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Helictite

Journal of Australasian Speleological Research

Entrance doline to Nowranie Cave, Camooweal. Stefan Eberhard

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Helictite was established in 1962 by Edward A. Lane and Aola M. Richards who were the foundation editors. It is intended to be wide ranging in scope from the scientific study of caves and their contents, to the history of caves and cave areas and the technical aspects of cave study and exploration. The territory covered is Australasia: Australia, New Zealand, the near Pacific Islands, Papua New Guinea and surrounding areas, Indonesia and Borneo.

In 1974 the Speleological Research Council agreed to support the Journal with financial assistance and in 1976 took over full responsibility for its production. From 1974 to 1997 the Journal was edited by Julia James assisted by other members of the Speleological Research Council Ltd. In 1998 Susan White and Ken Grimes took over as editors with Glenn Baddeley as Business manager.

In 2000 ownership was transferred to the Australian Speleological Federation, Inc. (ASF) and production is administrated by the Helictite Commission of the ASF. Stefan Eberhard joined the editorial team in 2003.

The aim of the Helictite Commission of the Australian Speleological Federation is:
To publish the results of scientific studies in all fields of speleology in Helictite — Journal of Australasian Speleological Research and other publications.

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Cover: Entrance doline to Nowranie Cave, Camooweal, Qld. Photo by Stefan Eberhard.

Helictite, Volume 38 consists of two issues. Price for volume 38 is Aust. $25.00 post paid (Australia and New Zealand) and Aust $27.00 (rest of the world). Commencingwith volume 39, the price will be Aust. $27.00 post paid (Australia and New Zealand) and Aust $30.00 (rest of the world). *Helictite* is printed and published by the Australian Speleological Federation Inc.

All correspondence to: 123 Manningham St., Parkville, Victoria, 3052, Australia.
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Editorial

Ken Grimes

In this issue of *Helictite* we welcome Stefan Eberhard as our third joint editor. Stefan will be broadening the scope of the editorial team by giving us his expertise in the biological side of speleology. Coincidently, we also include in this issue a paper by him on the underwater parts of Nowrania Cave at Camooweal, Queensland, and also a review of his recent masterpiece on the Jewel Cave system in Western Australia - both of which show the breadth of his interest which extends well beyond biology.

Helictite is a reviewed scientific publication and we would like to thank the various reviewers who have given their time to read and comment on the manuscripts which have been submitted in recent years. These include: Stefan Eberhard, Ken Grimes, Elery Hamilton-Smith, Bill Humphreys, David Lowe, Neville Michie, Bob Musgrave, Armstrong Osborne, Bert Roberts, Janeen Samuel, David Slaney, Barbara Sinkule, John Webb, and Nicholas White. We would also like to thank Glenn Baddeley who, as well as managing the business side of *Helictite,* is also our most efficient proof reader.

A new journal.

We would like to welcome the new electronic scientific journal: "Speleogenesis and Evolution of Karst Aquifers", which can be accessed at:

http://www.speleogenesis.info/

As well as online access to the papers (in HTML, ZIP or PDF format) the web site has a forum, and a search facility, and also has an area where authors can post "publication alerts" with abstracts of their recent papers. The first two "numbers" have included several useful reprints of prior, but less accessible, papers. These include three by Australian authors:

Wray R.A.L. 2003. *Quartzite dissolution: karst or pseudokarst?*. re-published from: Cave and Karst Science 24 (2), 1997, 81-86.

Osborne R.A.L. 2003. *Paleokarst: cessation and rebirth?*,. re-published from: GabrovSek, F. (Ed.), 2002, Evolution of karst: from prekarst to cessation. Postojna-Ljubljana: Zalozba ZRC. 43-60.

Osborne R.A.L. 2003. *Halls and Narrows: Network caves in dipping limestone, examples from eastern Australia,* re-published from: Cave and Karst Science 28 (1), 2001, 3-14.

Helictite Price change

Starting with volume 39 we have been forced to make a slight price rise for *Helictite.* This is to cover recent increases in postage. The new prices will rise from $25 to $27 (AUD) for Australian and New Zealand subscribers, and from $27 to $30 (AUD) for international subscriptions.

Helictite web page

The Helictite web page is maintained by our Business Manager, Glenn Baddeley.

The URL is: http://home.pacific.net.au/~gnb/helictite/

The web site provides subscription information, a list of contact addresses, information for contributors, and contents and abstracts for all issues of Helictite. We now also provide a down load area where readers may obtain data files for specific papers at: http://home.pacific.net.au/~gnb/helictite/data.html

Helictite, (2003) **38(2):** 27-38

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° 11' 05" East; 20° 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°C and the mean annual minimum is 17.3 °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.

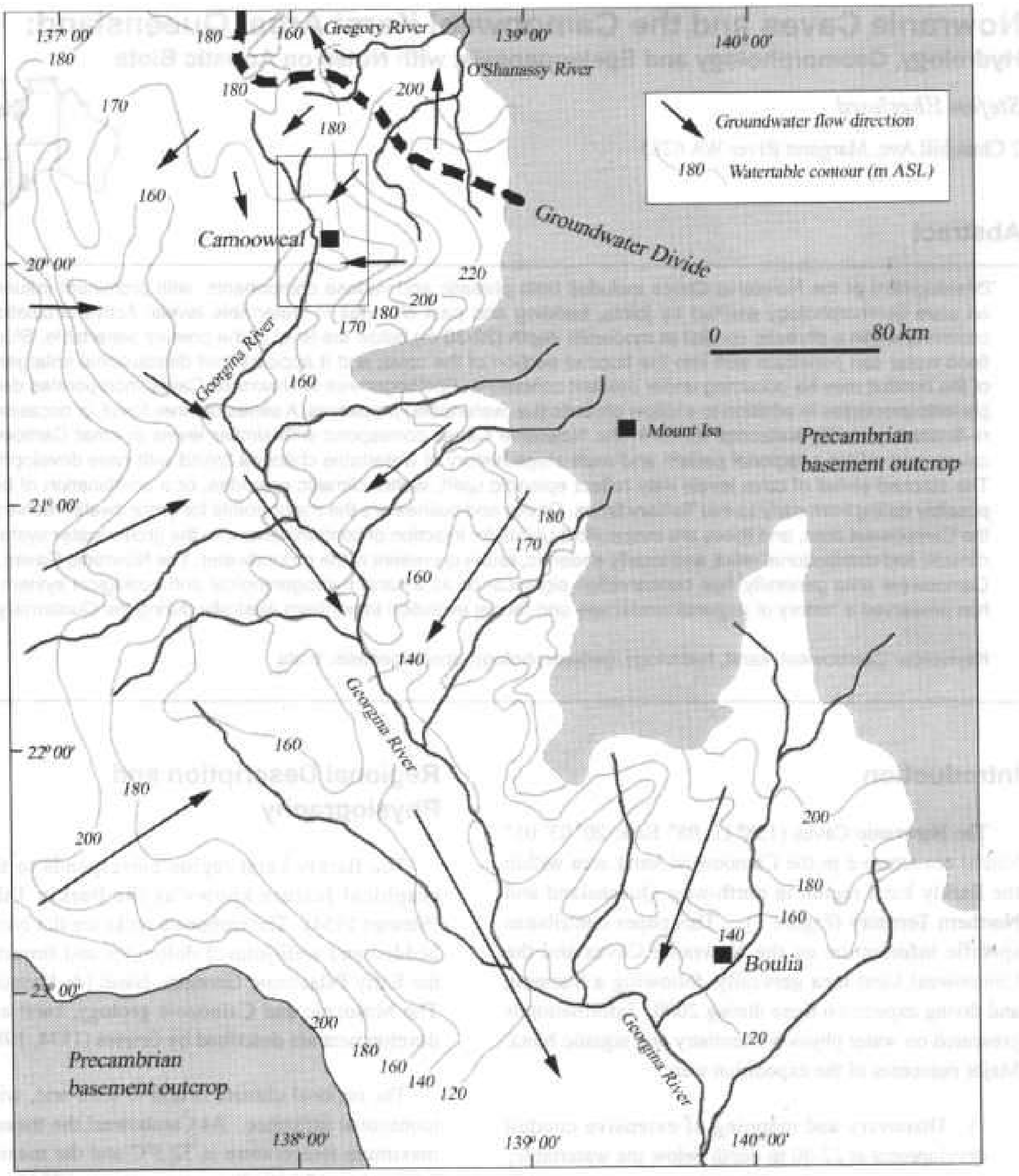

Figure 1. Southeastern Georgina Basin, showing surface drainage, watertable contours and inferred groundwater flow directions, including the groundwater divide inferred to exist between the headwaters of the Georgina River and Gregory –O'Shanassy Rivers. The Camooweal karst area (see Figure 2) is the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

