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Nowranie Caves and the Camooweal Karst Area, Queensland:
Hydrology, Geomorphology and Speleogenesis, with Notes on Aquatic Biota

Stefan Eberhard

2 Churchill Ave, Margaret River WA 6285

Abstract

Development of the Nowranie Caves includes both phreatic and vadose components, with prominent influences on cave geomorphology exerted by joints, bedding and past changes in watertable levels. Active circulation is occurring within a phreatic conduit at moderate depth (22-30 m) below the level of the present watertable. Slugs of flood water can penetrate well into the flooded section of the cave, and it appears that dissolutional enlargement of the conduit may be occurring under present conditions. Speleogenesis in Nowranie Caves incorporates deeper phreatic processes in addition to shallow phreatic (i.e. watertable) processes. A series of three fossil, or occasionally re-flooded, phreatic horizontal levels in the Nowranie Caves correspond with similar levels in other Camooweal caves, and reflect a regional pattern and multi stage history of watertable changes linked with cave development. The stacked series of cave levels may reflect episodic uplift, wetter climatic episodes, or a combination of both - possibly dating from early to mid Tertiary times. Caves and dolines are the major points for groundwater recharge in the Camooweal area, and these are susceptible points for injection of contaminants into the groundwater system. A climatic and distributional relict, and locally endemic, fauna is present in the groundwater. The Nowranie Caves, and Camooweal area generally, has conservation significance as a karst hydrogeological and ecological system that has preserved a history of regional landscape and faunal evolution in northern Australia during the Quaternary.

Keywords: Camooweal, karst, hydrology, geomorphology, speleogenesis, biota

Introduction

The Nowranie Caves (138^0 11' 05" East; 20^0 03' 05" South) are situated in the Camooweal karst area within the Barkly karst region in north-west Queensland and Northern Territory (Figure 1). This paper contributes specific information on the Nowranie Caves and the Camooweal karst area generally, following a mapping and diving expedition there during 2000. Information is presented on water physico-chemistry and aquatic biota. Major outcomes of the expedition were:

1) Discovery and mapping of extensive conduit development at 22-30 m depth below the watertable;

2) Mapping of Great Nowranie and Little Nowranie Caves, including differentiation of upper, mostly fossil, phreatic levels;

3) Investigation of geologic and hydrologic influences on cave development;

4) Collection of aquatic fauna and measurement of water physico-chemistry.

The aim of this paper is to document these discoveries and interpret them in relation to cave geomorphology, local and regional hydrology, speleogenesis, and biogeography.

Regional Description and Physiography

The Barkly karst region corresponds to the geographical feature known as the Barkly Tableland (Stewart 1954). The carbonate rocks are flat lying, well-bedded and well-jointed dolomites and limestones of the Early Palaeozoic Georgina Basin (de Keyser 1974). The Mesozoic and Cainozoic geology, karst and cave development are described by Grimes (1974, 1988).

The regional climate is arid to semi-arid, with some monsoonal influence. At Camooweal the mean annual maximum temperature is 32.5^{0}C and the mean annual minimum is 17.3 ^{0}C. Evaporation (annual 2744 mm/year) exceeds mean rainfall in every month of the year. Most rainfall occurs during summer, with the annual mean about 400 mm. The vegetation is a mosaic of treeless grasslands and low open savannah woodlands.

The Barkly karst region is an uplifted peneplain. The Camooweal karst area, located in the headwaters of the Georgina River and tributaries, contains the highest density of cave development in the Barkly region (Figure 1). About 60 karst features including dolines, streamsinks and 30 caves occur within an area of about 60 x 30 km in the vicinity of Camooweal township (Figure 2). At least ten caves intersect the regional watertable located about 70 m below the surface of the peneplain.

