well be one of such grikes (Plate 7.5). The chemistry of this dripwater also reflects the diversity of flow pathways, with Mg/Ca ratio showing relatively high variability (1000° Mg/Ca = 15.07 ± 8.35, range 38.79). This large range indicates that the discharge alternates between macropore and micropore flow depending on recharge, and suggests rapid response to rainfall.

Three dripwater sites are being monitored in the lowest level of Wollondilly Cave (plate 7.6). Dripwater

Plate 7.6. Monitoring sites 6A, 6B and 6C in Lower Wollondilly Cave. All drips are precipitating as flowstone and all stalactites and parent drips are aligned along a jointing plane. The scalloped ceiling indicates the phreatic origin of the cave formation. Jinee McDonald.

W6A displays an almost constant discharge rate showing no response to rainfall input, suggesting that its source comprises older groundwater stored deep within the aquifer. The dating of this water by tritium suggests it to be modern water, approximately one to two years old. Compared with those sites that are responsive to precipitation events, Ca values are higher (127.44 ± 23.2 μg/l) and Mg/Ca ratios lower (14.94 ± 2.86). Variation in trace element signal and subsequent ratios is lower than that found in the upper cave levels and cannot be related to precipitation events or site water balance. This suggests that water in the aquifer at this depth is not subject to processes such as prior calcite precipitation or changes in the aquifer water pressure head, which could activate greater capacity flow routes (Tooth & Fairchild 2003).

For all dripwater sites in lower Wollondilly there is no obvious link between chemical signature and response to precipitation events or effective precipitation. The discharge of W5A is erratic and has a large range in Mg/Ca suggesting a flow contribution from both macropore and micropore sources and perhaps flow-switching between competing flow routes due to the spatial, dynamical and physical heterogeneity of the bedrock (Baker & Brundson 2003). Site W6C also shows evidence of undergoing flow-switching behaviour, seemingly unrelated to

Plate 7.5. Wombeyan marble cross-section at Wombeyan Quarry showing a complex network of fractures, jointing and bedding planes (macropore or preferential flow routes). L. J. Henderson.

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