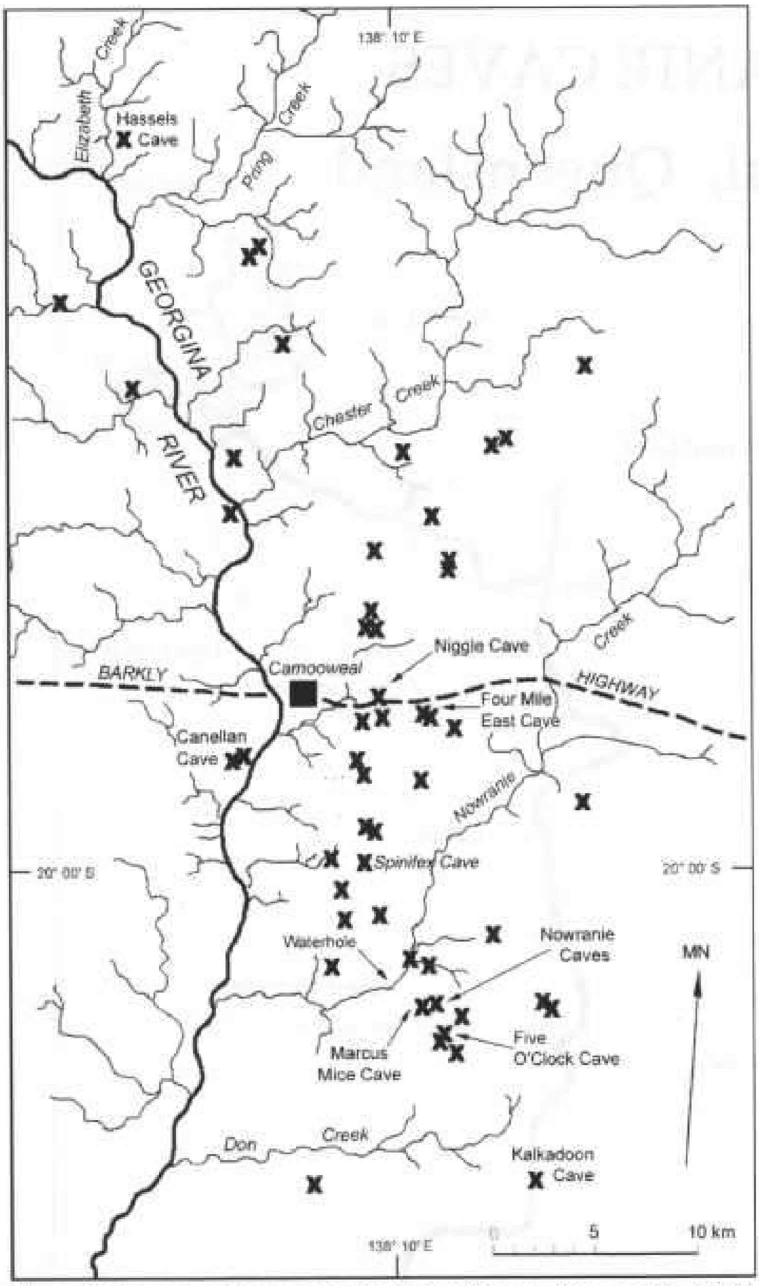

Figure 2. Camooweal karst area showing surface drainage and locations (X) of karst features (caves, dolines, stream sinks), including features named in text. Adapted from U.Q.S.S. Map 141, compiled by R. Canty and K. Grimes (1979).

(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

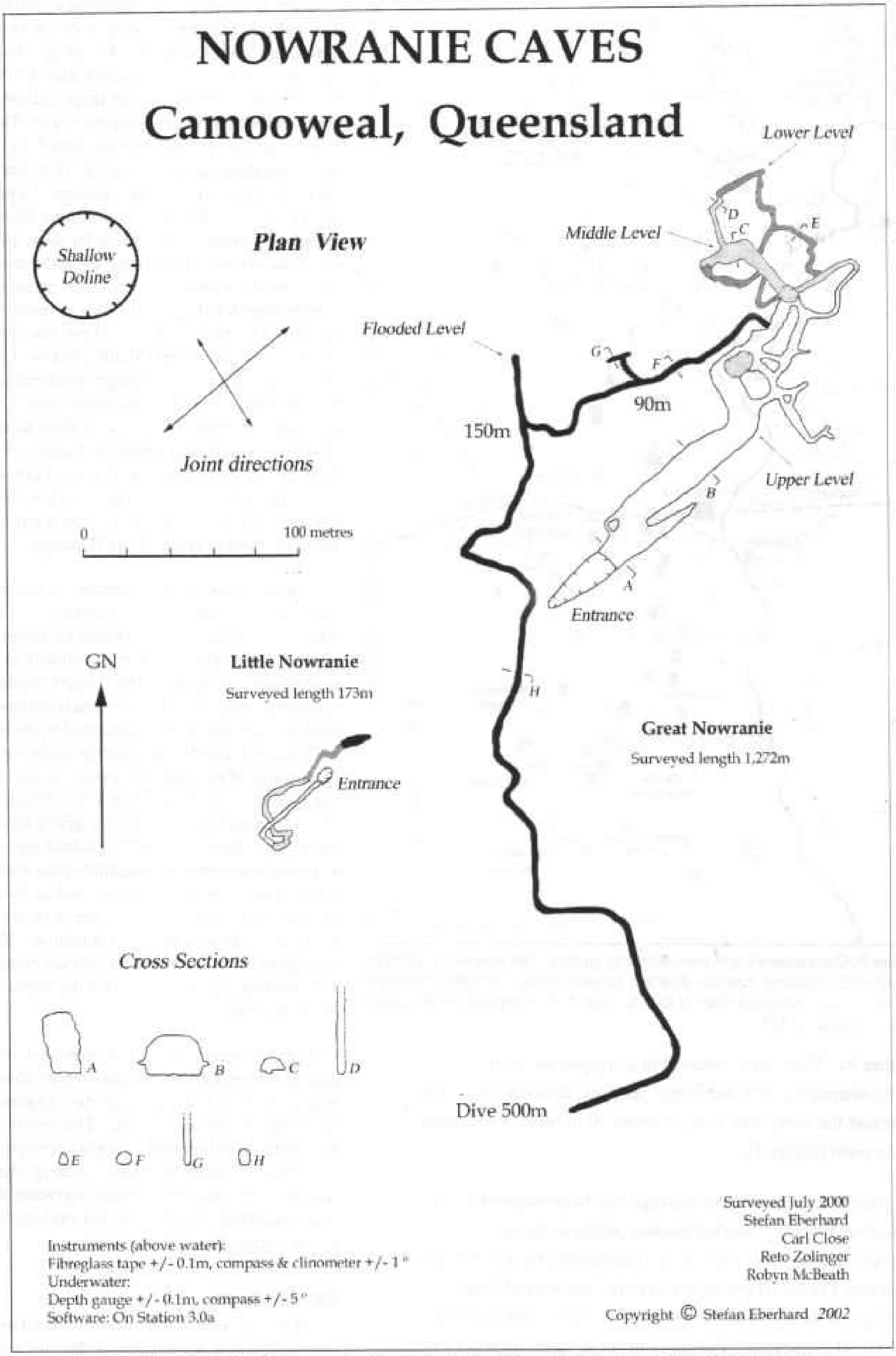

Figure 3: Plan of Nowranie Caves showing surveyed passages and levels, including joint directions.