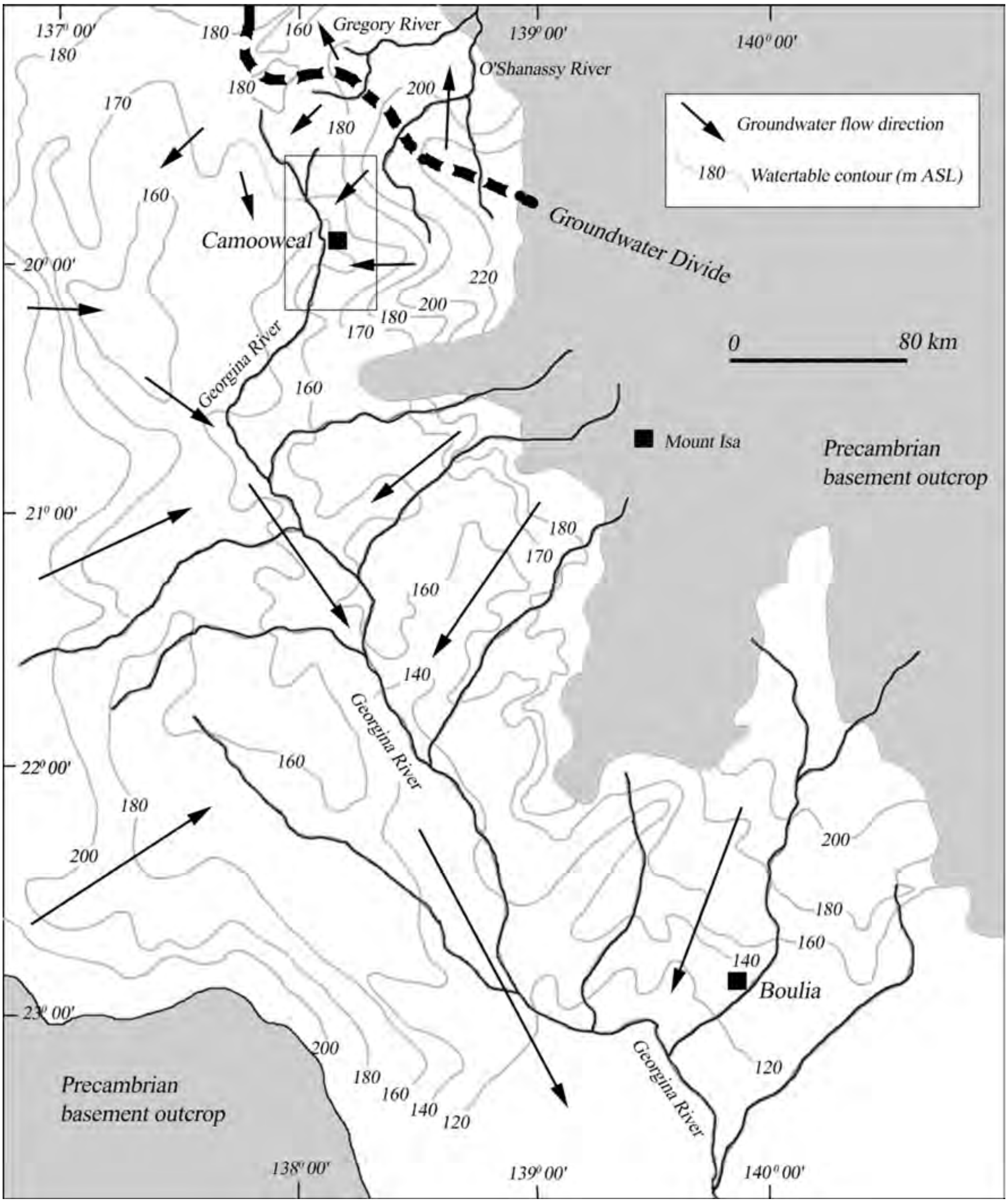


Figure 1. Southeastern Georgina Basin, showing surface drainage, watertable contours and inferred groundwater flow directions, including the groundwater divide inferred to exist between the headwaters of the Georgina River and Gregory –O'Shanassy Rivers. The Camooweal karst area (see Figure 2) is the area inside the box. Adapted from Randal (1978).

The Camooweal caves are located within 20 km, mostly on the eastern side, of the main channel of the Georgina River, which drains south through the Channel Country into the Lake Eyre Basin. A fully integrated surface drainage system is also present, whilst the extensive black soil cover restricts infiltration except where it has been stripped back to expose the carbonate surface (Grimes 1988). Where this has occurred then surface runoff may be diverted underground via cave entrances or sink points in dolines. The base of surface watercourses, and much of the peneplain surface generally, is otherwise sealed by the black clay soil that prevents downward leakage and diffuse recharge of the karst aquifer. Some surface runoff is detained in semi-permanent waterholes that may persist throughout the dry season, such as Nowranie Creek waterhole.

Geomorphology

Description of Nowranie Caves

The Nowranie Caves comprise Great Nowranie Cave (4C-6) and Little Nowranie Cave (4C-11). The entrances to the caves are situated 120 m apart, whilst a doline of 40 m diameter, with a depth of less than one metre, is located 200 m northwest of the cave entrances

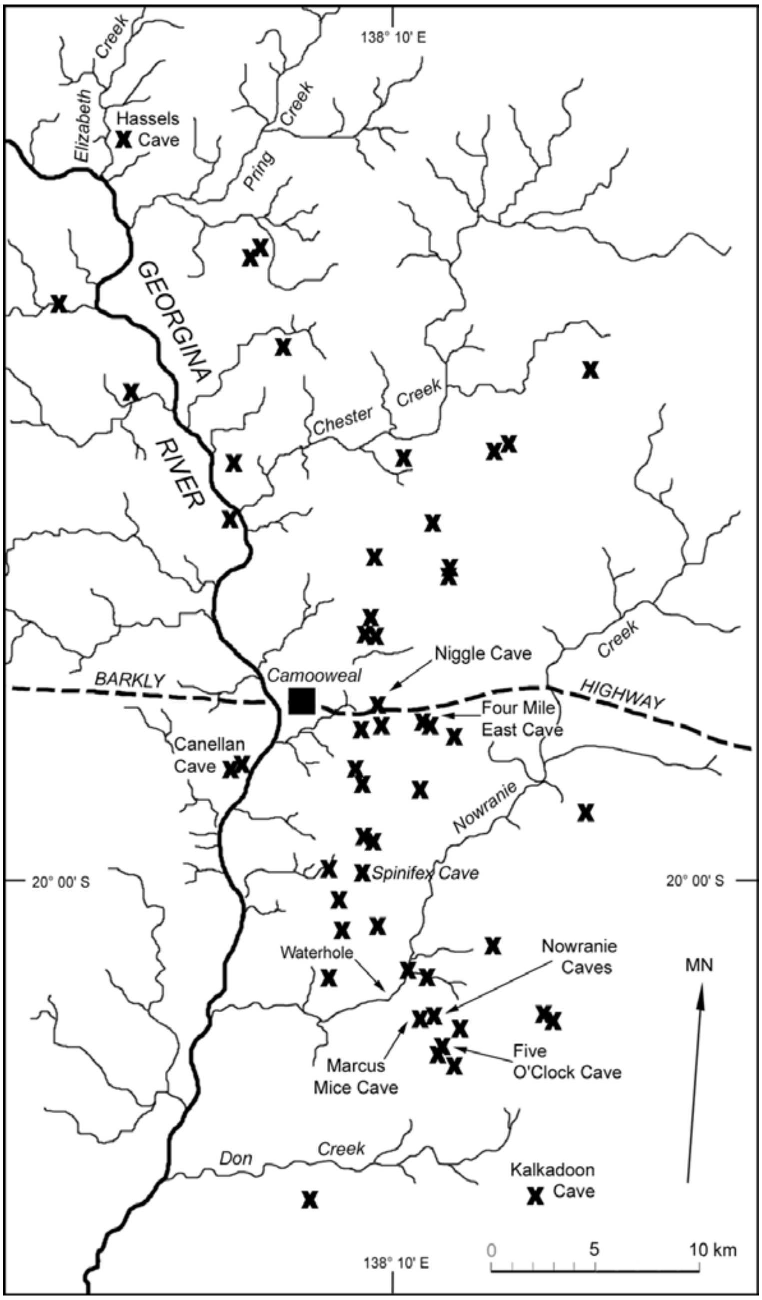


Figure 2. Camooweal karst area showing surface drainage and locations (X) of karst features (caves, dolines, stream sinks), including features named in text. Adapted from U.Q.S.S. Map 141, compiled by R. Canty and K. Grimes (1979).