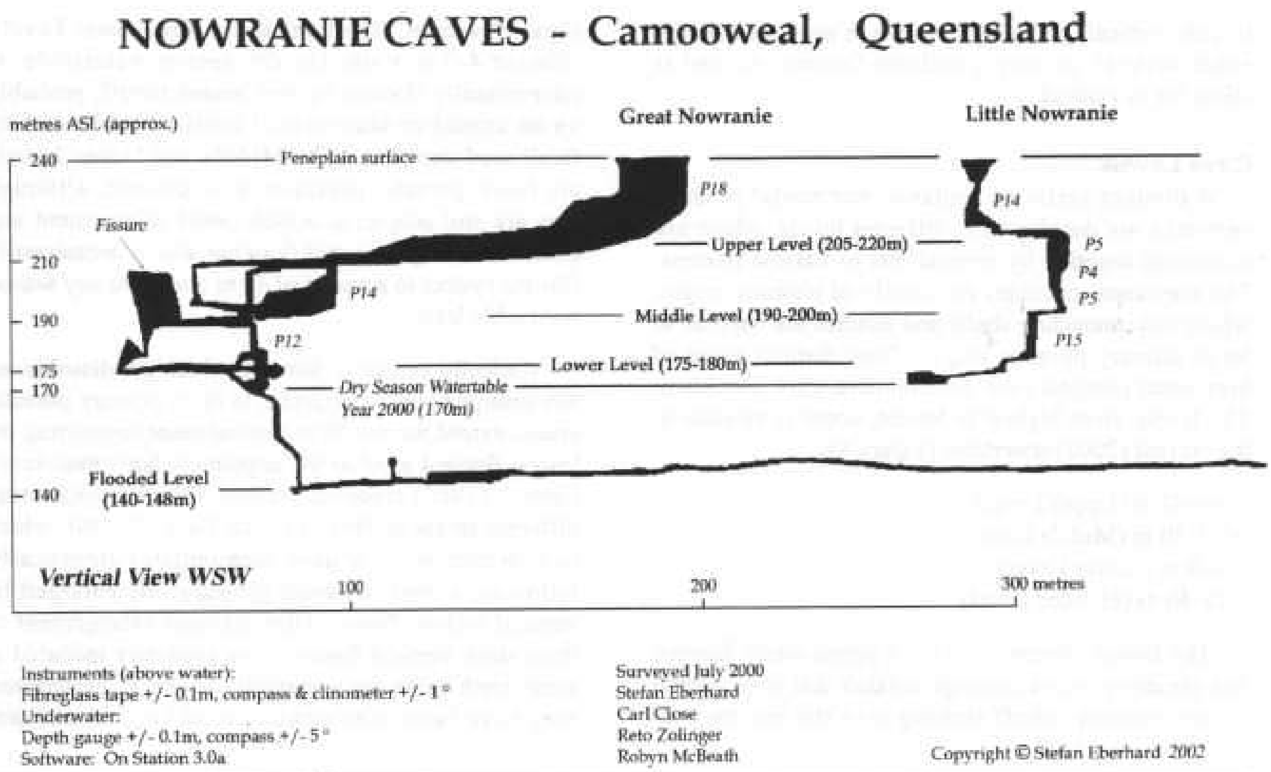

Figure 4: Projected profile view (projected onto a WSW plane) of Nowranie Caves showing elevation (in metres above sea level – m ASL) of the upper, middle and lower levels in relationship to the peneplain surface, present watertable, and the flooded conduit. Depth of vertical pitches (P) indicated in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

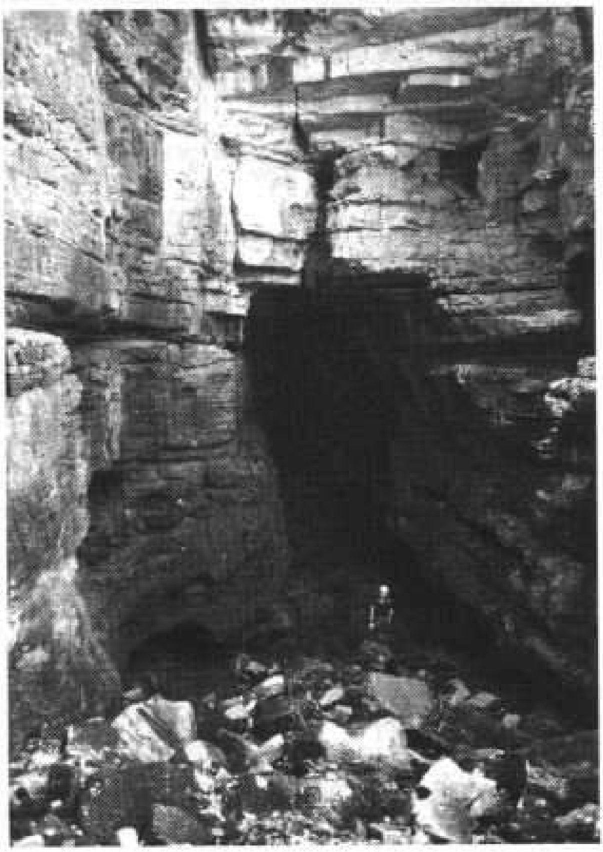

Figure 5. Great Nowranie Cave – view into upper level tunnel from base of 18m entrance pit. Note the influence on passage morphology of horizontal bedding and vertical / sub-vertical joint planes. Photo Stefan Eberhard.

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

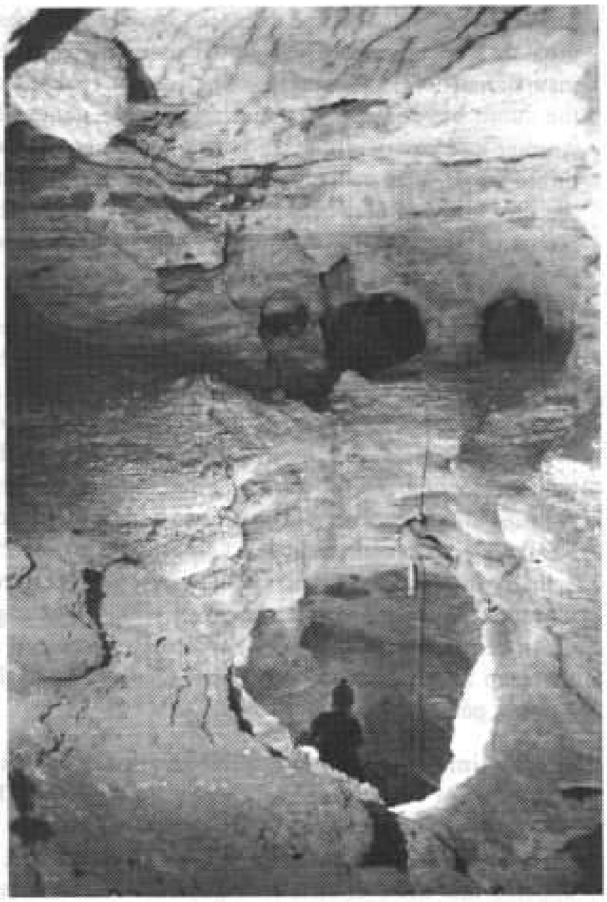

Figure 6. Upper Level in Great Nowranie Cave showing network of horizontal phreatic tubes and the vertical shaft (14 m deep) which connects below to the Middle Level. The shaft and horizontal levels have subsequently been modified by seasonal vadose inflow waters and back-flooding. Photo Ken Grimes.

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 °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° 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° 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° C. Beyond 150 m distance into the sump an abrupt thermocline at about –25 m water depth separated cooler (26°) underlying waters from warmer (29°) 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° 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° C, based on Randal's geothermal gradient. This is close to the 29° actually measured. The maximum water temperatures measured in the Nowranie sump fall within the range of air temperatures (28 – 30°) 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	0	0	26	6.78–6.89	340	20-40	30-6-00
Nowranie	0	-6	26	7.87	333	26	8-7-00
Cave	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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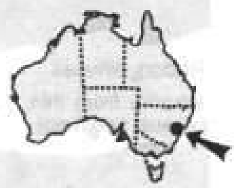
The relationship between local climate and radon concentrations in the Temple of Baal, Jenolan Caves, Australia

Stewart Whittlestone[1], *Julia James*[2] *and Craig Barnes*[2].

[1] Corresponding author: Atmospheric Chemistry Research Group, Department of Chemistry, University of Wollongong, NSW 2522, Australia.

[2] Heavy Metal Research Centre, School of Chemistry, F11, The University of Sydney, NSW 2006, Australia.



Abstract

Radon measurements were collected over a period of one year in a large chamber known as the Temple of Baal at Jenolan Caves, near Sydney, Australia. Correlation of radon concentrations with rainfall, surface air pressure and temperature confirmed that radon originating from different locations was predominant under different conditions. During periods of low rainfall, radon concentrations varied in strong anti-correlation with the surface air pressure, indicating that most of the radon was coming from remote locations of large pore or void volume in rock of limited permeability. On the other hand, in wet periods the observed radon levels were low and steady, suggesting a local source. In both wet and dry conditions the correlation of radon concentrations with rainfall on a time-scale of a few days was positive, proving that permeability of surface strata affected the ventilation rate in the cave. The study achieved a detailed understanding of radon concentrations in the Temple of Baal, and the main conclusion reached was that the magnitude and variation of radon concentrations in the Temple of Baal were closely related to the degree of water saturation in the local surrounds.

Keywords: karst, radon, cave climate.

Introduction

Climate influences the amount of any gas emanating from the earth, through both air pressure and temperature effects and by determining the movement and quantity of moisture in the sediment and underlying strata. More particularly, water in these strata is believed to be the major factor governing gas movement through the earth (Tanner 1980, Nielson *et al.* 1984, Schery *et al.* 1989). Consequently, if a source of a gas lies within the strata, climate can affect the amount of the gas escaping into the air. Potentially such a gas could be used as a tracer to reveal information about the affect of climate on the degree of water saturation in deep strata. Radon is a suitable gas for such studies.

Radon is an inert radioactive gas emitted by rocks and sediments. It is produced by decay of radium (Figure 1), which is present in trace quantities throughout the Earth's crust. Being a gas, radon can move from its source into the cave[1]. Once a given amount of radon is in the cave, its concentration depends on the cave volume and ventilation. An understanding of radon concentrations therefore requires knowledge of the location of the radon sources and the associated transport mechanisms.

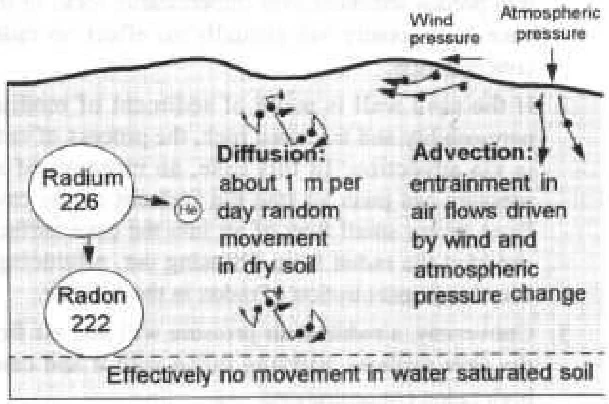


Figure 1. Radon movement in soil

Figure 1 illustrates the main mechanisms by which radon moves through sediment. After radon is produced there are four possibilities:

- It may decay close to where it is produced.
- It may diffuse through air filled pores in the sediment by virtue of the inherent kinetic energy of the radon atoms. Radon can migrate up to a metre a day in dry sediments through such movement, but much less when water fills the pores. Because of its short half-life of 3.8 days, only radon produced within a few metres of the surface of dry sediment can escape in this manner.
- It may be transported by advection, the entrainment of radon in air-flows driven by wind or atmospheric pressure change. Think of this as a form of suction; if

[1] For the purposes of this paper, "cave" includes both underground chambers and passages. The term "cave wall" implies all cave surfaces - floor, ceiling and walls.

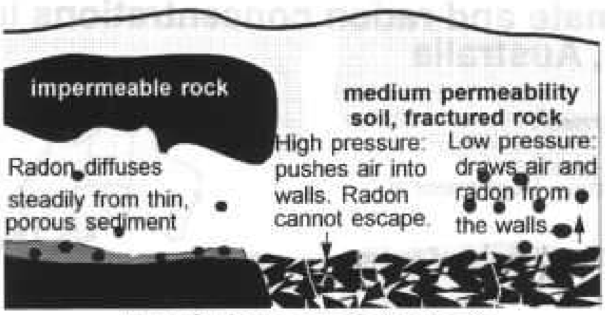


Figure 2. Radon entry into cave air

conditions are such that air is being pulled from the void spaces, radon can be carried along with it.

- If the sediment is water-saturated, there is effectively no radon movement. If there is rapid water flow through the sediments, there is the potential for radon to be transported from its site of generation since radon is nearly as soluble as carbon dioxide. Once removed from the zone of saturation, radon can degas from the water.

The main mechanisms of radon entry into cave air are diffusion (Figure 2, item 1) and advection (Figure 2, items 2 and 3):

1. Radon diffuses into the cave air at a steady rate from thin porous sediment over impermeable rock. In this case, air pressure has virtually no effect on radon concentration.
2. If the cave wall is made of sediment of medium permeability and fractured rock, the process of entry is via advection. In this case, an increase of air pressure can push air into the surfaces of the cave. Even a very small flow of air into the cave surfaces can stop the radon from diffusing out, producing a very low concentration of radon in the cave air.
3. Conversely, a reduced air pressure will pull air from the cave surfaces, carrying radon with it and cause high radon concentrations.

In caves the geologic strata may be complex, but the main effects of pressure can be understood in terms of the simple model shown in Figure 3. The main elements are the cave and the pores and larger voids in the strata containing finely divided rock, such as sediment, which emits radon. If these voids are connected to the cave by thin cracks, it is possible for changes in pressure to affect radon concentrations. Picture these pores and voids as a single large void and the connections as a pipe between the void and the cave.

A change in air pressure forces air through the pipe until the pressure within both the cave and void are again equal. If there is an increase in cave air pressure as the result of an external change, air is pushed through the pipe into the void. While the air pressure in the cave remains higher than that of the void, no air carrying radon from the void can enter the cave. On the other hand, if the cave air pressure is lower than that of the

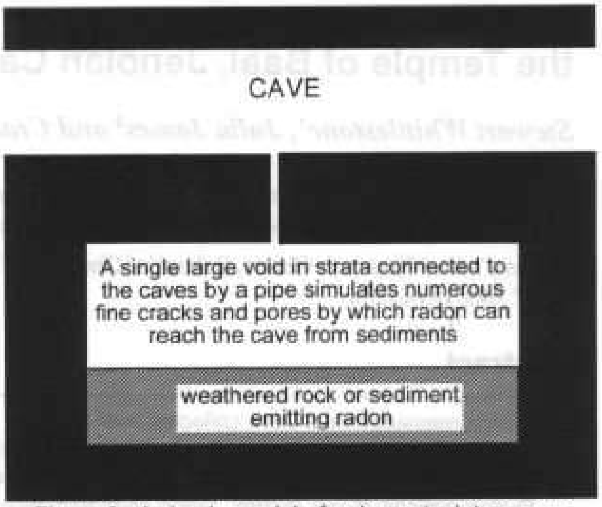


Figure 3. A simple model of radon entry into a cave

void, air laden with radon will be pulled through the pipe into the cave. If the pressures are equal, no advection-driven movement of radon occurs and the only change in radon concentration will be based upon diffusion. The speed at which the pressure differential between the cave and void equilibrates depends upon the size of the pipe connecting the void and cave. If the pipe is narrow, it will take a long time (days or even weeks). Alternatively, if the pipe is large, the pressure quickly equilibrates. In either case, radon can only enter the cave by advection when the pressure is lower than that of the void.

In both cases, the actual volume of air moving through the pipe is very small. Because of this, a high or increasing pressure will cut off the source of radon to the cave, but such a small amount of air moves from the cave that all but a few percent of the radon already in the cave stays there. Provided the total void space is not much greater than the volume of the cave, there will not be enough air movement into the void spaces to take up significant amounts of the radon. The radon in the cave either decays *in situ* or is blown out by ventilation processes. If pressure is low, radon starts to enter the cave. Either way, it will take time for the effect of a pressure change to show up in the radon concentration.

In the absence of ventilation, the concentration of radon will reach an equilibrium such that the rate of radon lost by radioactive decay matches the rate at which radon enters from all locations. In a cave with strong ventilation, radon can be diluted with outside air, resulting in a lower concentration. This is an important factor when the air exchange time is less than the radon half-life of 3.8 days.

This paper reports the results of a correlation analysis of radon concentrations with the external climatic variables of surface temperature, air pressure and rainfall, established to explain the behaviour of radon observed in the Temple of Baal, Jenolan Caves.

Site Description

In 1996, a comprehensive air quality monitoring system was established at Jenolan Caves to measure the seasonal variation of a number of parameters including radon gas (Zahorowski *et al.* 1998). The Temple of Baal is a large chamber with active speleothems which lies almost a kilometre away from any natural entrance and was originally selected as a site for radon monitoring because of its low ventilation rate and steady temperature. It appeared to be a relatively simple system, as opposed to another part of Jenolan Caves, Katies Bower, which can experience strongly varying radon concentrations on time scales as short as an hour. The 1996 study showed that, although the Temple of Baal was free from these rapid variations, there were changes on monthly time scales for which there was no immediately obvious explanation.

Instrumentation

The monitoring instrument consisted of a number of sensors interfaced to a computer. For measuring radon levels, a 1 L zinc sulfide coated scintillation cell was employed. The radon detector was calibrated by passing radon from a radon source, model RN1025 (Pylon Electronic Corp, Canada), through the cell. The flow rate for this calibration was determined using a bubble tube system by Gillian Instrument Corporation, USA. The total radon concentration was the sum of that from the source plus ambient radon. The latter was estimated by extrapolating from the time before the radon was injected, using radon progeny measurements to keep track of changes in radon concentration. Rainfall data and surface air pressure and temperature were obtained from Ernst Holland using the Australian Defence Force Academy meteorological station situated in the McKeowns Valley at Jenolan Caves.

Results and Discussion

From previous studies (Barnes *et al.* 2001) of the variation of radon concentrations, at 19 out of 20 sites spread throughout the Jenolan Caves a pattern of high radon levels in summer and low radon levels in winter has been established. In some cases the differential between the two seasons reaches a factor of 20. At all sites, with the exception of the Temple of Baal, the spring and autumn values are intermediate. Moreover, for these 19 sites, the variation in radon levels is largely determined by variations in temperature and air pressure.