(Figure 3). Both caves descend in a stepped series of vertical shafts alternating with horizontal sections, to sump pools that represent the watertable lying at about 70 m below the surface of the plain (Figure 4).

Nearly 1.5 km of cave passage has been mapped so far, including 500 m of flooded passage explored by cave diving. Further diving exploration will undoubtedly extend the presently known length of the system, and possibly result in a navigable subterranean connection between Little Nowranie and Great Nowranie. Passages in these caves approach to within 50 m horizontally and 25 m vertically of each other.

Great Nowranie Cave captures overland flow which otherwise would drain into Nowranie Creek located 1.5 km away. Two shallow drainage gullies, each about 500 m in length, converge at the large collapse doline entrance of Great Nowranie Cave. The doline engulfs episodic surface runoff from the surrounding plain. Below the 18 m deep entrance pit (Figure 5), a large passage (Upper Level) with a width and height up to 10 m, extends in a northwest direction for some 100 m to a second shaft 14 m deep. Near the level of the top of the second pit a maze of passages extends laterally (Figure 6). This network is intersected by two other vertical pits that also connect to the next level (Middle) below. The Middle Level includes passage development as a tall canyon, and an elliptical tube 5 m wide and 3 m high (Figure 7). A third series of vertical shafts and a narrow fissure drop 15 m to the third horizontal level (Lower Level) just above the watertable. This level comprises tubular passages of 1-2 m diameter that are subject to regular back flooding.

At a sump pool at the watertable, a steeply inclined fissure descends to a depth of 30 m below the water surface, from which a horizontal conduit 3-4 m diameter trends initially in a southwesterly direction. The flooded conduit meanders considerably but then trends in a more southerly direction to a point reached by diving at 23 m depth and 500 m from the sump pool. The profile of the conduit resembles that of a phreatic loop (*sensu* White 1988) between 22 – 30 m water depth, with very gently rising and falling limbs of several hundred metres wavelength and shallow amplitude (maximum 8 m). Two side passages located at 90 m and 150 m from the start of the dive were partly explored in a northerly direction. The passage at 90 m intersected a vertical fissure that continued upwards beyond the depth of 21 m explored.

Little Nowranie Cave has comparatively smaller dimensions and spirals steeply downwards with little horizontal development between the vertical shafts. The levels of horizontal development roughly correspond with those in Great Nowranie. A deep sump pool at 70 m below the surface represents the local watertable, but this was not explored by diving during the 2000 expedition.

Cave Patterns

The Nowranie Caves exhibit a predominantly branchwork pattern of development (*sensu* Palmer 1991, 2000). The cave patterns