Weekly averages of the radon concentrations in the Temple of Baal are shown in Figure 4. In order to show the variability of the weekly average concentrations, the distance between the lines represents the range of the values each week. These data fall naturally into three periods: summer, when radon levels were relatively low

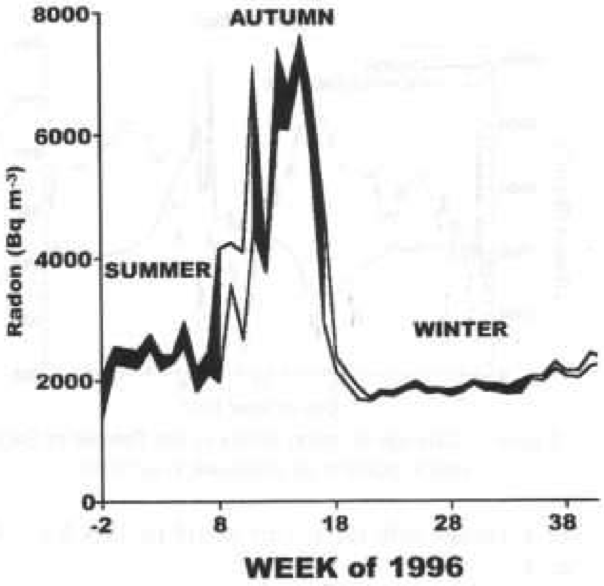


Figure 4. Weekly radon concentrations in the Temple of Baal

and moderately variable; autumn, where the radon levels were high and variable; and winter, when the radon level was lowest and remarkably steady. The shaded zones in Figure 4 are the periods used in this analysis. The data lying between the shaded zones have characteristics intermediate between those of their neighbouring periods and have been excluded. Table 1 summarises the data used in, and the results of, the correlation analyses of radon concentrations and the three major climate variables.

The results in Table 1 for the Temple of Baal show that the summer/winter pattern is only marginally discernible in this chamber (with a differential of just over 1), while there are anomalously high radon levels in autumn. The correlation analyses of radon concentration against climate variables were undertaken in an attempt to obtain an explanation for these results. Furthermore, from the raw data illustrated in Figure 4 and contained in Table 1, the following inferences can be made concerning the ventilation rates and sources of radon in the Temple of Baal during the period of this study.

The steady radon concentration in winter implies a low ventilation rate. In caves with strong ventilation, such as Katies Bower (Zahorowski *et al.* 1998, Barnes *et al.* 2001), the radon concentration can vary by more than an order of magnitude in a day. If there were a complete air exchange within the cave in 3.8 days (the half-life of radon), the loss by dilution would match the loss by radon decay and the radon concentration would drop by a factor of 2. In the Temple of Baal, Table 1 shows that the greatest change in radon concentration over the winter period was 70 Bq m^{-3} from the maximum of 1900 Bq m^{-3}, or 1 part in 13. Thus, even if all the variability is attributed to ventilation, there cannot have been more than 1/13th part of the air in the Temple of Baal diluted by surface air. The minimum time for complete

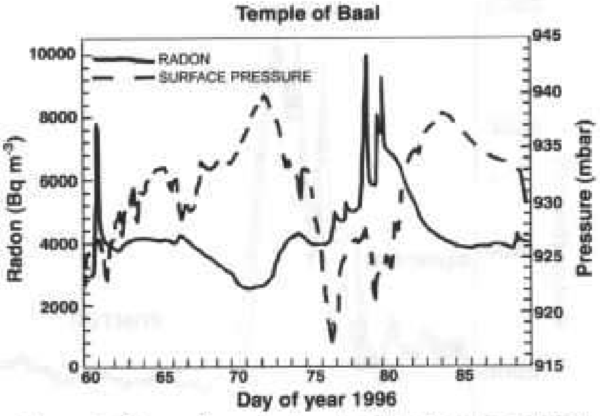


Figure 5. Change in radon levels in the Temple of Baal and in surface air pressure in autumn

air exchange with surface air would be 13 × 3.8 = 49 days.

Given the steadiness of the radon concentration within the Temple of Baal during winter, a local source of radon must be postulated. The argument used in the preceding paragraph can be expanded to air exchange with connected caves. However, if radon was being transported from other caves, it would cause a greater variability in the radon concentration in the Temple of Baal than is observed.

From Table 1, it can be seen that the summer and winter rainfall and pressure ranges are similar. Taking into account the steady local source observed in winter, the total radon concentration in summer must be produced by this steady source plus an additional, temperature dependent source. That is, the higher temperatures in summer must allow radon from an additional source to reach the Temple of Baal and that this source varies to cause an additional radon concentration between a minimum of 170 Bq m^{-3} (= 2000 – 1830) and a maximum of 600 Bq m^{-3} (= 2500 – 1900). Such a highly variable source is typical of well-ventilated chambers like Katies Bower. It is therefore reasonable to suggest that there is a small interchange of air between the Temple of Baal and the rest of the Jenolan Southside Caves. Indeed, an intrusion of just 1% of the volume of the Temple of Baal from the adjoining system would result in the observed increase. This cave air exchange could have been present in winter, but because of the low winter radon concentrations in the adjoining cave system (Zahorowski *et al.* 1998) there would not be a significant effect on the radon concentrations in the Temple of Baal.

Table 1 further shows how radon concentration in the Temple of Baal correlates with temperature, pressure and rainfall. The figure in brackets is the time in days it took for the influence of the change to take effect. The period of 6 days for the rainfall period was determined empirically. Shorter periods provided insufficient events to obtain a representative sample for each season, while longer periods resulted in weaker correlations. There are not enough data to fully understand why this is an optimum period, but it is likely that light rain in a single day is only important if there was rain within the few preceding days. On the other hand, if longer periods were taken, the correlation would be lost because the effect, with its lag time of 2.5 days, is short term.

Table 1. Radon concentrations, climate data and associated correlation analyses

	Summer	Autumn	Winter
Radon (Bq m^{-3})	2000 – 2500 Variable	4800 – 7000 Extremely Variable	1830 – 1900 Steady
Range* of surface temperature (°C) (average of day and night)	12.5 – 18.5	11.7 – 15.7	6.2 – 8.8
Correlation of radon with surface temperature (lag in days§ for best correlation)	0.41 (2.3)	< 0.1	0.21 (5)
Range of surface pressure (mbar)	922 – 930	927 – 934	924 – 934
Correlation of radon with surface pressure (lag in days for best correlation)	–0.24 (1.6)	–0.6 (3)	–0.6 (1.5)
Average rainfall (mm d^{-1})	2.8	0.5	2.2
Correlation of radon with average rainfall over a 6 day period# prior to radon measurement (lag in days from end of 6 day period for best correlation)	< 0.1	0.5 (2.5)	0.75 (0)

* where ranges are quoted they are for weekly averages
§ time between the end of climate variable measurement and the best correlation with trend in radon level
# a 6 day period was chosen to provide enough rainfall data to carry out the correlation analysis

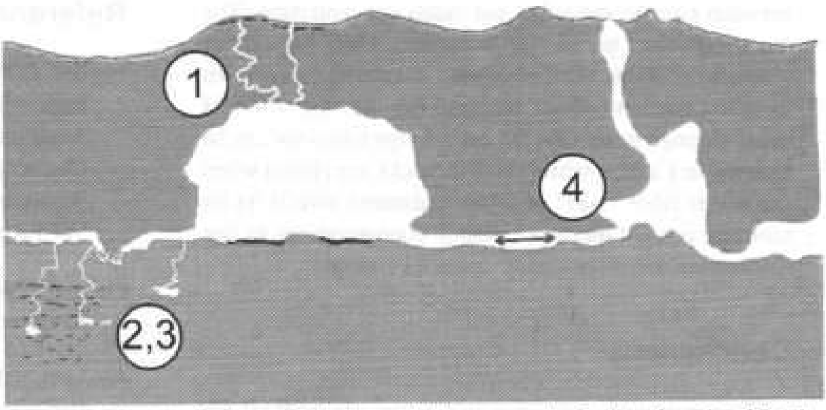


Figure 6. Model of effect of climate variables on radon in the Temple of Baal

1. Rainfall increases radon by reducing ventilation via small cracks to the surface (minor effect)
2. Rainfall reduces radon by blocking radon migration through strata (major effect)
3. Atmospheric pressure affects radon when voids in strata are connected to the cave by fine cracks which restrict air flow (major effect in dry seasons)
4. Temperature causes high, variable radon in chambers near the Temple of Baal in summer. Small air exchanges lead to a small, variable, temperature dependent source in the Temple of Baal

Surface temperature correlates most strongly with radon in summer. In fact, in summer the radon level in the Temple of Baal correlates with the same variables as radon concentrations in chambers like Katies Bower (Zahorowski *et al.* 1998, Barnes *et al.* 2001) where the diurnal radon concentrations are driven by surface temperature. There are two important differences. First, the response time in Katies Bower is about 3 hours, while in the Temple of Baal the response time is over two days. Second, the variation in radon levels in Katies Bower can be a factor of ten in a day but in the Temple of Baal it is only at most 30%. In other words, although there is a temperature effect seen in the Temple of Baal it is not as significant as that seen in other areas like Katies Bower.

The correlations of radon concentration with atmospheric pressure shown in Table 1 are always negative, albeit insignificant in summer. In autumn, the anti-correlation is quite strong and the radon levels indicate a sensitivity to pressure changes. Indeed, Figure 5 shows that during this season the Temple of Baal exhibits the characteristics of a cave connected by moderately permeable strata to a large volume of voids with radon-generating sediment. Although there is also a strong negative correlation of radon concentration with pressure in winter, the changes are relatively small. Evidently, access to the variable source was shut off, allowing a smaller and more steady local source to predominate.

It is the effect of rainfall on a seasonal time-scale which is responsible for the generally lower radon concentrations observed in summer and winter as compared to autumn. On a shorter time scale, rainfall in the previous six days had no effect in summer, but in autumn and winter there was a positive correlation with rainfall. In other words, an increase in radon concentration is observed if there is rain in the preceding few days, the opposite of the seasonal trend. The difference in these rainfall effects lies in their differing impacts. Rainfall correlated against radon levels over a season indicates the impact of rainfall on the source of radon. It is the sediment and voids that contain the major radon sources and moisture in the sediment and joints in the epikarst will prevent diffusion of radon into the cave air. On the other hand, sediment on the surface above the cave, while not a major radon source, influences how much air can enter or exit the cave through cracks to the surface. If there is less ventilation, such as when the sediment becomes wet, the radon concentration increases because the radon-laden air becomes trapped in the cave. Soil moisture levels are affected by particular showers of rain only for a few days. Thus, radon concentrations are positively correlated with recent rain but negatively correlated with rain falling many weeks earlier.

The correlations support the argument, based on the radon variabilities quoted in Table 1, that there is a small interchange of air between the Temple of Baal and the adjoining cave system. In winter the system has a very low radon concentration, so the contribution is negligible and the small effect of pressure and recent rainfall can be revealed by correlation analysis. In summer, the connection to the Jenolan Southside Caves adds a highly variable amount of radon depending on the average ambient temperature. This variable component swamps the small variable component of radon in the Temple of Baal, which itself is pressure and rain dependent. As a result there is no longer a significant correlation with pressure or recent rain.

The autumn pressure range lies within the ranges exhibited in summer and winter so is unlikely to be the cause of the variation in radon levels observed. Average surface temperature is higher in summer and lower in winter, so this also cannot be the cause of the high radon in autumn. However, average rainfall in autumn was one quarter of that for the other periods. Evidently low rainfall on a seasonal time scale allowed the sediment and strata to dry out, opening pores and cracks enough to increase radon movement. Thus, radon was able to reach the Temple of Baal from sources that were closed off in the other periods.

Figure 6 shows a model of the Temple of Baal, which explains the major features of a whole year's observations and illustrates the proposed relationship between climate variables and radon concentration. The most important parameter is rainfall. Over periods of weeks to months, rainfall caused substantial decreases in radon concentrations by blocking the migration of radon through strata into the cave. Large passages can be blocked in a sump, while smaller cracks are closed when the water table rises, or when sediment swells as its moisture content increases. Radon concentrations in wet seasons are therefore steady and not variable.

Conclusions

Concentrations of radon in the Temple of Baal are correlated with the climate variables, rainfall, surface air pressure and surface temperature, on time scales from hours to months. In the short term, a couple of days, rain causes a slight increase in radon concentrations because it reduces the permeability of the surface sediment and slightly reduces the cave ventilation rate (Figure 6.1). This effect was apparent in both dry and wet seasons. In the longer (seasonal) term, high rainfall saturates the epikarst preventing radon emission into the cave atmosphere (Figure 6.2).

Atmospheric pressure can have a large effect on radon concentrations, but only when the strata are dry to the point that radon can diffuse large distances (Figure 6.3). Some of the voids in the strata are then connected to the cave by cracks so fine that it takes days for the void pressure to equilibrate with the pressure at the surface. A high radon concentration and strong negative correlation with pressure is proof of relatively dry strata surrounding the cave.

The least important factor influencing radon concentrations in the Temple of Baal is temperature. Although neighbouring chambers are strongly affected by temperature, there are only small air exchanges with the Temple of Baal (Figure 6.4). This results in a small temperature dependent variation of radon in the Temple of Baal in summer.

Acknowledgments

We are grateful to the Jenolan Caves Reserve Trust for permission to carry out the work, and to the many guides who assisted with the project. Particular thanks are due to Ernst Holland and Karen Jones of the Trust for their weekly checks of the equipment and provision of the surface temperatures and rainfall data. The instrument recording the local meteorological data was supplied by Professor David Gillieson of the Department of Geography, James Cook University, Queensland. Wlodek Zahorowski, Bryan Stenhouse and Michael Hyde of ANSTO contributed to the construction and calibration of the instruments and at times provided a partial assessment of the data obtained.

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Tanner, A.B., 1980: Radon migration in the ground: A supplementary review, *The Natural Radiation Environment, vol. 3*, pp. 5-56. National Technical Information Service, Springfield, Va.

Zahorowski,W., Whittlestone, S., and James, J.M., 1998: Continuous measurements of radon and radon progeny as a basis for management of radon as a hazard in a tourist cave, *J. Radioanalytical and Nuclear Chemistry*, **236(1-2)**, 219-225.

Appendix: Statistical methods.

The statistical methods used in this discussion involve deductions from simple correlations, lagged correlations and the evaluation of concentration variabilities resulting from factors which are known to affect radon concentrations in other situations.

Correlation analysis is used to establish that two parameters tend to increase and decrease at the same time. This does not establish cause and effect, but is a powerful constraint on hypotheses.

Lagged correlations are used to test whether a change in one parameter tends to follow a change in another. This is valuable in ruling out certain cause-effect relationships since a cause cannot follow an effect.

Variability of data over a time period is gauged from the range of values, maximum and minimum. This is important in assessing the consistency of hypotheses. When different factors affect radon concentration, there can be times when one source is dominant and produces so much variability that a second factor is not apparent. In this case a correlation analysis will not show the second factor, even though it is still operating.

Jewel Cave Karst System, Western Australia - environmental hydrogeology and groundwater ecology.

by S.M., Eberhard, 2002:

Report prepared for the Augusta Margaret River Tourism Association Inc., Western Australia. 121 pp. Available as a printed A4 report or as a PDF file on CD-ROM.

This excellent report is a detailed study of the hydrology, ecology and management aspects of the Jewel Cave Karst System (JCKS) in the dune limestones of the Augusta area of Western Australia.

The area is part of the syngenetic karst that forms in the Quaternary dune limestone belt that follows the western Australian coast. The JCKS is a group of horizontal maze caves, with collapse modification, whose development has been controlled by variations in past water levels. The system differs from cave patterns elsewhere in the region which have linear stream passage forms. The study was stimulated by a drop in the water table over the last 25 years that had affected the lakes in the tourist caves and possibly threatened root-mat and other aquatic cave communities. This review summarises Eberhard's interpretation of the speleogenesis, hydrology and history of cave development of the system.

Speleogenesis:

Detailed studies of the surface and cave features allowed recognition of a complex stratigraphy of the host dunes and associated paleosoils, backed up by TL dating and altitudinal correlation with paleoshorelines in the region. A basal marine sand, on top of the granitic basement, may be late Pliocene to early Pleistocene in age. The caves are in a narrow belt on the inland margin of the dunefield and lie within the oldest of the dunes. Speleothem dates indicate that parts of the cave system are older than 627ka. Speleogenesis was initially syngenetic with dune lithification, but has continued with a complex history. Solution has been concentrated at the water table and is a consequence of mixing between vertical vadose seepage and the regional groundwater. Lateral input of water from swamps at the edge of the dunefield may also have contributed. Colonisation by aquatic stygofauna could have occurred quite early.

The hydrology:

The aquifer has a triple porosity comprising the intergranular matrix, joints and bedding planes and the cave conduits. The saturated zone has a thickness of 2-6 m and is perched on the basement. Recharge is mainly by slow diffuse flow down through the overlying sand, with some rapid vertical point input through solution pipes and cave entrances. There might also be some minor lateral, allogenic, input. Storage is mainly in the matrix porosity, including significant storage in the unsaturated zone which delays the response of the water table. The watertable shows an annual response to the seasonal rainfall, with lag times of 4-10 months, but this is superimposed on longer term variations related to groups of dryer or wetter years. There has been a long term drop of about 1.5 metres in the last 25 years. Evapotranspiration, via deep rooted vegetation, is a major component of discharge. The extent of lateral groundwater flow to the coast is uncertain as few karst springs are known – possibly the water is discharged offshore or into adjacent groundwaters.