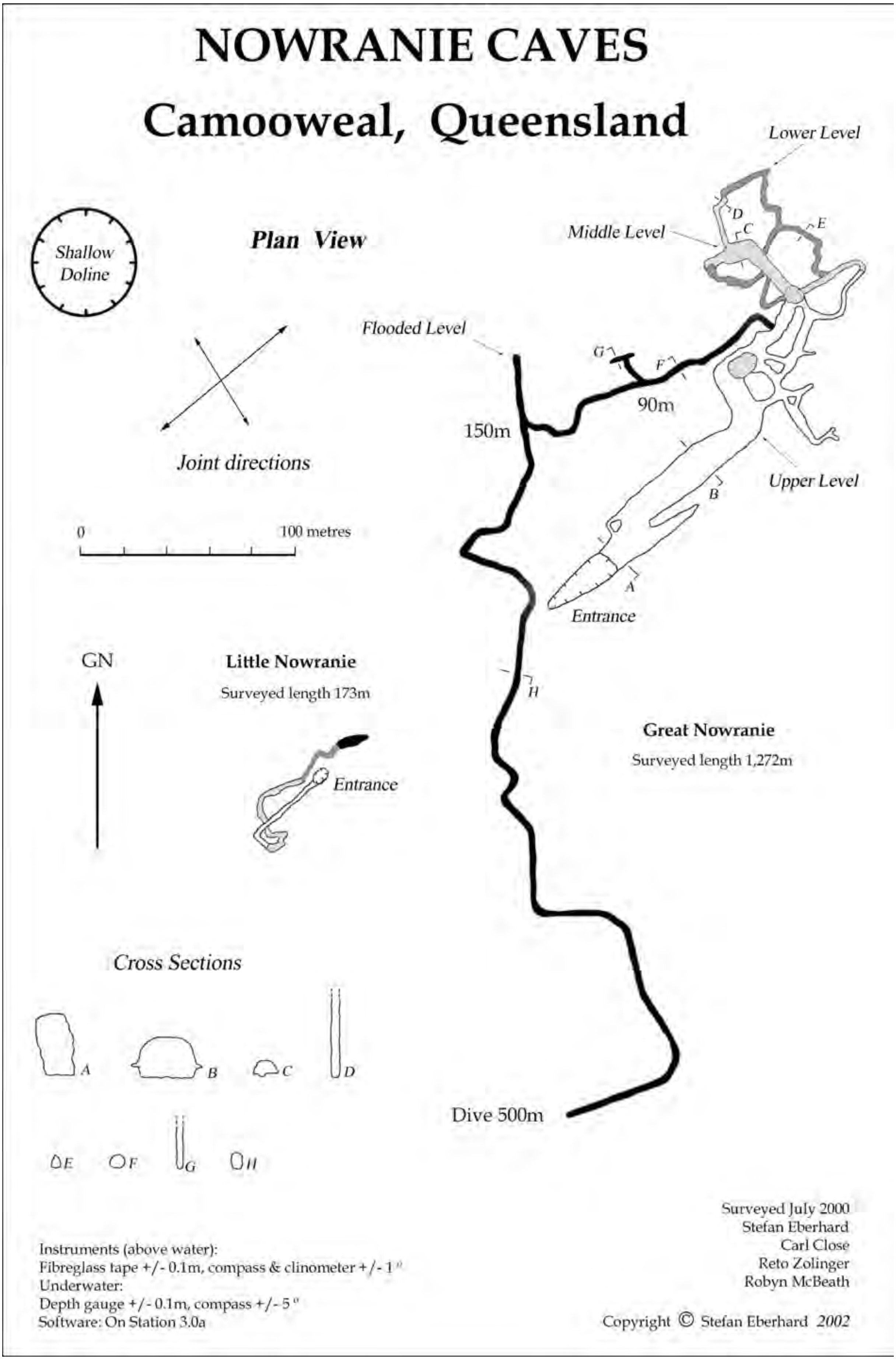
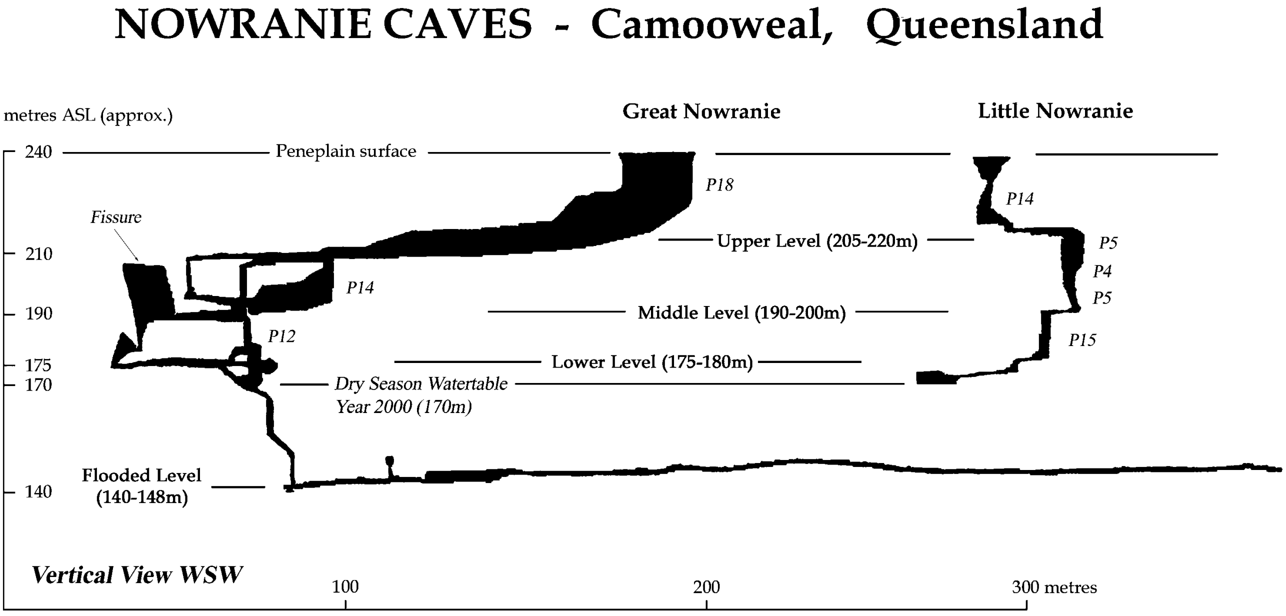


Figure 3: Plan of Nowranie Caves showing surveyed passages and levels, including joint directions.


NOWRANIE CAVES - Camooweal, Queensland

Instruments (above water):
Fibreglass tape +/- 0.1m, compass & clinometer +/- 1 °
Underwater:
Depth gauge +/- 0.1m, compass +/- 5 °
Software: On Station 3.0a

Surveyed July 2000
Stefan Eberhard
Carl Close
Reto Zolinger
Robyn McBeath

Figure 4: Projected profile view (projected onto a WSW plane) of Nowranie Caves showing elevation (in metres above sea level – m ASL) of the upper, middle and lower levels in relationship to the peneplain surface, present watertable, and the flooded conduit. Depth of vertical pitches (P) indicated in metres.

include angular alignments and irregular networks of passages controlled by jointing, in addition to curvilinear passages with minor anastomotic maze and spongework development. The cave morphology includes both phreatic and vadose components, with prominent influences on development exerted by joints, bedding and higher watertables in the past. A vertically stacked series of horizontal levels indicates a multi stage history of development linked with changes in watertable levels. Since lowering of the watertable there has been ongoing enlargement and modification of upper level passages by ephemeral vadose flows and back-flooding.

Stratigraphic and Structural Influences

Geologic structure and lithology can exert strong influences on cave development and morphology (Ford & Williams 1988, White 1988), and a number of such possible controls are evident in the development of Nowranie Caves. The majority of passage development above the present watertable occurs along a series of closely spaced parallel joints oriented at SW-NE (60-240^0 magnetic). The entrances of Great Nowranie and Little Nowranie Caves are developed along the same joint, whilst the plan survey indicates at least 5 parallel joints spaced about 5 to 20 m apart. Horizontal passages, some meandering but aligned approximately perpendicular to the major joint direction, connect sections of cave developed along separate joints. Another set of joints, aligned approximately SE-NW, is inferred to be influencing the perpendicular passage alignments (Figure 3). The joint planes are vertical


Figure 5. Great Nowranie Cave – view into upper level tunnel from base of 18m entrance pit. Note the influence on passage morphology of horizontal bedding and vertical / sub-vertical joint planes. Photo Stefan Eberhard.

to sub vertical, resulting in passage profiles that are either vertical, or steeply inclined fissures inclined at about 80^0 to vertical.

Cave Levels

A distinct series of coplanar, horizontal passage networks are developed at different levels, which are connected together by vertical pits or narrow fissures. The horizontal passages are clearly of phreatic origin, whilst the connecting shafts and fissures also appear to be of primary phreatic origin. Four distinct zones of horizontal phreatic tube development were identified. The levels, from highest to lowest, occur in relation to the present (2000) watertable (Figure 4):

+ 40-47 m (Upper Level);
+ 23-30 m (Middle Level);
+ 4-9 m (Lower Level);
- 22-30 m (Flooded Level).