History of cave development:

There are complex time relationships between solutional features such as flat ceilings and spongeworks, speleothems (subaerial and subaquatic), clastic cave sediments (including bone material) and flood marks (e.g. thin charcoal lines on the walls). These provide evidence of multiple stages of solution, draining, collapse, sedimentation and speleothem development - all of which are related to water table fluctuations within a vertical range of 5 metres. Detailed levelling allowed correlation between chambers and caves. The sequence is well calibrated by radiocarbon and uranium series dates for the last 35ka, and there are older dates also. There have been times in the past when the watertable was even lower than its present level.

Cave ecosystems:

Eberhard has documented the species and communities present in the caves. Although the initial emphasis was on the root mat communities, both above and below the watertable, he found that the fauna extends into other root-free areas of the cave systems, but in a much lower abundance that is difficult to sample in a statistically meaningful manner.

Conclusions:

In discussing the possible causes of the decline in the water table, the author concludes that although there has been a decrease in annual rainfall at the regional scale, this has not been significant in the immediate area of the JCKS. Nor is groundwater pumping or tree plantations a factor. The most likely cause of the water table decline has been a reduction in groundwater recharge due to an increase in the dense understorey vegetation and ground litter as a result of the decrease in fire frequency from an average of 4.3 fires per decade prior to 1977 to less than 0.3 over the last 25 years.

The root mat communities are more extensive than previously thought, but their ecological status and management requirements (especially the watertable level) remains to be determined.

Reviewed by Ken Grimes.

Beneath the Cloud Forests

A History of Cave Exploration in Papua New Guinea

by Howard Beck

Published in 2003 by Speleo Projects, Switzerland. ISBN 3-908495-11-3. 352 pages, hardback.
The Australian (wholesale) distributer is Macstyle Media: www.macstyle.com.au, and it will be on sale in various "outdoor" shops for RRP $ 79.95 AUD (Hard Cover).

This book recounts, in dramatic style, thirty years of cave exploration in Papua New Guinea. More specifically it narrates the activities of 29 international expeditions between 1965 (the Star Mountains expedition) and 1998. There is also some mention of smaller exploration trips by local cavers, and reconnaissance trips ahead of the main expeditions, and a brief postscript for 2000-2001. The caves explored were up to 54 km long and 1178 m deep, some with enormous collapse doline entrances.

Beck lived and caved in New Guinea for several years and took part in a British cave expedition. As well as drawing on the official expedition reports, and his own experiences, Beck has sought out a wealth of anecdotal information from many of the cavers involved. The style is aimed at the caver in search of a good adventure read, but tends to be over-dramatised.

The book has some excellent photos (B&W and colour) taken by a variety of cavers, including its author. These include spectacular doline and cave river pictures, action caving shots and also quite a lot of photos of wildlife and of the local people, who must be the world's leaders in the art of body decoration.

There are 30 surface and cave maps - these are good quality, though of necessity lacking details given the large size of the systems. They have been redrawn in a consistent style for the book by Beck, but, sadly about one third have no credits at all to the original surveyors or compilers, and for the rest many of the credits are frustratingly brief. The map of Ora Cave (credited to D.Gill) is quite inaccurate in parts, Beck would have done better to use the original map, by Lex Brown, published in the expedition report in *Niugini Caver* 1(2).

The five page index lists mainly names of cavers and places, as you would expect - but is a bit idiosyncratic as to which pages are referred to - e.g. you cannot use it to track all activities of a particular caver.

As a historical work, alas, it ignores much of the non-expedition cave exploration, and says litttle about the inhabitants views of the caves. But its main weakness is the lack of any documentary backing. The book has only 22 publications listed in its so-called "bibliography" - and those include some quite general books such as Sweeting's 1972 text "Karst Landforms" as well as some quite obscure ones (a microfilmed manuscript of the Star Mountains expedition at the Australian National University). It does not even list all the expedition reports. Nor does it provide any lead to the excellent speleo-bibliographies for the region which have been compiled by Mike Bourke and others.

It is amazing that a book on cave exploration in PNG should have only a couple of brief mentions of *Niugini Caver* (which is not listed in the index, even though the *Sydney Morning Herald* gets an entry). *Niugini Caver* first appeared in 1973 and continued to 1982 under editorship of firstly Mike Bourke and later Mal Pound and Geoff Francis. It was a prime source of cave information for the region. As well as numerous reports on local explorations, smaller karst areas, and rock art, it published four major expedition reports: Volume **1(2)** had the report of the UQSS New Britain expedition of 1972-3, **4(3)** was the report of the 1975 New Ireland expedition to the Lelet, **5(3)** was the report of the later 1976 New Ireland expedition (Lelet and Dalum resurgence) and **5(4)** was the official report of the Muller '76 expedition - though a specialist scientific report on Atea Kananda also appeared in *Helictite* **14(2)**. None of these are listed in Beck's bibliography.

Scientifically, the book has very little of use, beyond what one can interpret from the maps and photos and scattered titbits of information in the text. Although there is mention of scientific work being done on the expeditions we hear little about the results and there are no leads to the literature.

In summary: from a caver's point of view this book is an excellent read. However, speleo-historians will find its narrow viewpoint and lack of documentation frustrating and there is little of value for cave scientists.

Reviewed by K. G. Grimes.

Beneath The Surface: A Natural History of Australian Caves

Edited by Brian Finlayson and Elery Hamilton-Smith

Published in September 2003 by UNSW PRESS. ISBN 0 86840 595 7. 216pages, paperback, 275x162mm.
Distributed by UNSW PRESS. RRP $49.95 AUD

This long awaited book is the first time that a popular science account has been attempted for the non-specialist but educated reader interested in the natural history of Australian caves and karst. It was first conceived as a memorial volume for the late Joe Jennings, and as such is an excellent and affordable popular science account of caves in Australia.

It is clearly written and has a range of appropriate photographs and diagrams illustrating the chapters. A few of the Black & White photographs lack some clarity and contrast but overall the illustrations are excellent. The diagrams are particularly clear. The colour plates are grouped in the centre of the book but unfortunately their acknowledgements are listed separately at the back of the book.

Chapter 1 is an overall summary of caves in Australia, in both limestone and other lithologies. It is the chapter which has the most consistency problems as some mentioned areas are better discussed than others which reflects the authors expertise; e.g. the discussion of the Northern Territory Gregory Karst where Australia's longest cave system is located, is minimal and reflects the limited knowledge of the area. On the other hand, the discussion of the Nullarbor karst is more up to date. Overall this chapter reflects both the strengths and weaknesses of the authors involved in what is discussed and how it is explained. It is nevertheless a good summary of the current understanding of much of the cave estate.

The chapters on mineralogy, clastic and fossil deposits, bats and cave biota are the clearest and most successful ones of the book. All give excellent, clearly written and appropriately illustrated summaries for the non-specialist. There is an especially useful discussion of speleothem dating and all chapters have pertinent case studies. Chapter 5 is enhanced by discussion of the karstic nature of calcrete and other aquifers and the related biota. The concept that Australia is karst poor compared to other continents is one that has still not been challenged for over 30 years despite extensive new discoveries. The discussion in Chapter 5 of the variety of subterranean habitats has potential to open this challenge. Only in this chapter is the issue of how many exciting research opportunities there are in the whole area of cave and karst in Australia given more than a passing comment.

The final historical chapter on people and caves is a comprehensive account of cave exploration and exploitation, enlivened with some fascinating anecdotes, until the 1940's. Unfortunately only a short section on the developments since then is included. This is sad as it is where a more in depth discussion could have occurred of the role in interpreting caves and their contents, of Joe Jennings in particular, and other cave scientists such as Wakefield, Lundelius and Ollier to name only a few.

The Preface and dedication give context to the publication. The appendices are useful and the index useable and competent. Nevertheless, in the absence of any specific information, there is an implication that Joe Jennings worked in all cave areas in Australia. In reality his work was successful partly because he did not attempt to do everything everywhere. For example there is a great deal of material on Victorian caves and karst in this book, especially Chapter 1, but Joe did little if any work in Victoria although he inspired others to do so. This is minor criticism that could have been easily solved by a couple of well-placed short paragraphs in the Preface or Chapter 6.

The major limitations of the book are the lists of Further Reading and References. The Further Reading list is an odd and limited collection with a major focus on biology. Several additions could have been made here including specific karst journals such as *Helictite*. The absence of several monographs such as the Wee Jasper book mentioned in the dedication is noticeable, as these would strengthen the list without making it overly long.

A more basic concern is the citations and references. In a time when non-attribution of sources is often highlighted in the press, the absence of virtually all citation for other people's work is of concern for a book aimed at the general public. Whereas extensive citation of sources would be inappropriate in this style of book more acknowledgment of sources would be appropriate. Diagrams and Photographs are meticulously acknowledged but information in the text, e.g. some of the dating information in Chapter 1, is not. This is a problem across the whole book.