The lowest phreatic level is a permanently flooded and presently active drainage conduit that is recharged by wet season runoff sinking into the entrance of Great Nowranie. The level above this (Lower Level), situated 4-9 m above the dry season watertable, is intermittently flooded by wet season runoff, probably on an annual or semi-annual basis as evidenced by fresh mud deposits. The Middle and Upper Levels are fossil phreatic passages, now drained, although they are still subject to dissolutional enlargement and modification by seasonal flooding which occasionally fills the system to a height of 40 m above the dry season watertable level.

Vertically extensive fissures, which are dissolutionally enlarged joints interpreted to be of primary phreatic origin, extend the full 70 m vertical range connecting the lowest flooded level to the uppermost horizontal level. Grimes (1988) reported vertical fissures connecting different levels in Five O'Clock Cave (4C-36), which he also interpreted to have been initiated phreatically, following a joint, although subsequently enlarged by vertical vadose flows. Dissolutional enlargement of these deep vertical fissures was evidently initiated at some depth below the watertable, and their development may have been synchronous with horizontal maze

Table 1. Comparison of levels between different caves (listed from north to south), including altitude of entrance on the peneplain (estimated from 20 m interval contour maps), metres below ground level (m BGL) to standing water level (SWL), and approximate altitudinal range of identified phreatic levels (Upper, Middle, Lower, Flooded). Altitudes are metres above present sea level (m ASL). The source and accuracy (standard ASF/BCRA grades) of cave survey information is indicated. Cave maps done by UQSS are held in records of the Chillagoe Caving Club and the Central Queensland Speleological Society. The maximum expected error for altitude values is +/- 5m.

Cave Name	Reference levels			Approx. altitudinal range of levels (m ASL)				Survey notes
	Entrance (m ASL)	**SWL** (m BGL)	**SWL** (m ASL)	**Upper**	**Middle**	**Lower**	**Flooded**	
Hassels 4C-3	245	75	170	absent	absent	absent	136-170	UQSS 1978, grades 2 to 5
Niggle 4C-15	240	70	170	?	?	175-190	140-170	Estimated, dived to 30m
Four Mile East 4C-13	240	73	167	217-221	201-203	171-173	<167	SSS 1970, grade 2
Canellan 4C-10	240	75	165	?	?	?	<165	UQSS, Bourke et al. 1969, grade 4
Great Nowranie 4C-6	240	70	170	205-212	190-194	177-179	140-170	Grade 4 survey, Eberhard et al. 2000
Little Nowranie 4C-11	240	70	170	215-217	191-193	173-178	<170	As above
Five O'Clock 4C-36	240	55 (perched) 70 (SWL)	170	218-220	195-200	184-187	<170	UQSS surveys 1974-78, grade 2 - 4
Marcus Mice 4C-34	240	68	172	223 +/-	?	?	159-172	UQSS 1978, grades 2 to 5
Spinifex 4C-33	240	Est. 70	170	?	?	?	130-170	Unsurveyed, dived to -40m
Kalkadoon 4C-18	240	75	165	?	?	?	<165	UQSS

Figure 6. Upper Level in Great Nowranie Cave showing network of horizontal phreatic tubes and the vertical shaft (14 m deep) which connects below to the Middle Level. The shaft and horizontal levels have subsequently been modified by seasonal vadose inflow waters and back-flooding. Photo Ken Grimes.

development (at different times and levels) in the shallow phreatic zone within a few metres of the watertable surface.

The levels identified in the Nowranie Caves correspond with similar levels in other Camooweal caves, thus reflecting a regional pattern and history of watertable changes linked with cave development. The different levels and their respective heights in relation to the local watertable and present sea level, are compared with other caves in the Camooweal area in Table 1. The altitude of cave entrances on the peneplain is about 240 m above present sea level (ASL). At least ten caves intersect the regional watertable located about 70 m below the surface of the plain at about 170 m ASL. The Upper, Middle and Lower Levels in the Nowranie Caves corresponds with similar levels recorded by Grimes (1988) in Five O'Clock Cave, located 1.5 km east. Three distinct phreatic levels at approximately similar elevations also occur in Four Mile East Cave (4C-13) located 14 km north. The concordance in levels between these different caves suggests they are of similar ages, and share a common evolutionary history of development.

Distinct levels are evident in five other deep Camooweal caves, although further survey work is needed to define the different levels in these caves (4C-10, 15, 18, 33, 34), however, it appears that these also reflect a general regional pattern. Extensive flooded horizontal conduits have still to be explored in other caves, although several sumps have been dived to depths between 30 – 40 m (4C-3, 15, 33) with exploration still incomplete in some of them.

An exception to the general pattern of cave morphology occurs in Hassels Cave (4C-3), which has the form of a single narrow vertical fissure with no upper-level horizontal phreatic development. This cave, which is a geographic isolate in the Camooweal area, may have been subject to different hydrogeological conditions during development, or it may be younger in age than the other caves.

Figure 7. Middle Level in Great Nowranie Cave – phreatic tube subsequently modified by lateral undercutting from vadose flood waters. The Flooded Level is a phreatic tube of similar dimensions. Photo Stefan Eberhard.

Hydrology

Recharge

Groundwater recharge appears to be more or less restricted to areas where the clay soils have been stripped back and the underlying carbonate bedrock exposed. This occurs in dolines and cave entrances that act as the major groundwater recharge points in the area, due to the impermeability of the black soil which prevents diffuse infiltration. Groundwater recharge is therefore highly localized and dependent on wet season rainfall events of sufficient intensity to cause surface runoff within the small cave catchment areas. When these precipitation events occur then rapid and direct recharge occurs, often associated with severe flooding of cave passages.

The catchment areas for groundwater recharge are relatively small in relation to the surface drainage system, and the size of the caves seems to reflect the size of the surface catchment around their dolines. The relatively large size of Great Nowranie Cave is attributed to a catchment area estimated at about 2 km^2, although the catchments of some other large caves such as Kalkadoon (4C-20) are smaller than this.

Point source inflows in dolines and cave entrances are especially susceptible points for injection of contaminants into the groundwater system. This risk is exacerbated when dolines and caves are utilized for dumping of rubbish such as occurred in the past at Niggle Cave (4N-15)and Tar Drum Sink (4N-12).

Water Physico-Chemistry

Water temperature was measured *in situ* with a divers underwater digital thermometer (+/- 1 ^{0}C). Water samples were collected for *in vitro* measurement of pH, conductivity and dissolved oxygen. Samples were measured within 24 hours of collection using calibrated portable instruments (WTW pH 320, WTW LF320 conductivity, and WTW OXI 320). Observations of water clarity and stratification were made during diving. Results are shown in Table 2.

The Nowranie sump waters were fresh (EC range 333 – 375 µS/cm @ 25^0 C) and oxygenated (DO range 20–40% saturated), with a measured pH range from 6.78 to 7.87. The waters varied in both temperature (range 26 - 29^0 C) and clarity along the longitudinal profile, as well as displaying distinct thermal stratification. The entire water column in the initial 150 m of the sump was isothermal at 26^0 C. Beyond 150 m distance into the sump an abrupt thermocline at about –25 m water depth separated cooler (26^0) underlying waters from warmer (29^0) upper waters. The thermocline also coincided with a distinct change in turbidity – the cooler bottom waters being turbid which limited diver visibility from 0 to 2 m , whilst the warmer waters above were 'crystal' clear and had excellent visibility (> 10 m). The turbid waters were interpreted as being a recent injection of cooler surface floodwater, that had displaced warmer less dense groundwaters upwards where flow conditions had been insufficient to cause mixing. The further reaches of the sump beyond 200 m penetration were generally warmer and clearer although isolated patches of cool turbid water were encountered. These might indicate the proximity of other vertical injection points, or be remnants of earlier slow-moving slugs of floodwater traversing the flow path within the Nowranie sump.

The mean annual surface temperature at Camooweal is about 25^0 C, whilst the geothermal gradient in the Nowranie area, mapped from boreholes by Randal (1978), is about 15 m per degree. The sump waters in Nowranie are about 100 m below the surface so the temperature of groundwaters in thermal equilibrium with the surrounding rock should be around 31.5^0 C, based on Randal's geothermal gradient. This is close to the 29^0 actually measured. The maximum water temperatures measured in the Nowranie sump fall within the range of air temperatures (28 – 30^0) typically measured in the deep zone of Camooweal caves (Halbert 1970, K. Grimes, pers. comm.).

The limited data on the water chemistry indicate that slugs of flood water can penetrate well into the flooded section of the cave, and since this water is probably undersaturated with respect to carbonate, it appears that dissolutional enlargement of the conduit is presently occurring.

Local Drainage Patterns

Local drainage patterns and flow directions within the Camooweal caves are indicated by the diving discoveries and surveys of the air-filled sections of caves. The major trend of base level flow in Great Nowranie and Five O'Clock Caves is southwards, although meanders and abrupt directional changes occur in these curvilinear conduits. Upper level passage development in Four Mile East Cave follows joints aligned SW-NE and WNW-ESE, whilst low level development just above the present watertable (The Bowel) directs flood overflow drainage towards the SW. In Marcus Mice Cave, a narrow vertical fissure at the level of the watertable extends for several hundred metres, apparently following a joint oriented approximately SW-NE. Hassels Cave is similarly developed as a narrow vertical fissure aligned roughly E-W, whilst diving in 1998 explored the fissure to 34 m water depth (S. Eberhard unpubl. data).

The drainage patterns in Kalkadoon Cave and Niggle Cave consist of ramifying distributary networks that radiate away from the entrance inflow area (Grimes 1988). In Niggle Cave the major flow is directed WSW from the entrance to a large sump at the Melting Pots which has been dived to 30 m depth. In Kalkadoon Cave, significant passage development of the CASA and UQSS Extensions suggests that major flow occurs in both southerly and westerly directions respectively, although passages also branch outwards in easterly and northerly directions as well. A pool in the UQSS West Passage may be the dry season watertable.

Regional Drainage Pattern

In the Camooweal area the regional watertable is intersected in the caves at an elevation of about 170 m above sea level (ASL). Within the level of error (+/-5 m) expected from land surface elevations interpolated from 20 m contour intervals on topographic maps (1: 100,000), and levels reduced from cave surveys which ranged in precision from ASF Grade 2 to 5, there is no obvious gradient in the watertable, at least in a north-south direction (Table 2). The deduced level of the watertable in Hassels Cave is similar to that in Four Mile East, Niggle and Canellan (4C-10) Caves located some 30 km south, as well as Nowranie and Marcus Mice (4C-18) Caves located 45 km south of Hassels. Thus the level of the watertable measured in the caves lies within the range for the regional watertable surface interpreted from measurements in bores made by Randal (1978).

A locally perched (+15 m) sump at about 185 m ASL occurs in Five O'Clock Cave. Beyond the sump a gently rising phreatic loop passage extends for 350 m before continuing in a gentle decline for a further 350 m to the brink of a shaft that drops about 15 m into a pool, presumably at the level of the regional watertable.

The destination of the groundwater draining the Camooweal karst remains somewhat of a mystery, there being no major springs in the immediate area. At Lawn Hill and Riversleigh located some 150 km north of Camooweal there occur large karst springs that emerge from the edge of the Barkly Tableland and drain northwards into the Gulf of Carpentaria via the Gregory and O'Shanassy Rivers (Drysdale 2001; Drysdale, Taylor & Ihlenfeld in press). The springs in the Lawn Hill – Riversleigh area are at elevations of between 135 to 170 m ASL, but they are in a separate sub-basin to the Georgina River. Randal (1978) mapped the regional watertable surface of the southeastern Georgina Basin from boreholes, and identified a groundwater divide at a minimum elevation of about 175 m ASL some 60 km north of Camooweal. From here the regional gradient of the watertable is southwards, so groundwater movement in the Camooweal karst must be in this direction (Figure 1).