Despite these criticisms, this is a very interesting and useful natural history of Australian caves and karst. It is not presented as showing the current state of speleology but as a readable account for a non-specialist audience. For the specialist it has the advantage of a being a well-written and reasonably current summary. It is certainly worth the very modest cost. However, I doubt the publisher's extravagant claim that it is all we need to know about Australian caves and their contents and history.

Reviewed by Susan White

New Book: Geology of Victoria

Geology of Victoria GSA Special Publication No 23 W.D. Birch (ed) 2003. Hard bound 842pp. Available from Geological Society of Australia Inc 706 Thrakal House, 301 George St Sydney NSW 2000. Cost AU$170.50 (Australia), AU$175.00 (Overseas). GSA members discount available.

The new third edition of this publication has just been published. Although not a specifically karst publication, it is a valuable source of background geological information for karst. Over a hundred authors have contributed to this authoritative, up to date and well illustrated book. Karst material is included especially in the chapters on the Quaternary Period, Geomorphology, Mineralogy (a short case study of Skipton Lava Cave minerals), and Conservation and Heritage. The illustrations include some excellent cave and karst examples including an oblique aerial of The Potholes doline field at Buchan by Neville Rosengren.

Conference: Limestone Coast 2004

The closing workshop of IGCP 448 (Global Correlation of Karst Hydrogeology and Relevant Ecosystems) and The First International Workshop on RAMSAR Subterranean Wetlands will be held at Naracoorte, South Australia, 10-17th October 2004.

This workshop will pursue the overall concept of understanding the relationship between karst resources, the biotic environment and the human situation. It will emphasise the relationships between earth sciences and bio-sciences and between scientific understandings and human activities.

The workshop will be based at the Naracoorte Caves World Heritage Area, with its remarkable fossil deposits. This is located in what is now known as the Limestone Coast region of Southern Australia.

The conference will comprise 4 days of workshops and presentations and two days of field trips. The two separate, day-long field trips within the conference will visit a wide variety of sites across the Limestone Coast region. Trip A will concentrate on the geology, hydrology and karst evolution of the region. Trip B will review human utilisation and modification of the karstic environment. Each trip will be self-contained and participants should partake in both trips in order to gain a full appreciation of the region and its use.

Bus transport will be available between Melbourne and Naracoorte at the start and end of the conference. Pre and post-conference field trips are being organised to other parts of Australia.

Formal mail address: Limestone Coast Karst 2004, PO Box 134, Naracoorte, South Australia, Australia, 5271. Or visit the web site at:

http://www.limestonecoastkarst2004.com.au/

Convenor: Professor Elery Hamilton-Smith,
Telephone 61 3 9489 7785;
Email: elery@alphalink.com.au

CAVEPS 2005 and Quaternary Extinction Symposium

The 10th Conference on Vertebrate Evolution Palaeontology and Systematics will be held at the Naracoorte Caves World Heritage Area, South Australia, on 29th March to 2nd April 2005.

CAVEPS is a biennial meeting of vertebrate palaeontologists from around Australia and overseas. CAVEPS 2005 will consist of 3 days of general sessions including papers on all aspects of vertebrate palaeontology, culminating in a 2 day symposium which will focus on Quaternary extinctions and dating applications. In addition to the main sessions, a student forum is also proposed where students can present their project proposals or work in progress and benefit from professional input. As the conference is field-based there will be opportunities throughout the week to inspect key Pleistocene vertebrate sites, show caves and quarry sites. The park also has an interpretive fossil centre, fossil laboratory and collection storage facility, and bat observation centre. Visit the park website for more details about the facilities:

http://www.environment.sa.gov.au/parks/naracoorte/

A post-conference trip is planned for the week following the conference (ie. April 4th to 8th). The trip will include a visit to the South Australian museum to inspect the fossil galleries, visits to mid-North Quaternary megafauna localities, the Flinders Ranges (Ediacaran localities), the Barossa Valley and Tertiary fossil localities along the River Murray.

Details are available from the organisers and expressions of interest are sought for CAVEPS 2005 from the conference organisers:

Liz Reed: liz.reed@flinders.edu.au
Steven Bourne: Bourne.Steven@saugov.sa.gov.au

Formal mail address:

CAVEPS 2005, c/- Naracoorte Caves National Park, PO Box 134, Naracoorte, South Australia, 5271, AUSTRALIA.

Phone: +61 (08) 8762 3412

Information for Contributors to Helictite

Scope

Contributions from all fields of study related to speleology will be considered for publication. Suitable fields include Earth Sciences, Speleochemistry, Hydrology, Meteorology, Conservation, Biospeleology, History, Major Exploration (Expedition) Reports, Equipment and Techniques, Surveying and Cartography, Photography and Documentation. Comprehensive descriptive accounts of the exploration and morphology of individual caves will be welcomed, but simple trip reports and brief cave descriptions are not adequate. Papers overall should not exceed 20 printed pages in length. Contributors intending to write at greater length or requiring any advice on details of preparation are invited to correspond with the Editors. All manuscripts will be assessed by referees. "News and Views", "Short Notes" and "Letters to the Editor", expressing a personal view or giving a preliminary report of interesting findings, are welcomed, and will be given preference for speedy publication.

Manuscripts

Submitted manuscripts should initially be in printed form. Manuscripts should be typed, double spaced, on one side of the paper. Do not use multiple columns - this manuscript is for the editors and referees use and does not have to look like the final production.

The **title** should be followed by the author's names and addresses, including email address if appropriate. A brief and explicit summary of the notable aspects of the paper, headed **abstract**, should precede the main text. **Acknowledgements** should be placed at the end of the text before the references.

Once authors have dealt with referees comments, they are requested to submit a copy of their final manuscript by email or on floppy disk or CD as well as hard copy. Disks may be 3 ˜m or 5 · ¥in either IBM or Macintosh format. If sending text as a word processing document (Microsoft Word etc.), please also send a copy as plain text on the same disk. Illustrations and tables are best sent in separate files, not embedded in the main document. Separate instructions concerning electronic layout are available from ken-grimes@h140.aone.net.au.

References

References should be listed alphabetically at the end of the manuscript and cited in the text by the author's name and the year of publication, e.g. "(Gray, 1973)". Where there is more than one reference to the same author in one year the letters a, b, c, etc. should be added. If there are more than two authors, they should all be named at the first citation and in the reference list, but the first name followed by et al. should be used in subsequent citations. References should be checked particularly carefully for accuracy. If journal titles are abbreviated, this should follow the "World List of Scientific Periodicals", which is available in most large libraries.

The following examples illustrate the style:

GRAY, M.R., 1973 Cavernicolous spiders from the Nullarbor Plain and south-west Australia. *J. Aust. ent. Soc.* **12:** 207-221.

VANDEL, A., 1965 *Biospeleology. The Biology of the Cavernicolous Animals.* Pergamon, London. pp. xxiv, 524.

WIGLEY, T.M.L. and WOOD, I.D., 1967 Meteorology of the Nullarbor Plain Caves. *In:* J.R. DUNKLEY and T.M.L. WIGLEY (eds), *Caves of the Nullarbor. A Review of Speleological Investigations in the Nullarbor Plain, Southern Australia*: 32-34. Speleological Research Council, Sydney.

Illustrations

Figures and plates should be numbered in a single sequence and specifically referred to in the text. Captions should be typed on a separate sheet (or supplied at the end of the text file).

For papers that have a geographical location we will provide a small location map in a standardised style (typically a map of Australia with a dot, rectangle or arrow—see recent issues for examples). Figures and photographs should not duplicate information in tables or other material. Photographs should be relevant to the text, and supplied as clear prints with sharp focus. Figures should be supplied as Laser prints or drawn in Indian ink on heavy paper or tracing material and lettered using stencils or stick-on lettering. Ink-jet prints should be enclosed in plastic to reduce the risk of water damage in transit. Most computer drawn documents and photographic images can also be handled. Please ask for additional instructions on file formats, pixel widths and photo "enhancements".

All illustrations should be designed to fit within a full page print area of 170 x 258 mm and ideally should be a column width (80 mm) or double-column width (170 mm). They may be supplied larger provided that these proportions are maintained, but allowance for reduction must be made when choosing letter sizes and line thickness.

Fold-outs or colour photographs and maps will be subject to negotiation, and the authors may be asked to make a contribution to the production costs.

Units

The S.I. system (Australian Standard AS 1000) should be used unless citing historical data, in which case the original units should be quoted and appropriately rounded metric equivalents added; 100 feet (30 m).

Offprints

A PDF file and Twenty free offprints of papers will be supplied after publication. Additional offprints can be arranged at the author's expense. The number required should be stated when submitting the final manuscript.

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