Speleogenesis

The discovery in Nowranie Caves of an active phreatic conduit at 22-30 m depth below the present watertable is significant for understanding present and past hydrology within the Camooweal karst. It clearly shows that speleogensis in this karst incorporates deeper phreatic components in addition to watertable components.

The mixture of phreatic loops and watertable leveled components within the Nowranie Caves system resembles a Type 3 cave in the Four State Model for the development of common cave systems (Ford & Ewers 1978; Ford & Williams 1989). These types of cave are a mixture of shorter, shallower loops and quasi-horizontal canal (i.e. watertable) representing a higher state of fissure frequency and greater exploitation of joints and bedding planes than found in Type 2 (phreatic cave with multiple loops) and Type 1 (bathyphreatic cave). The discovery of an active phreatic conduit at moderate depth below the present watertable excludes the Nowranie Caves from classification as Type 4 (ideal watertable cave).

In a study of the depth of conduit flow in unconfined carbonate aquifers, Worthington (2001) found that the flow depth of conduits was directly proportional to flow path length and stratal dip. Deep conduit development was favored in steeply dipping strata for flow paths > 3 km, with steeply dipping strata aiding the flow of undersaturated water to depth along bedding planes. The absence of springs near to Camooweal indicates a long subterranean flow path, with a distance of ca. 400

Location	Distance (m from start of dive)	Water depth (m)	Temp (°C)	pH	Conductivity (µS/cm @ 250C)	DO (% Sat.)	Date
Great Nowranie Cave	0	0	26	6.78–6.89	340	20-40	30-6-00
	0	-6	26	7.87	333	26	8-7-00
	100	-26	26	-	-	-	3-7-00
	200	-25	28	-	-	-	3-7-00
	300	-24	29	-	-	-	3-7-00
	370	-25	29	-	-	-	3-7-00
	475	-23	29	7.49	375	30	7-7-00
Nowranie Ck Waterhole	-	0	18	7.96	540	100	1-7-00

Table 2. Physico-chemical characteristics of water measured at different depths and distance in Great Nowranie sump, compared with stagnant surface runoff waters in Nowranie Creek Waterhole.

km to the nearest likely output south of Boulia (Figure 1). This could help explain the existence of submerged phreatic passages well below the present watertable, although conduit depths at Camooweal are an order of magnitude less than the depths reached in some of the world's largest cave-spring systems developed in dipping limestones. In these systems depths of > 100 to 400 m are reached along flow path lengths of under 14 km. At Camooweal the inferred flow path length is an order of magnitude greater than these other systems, although the horizontal bedding dips would not be conducive to the development of deep conduits in the manner suggested by Worthington's model. At Camooweal, it seems that the flow path is able to follow joints to moderate depth.

The degree to which deeper phreatic and watertable speleogenetic processes may have been temporally coupled during the evolutionary development of the cave system remains to be fully elucidated. Deeper phreatic circulation, as opposed to shallow phreatic (i.e. within a few metres of the watertable) circulation, appears to dominate the present hydrological regime, however the upper horizontal levels indicate strong piezometric influences under elevated watertables in the past. The apparent absence of a similar zone of intense lateral dissolution at the level of the present watertable is somewhat puzzling in this regard, although such a zone may in fact be represented by the Lower Level which is only 4 – 9 m above the dry season watertable, and which is subject to re-flooding at annual or semi-annual intervals. Alternatively, the watertable may be in a state of flux and presently undergoing readjustment to a new, lower base level.

In Five O'Clock Cave, Grimes (1988) observed bedding control in the development of phreatic passage levels, with preferential enlargement along more soluble beds. Whilst it may be difficult to distinguish bedding and piezometric effects in these flat lying rocks, the occurrence of horizontal zones of intense dissolution and flat roofs to passages and chambers, suggests that this development occurred near to the watertable surface at the time, albeit under the influence of flat bedding. Spongework dissolution features at these levels indicate conditions of slow phreatic flow.

Assuming that the Upper, Middle and Lower Levels in the Nowranie Caves were developed near to the watertable surface at the time, then they represent palaeo watertables at circa 205-220, 190-200, and 175-180 m ASL. These are now perched, essentially fossil features, which are only occasionally subject to re-flooding. The levels are interpreted to represent discrete still-stand periods in the regional watertable history, with presumably younger still-stands developed at successively lower levels. However, the probability of deeper circulation needs to be considered in interpreting the different cave levels in relation to palaeo watertables and history of the region. Nonetheless, the upper horizontal levels are interpreted as lying close to the original watertable surfaces due to the enhanced dissolution in these zones.

The pattern of cave development throughout the Camooweal area is characterized by passages which extend away from cave entrances, and even bifurcate into smaller distributaries further away from the inflow point. This pattern implies that the caves are not collapse windows into underlying conduits that originated elsewhere, but are themselves the points of origin for speleogenesis. Caves occur only where the black soil cover is breached. Gaps in the black soil cover occur in a variety of settings, including dolines and the edges of limestone rises, in areas of more porous lateritic soil, and, sink points within, or beside, major stream courses (K. Grimes pers. comm.). Cave initiation is not suspected where the soil cover has not been breached, or leakage through it does not occur. The high density of caves and dolines in the Camooweal area may be because the black soil cover is not as extensive there as elsewhere in the Barkly region (Grimes 1988, Figure 1). Because the caves could only have started to form once the black soil cover was breached the caves must be younger than the black soil, although the origin and age of the soil remains uncertain.

Whilst speleogenesis post dates formation of the black soil, the timing of cave formation also remains poorly constrained. The Mesozoic and Cainozoic development of the area is discussed by Grimes (1974). East of Camooweal the limestones are overlain by thin Mesozoic sediments and lateritic soils, which developed on a mid Tertiary planar land surface. This surface was uplifted in mid and late Tertiary times, but the tableland has been subject to little erosion since then (Grimes op. cit.). Minimal downcutting of the Georgina River has occurred, although stream incision and dissection is continuing in the northern margins of the tableland. Most of the higher levels in the caves could have developed during wetter climates of the early - mid Tertiary, and they could have been drained during uplift of the peneplain in the mid - late Tertiary (Grimes 1988). The stacked series of cave levels indicate a multi stage history of cave development, which may reflect episodic uplift, wetter climatic episodes, or a combination of both. If sequential downward development of the cave levels occurred in response to uplift, then the lowest cave levels must have formed after the last uplift period and therefore cannot be older than late Tertiary. The upper cave levels must be somewhat older than this.

Aquatic Biota

Growths of red-brown filaments up to 50 mm long occur suspended from the ceiling in the warm waters beyond 200 m in the submerged passage of Great Nowranie (Figure 3). It is postulated that these might be colonies of filamentous, possibly iron metabolizing, bacteria. Similar colored deposits of flocculent matter on the floor of the 90 m side passage, and further into the sump, might also be partly bacterial in origin. Bacterially mediated conversion and precipitation of soluble ferrous iron (Fe^{2+}), into $Fe(OH)_3$, occurs rapidly at pH 7.5 – 7.7 (Boulton & Brock 1999), which is within the pH range measured in Nowranie sump waters.

One species of aquatic macro-invertebrate - an amphipod crustacean - was collected from Great Nowranie and Hassels (4C-3). The amphipods were most abundant near the beginning of the sump pools, presumably due to the supply of fresh food sources in the form of organic material (vegetation and animals) transported into the cave by gravity and flood waters.

The amphipod is a new, undescribed species of stygobite belonging to the genus *Chillagoe* (J. Bradbury pers. comm.). This new species is known only from this karst groundwater system, where it is likely to be endemic. It is morphologically similar to, but distinct from, *Chillagoe thea*, a species that inhabits the Chillagoe caves 600 km to the east of Camooweal (Barnard & Williams 1995, Bradbury & Williams 1997a).

Both species are stygobites and entirely restricted to their respective karstic groundwater habitats. The distributions of the Camooweal and Chillagoe species extends more to the north in Australia – by many hundreds of kilometres - than any surface aquatic amphipod. An explanation for this is that freshwater amphipods are not common in subtropical and tropical waters and only subterranean waters in these regions provide the low temperatures and more stable environmental conditions required to support amphipod populations (Bradbury & Williams 1997b).

Many groundwater invertebrates have strikingly restricted distributions, combined with low dispersal powers that set strong limits on their ranges (Strayer 1994). The Camooweal and Chillagoe species are derived from old freshwater ancestors that presumably once occurred on the surface at both locations in the distant past. Their biogeography reflects the general pattern observed for stygobiont amphipods of freshwater origin in Australia, that of geographically restricted ranges which coincide with areas of the continent not inundated by the sea during the Cretaceous marine transgression (Bradbury & Williams 1997a, b). The Cretaceous marine transgression inundated most of the land area between Camooweal and Chillagoe, so it is considered unlikely that stygobiont amphipods of freshwater origin will be found in the intervening area, although stygobionts with marine affinities might occur. If the Camooweal and Chillagoe species share a common ancestry, then this lineage of amphipods was presumably present in both regions prior to the Cretaceous marine transgression.

The timing of colonization of groundwater environments by this lineage remains uncertain, however Bradbury & Williams have suggested that a succession of favourable (wetter and colder) and unfavourable (drier and warmer) climates during the previous 65 million years or so, could have driven the surface populations to seek subterranean refugia. The surface dwelling ancestors became extinct whilst the subterranean populations survived and gradually evolved into new and highly specialized underground species. Thus, colonization of the Camooweal groundwaters presumably occurred at a time in the past when climatic conditions still remained favorable for surface-dwelling amphipods, whilst at the same time, karstification of the Camooweal carbonates had proceeded to the degree of providing a suitable groundwater habitat. Investigation of evolutionary relationships and divergence within the genus *Chillagoe,* might therefore help to constrain the ages of cave development at both Camooweal and Chillagoe.

Conclusions

1) The Nowranie Caves includes both phreatic and vadose components, with prominent influences on cave geomorphology exerted by joints, bedding and past changes in watertable levels.

2) Active circulation is occurring within a phreatic conduit at 22-30 m depth (140 – 148 m ASL) below the level of the present watertable (170 m ASL) in the Nowranie Caves. Slugs of flood water can penetrate well into the flooded section of the cave, and as these waters are probably dissolutionally aggressive, ongoing enlargement of the conduit may be occurring under present conditions.

3) The discovery of an active phreatic conduit at moderate depth below the present watertable in Nowranie Caves shows that speleogenesis in this karst incorporates deeper phreatic processes in addition to shallow phreatic (i.e. watertable) processes. Deep and shallow phreatic processes may have occurred synchronously.

4) A series of three fossil, or occasionally re-flooded, phreatic horizontal levels in the Nowranie Caves correspond with similar levels in other Camooweal caves, and reflect a regional pattern and multi stage history of watertable changes linked with cave development. The stacked series of cave levels may reflect episodic uplift, wetter climatic episodes, or a combination of both - possibly dating from early to mid Tertiary times.

5) Because of the impermeability of the black clay soils, which prevents diffuse infiltration, caves and dolines are the major groundwater recharge points in the Camooweal area. These sites are susceptible points

for injection of contaminants into the groundwater system.

6) A climatic and distributional relict fauna is present in the Camooweal karst groundwater. Colonization of the Camooweal groundwaters presumably occurred at a time in the past when climatic conditions remained favorable for surface-dwelling amphipods, whilst at the same time, karstification of the Camooweal carbonates had proceeded to the state of providing a suitable groundwater habitat.

7) The Nowranie Caves and Camooweal area generally, has conservation significance as a karst hydro-geological and groundwater ecosystem that has preserved a history of regional landscape and faunal evolution in northern Australia during the Quaternary.

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